Characterization of groundwater quality in Small Island developing states (SIDS): A case study in the island of Mauritius

By

VARSHA GUNGOA

Submitted in fulfilment of the academic requirements of

Doctor of Philosophy

In Hydrology

School of Agriculture, Earth and Environmental Science

College of Agriculture, Engineering and Science

University of KwaZulu-Natal

Pietermaritzburg

South Africa

August 2025

PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Hydrology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was financially self-supported with the assistance of the National Environment Laboratory the Central Water Authority of Mauritius.

This work represents original research by the candidate examining groundwater quality characteristics in Small Island Developing States (SIDS), using Mauritius as a case study. The research investigated temporal changes in groundwater quality, impacts of climate variability, and isotopic characterization of groundwater resources across Mauritius' five main aquifers over an 11-year period (2010-2021).

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate. The thesis contains five chapters including 3 research papers, of which two are under review and one has been published:

- Chapter 1 and 2 are Introduction and Literature Review respectively
- Chapter 3 is a research paper under review at the International Water Association
- Chapter 4 is a research paper that has been published in Journal: Frontiers in Waters
- Chapter 5 is a research paper under review in the Journal of Hydrology: Regional Studies
- Chapters 6 is the conclusions and recommendations for further research

Signed: Professor Seifu Kebede [redacted] (Supervisor)
Date: August 14, 2025

[redacted]

Signed: Varsha Gungoa (Candidate)

Date: August 14, 2025

DECLARATION 1 PLAGIARISM

I, Varsha Gungoa, declare that

(i) The research reported in this thesis, except where otherwise indicated or acknowledged, is my original work I declare having made use of AI for enhancing the writing of the thesis only. The data collection, analysis, interpretation and presentation are all my original work.

(ii) This thesis has not been submitted in full or in part for any degree or examination to any other university.

(iii) This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

(iv) This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then: a) their words have been re-written but the general information attributed to them has been referenced; b) where their exact words have been used, their writing has been placed inside quotation marks and referenced.

(v) Where I have used material for which publications followed, I have indicated in detail my role in the work.

(vi) This thesis is primarily a collection of material, prepared by myself published as journal articles or presented as oral presentations at conferences. In some cases, additional material has been included.

(vii) This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

Signed: [redacted]

Varsha Gungoa

Date: August 14, 2025

DECLARATION 2 PUBLICATIONS

Publications from this thesis:

1. Gungoa, V., & Kebede, S. (2024). Climate variability impact on groundwater quality in Small Island Developing States: Mauritius Island as a case study. Frontiers in Water, 6, 1432908. DOI: 10.3389/frwa.2024.1432908

- Candidate's contribution: Primary author responsible for data collection, analysis, interpretation and manuscript writing
- Co-author's contribution: Supervision, review and editing of manuscript

2. Gungoa, V., & Kebede, S. (2024). Temporal Analysis of Groundwater Quality in Small Island Developing States: Case Study in the Island of Mauritius. Journal of Hydrology (under review)

- Candidate's contribution: Primary author responsible for data collection, analysis, interpretation and manuscript writing
- Co-author's contribution: Supervision, review and editing of manuscript

3. Gungoa, V., & Kebede, S. (2024). Isotopic characterization of groundwater systems in small island developing states: Implications for recharge, flow dynamics, and resource management: Mauritius island as a case study. Journal of Hydrology: Regional Studies (under review)

- Candidate's contribution: Primary author responsible for data collection, analysis, interpretation and manuscript writing
- Co-author's contribution: Supervision, review and editing of manuscript

Signed: [redacted]

Varsha Gungoa

Date: August 14, 2025

ABSTRACT

This thesis presents a systematic investigation of groundwater systems in Mauritius through three interconnected studies examining temporal patterns, climate impacts, and flow dynamics. The research addresses the knowledge gaps regarding groundwater vulnerability in Small Island Developing States (SIDS) while developing a framework for sustainable resource management.

The temporal analysis spanning 2010-2021 revealed significant trends in groundwater quality across Mauritius's five major aquifers (Aquifer I: Curepipe-Vacoas-Flic en Flac; Aquifer II: Phoenix-Beau Bassin-Albion-Moka-Coromandel; Aquifer III: Nouvelle France-Rose Belle-Plaisance; Aquifer IV: Nouvelle Découverte-Plaine des Roches-Midlands-Trou d'Eau Douce; and Aquifer V: Northern Aquifer). Conductivity showed decreasing trends in four aquifers (-0.09 to -0.40 µS/cm per month), while pH demonstrated significant changes in Aquifers II and V. Total Dissolved Solids decreased notably in Aquifers I and II (-0.12 and -0.18 units/month respectively), indicating spatially variable water quality evolution.

The investigation of climate impacts revealed generally weak correlations between groundwater quality and climate indices. The 12-month Standardized Precipitation Index showed strongest correlations with sulphate in Aquifers II and III ($r = -0.40$ and -0.33), while global climate modes demonstrated minimal influence. Analysis of Cyclone Esami (January 2020) indicated short-term impacts on water quality parameters, though data limitations prevented a complete statistical analysis of extreme event impacts.

Isotopic analysis conducted during 2022-2023 using 67 boreholes across all five aquifer systems revealed distinct spatial and temporal patterns in groundwater composition. Results showed δ2H values ranging from -22.8per mil to -5.6per mil and δ18O values from -4.2per mil to -1.56per mil, with systematic variations corresponding to elevation and aquifer characteristics. Inter-aquifer connectivity was evident between Aquifers I and II, while Aquifer V showed clear evidence of marine influence with elevated chloride concentrations (42 mg/L) and enriched isotopic signatures in coastal areas.

The research provides a framework for assessing groundwater vulnerability in SIDS through integration of temporal trend analysis, climate correlation studies, and isotopic characterization. Key findings include the importance of spatial heterogeneity in system response, the primacy of local hydrogeological conditions over regional climate patterns, and the need for spatially targeted management approaches. These insights enable development of evidence-based strategies for sustainable groundwater management in SIDS contexts.

Keywords: Groundwater quality, Climate variability, Stable isotopes, Small Island Developing States, Mauritius

EXTENDED ABSTRACT

This thesis examines groundwater systems in Mauritius through three interconnected studies that progress from identifying temporal patterns, through understanding climate impacts, to explaining flow dynamics. The research addresses the knowledge gaps regarding groundwater vulnerability in Small Island Developing States (SIDS) while developing evidence-based frameworks for sustainable management.

Temporal Trend Analysis (2010-2021)

The first study revealed complex patterns of change in groundwater quality across Mauritius's five major aquifers. Conductivity showed significant decreasing trends in four aquifers, with rates ranging from -0.09 to -0.40 μS/cm per month. pH variations demonstrated notable spatial heterogeneity, with significant acidification observed only in Aquifers II and V. Total Dissolved Solids revealed significant decreasing trends in Aquifers I and II (-0.12 and -0.18 units/month respectively), while remaining stable in others. Nitrate showed no significant changes across any aquifer, while chloride and sulphate demonstrated notable changes specifically in Aquifer II (-0.09 and -0.04 mg/L per month respectively). Salinity patterns mirrored conductivity trends, with significant decreases in Aquifers I and II (-1.79E-04 and -1.65E-04 ppt/month respectively).

Climate Impact Assessment

The second study investigated relationships between climate variables and groundwater quality. The 12-month Standardized Precipitation Index (SPI) showed strongest correlations with sulphate in Aquifers II and III ($r = -0.40$ and -0.33). The Standardized Precipitation Evapotranspiration Index demonstrated weaker correlations, with highest relationship in nitrate levels for Aquifer II ($r = 0.20$). Global climate modes showed minimal influence, with Antarctic Oscillation demonstrating modest correlation with sulphate in Aquifer III ($r = -0.33$) and El Niño-Southern Oscillation showing weak relationship with chloride in Aquifer V ($r = 0.30$). Analysis of Cyclone Esami (January 2020) indicated short-term impacts on conductivity, TDS, and salinity in Aquifers I, II, and III, though data limitations prevented comprehensive statistical analysis.

Isotopic Characterization

The third study revealed distinct patterns in groundwater dynamics through isotopic analysis conducted during 2022-2023. Results showed δ^2H values ranging from -22.8per mil to -5.6per

mil and $\delta^{18}O$ values from -4.2per mil to -1.56per mil, with systematic variations corresponding to elevation, distance from coast, and aquifer characteristics. Inter-aquifer connectivity was particularly evident between Aquifers I and II, demonstrated by progressive evolution of isotopic values along flow paths. The analysis revealed varying degrees of system resilience - Aquifers I and II maintained relatively stable isotopic compositions (seasonal variations <2per mil in $\delta^{2}H$), while Aquifer V showed greater temporal variability (variations up to 4-6per mil), particularly in coastal areas. Coastal vulnerability analysis integrated both isotopic and chemical indicators, with Aquifer V showing clear evidence of marine influence through elevated chloride concentrations (42 mg/L) and enriched isotopic signatures.

Management Implications

The research establishes a framework for assessing groundwater vulnerability in SIDS through integration of temporal trend analysis, climate correlation studies, and isotopic characterization. Key management implications include.

- The need for spatially targeted protection measures based on observed patterns of system response
- The importance of long-term monitoring focused on parameters showing strongest climate correlations
- The role of isotopic analysis in identifying vulnerable areas and recharge zones
- The value of integrated assessment approaches combining multiple analytical methods

The findings challenge assumptions about uniform aquifer responses to environmental stresses while providing practical tools for sustainable groundwater management in SIDS contexts. The research demonstrates that while climate variability influences groundwater quality, local hydrogeological conditions play a dominant role in determining system response. This improved understanding enables development of more effective, targeted approaches to groundwater protection and management.

Keywords: **Groundwater quality, Climate variability, Stable isotopes, Small Island Developing States, Mauritius, Environmental monitoring, Water resource management**

ACKNOWLEDGEMENTS

The completion of this doctoral thesis would not have been possible without the support, guidance, and contributions of many individuals and institutions. I would like to express my profound gratitude to all those who have assisted me throughout this academic journey.

First and foremost, I extend my deepest appreciation to my supervisor, Professor Seifu Kebede Gurmessa, for his exceptional guidance, unwavering support, and invaluable insights throughout this research. His expertise in hydrology and dedication to scientific excellence has profoundly shaped both this work and my development as a researcher.

I would like to express my heartfelt gratitude to the strong pillar of my life for always being by my side throughout for his unwavering support, patience, and understanding during this academic pursuit. His constant encouragement and motivation during challenging times have been instrumental in helping me complete this work.

I would also like to thank my children Araci and Paramesh, Thressen, Medha for their unconditional love and constant support.

I am deeply grateful to the Central Water Authority (CWA) of Mauritius for providing access to groundwater quality data and supporting the field sampling campaigns. Special thanks go to the technical staff who assisted with sample collection and data compilation. Their cooperation was instrumental in making this research possible.

I would like to acknowledge the contribution of the National Environmental Laboratory of Mauritius for their assistance with isotopic analysis, and the Mauritius Meteorological Services for providing essential climate data. The technical support from the laboratory staff was invaluable in ensuring the quality and reliability of the analytical results. My sincere appreciation goes Mr Harish Dindyal and Jannick Fanny of the National Environmental Laboratory (NEL) which made the isotope analysis possible.

I also thank the Centre for Water Resources Research at the University of KwaZulu-Natal for providing an excellent motivating environment and necessary resources. The administrative staff at the School of Agricultural, Earth and Environmental Sciences, especially Mrs Jothimala Manickum and Marsha Manjoo deserve recognition for their efficient handling of administrative matters and continuous support throughout my studies. I would like to express my heartfelt gratitude to my family for their unwavering support, patience, and understanding during this academic pursuit. Their encouragement during challenging times was instrumental in helping me complete this work.

Finally, I am grateful to the anonymous reviewers of the published papers that form part of this thesis. Their constructive feedback and suggestions have significantly improved the quality of this research.

This work represents not just individual effort but the culmination of support, guidance, and collaboration from many individuals and institutions. To everyone who contributed to this research in any way, I extend my sincere appreciation.

Varsha Gungoa

25 January 2025

Contents

PREFACE ii
DECLARATION 1 PLAGIARISM iii
DECLARATION 2 PUBLICATIONS iv
ABSTRACT v
EXTENDED ABSTRACT vii
ACKNOWLEDGEMENTS ix
LIST OF TABLES xvii
LIST OF FIGURES xix
LIST OF ABBREVIATIONS xxi
LIST OF NOMENCLATURE xxiv
1. CHAPTER 1: INTRODUCTION 1
1.1 Rationale for the research (nature and scope) 1
1.2 Justification for the Research 3
1.2.1 Critical Knowledge Gaps in SIDS Groundwater Management 3
1.2.2 Escalating Water Security Challenges 3
1.2.3 Limitations of Current Research Approaches 4
1.2.4 Mauritius as an Ideal Case Study 4
1.3 Research Significance 5
1.3.1 Scientific Contributions 5
1.3.2 Methodological Innovations 5
1.3.3 Practical Management Applications 5
1.3.4 Climate Change Adaptation 6
1.3.5 Policy and Planning Implications 6
1.3.6 Capacity Building and Knowledge Transfer 6
1.3.7 Sustainable Development Contributions 7
1.4 Research Framework 7
1.4.1 Key Water Quality Parameters 7
1.4.2 Systematic Investigation Framework 8
1.4.3 Study Progression and Integration 9
1.4.4 Trend Analysis and Hypothesis Testing 10
1.5 Research Aim and Objectives 10
1.6 Specific Objectives-Hypothesis Tested 11
1.7 Study Area 14
1.8 Research Significance 16
1.9 Geographical Setting 16
1.9 Outline of dissertation/thesis structure 22

1.10 References 24
2. CHAPTER 2: LITERATURE REVIEW 25
2.1 Introduction 25
2.2 Groundwater Quality Degradation Patterns in Small Island Developing States 25
2.2.1 Temporal Patterns of Groundwater Quality Changes in SIDS 26
2.2.2 Spatial Variations in Groundwater Quality Degradation 27
2.2.3 Key Degradation Indicators and Monitoring Approaches 28
2.2.4 Case Study: Mauritius Groundwater Quality Trends 29
2.3 Climate Variability Impacts on Groundwater Systems in SIDS 53
2.3.1 Climate-Groundwater Interaction Mechanisms 54
2.3.2 Precipitation Variability and Recharge Dynamics 57
2.3.3 Sea-Level Rise and Saltwater Intrusion 60
2.3.4 Extreme Weather Events and Groundwater Response 63
2.3.5 Climate Change Projections for Island Groundwater Systems 68
2.4 Groundwater Flow Dynamics and Recharge Mechanisms in Volcanic Island Settings. 72
2.4.1 Hydrogeological Characteristics of Volcanic Aquifers 72
2.4.2 Isotopic Tracers for Groundwater Flow Analysis 73
2.4.3 Recharge Mechanisms in Tropical Island Settings 76
2.4.4 Flow Path Identification Using Environmental Tracers 77
2.4.5 Application of Isotope Hydrology in SIDS Research 77
2.5 Groundwater Vulnerability Assessment Frameworks for SIDS 78
2.5.1 Vulnerability Assessment Methods and Indicators 79
2.5.2 SIDS-Specific Vulnerability Factors 80
2.5.3 Integrated Assessment Approaches 81
2.5.4 GIS-Based Vulnerability Mapping 83
2.5.5 Comparative Vulnerability Assessment: Pacific, Caribbean, and Indian Ocean SIDS 85
2.6 Case Studies of SIDS 88
2.6.1 Regional Overview and Comparative Framework 88
a) Pacific SIDS 90
b) Caribbean Islands 96
c) Indian Ocean SIDS 99
2.6.2 Comparative Analysis of Groundwater Challenges in Different Small Island Developing States (SIDS) 103
2.7 Sustainable Groundwater Management Strategies for Small Island Developing States (SIDS) 117
2.7.1 Assessment, Monitoring, and Early Detection Systems 117

2.7.2 Technological Solutions and Infrastructure Development 117
2.7.3 Policy and Governance Frameworks 119
2.7.4 Community-Based Management and Stakeholder Engagement 120
2.7.5 Integrated Water Resources Management in Island Settings 122
2.7.6 Climate Adaptation Strategies for Groundwater Systems 123
2.7.7 Implementation Challenges and Future Directions 124
2.8 Knowledge Gaps and Research Needs 125
2.9 Discussion 130
2.9.1 Groundwater Vulnerability in SIDS 130
2.9.2 Assessment Approaches and Methodologies 131
2.9.3 Management Approaches and Strategies 132
2.9.4 Evidence-Based Framework for Groundwater Assessment and Management 134
2.9.5 Research Gaps and Future Directions 136
References 145
3. CHAPTER 3: TREND ANALYSIS 158
Temporal Analysis of Groundwater Quality in Small Island Developing States: Case Study in the Island of Mauritius. 158
3.1 Abstract 158
3.2 Introduction 158
3.3 Materials and methods 160
3.3.1 In-situ data and collection 160
3.4 Data handling 160
3.4.1 Data Quality Assessment and Validation 162
3.5 Results 164
3.5.1 Water quality parameters 164
3.5.2 pH 165
3.5.3 TDS 166
3.5.4 Chloride 168
3.5.5 Nitrate 169
3.5.6 Sulphate 170
3.5.7 Salinity 172
3.6 Trend analysis and hypothesis testing 175
3.6.1 Conductivity hypothesis test 175
3.6.2 pH hypothesis test 178
3.6.3 TDS hypothesis test 179
3.6.4 Chloride hypothesis test 180
3.6.5 Nitrate hypothesis test 181

3.6.6 Sulphate hypothesis test ... 182
3.6.7 Salinity hypothesis test ... 183
3.7 Discussion ... 184
3.7.1 Interpretation of Groundwater Quality Trends ... 184
3.7.2 Aquifer-Specific Variations and Underlying Mechanisms ... 185
3.7.3 Implications for Water Resource Management ... 186
3.7.4 Limitations and Data Quality Considerations ... 186
3.7.5 Broader Context for Small Island Developing States ... 187
3.8 Conclusions and Recommendations ... 188
3.9 References ... 189
3.9 Data Availability ... 191
4. CHAPTER 4: CLIMATE VARIABILITY IMPACT ON GROUNDWATER QUALITY IN SMALL ISLAND DEVELOPING STATES: MAURITIUS ISLAND AS A CASE STUDY ... 192
4.1 Abstract ... 192
4.2 Introduction ... 192
4.3 Materials and methods ... 195
4.3.1 Data acquisition and preparation ... 195
4.3.2 Theoretical Framework and Study Approach ... 196
4.4 Rainfall data ... 196
4.5 Methods ... 198
4.5.1 Standardized precipitation index ... 198
4.5.2 Standardized precipitation evapotranspiration index ... 199
4.5.3 Dry spells ... 199
4.6 Climate oscillations and synoptic scale features ... 199
4.6.1 Large-scale oscillation indices ... 199
4.6.2 Tropical cyclones ... 201
4.7 Results ... 202
4.7.1 Water quality time-series data ... 202
4.7.2 Trend analysis and hypothesis testing ... 202
4.7.3 SPI correlation with aquifer groundwater quality ... 204
4.7.4 SPEI correlation with aquifer groundwater quality ... 205
4.7.5 Dry spell correlation with aquifer groundwater quality ... 206
4.7.6 Global climatic forcing ... 207
4.7.7 Rainfall spikes or tropical cyclone impact ... 212
4.8 Discussion ... 213
4.9 Conclusion ... 215

4.10 References 217
5. CHAPTER 5: ISOTOPIC CHARACTERIZATION OF GROUNDWATER SYSTEMS IN SMALL ISLAND DEVELOPING STATES: IMPLICATIONS FOR RECHARGE, FLOW DYNAMICS, AND RESOURCE MANAGEMENT: MAURITIUS ISLAND AS A CASE STUDY 222
5.1 Abstract 222
5.2 Introduction 223
5.3 Materials and Methods 225
5.3.1 Study Area 225
5.3.2 Site Selection and Sampling 230
5.3.3 Hydrological and Climatic Context 230
5.3.4 Isotope Analysis for $\delta^{18}O$ and $\delta^{2}H$ 230
5.3.5 Isotope Analysis 233
5.3.6 Precipitation Data 234
5.3.7 Reporting of Isotope Analysis 235
5.4 Results and Interpretation of Isotopic Patterns, Characterization of Groundwater Systems 236
5.4.1 Spatial Distribution of Isotopic Compositions 236
5.4.2 Hydrogeological System Conceptualization 250
5.4.3 Implications for Water Resource Management 279
5.5 Conclusion 285
5.6 References 287
6. CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH 290
6.1 Introduction 290
6.2 Synthesis of Key Findings 291
6.2.1 Pattern Recognition: Temporal Trends in Groundwater Quality 291
6.2.2 Understanding Drivers: Climate-Groundwater Relationships 292
6.2.3 Explaining Mechanisms: Isotopic Insights 293
6.2.4 Integration of Findings: A Coherent Picture 294
6.3 Conceptual Model Evolution and Implications 295
6.4 Conclusions 296
6.5 Recommendations 297
6.5.1 Monitoring and Assessment 297
6.5.2 Protection Measures 297
6.5.3 Climate Adaptation 298
6.5.4 Long-term Strategic Priorities 298
6.6 Future Research Directions 298

6.7 References 300

LIST OF TABLES

Table 2-1 Groundwater abstraction in Aquifer I 38
Table 2-2 Groundwater abstraction in Aquifer II........ 41
Table 2-3 Groundwater abstraction on Aquifer III 43
Table 2-4 Groundwater abstraction in Aquifer IV 46
Table 2-5 Groundwater abstraction in Aquifer V 49
Table 2-6 Groundwater abstraction in the Secondary Aquifers 51
Table 2-7 Comparative Analysis of Groundwater Challenges in different SIDS 114
Table 3-1 Calculations for Each Aquifer (Based on Figure 3.4) 167
`Table 3-2 Summary of results from linear regression analysis of conductivity trends across aquifers. 177
Table 3-3 Summary of results of a Linear Regression Model of pH displays 178
Table 3-4 Summary of results of a Linear Regression Model of TDS 180
Table 3-5 Summary of results of a Linear Regression Model of Chloride which displays the coefficient of variation, standard error, t-value, p-value and the significance at a 95% confidence level. 181
Table 3-6 Summary of results of a Linear Regression Model of Nitrate which displays the coefficient of variation, standard error, t value, p-value and the significance at a 95% confidence level. 182
Table 3-7 Summary of results of a Linear Regression Model of Sulphate which displays the coefficient of variation, standard error, t-value, p-value and the significance at a 95% confidence level. 183
Table 3-8 Summary of results of a Linear Regression Model of Salinity which displays the coefficient of variation, standard error, t-value, p-value and the significance at a 95% confidence level 184
Table 4-1The SPI and SPEI Table describes the meaning of the SPI Anomaly Index 201
Table 4-2 Summary of results of a Linear Regression Model of Conductivity displaying the coefficient of variation, standard error, t-value, p-value, and significance at a 95% confidence level. $\rho = 0$ (There is no significant relationship between conductivity and time (months)) $\rho \neq 0$ (There is a significant relationship between conductivity and months). $\alpha = 0.05$. 212
Table 5-1 Summary of Isotopic Compositions by Aquifer System 236
Table 5-2 Aquifer Classification by Depth and Temporal Response 247
Table 5-3 Recharge Characteristics of Mauritius Aquifer Systems (2017-2023) 250
Table 5-4 Temporal Isotopic Variations and Flow Characteristics in Mauritius Aquifers systems based on seasonal δ2H patterns. 272
Table 5-5 Aquifer Vulnerability Assessment based on combined analysis of isotopic trends, mixing zone characteristics, and climate response patterns observed during 2017-2023 277
Table 5-6 Raw Isotopic Data from Mauritius Aquifer Systems (2022-2023) showing Isotopic composition (δ2H and δ18O), sampling locations, and aquifer characteristics for selected groundwater samples collected across Mauritius. Deuterium excess values calculated as d = δ2H - 8×δ18O. All 67 Boreholes are shown. 302
Table 5-7 Showing Statistical Summary of Stable Isotope Compositions in Mauritius's Major Aquifer Systems (2017-2023) where Wet season: December-April; Dry season: May-November; ±values represent standard deviation; GMWL: Global Meteoric Water Line (δ2H = 8×δ18O + 10) 306

Table 5-8 Showing boreholes elevation, depth of boreholes and distance of each borehole from the coast 307

LIST OF FIGURES

Figure 1-1 Research Framework Flowchart 9
Figure 1-2 Map showing Geographical distribution of SIDS 19
Figure 1-3 World map showing location of Mauritius 20
Figure 1-4 Mauritius Island showing the 5 main aquifers 20
Figure 2-1Average annual rainfall over Mauritius (Source: Mauritius Meteorological Services) 31
Figure 2-2 Isohyet map of Mauritius (Source: Mauritius Meteorological Station 33
Figure 2-3 The 5 main aquifers of Mauritius (adapted from Giorgi et al., 1999). 35
Figure 2-4 Aquifer I - Aquifer of Curepipe - Vacoas – Flic enFlac 37
Figure 2-5 Aquifer II- Aquifer of Phoenix – Beau Bassin -Albion – Moka - Coromandel40
Figure 2-6 Aquifer III - Aquifer of Nouvelle France – Rose Belle - Plaisance 42
Figure 2-7 Aquifer IV – Aquifer of Nouvelle Découverte – Plaine des Roches – Midlands-Trou d'Eau Douce 45
Figure 2-8Aquifer V– Northern Aquifer 48
Figure 2-9 Secondary Aquifers 50
Figure 2-10 Preliminary Conceptual Hydrogeological Cross-section of Mauritius Groundwater Systems 75
Figure 3-1 Mauritius Island 5 main Aquifers are displayed. 161
Figure 3-2 Conductivity Monthly Signal across various Aquifers. 165
Figure 3-3 pH Monthly Signal across various Aquifers. 167
Figure 3-4 TDS Monthly Signal across various Aquifers. 169
Figure 3-5 Chloride Monthly Signal (mg/L) across various Aquifers. 171
Figure 3-6 Nitrate Monthly Signal across various Aquifers. 172
Figure 3-7 Sulphate Monthly Signal across various Aquifers. 173
Figure 3-8 Salinity Monthly Signal across various Aquifers. 174
Figure 3-9 Salinity Model Validation Signal across 5 main Aquifers. 176
Figure 4-1 Five main Aquifers of Mauritius Island: The Secondary Aquifers (Chamarel, Frederika, Chemin Grenier, and Yemen) in the South West are excluded from this study due to their lack of continuous data record. This illustration figure is courtesy of Devi Nowbuth et al., (2012). 197
Figure 4-2 Conductivity Time Series as a Water Quality Indicator in Mauritius. 204
Figure 4-3Conductivity Model Validation Signal across five main Aquifers. 206
Figure 4-4 The SPL Correlation Matrix plot showing the relationship strength of the Water Quality Indicators vs. the 12-month SPI. Aquifer Correlation plots vs. (A) Chloride, (B) Conductivity, (C) Nitrate, (D) pH, (E) Salinity, (F) TDS and (G) TDS heat map plots. 209
Figure 4-5 The SPEI Correlation Matrix plot showing relationship strength of the Water Quality Indicators vs. the 1-month SPEI. Aquifer Correlation vs. (A) Chloride, (B) Conductivity, (C) Nitrate, (D) pH, (E) Salinity, (F) TDS and (G) TDS heat map plots. . 210
Figure 4-6 SPI Correlation Matrix plot showing the relationship strength of the Water Quality Indicators vs. the Dry-Spells SPI. Aquifer Correlation vs. (A) Chloride, (b) Conductivity, (C) Nitrate, (D) pH, (E) Salinity, (F) TDS and (G) TDS heat map plots. . 211
Figure 4-7 Environmental Correlation Heat map plot showing relationship between the Environmental Factors (IOD, AAO, and ENSO) and the Water Quality Indicators. Global climate modes and water quality parameter correlation vs. (A) Aquifer 1, (B) Aquifer 2, (C) Aquifer 3, (D) Aquifer 4 and (E) Aquifer 5 heat map plots. 214

Figure 4-8 Daily Groundwater Parameter readings versus storm Esami event analysis. 215
Figure 5-1 Study are map showing Contour lines with elevation details across the 5 Aquifers and 67 of 429 boreholes ... 227
Figure 5-2 Map showing Groundwater Aquifers and Boreholes in Mauritius Island for Isotope Analysis ... 229
Figure 5-3 Comparison of Global Meteoric Water Line (GMWL) and Local Meteoric Water Line (LMWL) relationships derived from isotopic analysis of 67 boreholes across Mauritius's five aquifer systems during 2017-2023. The plot demonstrates the systematic deviation of local isotopic compositions from global patterns, reflecting distinct regional hydrological processes. ... 232
Figure 5-4 Annual precipitation over Mauritius at different topographical elevation (Source Mauritius Meteorological station) ... 234
Figure 5-5 Monthly average rainfall in Mauritius. ... 235
Figure 5-6 The Aquifer system of Mauritius and the ancient Basalt representing boundaries of the Aquifers ... 239
Figure 5-7 Elevation and Isotopes over Aquifers showing on the left panel is elevation contour map overlaid with δ18O boreholes concentrations. On the right panel, the elevation contour map with δ2H boreholes and concentration ... 240
Figure 5-8 Composition of stable Isotope of main Aquifers during Dry season ... 244
Figure 5-9 Composition of stable Isotope of main Aquifers during Wet season ... 245
Figure 5-10 Relationship between δ2H and δ18O in Mauritius groundwater sample, LMWL shown as dashed line. Samples color-coded by Aquifer unit showing progressive enrichment from highland to coastal areas. ... 250
Figure 5-11 Conceptual hydrogeological model showing potential groundwater flow paths from central plateau recharge areas to Aquifer V, based on isotopic evidence and topographic gradients ... 254
Figure 5-12 Showing direction of recharge flow to Aquifer I from the central plateau ... 255
Figure 5-13 Showing direction of recharge flow to Aquifer II from the central plateau ... 255
Figure 5-14 Showing direction of recharge flow to Aquifer III from the central plateau 255
Figure 5-15 Showing direction of recharge flow to Aquifer IV from the central plateau 256
Figure 5-16 Borehole distance from the coast ... 260
Figure 5-17 Groundwater Flow Dynamics and Mixing Patterns showing the combined analysis of vertical and lateral flow patterns in Mauritius aquifers. ... 263
Figure 5-18 Conceptual Hydrogeological cross-section showing groundwater flow paths from highland recharge zones to coastal areas. ... 270
Figure 5-19 Conceptual Hydrogeological cross-section showing isotopic evolution along groundwater flow paths from highland recharge zones to coastal areas. Mixing zones and seawater intrusion interface indicated. ... 270
Figure 5-20 Relationship between Chloride Concentrations and δ^2H Values Across Mauritius Aquifer Systems ... 273

LIST OF ABBREVIATIONS

Category	Abbreviation	Definition
Units of Measurement		
	a.m.s.l	Above mean sea level
	km	Kilometres
	km^2	Square kilometres
	m	Meters
	mg/L	Milligrams per litre
	µS/cm	Microsiemens per centimetre
	ppt	Parts per thousand
	per mil	Per mile (parts per thousand)
	Mm^3	Million cubic meters
Isotopes and Chemistry		
	δ^2H	Deuterium (isotope composition)
	$\delta^{18}O$	Oxygen-18 (isotope composition)
	Cl-	Chloride ion
	NO_3	Nitrate
	TDS	Total Dissolved Solids
	EC	Electrical Conductivity
	pH	Potential of Hydrogen
Climate and Environmental Terms		
	AAO	Antarctic Oscillation
	AO	Antarctic Oscillation (alternative abbreviation)
	AIMS	Atlantic, Indian Ocean, Mediterranean and South China Seas
	CLEWs	Climate, Land-use, Energy and Water strategies
	ENSO	El Niño-Southern Oscillation
	FVI	Freshwater Vulnerability Index
	GMWL	Global Meteoric Water Line
	IOD	Indian Ocean Dipole
	IWRM	Integrated Water Resources Management
	LMWL	Local Meteoric Water Line
	SIDS	Small Island Developing States
	SOI	Southern Oscillation Index
	SPI	Standardized Precipitation Index

	SPEI	Standardized Precipitation Evapotranspiration Index
	SST	Sea Surface Temperature
	SLP	Sea Level Pressure
	SWI	Saltwater Intrusion
Statistics and Mathematics		
	CI	Confidence Interval
	SE	Standard Error
	H0	Null Hypothesis
	H1	Alternative Hypothesis
	ρ	Rho (correlation coefficient)
	α	Alpha (significance level)
Organizations and Other		
	AHP	Analytic Hierarchy Process
	API	Application Programming Interface
	BH	Borehole
	CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
	CWA	Central Water Authority
	GCOS	Global Climate Observing System
	GEBCO	General Bathymetric Chart of the Oceans
	GIS	Geographic Information Systems
	ICT	Information and Communication Technology
	IoT	Internet of Things
	IWA	International Water Association
	MEPU	Ministry of Energy and Public Utilities
	MIT	Massachusetts Institute of Technology
	NCEI	National Centres for Environmental Information
	NEL	National Environmental Laboratory
	NOAA	National Oceanic and Atmospheric Administration
	PICs	Pacific Island Countries
	UN	United Nations
	UNCED	United Nations Conference on Environment and Development
	UNFCCC	United Nations Framework Convention on Climate Change

VSMOW	Vienna Standard Mean Ocean Water
WHO	World Health Organization
WMO	World Meteorological Organization
WQI	Water Quality Index
WRI	World Resources Institute
WRU	Water Resources Unit

LIST OF NOMENCLATURE

Aquifer Designations

Designation	Full Name	Geographic Coverage
Aquifer I	Curepipe-Vacoas-Flic en Flac Aquifer	Central-Western Mauritius
Aquifer II	Phoenix-Beau Bassin-Albion-Moka-Coromandel Aquifer	Central-Northern Mauritius
Aquifer III	Nouvelle France-Rose Belle-Plaisance Aquifer	Eastern Mauritius
Aquifer IV	Nouvelle Découverte-Plaine des Roches-Midlands-Trou d'Eau Douce Aquifer	Eastern-Central Mauritius
Aquifer V	Northern Aquifer	Northern Plains
Secondary Aquifers	Chamarel, Frederika, Chemin Grenier, and Yemen Aquifers	South-Western Mauritius

Isotopic Notation

Symbol	Definition	Units
δ^2H	Deuterium isotope composition relative to VSMOW	per mil
$\delta^{18}O$	Oxygen-18 isotope composition relative to VSMOW	per mil
d-excess	Deuterium excess ($d = \delta^2H - 8\times\delta^{18}O$)	per mil
VSMOW	Vienna Standard Mean Ocean Water	-
GMWL	Global Meteoric Water Line ($\delta^2H = 8\times\delta^{18}O + 10$)	-
LMWL	Local Meteoric Water Line ($\delta^2H = 7.86\times\delta^{18}O + 9.5$)	-

Water Quality Parameters

Parameter	Definition	Units
EC	Electrical Conductivity	µS/cm
TDS	Total Dissolved Solids	mg/L
pH	Potential of Hydrogen (acidity/alkalinity)	-
Cl^-	Chloride ion concentration	mg/L
NO_3^-	Nitrate concentration	mg/L
SO_4^{2-}	Sulfate concentration	mg/L
Salinity	Total dissolved salt content	ppt (parts per thousand)

Climate Indices

Index	Definition	Application
SPI	Standardized Precipitation Index	Drought assessment
SPEI	Standardized Precipitation Evapotranspiration Index	Drought assessment including temperature
ENSO	El Niño-Southern Oscillation	Global climate pattern
SOI	Southern Oscillation Index	ENSO measurement
AAO/AO	Antarctic Oscillation	Southern hemisphere climate pattern
IOD	Indian Ocean Dipole	Regional climate pattern

Statistical Terms

Term	Definition	Application
r	Correlation coefficient	Climate-groundwater relationships
p-value	Probability value for statistical significance	Hypothesis testing
α	Significance level (typically 0.05)	Statistical testing
CI	Confidence Interval	Uncertainty assessment
H_0	Null hypothesis	Statistical testing
H_1	Alternative hypothesis	Statistical testing

Organizations and Institutions

Abbreviation	Full Name	Role
CWA	Central Water Authority	Groundwater data provider
WRU	Water Resources Unit	Water resource management
NEL	National Environmental Laboratory	Isotopic analysis
MEPU	Ministry of Energy and Public Utilities	Policy and regulation
IAEA	International Atomic Energy Agency	Isotopic standards and methods
GNIP	Global Network of Isotopes in Precipitation	Precipitation isotope data

Geographic and Technical Terms

Term	Definition	Context
SIDS	Small Island Developing States	Study context
a.m.s.l	Above mean sea level	Elevation reference
BH	Borehole	Sampling point designation
Mm^3/year	Million cubic meters per year	Recharge rate units
Wet Season	November to April	Mauritius climate
Dry Season	May to October	Mauritius climate

Hydrogeological Terms

Term	Definition	Application
Recharge	Water infiltration into aquifer	Groundwater replenishment
Discharge	Groundwater outflow	Natural or artificial extraction
Mixing Zone	Area where different water types combine	Vulnerability assessment
Seawater Intrusion	Marine water infiltration into freshwater aquifer	Coastal vulnerability
Hydraulic Gradient	Water table slope driving flow	Flow direction determination
Residence Time	Duration water remains in aquifer	System characterization

CHAPTER 1: INTRODUCTION

1.1 Rationale for the research (nature and scope)

At the 1992 Rio de Janeiro Earth Summit (UNCED), a new classification emerged for a group of nations facing distinct challenges: Small Island Developing States (SIDS). Today, this group encompasses 58 territories, including 38 UN member nations and 20 associate or non-UN members. These islands are geographically clustered in three main areas the Caribbean region, the Pacific waters, and the AIMS zone (Atlantic, Indian Ocean, Mediterranean, and South China Seas), with a combined population reaching approximately 65 million people.

Water scarcity stands as a critical obstacle to the advancement of SIDS communities. Their predominantly tropical locations, with 90% situated within this climate zone, make them susceptible to intense weather patterns including severe tropical cyclones, extended droughts, sudden heavy downpours, and rapid transitions between wet and dry conditions that can overwhelm infrastructure and contaminate freshwater supplies. These islands regularly cope with seasonal weather extremes, from powerful tropical storms to devastating cyclones. The El Niño Southern Oscillation phenomenon further complicates their situation by disrupting typical rainfall patterns, affecting ocean levels, and triggering various meteorological disturbances (UNFCCC, 2005).

The climate crisis poses an existential threat to these island nations. Rising sea levels increasingly contaminate their freshwater aquifers with saltwater, while drought conditions have become more frequent and intense over recent decades a trend that scientists predict will worsen. This situation particularly affects nations like the Bahamas and Barbados, which depend heavily on ground water sources. Similarly, Mauritius draws 60% of its water from groundwater aquifers to support its domestic, agricultural, and industrial needs. The proximity of many water extraction points to coastlines makes them especially vulnerable to seawater contamination (UNFCCC, 2005).

Small Island Developing States continue to face water management and water access challenges, caused in part by deficiencies in water availability, water catchment and storage, pollution of water resources, saline intrusion (which may be exacerbated, inter alia, by sea level rise, unsustainable management of water resources, and climate variability and climate change) and leakage in the delivery system (Chacowry et al., 2018).

Projections from leading research institutions, including WRI and MIT, paint a concerning picture of global water availability. Their studies suggest that by mid-century, more than half the world's population will experience water stress (Maddocks et al., 2015). This challenge will disproportionately affect Small Island Developing States due to their inherent vulnerabilities and limited access to freshwater resources. As these island nations face population growth and changing precipitation patterns, their water security becomes increasingly precarious (Gheuens et al., 2019).

The water management situation in SIDS requires specialized approaches due to their unique geographical constraints. Despite their location in predominantly humid tropical environments, many of these islands lack significant surface water features like rivers or lakes. Instead, they rely primarily on thin layers of ground freshwater, which form delicate lens-shaped deposits above denser saltwater. This limited water resource demands careful stewardship to ensure long-term sustainability (Falkland, 1999).

Groundwater from aquifers is impacted by various factors in Mauritius. Due to scarce surface water resources, communities increasingly tap into groundwater aquifers to meet their expanding water needs. Over exploitation due to growing economic and urbanization activities coupled with climate change represent a high risk to the groundwater water quality. It is therefore necessary to monitor the quality of the groundwater for the preservation of this fresh water source.

Due to the geological nature of the existing aquifer matrix which is characterized by highly fractured and porous volcanic basalt formations with extensive lava tunnel networks, scoraceous zones with transmissivities ranging from 10-6 to 10-1 m2/s (Ministry of Public Utilities, 2005), and preferential flow paths through interconnected fracture systems (Giorgi et al., 1999); the possibility of rapid movement of agro-chemicals down to the water table may exist over the long term, particularly in areas where recent basaltic series and lava tunnels create direct conduits for contaminant transport , particularly in areas where scoraceous lava tunnels provide hydraulic conductivities of at least 10^{-1} m^2/s. This vulnerability is compounded by the multi-layered aquifer structure where intermediate basaltic flows with variable permeability (10^{-6} to 10^{-3} m^2/s) rest on impermeable ancient bedrock, creating conditions for both rapid surface infiltration and pressurized groundwater flow (Kowlesser, 2018). Similarly, the aquifers may be vulnerable to pollution from domestic sewage & wastewater. Moreover, there is also possibility of seawater intrusion in boreholes located along the coast which could be due to reduced groundwater recharge during the dry season or over-exploitation. These threats are likely to be exacerbated in the future with climate change. Climate change does not only affect groundwater quantity, but also its quality. Sea level rise may lead to saltwater intrusion into coastal aquifers affecting groundwater quality and contaminating drinking water sources. This complex web of threats necessitates an understanding of groundwater dynamics to ensure sustainable management of these vital water resources. Therefore, there is a need to assess the vulnerability of the aquifers for the protection of the aquifers.

1.2 Justification for the Research

1.2.1 Critical Knowledge Gaps in SIDS Groundwater Management

Small Island Developing States face unique hydrogeological challenges that are not adequately addressed by conventional groundwater management approaches developed for continental settings. Despite representing 58 territories with approximately 65 million people globally, SIDS have received limited attention in hydrogeological research, creating substantial knowledge gaps in understanding their groundwater systems (UNFCCC, 2005). The existing literature lacks comprehensive frameworks that integrate temporal quality trends, climate impacts, and hydrogeological processes specific to island settings.

Current groundwater management in SIDS often relies on simplified assumptions about aquifer behaviour and uniform management approaches that fail to account for the spatial heterogeneity and unique vulnerability patterns characteristic of island hydrogeological systems. This research addresses these critical gaps by developing an evidence-based framework that recognizes the complexity and variability inherent in SIDS groundwater systems.

1.2.2 Escalating Water Security Challenges

Water scarcity stands as the most critical obstacle to sustainable development in SIDS, with 90% of these territories located in tropical zones making them particularly susceptible to climate variability and extreme weather events (Thomas et al., 2020). The El Niño Southern Oscillation phenomenon and increasing frequency of tropical cyclones further compound water security challenges by disrupting rainfall patterns and threatening freshwater resources.

Projections from leading research institutions indicate that by mid-century, more than half the world's population will experience water stress, with SIDS disproportionately affected due to their limited freshwater resources and high vulnerability to climate change (Maddocks et al., 2015). Rising sea levels increasingly contaminate freshwater aquifers through saltwater intrusion, while drought conditions have intensified over recent decades—a trend predicted to worsen substantially.

1.2.3 Limitations of Current Research Approaches

Previous studies of SIDS groundwater systems have typically focused on single analytical approaches, examining either water quality trends, climate impacts, or hydrogeological processes in isolation. This fragmented approach fails to capture the complex interactions between these factors and limits the development of comprehensive management strategies. Most existing research also lacks the temporal depth necessary to identify long-term trends and understand system responses to environmental pressures.

Furthermore, few studies have attempted to develop transferable frameworks that can be applied across different SIDS contexts while remaining sensitive to local hydrogeological conditions. This research addresses these limitations by integrating multiple analytical approaches over an extended temporal period, providing both depth of understanding and breadth of applicability.

1.2.4 Mauritius as an Ideal Case Study

Mauritius provides an exceptional case study for investigating SIDS groundwater vulnerability due to several key characteristics. The island's dependence on groundwater for 60% of its domestic water supply mirrors the situation faced by many SIDS globally, while its five distinct aquifer systems provide diverse hydrogeological contexts for investigation. The availability of an 11-year continuous groundwater quality dataset, combined with comprehensive climate records and the possibility for detailed isotopic analysis, creates a unique opportunity for integrated research.

The island's geological diversity, ranging from volcanic basalts to coastal sediments, and its elevation gradient from sea level to over 800 meters, encompasses the range of hydrogeological conditions found across many SIDS. Additionally, Mauritius's experience with tropical cyclones, seasonal climate variations, and development pressures provides a representative context for understanding the challenges faced by SIDS globally.

1.3 Research Significance

1.3.1 Scientific Contributions

This research makes several important contributions to the scientific understanding of island hydrogeology and groundwater management. The integration of temporal trend analysis, climate impact assessment, and isotopic characterization represents a novel approach to understanding groundwater vulnerability in SIDS contexts. The development of quantitative relationships between climate variables and groundwater quality parameters provides new insights into the mechanisms driving water quality changes in island settings.

The isotopic characterization of groundwater flow dynamics and recharge mechanisms fills a significant gap in understanding the hydrogeological processes operating in volcanic island aquifers. The identification of spatial patterns in aquifer vulnerability and the quantification of climate sensitivity across different hydrogeological settings contribute fundamental knowledge to island hydrogeology.

1.3.2 Methodological Innovations

The research develops and demonstrates a transferable framework for assessing groundwater vulnerability that can be adapted to other SIDS contexts. The integration of multiple analytical approaches combining statistical trend analysis, correlation studies, and isotopic investigation provides a template for comprehensive groundwater assessment in data-limited island settings. The methodological approach addresses key challenges in SIDS groundwater research, including limited data availability, complex hydrogeological conditions, and the need for cost-effective assessment methods. The framework demonstrates how existing monitoring data can be leveraged more effectively through integrated analysis, providing maximum insight from available resources.

1.3.3 Practical Management Applications

The research provides directly applicable tools and insights for groundwater management in SIDS. The identification of aquifer-specific vulnerability patterns enables targeted protection measures, while the understanding of climate-groundwater relationships supports the development of adaptive management strategies. The delineation of critical recharge areas and vulnerable zones provides a scientific basis for land use planning and resource protection.

The development of evidence-based recommendations for monitoring, protection, and adaptation strategies addresses immediate management needs in SIDS. The research demonstrates how scientific understanding can be translated into practical management actions, bridging the gap between research and application.

1.3.4 Climate Change Adaptation

As SIDS face increasing pressures from climate change, this research provides essential insights for developing effective adaptation strategies. The quantification of climate impacts on groundwater quality and the identification of system resilience factors enables the development of targeted adaptation measures. The understanding of how different aquifers respond to climate variability supports the design of flexible management approaches that can adapt to changing conditions. The research contributes to the growing body of knowledge on climate change impacts in SIDS, providing specific insights into groundwater system responses that complement broader climate impact assessments. This understanding is crucial for developing comprehensive climate adaptation strategies that protect vital water resources.

1.3.5 Policy and Planning Implications

The findings have important implications for water resource policy and planning in SIDS. The demonstration of spatial variability in aquifer vulnerability challenges assumptions about uniform management approaches and supports the development of zone-specific policies. The identification of critical factors controlling groundwater quality and availability provides essential information for strategic planning and resource allocation. The research supports evidence-based policy development by providing quantitative assessments of vulnerability patterns and management effectiveness. This scientific foundation is essential for developing robust policies that can withstand scrutiny and provide long-term protection for vital groundwater resources.

1.3.6 Capacity Building and Knowledge Transfer

This research contributes to capacity building in SIDS by demonstrating how local monitoring data and analytical capabilities can be leveraged to develop comprehensive understanding of groundwater systems. The methodological framework provides a template that can be adapted and applied by local water management agencies, supporting the development of indigenous technical capacity. The research also contributes to knowledge transfer between SIDS by providing insights and approaches that can be shared across similar contexts. This peer-to-peer learning potential is particularly valuable for SIDS, which often face similar challenges but have limited opportunities for collaboration and knowledge exchange.

1.3.7 Sustainable Development Contributions

The protection and sustainable management of groundwater resources is fundamental to achieving multiple Sustainable Development Goals in SIDS contexts, including clean water and sanitation (SDG 6), sustainable cities and communities (SDG 11), and climate action (SDG 13). This research directly contributes to these goals by providing tools and knowledge for improving water resource management. The research also supports broader sustainable development objectives by providing a foundation for integrated water resource management that considers environmental, social, and economic factors. The emphasis on evidence-based management and adaptive strategies aligns with sustainable development principles and supports long-term resilience building in SIDS communities.

1.4 Research Framework

To address the challenges facing Small Island Developing States' groundwater resources, this thesis employs a systematic approach structured around three interconnected research questions. First, it examines temporal patterns in groundwater quality across Mauritius's five major aquifers from 2010-2021, establishing which aquifers show significant changes. Second, it investigates how climate variability drives these changes by analyzing relationships between groundwater quality and climate factors. Finally, it employs isotopic analysis to understand why different aquifers show varying responses to these pressures.

1.4.1 Key Water Quality Parameters

Understanding groundwater quality requires comprehensive assessment of physical and chemical parameters that indicate water suitability for domestic, industrial, and agricultural purposes. This research focuses on seven critical parameters:

Conductivity is the measure of water's ability to conduct electrical flow, influenced by the presence of inorganic material ions. It holds significance in groundwater quality assessments for both drinking and irrigation purposes, as it reflects the concentration of charged particles in the water. Higher conductivity values indicate lower water purity due to the elevated density of inorganic ionic material. To estimate total dissolved solids, conductivity is commonly converted using a factor ranging from 0.55 to 0.90. The variation in conductivity provides essential information about the evolution of water quality over time.

pH is an essential parameter to monitor because it can influence the solubility of various elements and compounds, affecting the water's taste and corrosiveness. Extreme pH levels in groundwater can indicate pollution or contamination, which can have serious environmental and health implications. Regular testing of groundwater pH is important to ensure water quality and to detect any changes that might require remediation measures.

Total Dissolved Solids (TDS) represents the total concentration of dissolved substances in water. Conductivity and TDS are closely correlated water quality parameters, useful in describing salinity quantity in water. These parameters are typically expressed by the equation: $TDS = k \times EC$ (at 25°C), where k is a constant factor.

Chloride (Cl^-) and stable isotopes of water (^{18}O and ^{2}H) are widely used in catchment hydrology as natural tracers that are assumed to be conservative. Chloride represents one of the most abundant anions in groundwater and needs to be measured. Concentrations typically range between 1 and 100 mg/L in groundwater, with concentrations of 200-300 mg/L still within the drinking range according to WHO standards.

Nitrate (NO_3) is a nitrogen compound that forms one of the most common nutrients in water masses. Nitrate has been reported above baseline concentrations in groundwater worldwide and has been identified as the most common and widespread chemical contaminant in groundwater. Nitrate is heavily influenced by farming activity as fertilizers are mostly nitrogen-based.
Sulphate is the most abundant form of sulphur in water due to the presence of minerals like gypsum. Sources can also be anthropogenic through mining and atmospheric deposition. It is essential to analyze sulphate trend behavior across time to detect potential deterioration in water quality.

Salinity is a measure of the amount of dissolved salts in water. High salinity levels can make water unsuitable for drinking, irrigation, and other domestic or industrial purposes. Groundwater salinity can be caused by various natural factors (geological formation characteristics, saltwater intrusion from coastal areas) and human-induced factors (agricultural practices, excessive fertilizer use, industrial processes, poor waste management practices).

1.4.2 Systematic Investigation Framework

This thesis presents a systematic investigation of groundwater systems in Mauritius through three interconnected studies:

1. Long-term trend analysis of groundwater quality (2010-2021)
2. Assessment of climate variability impacts on groundwater systems
3. Isotopic characterization of aquifer processes and flow dynamics

Research Framework Flow Diagram

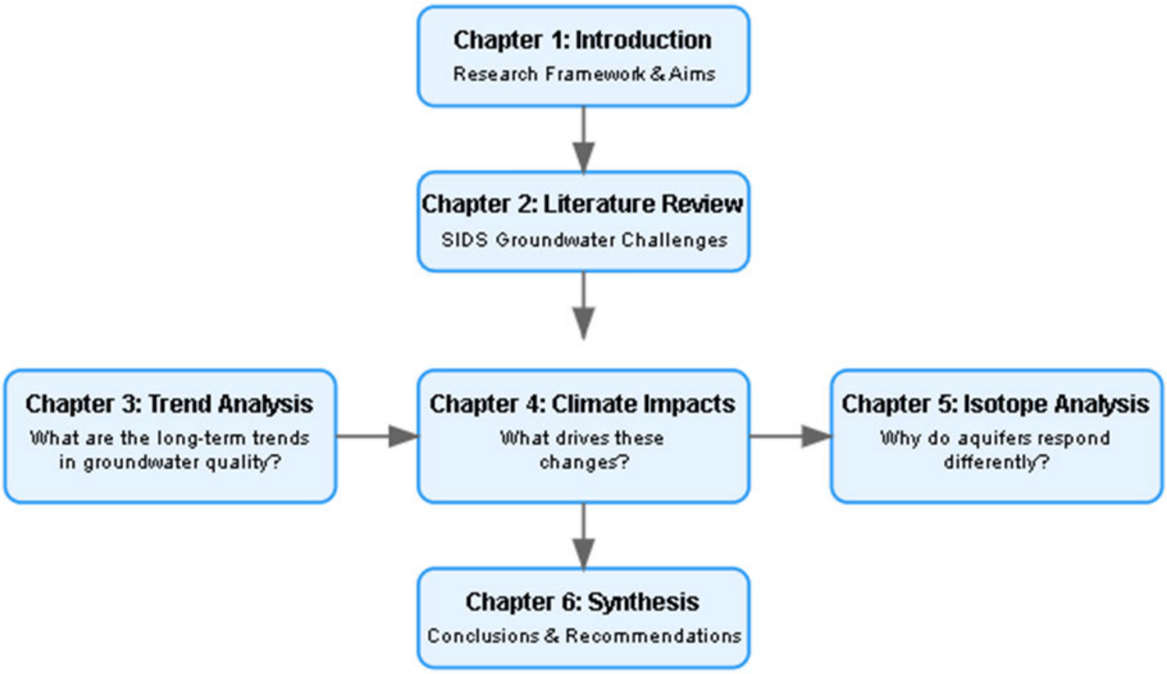


Figure 1-1 Research Framework Flowchart

The thesis presents three interconnected studies that progressively deepen understanding of groundwater dynamics in SIDS. The research progresses from fundamental questions about groundwater quality changes toward mechanistic understanding of aquifer processes.

1.4.3 Study Progression and Integration

The first study (Chapter 3) establishes the foundation through trend analysis of groundwater quality from 2010-2021. Mauritius's groundwater resources are contained within five major coastal aquifers: (I) Curepipe-Vacoas-Flic en Flac, (II) Phoenix-Beau Bassin-Albion/Moka-Coromandel, (III) Nouvelle France-Rose Belle-Plaisance, (IV) Nouvelle Decouverte-Plaines des Roches-Midlands-Trou d'Eau Douce, and (V) Northern Plains aquifer. Through examination of temporal patterns across these five major aquifers, this study identifies aquifers showing significant changes in water quality parameters. The analysis reveals that certain aquifers, particularly in coastal regions, demonstrate concerning trends in parameters such as salinity and nitrate levels, raising questions about the drivers of these changes.

Building on these findings, the second study (Chapter 4) investigates the controls behind these observed changes. Through analysis of relationships between groundwater quality and climate variables, this research examines whether factors such as drought periods, rainfall patterns, or extreme weather events correlate with the identified trends. The investigation reveals how different aquifers respond to climatic stressors, with some showing greater sensitivity to climate variability than others.

The third study (Chapter 5) employs isotopic analysis to explain why aquifers respond differently to these pressures. Through detailed characterization of groundwater recharge mechanisms and flow patterns, this research explains the underlying hydrogeological processes that make certain aquifers more vulnerable to climate impacts and contamination. The isotopic investigation provides crucial insights into aquifer connectivity and recharge processes, explaining the varying responses observed in the previous studies.

1.4.4 Trend Analysis and Hypothesis Testing

Regression analysis on each water quality indicator is undertaken to assess long-term change through the time series. Simple linear regression is conducted based on parametric statistical methods, preceded by model validation testing underlying assumptions including:

1. Test for normality of residual distribution
2. Test for normality of theoretical quantiles compared to observation quantiles.
3. Test for randomness of distribution in residuals across predicted values

Together, these three papers progress from identifying patterns (what is changing?), through understanding drivers (what causes these changes?), to explaining mechanisms (why do different aquifers respond differently?). This structured approach enables comprehensive understanding of groundwater vulnerability in SIDS while ensuring findings contribute directly to improved management practices.

1.5 Research Aim and Objectives

The primary aim of this research is to develop an evidence-based framework for assessing and managing groundwater vulnerability in Small Island Developing States through a detailed analysis of Mauritius aquifer systems.

The specific objectives are.

1. Determination of groundwater quality degradation patterns across Mauritius's aquifer systems over an 11-year period (2010-2021)
2. Quantification of climate variability impacts on groundwater quality in Mauritius's aquifer systems
3. Characterization of groundwater flow dynamics and recharge mechanisms using isotopic analysis
4. Development of a systematic framework for evaluating groundwater vulnerability in Small Island Developing States
5. Formulation of evidence-based recommendations for sustainable groundwater management

1.6 Specific Objectives-Hypothesis Tested

Objective 1: Determination of groundwater quality degradation patterns across Mauritius's aquifer systems over an 11-year period (2010-2021)

Hypotheses tested:

- **H_0**: There is no significant relationship between water quality parameters (conductivity, pH, TDS, chloride, nitrate, sulphate, salinity) and time (months) across the five main aquifers
- **H_1**: There is a significant relationship between water quality parameters and time, indicating temporal degradation or improvement patterns

Statistical framework: Linear regression analysis at 95% confidence level ($\alpha = 0.05$) for each parameter:

$\beta(\text{Parameter}) = \beta_0 + \beta_1(\text{Months}) + \epsilon_i$

Objective 2: Quantification of climate variability impacts on groundwater quality in Mauritius's aquifer systems

Hypotheses tested:

- **H_0**: Climate variability indices (SPI, SPEI, dry spells, global climate modes) have no significant correlation with groundwater quality parameters
- **H_1**: Climate variability indices demonstrate measurable correlations with groundwater quality parameters, indicating climate-driven impacts

Specific sub-hypotheses:

- Drought indicators (SPI, SPEI) correlate with groundwater quality concentrations
- Global climate modes (ENSO, AAO, IOD) influence groundwater quality parameters
- Extreme weather events (cyclones) cause detectable short-term changes in groundwater quality

Objective 3: Characterization of groundwater flow dynamics and recharge mechanisms using isotopic analysis

Hypotheses tested:

- **H_0**: Isotopic compositions (δ^2H and $\delta^{18}O$) show no systematic spatial or temporal patterns across aquifer systems
- **H_1**: Isotopic signatures reveal distinct patterns indicating:
  - Central plateau as primary recharge zone (depleted isotopic values)
  - Progressive enrichment from highland to coastal areas
  - Inter-aquifer connectivity through mixing relationships
  - Seawater intrusion in coastal areas through enriched signatures

Specific sub-hypotheses:

- Elevation effects: Higher elevations show more depleted isotopic values
- Coastal proximity effects: Marine influence increases with proximity to coast
- Temporal variations reflect seasonal recharge patterns and climate impacts

Objective 4: Development of a systematic framework for evaluating groundwater vulnerability in Small Island Developing States

Hypotheses tested:

- **H_0**: Different aquifers show uniform vulnerability patterns to environmental stresses
- **H_1**: Aquifer vulnerability varies systematically based on:
  - Hydrogeological characteristics
  - Climate sensitivity patterns
  - Isotopic evidence of mixing and recharge processes

Framework validation hypotheses:

- Aquifers showing greater temporal variability also demonstrate higher climate sensitivity
- Isotopic patterns explain observed differences in temporal trends and climate responses
- Coastal aquifers are more vulnerable than inland systems

Objective 5: Formulation of evidence-based recommendations for sustainable groundwater management

Hypotheses tested:

- **H_0**: Current management approaches are adequate regardless of aquifer-specific characteristics
- **H_1**: Management strategies must be tailored based on:
  - Aquifer-specific vulnerability patterns identified through temporal analysis
  - Climate sensitivity variations revealed through correlation studies
  - Hydrogeological processes understood through isotopic characterization

Management effectiveness hypotheses:

- Zone-specific protection measures are more effective than uniform approaches
- Climate-responsive management strategies improve resource sustainability

- Integrated monitoring combining quality trends, climate indicators, and isotopic signatures enhances management capabilities

Integration Hypothesis (Overarching)

H_0: The three analytical approaches (temporal trends, climate impacts, isotopic characterization) provide independent, unrelated information about groundwater systems

H_1: The three approaches provide complementary evidence that integrates to reveal:

- Consistent patterns of aquifer vulnerability across all three analytical methods
- Mechanistic explanations for observed temporal trends and climate responses
- A coherent framework for understanding and managing groundwater vulnerability in SIDS

This integrated hypothesis testing approach ensures that each objective contributes to building a wide-ranging understanding of groundwater vulnerability while providing multiple lines of evidence for management recommendations.

1.7 Study Area

This research was conducted in Mauritius, located in the south-western Indian Ocean (57°16'-57°49'E, 19°58'-20°34'S), with a surface area of 2,030 km^2. The island's volcanic origin has created a complex hydrogeological framework comprising five major aquifer systems that provide an ideal setting for investigating groundwater dynamics, representing diverse hydrogeological conditions and management challenges typical of Small Island Developing States (SIDS).

Aquifer I: Curepipe-Vacoas-Flic en Flac System

This multi-layered aquifer covers the western plateau and coastal regions, characterized by the superposition of basaltic flows with varying permeabilities. The system comprises three distinct reservoirs: the western intracaldera groundwater reservoir, the median Palma-Beaux-Songes reservoir, and the coastal Flic-en-Flac Tamarin reservoir (Giorgi et al., 1999). The aquifer features extensive lava tunnel networks and scoraceous formations that facilitate rapid groundwater flow, with transmissivity values ranging from 10^{-6} to 10^{-2} m^2/s (Ministry of Public Utilities, 2005).

Aquifer II: Phoenix-Beau Bassin-Albion/Moka-Coromandel System

Located in the densely populated northwestern region, this aquifer serves the capital Port Louis and surrounding urban areas. The system contains two deep valleys filled with intermediate and recent basalt flows, creating preferential groundwater flow paths. Borehole investigations reveal fossil alluvium layers at the base of flows, with the upper aquifer zones showing semi-confined characteristics due to clayish semi-impermeable basalts (Giorgi et al., 1999). This aquifer faces significant anthropogenic pressure from urban development and industrial activities.

Aquifer III: Nouvelle France-Rose Belle-Plaisance System

Spanning the southeastern region, this aquifer exhibits variable hydraulic behaviour across different sectors. In the northern areas, groundwater flow is controlled by breaches along the caldera rims, while southern regions experience enhanced recharge from superficial aquifer contributions. The aquifer shows significant seasonal water level fluctuations of 5-10 m at Nouvelle France and 20-30 m at Mare Tabac, influenced by the presence of ancient basalt formations and intermediate basalt channeling (Giorgi et al., 1999). This region is predominantly agricultural, making it vulnerable to agrochemical contamination.

Aquifer IV: Nouvelle Decouverte-Plaines des Roches-Midlands-Trou d'Eau Douce System

This eastern coastal aquifer comprises three main reservoirs: the eastern intracaldera reservoir, the median Camp Thorel-Pont Bon Dieu and Melrose-Belle Mare reservoirs, and the coastal Plaines des Roches and Trou d'eau Douce reservoirs. The system is bounded by the N20 fault affecting the caldera border and ancient basalt ridges. Seasonal water level variations are substantial, ranging 10-20 m, reflecting the aquifer's sensitivity to climatic variations (Giorgi et al., 1999). The coastal sections are particularly vulnerable to seawater intrusion due to intensive groundwater abstraction and proximity to the ocean.

Aquifer V: Northern Plains System

Located beyond the calderic rim, this aquifer is recharged through discontinuities that create permeable zones allowing groundwater flow northward. The system includes multiple recharge zones from the Creve Coeur-Notre Dame and Les Mariannes-Congomah valleys, with important fractures providing direct recharge to the central-eastern northern plains. The aquifer features two main breaches in the northern plains caldera that allow seawater intrusion for several kilometres inland (Giorgi et al., 1999). This region supports significant tourism infrastructure, creating competing demands between freshwater supply and coastal development.

Hydrogeological Framework

These aquifers are developed within a multilayered volcanic sequence consisting of recent basaltic series (highly porous and fractured), intermediate basaltic series (variable permeability), and ancient basaltic bedrock (generally impermeable). The recent series exhibit transmissivities of 10^{-5} to 10^{-2} m^2/s, while scoraceous lava tunnels can achieve values exceeding 10^{-1} m^2/s (Ministry of Public Utilities, 2005). Groundwater recharge occurs primarily through direct precipitation infiltration in the central plateau, with an estimated 10% of annual rainfall (approximately 443 Mm^3) contributing to groundwater recharge (Kowlesser, 2018).

These five aquifer systems collectively provide approximately 50% of Mauritius's potable water supply and represent diverse challenges including seawater intrusion in coastal zones, agricultural contamination in inland areas, urban pollution pressure, and climate variability impacts. Their varying geological contexts, from highly permeable volcanic formations to semi-confined systems, provide a framework for investigating groundwater quality dynamics in tropical island settings.

1.8 Research Significance

This research contributes to both theoretical understanding and practical management of groundwater resources in SIDS. By integrating long-term monitoring data, climate analysis, and isotopic characterization, it provides insights into aquifer vulnerability patterns and their underlying mechanisms. The findings will inform development of protective measures for groundwater resources in SIDS, particularly crucial as these nations face increasing pressures from climate change and development demands.

1.9 Geographical Setting

The three figures presented in this section progressively establish the geographical and hydrogeological context of the research.

Figure 1.2 illustrates the global distribution of SIDS across three key regions (Caribbean, Pacific, and AIMS), directly supporting the thesis's broad focus on SIDS water management challenges. This visualization helps readers understand the scale and scope of SIDS vulnerability to water scarcity and climate change impacts, which is central to the research rationale outlined in Section 1.1.

Figure 1.3 narrows the focus to Mauritius's location in the Indian Ocean, establishing the geographical context for the case study. This positioning is crucial because it shows Mauritius's isolation and vulnerability as a SIDS nation, making it an ideal representative case for studying groundwater management challenges faced by island states. The location also reinforces the research framework outlined in Section 1.2, as Mauritius experiences typical SIDS challenges including climate variability and seawater intrusion risks.

Figure 1.4 provides the most detailed technical view, mapping Mauritius's five major aquifer systems with their distinct hydrogeological characteristics. The map illustrates Aquifer I (Curepipe-Vacoas-Flic en Flac) in the western region showing extensive green areas indicating ancient lavas (impermeable), Aquifer II (Phoenix-Beau Bassin-Albion/Moka) in the northwestern zone displaying the common recharge zone in blue, Aquifer III (Nouvelle France-Rose Belle-Plaisance) spanning the southeastern area, Aquifer IV (Nouvelle Decouverte-Plaines des Roches-Midlands) covering the eastern coastal region, and Aquifer V (Northern Plains) in the northern sector. The figure clearly delineates piezometric contours (black lines) showing groundwater flow directions, fracture patterns (black dashed lines), and the limits of the central caldera. Significantly, the map highlights areas of seawater intrusion (dark blue zones) particularly affecting the coastal boundaries of Aquifers II, IV, and V, while secondary aquifers including Chamarel (Ch), Frederika (F), Chemin Grenier (CG), and Yemen (Y) are shown in the southwestern region. The colour gradient from green (ancient impermeable lavas) through light blue (intermediate permeability) to dark blue (high permeability and seawater zones) effectively demonstrates the complex hydrogeological zonation across the island's 2,030 km² area. This hydrogeological map directly supports the research objectives outlined in Section 1.3, particularly.

i. The study of groundwater quality degradation patterns (Objective 1)
ii. The assessment of climate variability impacts (Objective 2)
iii. The characterization of groundwater flow dynamics (Objective 3)

The map's detail of aquifer zones, seawater intrusion areas, and geological features provides essential baseline information for the three interconnected studies described in the research framework. This spatial framework directly supports the three research objectives outlined in Section 1.3.

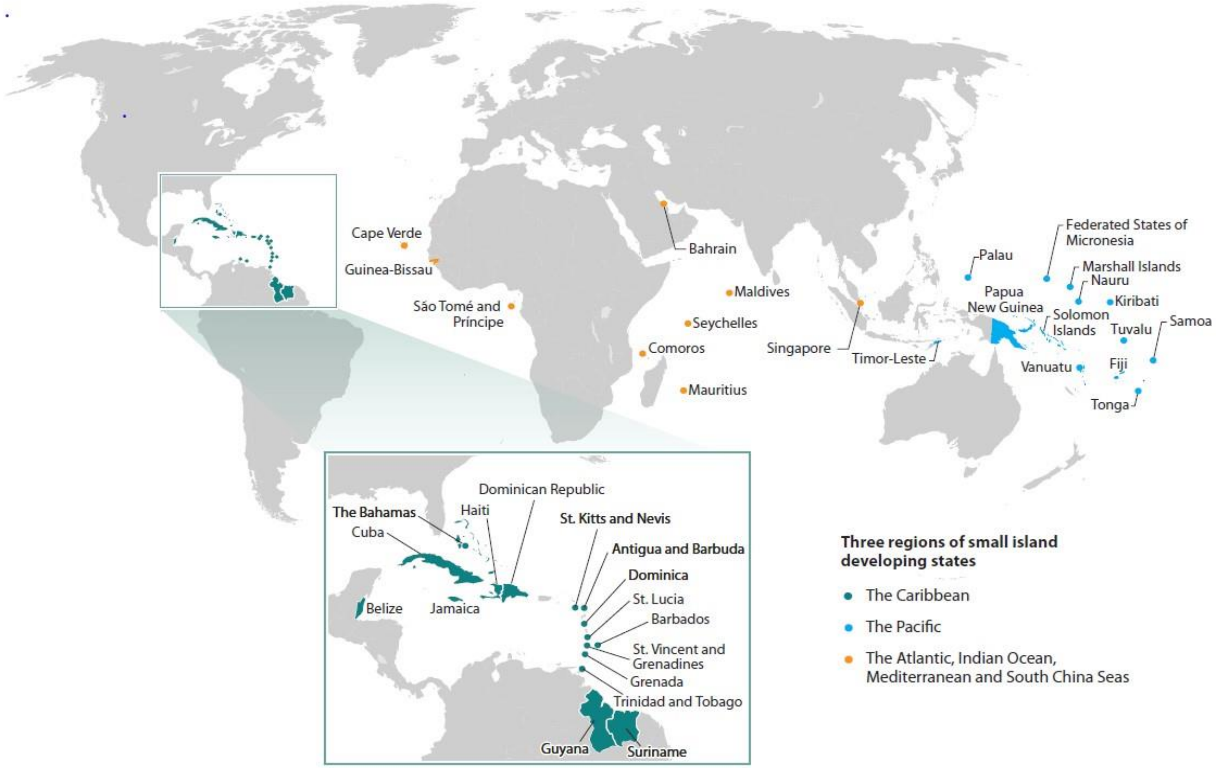


Figure 1-2 Map showing Geographical distribution of SIDS

Source: Thomas (2020)

Source: Map Data@Google.INEGI

Figure 1-3 World map showing location of Mauritius

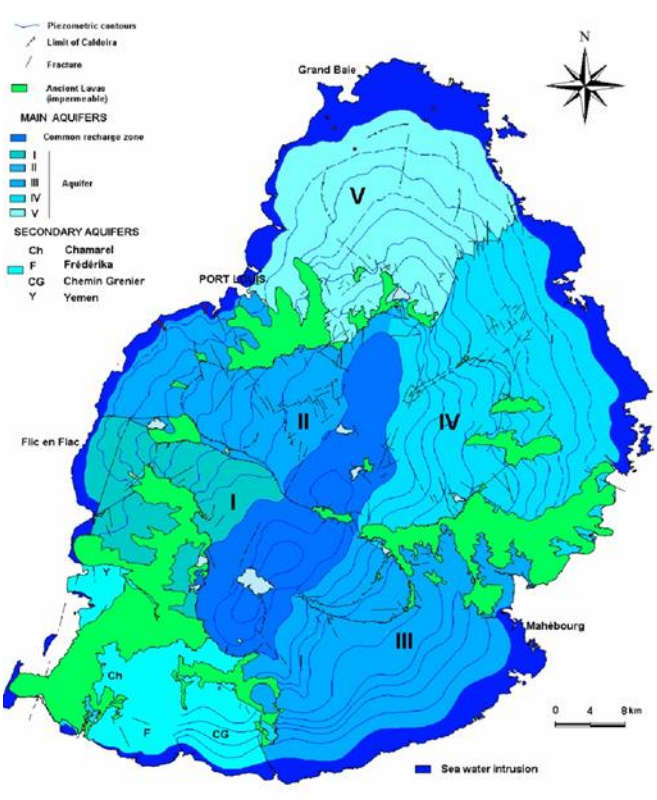


Figure 1-4 Mauritius Island showing the 5 main aquifers

Source: Hydrological Data Book 2000-2005.

Figure 1.4 presents the comprehensive hydrogeological framework of Mauritius, illustrating the five major coastal aquifer systems that form the foundation of the island's groundwater resources. The map reveals the complex spatial distribution and characteristics of these aquifer systems, critical hydrogeological features, and geological zonation that collectively demonstrate the diverse groundwater conditions across this Small Island Developing State.

In terms of Aquifer Systems and Their Characteristics, the map delineates five distinct systems each with unique hydrogeological properties. Aquifer I (Curepipe-Vacoas-Flic en Flac), located in the western region, is characterized by extensive green zones representing ancient impermeable lavas interspersed with intermediate permeability areas (light blue) that form the productive groundwater zones. Aquifer II (Phoenix-Beau Bassin-Albion/Moka) spans the northwestern urban corridor, prominently displaying the common recharge zone (dark blue) that receives precipitation from the central plateau and serves the densely populated capital region. Aquifer III (Nouvelle France-Rose Belle-Plaisance) covers the southeastern agricultural region, showing varied permeability zones transitioning from ancient lavas to recent permeable formations that support extensive agricultural activities. Aquifer IV (Nouvelle Decouverte-Plaines des Roches-Midlands) extends across the eastern coastal plains, with significant seawater intrusion zones evident along coastal boundaries, while Aquifer V (Northern Plains) occupies the northern tourism zone, displaying extensive seawater intrusion along coastal areas and complex piezometric patterns that reflect intensive groundwater exploitation for tourism infrastructure.

The Hydrogeological Features depicted in the map include several essential elements that control groundwater flow and quality. Piezometric contours, represented by black curved lines, indicate groundwater flow directions from the central recharge zone moving radially toward the coast, demonstrating the island's characteristic dome-shaped flow system. Fracture systems, shown as black dashed lines, reveal structural controls on groundwater movement, particularly evident along the caldera rim areas where geological discontinuities create preferential flow paths. Seawater intrusion zones, highlighted as dark blue coastal areas, identify critical vulnerability areas where saltwater has penetrated inland, particularly affecting the coastal boundaries of Aquifers II, IV, and V, indicating ongoing saltwater contamination threats. The central recharge zone, located in the elevated plateau area, represents the primary area where rainfall infiltration replenishes all aquifer systems, while secondary aquifers including Chamarel (Ch), Frederika (F), Chemin Grenier (CG), and Yemen (Y) are distinctly mapped in the southwestern region, showing their limited spatial extent compared to the major systems. In terms of Geological Zonation, the map employs a colour gradation system that effectively represents permeability variations across the volcanic landscape. Green areas indicate ancient impermeable lavas with low transmissivity values (10^{-7} to 10^{-6} m²/s) that form aquitards and guide groundwater flow boundaries. Light blue zones represent intermediate basaltic series with moderate transmissivity (10^{-6} to 10^{-3} m²/s) that constitute the primary productive aquifer layers, while dark blue areas signify recent highly permeable basalts with high transmissivity (10^{-5} to 10^{-2} m²/s) and seawater intrusion zones where saltwater contamination has occurred. This geological zonation demonstrates the complex multilayered volcanic structure that characterizes Mauritius's groundwater system, where recent and intermediate basaltic flows create the main aquifer framework overlying impermeable ancient bedrock formations. This spatial framework demonstrates why these five aquifer systems represent diverse hydrogeological conditions: from highly vulnerable coastal zones experiencing seawater intrusion to inland recharge areas affected by agricultural contamination, providing an ideal setting for comprehensive groundwater quality assessment in Small Island Developing States.

1.10 Outline of dissertation/thesis structure

This thesis is written in paper format according to guidelines of the University of KwaZulu-Natal whereby each paper represents a chapter. It comprises six chapters, including one published paper and two papers intended for publication (Chapter 3 to Chapter 5). The chapters progressively build understanding of groundwater dynamics in Small Island Developing States. A list of reference is provided at the end of each chapter.

Chapter 1 introduces the research context and framework, establishing the significance of groundwater quality in SIDS. This chapter outlines the research aims and objectives while providing background on Mauritius as a case study. It presents the logical progression of the research from trend analysis through mechanistic understanding.

Chapter 2 examines the existing literature to establish the theoretical foundation for investigating climate variability impacts on groundwater resources in Mauritius's volcanic aquifer systems using isotope hydrology techniques. The review specifically addresses three key knowledge domains aligned with the thesis objectives: (1) the limited understanding of how climate variability affects groundwater recharge patterns and quality in multi-layered volcanic aquifers typical of SIDS like Mauritius, (2) the insufficient application of isotope hydrology methods to trace groundwater sources and quantify climate-groundwater interactions in tropical island settings, and (3) the lack of integrated frameworks combining hydrogeochemical and isotopic approaches for sustainable groundwater management in climate-vulnerable SIDS. Through systematic analysis of global SIDS case studies, regional climate-groundwater research, and isotope hydrology applications, this chapter identifies critical research gaps that justify the need for comprehensive isotopic investigation of Mauritius's groundwater systems under varying climatic conditions, ultimately informing evidence-based adaptation strategies for similar volcanic island states..

Chapter 3 presents a detailed temporal analysis of groundwater quality across Mauritius's five major aquifers from 2010-2021. Through statistical analysis of key water quality parameters, this chapter identifies significant trends and patterns in groundwater quality evolution. The analysis establishes baseline conditions and highlights aquifers showing notable changes, providing the foundation for investigating causal factors.

Chapter 4 investigates the relationships between climate variability and groundwater quality changes identified in Chapter 3. By analysing correlations with drought indices, rainfall patterns, and extreme weather events, this chapter reveals how different aquifers respond to climatic stressors. The findings demonstrate varying levels of aquifer vulnerability to climate impacts across the island.

Chapter 5 employs isotopic techniques to understand the underlying mechanisms driving differential aquifer responses. Through analysis of stable isotopes (δ^2H and $\delta^{18}O$), this chapter characterizes groundwater recharge processes, delineates flow patterns, and assesses aquifer connectivity. The isotopic investigation provides crucial insights into why certain aquifers show greater sensitivity to climate impacts.

Chapter 6 synthesizes findings from the three research studies to develop recommendations for groundwater management in SIDS. This chapter integrates the understanding of trends, drivers, and mechanisms to propose practical strategies for sustainable groundwater protection. It concludes by identifying priorities for future research and highlighting implications for other SIDS facing similar challenges.

.

1.11 References

Baptiste A, Martyr-Koller R, Pringle P and Rhiney K. 2020. Climate change and small island developing states. Annual Review of Environment and Resources 45, 1–27.

Chacowry A, McEwen LJ and Lynch K. 2018. Recovery and resilience of communities in flood risk zones in a small island developing state: A case study from a suburban settlement of Port Louis, Mauritius. International Journal of Disaster Risk Reduction 28, 826–838.

Falkland T. 1999. Water resources issues of small island developing states. Natural Resources Forum 23, 245–260.

Gheuens J, Nagabhatla N and Perera EDP. 2019. Disaster-risk, water security challenges and strategies in Small Island Developing States (SIDS). Water 11(4), 637.

Giorgi L, Borchiellini S and Delucchi L. 1999. Appui a la Gestion des Ressources en Eau et a la Preservation de leur Qualite: Le Schema Hydrogeologique. Water Resources Unit, Mauritius.

Kowlesser A. 2018. Sustainable aquifer management in Small Island Developing States: A case study of Mauritius. MSc thesis, KTH Royal Institute of Technology, Sweden.

Maddocks A, Young RS and Reig P. 2015. Ranking the world's most water-stressed countries in 2040. World Resources Institute 26, 1–15.

Ministry of Public Utilities. 2005. Hydrology data book 2000-2005, Chapter 1: Introduction. Government of Mauritius. Available at https://publicutilities.govmu.org/Documents/2020/Legislation/Water/Hydrology%20Data%20Book/Book%202000-2005/Chapter%201/INTRODUCTION.pdf

United Nations. 1992. Conferences | Small Island Developing States. Available at https://www.un.org/en/conferences/small-islands

United Nations Framework Convention on Climate Change. 2005. Climate change, small island developing states. Climate Change Secretariat, Bonn, Germany.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter is structured in seven main sections that follow a logical sequence to establish the theoretical foundation for this research. Section 2.2 examines current water stresses on groundwater resources in SIDS, establishing the global context of challenges. Section 2.3 provides a detailed case study of Mauritius, including its water resources, geological framework, and aquifer systems. Section 2.4 presents comparative case studies from Pacific and Caribbean SIDS to contextualize Mauritius within the broader SIDS experience. Section 2.5 evaluates strategies to address groundwater quality challenges, including technological solutions, policy frameworks, and community-based approaches. Section 2.6 provides a comprehensive discussion synthesizing findings across all sections. Finally, Section 2.7 concludes with key insights and implications for future research and practice.

At the present time and also for future generations humankind and nature need water of good quality and in sufficient quantity. Water needs urgently to be protected against deterioration, to protect both humanity and nature. Therefore, the effects caused by climate change variabilities and anthropogenic activities should be assessed and managed. Groundwater presently provides half of the volume of water withdrawn for domestic use by the global population, including drinking water for the vast majority of the rural population who do not get their water delivered to them via public or private supply systems, and around 25% of all water used for irrigation. Water use has been increasing worldwide by about 1% per year since the 1980s, over the next 30 years driven by a combination of population growth, socio-economic development and changing consumption patterns (UN World Water Development Report, 2022). Global water demand is expected to continue increasing at a similar rate until 2050, accounting for an increase of 20 to 30% above the current level of water use (UN World Water Development Report, 2019). The overall dependence on groundwater is expected to rise as surface water availability becomes increasingly limited due to climate change (UN World Water Development Report, 2019; Water, 2022). The vulnerability of SIDS is directly affected by limited freshwater (groundwater and surface water) resources that are likely to be seriously compromised due to anthropogenic activities, rising sea levels and climate variability and change (Gheuens et al., 2019; Thomas et al., 2020).

2.2 Groundwater Quality Degradation Patterns in Small Island Developing States

Climate stressed groundwater resources present a growing challenge for protecting food security and economic sustainability, notably in Small Island Developing States (SIDS). Reduced water availability induced by climate change could result in undesirable consequences on both economic activities and environmental sustainability. Better understanding the economic impacts of climate change on water use, water availability, water supplier livelihoods, and consumer welfare is needed to facilitate more efficient and sustainable adaptation and mitigation measures to improve water sustainability and allocation among competing water sectors (Gohar et al., 2019).Climate change is likely to have considerable impacts on groundwater resources availability by reducing groundwater recharge as well as promoting greater discharge through more pumping to meet current and emerging economic demands (Gohar et al., 2019). Evidence of climate change impacts on groundwater resources has been found in Central Europe and South America (Dams et al., 2012; Melo & Wendland, 2017). Despite increasing attention directed to the management of groundwater resources and the potential impact of climate change on those resources, little attention has been paid to the impact of climate change on aquifers for the special needs and unique conditions facing all SIDS and the challenges that they face (Gohar & Cashman, 2016). It has been pointed out by Latha Shri and Mahesha that further growing water scarcity in many small islands aquifer systems climate change could increase saltwater intrusion pressure on groundwater and reduce effective storage capacity (Lathashri & Mahesha, 2016).

The vulnerability of SIDS groundwater systems is particularly acute due to their limited freshwater resources, high exposure to climate variability, and complex hydrogeological settings. A comprehensive assessment of 199 transboundary aquifers and 46 groundwater systems of SIDS reveals that the situation calls for immediate attention, with low-lying Pacific islands highly dependent on scarce, polluted, and increasingly saline groundwater resources facing dramatic choices in the absence of coordinated remedial action (UNESCO-IHP, 2016). Population density emerges as the main driver of water stress in all, but one of the 43 representative islands assessed, with 71% of islands at risk of water scarcity, peaking at 91% for low-lying islands (Holding et al., 2016).

2.2.1 Temporal Patterns of Groundwater Quality Changes in SIDS

Understanding temporal variations in groundwater quality is fundamental to assessing degradation patterns and developing effective management strategies for SIDS. Global analysis of approximately 170,000 monitoring wells and 1,693 aquifer systems reveals that rapid groundwater-level declines (>0.5 m $year^{-1}$) are widespread in the twenty-first century, with groundwater-level declines having accelerated over the past four decades in 30% of the world's regional aquifers (Jasechko & Perrone, 2024). This global trend is particularly concerning for SIDS, where groundwater resources are already limited and vulnerable.

Recent comprehensive analysis of an 11-year continuous groundwater quality dataset from Mauritius provides rare insights into temporal degradation patterns in a volcanic SIDS context. The study, utilizing monthly groundwater quality parameters including pH, conductivity, total dissolved solids (TDS), salinity, chloride, sulphate, and nitrate from 2010-2021, reveals complex temporal dynamics that challenge conventional understanding of climate-groundwater relationships (Seenath et al., 2024). Contrary to expectations, the Standardized Precipitation Index (SPI) and Standardized Precipitation-Evapotranspiration Index (SPEI) showed minimal correlation with water quality indicators, with only sulfate demonstrating correlations above 0.4 in specific aquifers against a 12-month SPI.

The temporal analysis reveals that groundwater quality responses to climate variability are more nuanced than previously understood. Sulphate and chloride showed what researchers' term "notable correlations" (defined as correlations above 0.3) when assessed against global climate modes such as the El Niño-Southern Oscillation (ENSO) and Antarctic Oscillation (AAO), respectively. This suggests that global climate patterns may have more influence on groundwater quality than local precipitation indices, highlighting the complex teleconnections affecting SIDS groundwater systems.

Long-term trends in groundwater quality parameters reveal concerning patterns of degradation across different geographical regions. A comprehensive 20-year analysis (2002-2022) of spatio-temporal variations in pH, electrical conductivity (EC), and bicarbonate (HCO_3^-) in irrigation-dependent regions demonstrates that over-extraction, erratic precipitation patterns, and intensive agricultural practices progressively worsen groundwater quality, impacting soil health and crop productivity (Bahrami et al., 2025). While this study focuses on the Indian Peninsula, the mechanisms identified particularly the interplay of alkalinity, salinity, and sustainability provide valuable insights for understanding degradation processes in SIDS agricultural systems.

2.2.2 Spatial Variations in Groundwater Quality Degradation

Spatial heterogeneity in groundwater quality degradation across SIDS reflects the complex interplay of geological, hydrogeological, and anthropogenic factors. The global assessment of SIDS groundwater systems reveals significant spatial variations in vulnerability and degradation patterns, with coastal aquifers showing the highest susceptibility to quality deterioration due to saltwater intrusion and proximity to pollution sources (UNESCO-IHP, 2016).

Regional variations in degradation patterns are influenced by several key factors. In Pacific SIDS, the limited land area and high permeability of volcanic and coral formations result in rapid contaminant transport and widespread aquifer vulnerability. Caribbean SIDS demonstrate different degradation patterns, with karst aquifers showing particular susceptibility to surface contamination due to rapid infiltration through dissolution features. Indian Ocean SIDS, including Mauritius, exhibit complex degradation patterns influenced by volcanic geology, varying topography, and diverse land use practices. The spatial distribution of degradation is closely linked to population density and economic activities. Areas with high population density consistently show elevated groundwater contamination levels, with urban centres and industrial zones representing hotspots of quality degradation. Agricultural areas demonstrate distinct degradation patterns, with intensive farming practices leading to elevated nitrate concentrations and pesticide contamination in underlying aquifers.

Hydrogeological controls on spatial degradation patterns are particularly important in volcanic island settings. The multi-layered nature of volcanic aquifers creates complex flow systems where contamination can occur at different depths and migrate along preferential flow paths. Fracture systems and scoraceous zones provide rapid pathways for contaminant transport, while clayey inter-layers can create perched contamination zones that persist for extended periods.

2.2.3 Key Degradation Indicators and Monitoring Approaches

Effective assessment of groundwater quality degradation in SIDS requires identification of appropriate indicators and development of monitoring approaches suited to island-specific conditions. Primary degradation indicators include salinity parameters (electrical conductivity, total dissolved solids, chloride concentration), chemical indicators (pH, sulphate, nitrate, bicarbonate), and biological indicators (bacterial contamination, particularly E. coli).

Salinity-related parameters serve as primary indicators of degradation in SIDS due to the omnipresent threat of saltwater intrusion. Electrical conductivity provides a rapid, cost-effective measure of overall water mineralization, while chloride concentration specifically indicates seawater influence. The ratio of major ions (Na/Cl, Ca/SO_4) can help distinguish between different contamination sources, including seawater intrusion, agricultural pollution, and domestic wastewater.

Chemical indicators reflect various degradation processes affecting SIDS groundwater systems. Elevated nitrate concentrations typically indicate agricultural or domestic contamination, while sulfate variations may reflect both natural geological processes and anthropogenic inputs. pH changes can indicate acid-base reactions related to mineral weathering, organic matter decomposition, or industrial contamination. The integration of multiple chemical parameters provides a more comprehensive understanding of degradation processes than reliance on individual indicators.

Monitoring approaches for SIDS must account for logistical constraints, limited resources, and the need for sustainable long-term data collection. Traditional monitoring networks based on regular sampling from fixed locations remain the foundation of degradation assessment. However, innovative approaches are increasingly important, including continuous monitoring systems for key parameters, remote sensing applications for large-scale assessment, and citizen science initiatives to expand spatial and temporal coverage.

The application of standardized indices for degradation assessment provides valuable tools for comparative analysis and management decision-making. Water Quality Indices (WQI) integrate multiple parameters into single values representing overall quality status, while specific indices for saltwater intrusion (such as the Saltwater Intrusion Index) focus on key threats to SIDS groundwater resources. These indices must be adapted to local conditions and validated against site-specific quality standards and water use requirements.

2.2.4 Case Study: Mauritius Groundwater Quality Trends

Mauritius provides an exemplary case study for understanding groundwater quality degradation patterns in a volcanic SIDS context, with extensive hydrogeological characterization and an 11-year continuous quality monitoring dataset representing one of the most comprehensive temporal analyses available for SIDS groundwater systems.

The small island developing state of Mauritius is ranked 51st worldwide for greatest disaster risk according to the World Risk Report 2021 (World Risk Report 2021 Focus: Social Protection, 2020). This high ranking is principally attributed to the geographical positioning of the island which results in very high exposure to cyclones, floods, droughts, and sea-level rise. In the 20th Century, the frequency of tropical cyclones in the vicinity of Mauritius has increased with a relative fall in intensity over the years, resulting in increased vulnerability for the communities exposed to these high occurrences of low or average intensity extreme events (Garnier & Desarthe, 2013). A significant increase in the frequency and intensity of other extreme weather events, including floods and droughts, have been reported over the years on the island (Seebocus et al., 2021; Chacowry et al., 2018). Additionally, Mauritius has experienced a relative rise in sea level of 4–6 mm per year over the past 30 years, corresponding to an increase of 2–3 times higher than global average (Becker et al., 2019). In the face of these extreme events, it is imperative to multiply adaptive strategies to dampen vulnerability. However, robust adaptation strategies would necessitate a knowledge of the spatial and temporal evolutions of groundwater parameters with regards to climate change on the island. The tropical savanna climate of Mauritius would therefore provide an ideal case study, with potentially highly insightful results on the extents to which a vulnerable small island state has been impacted by the changing climate.

In Mauritius, 46% of domestic water comes from groundwater which is being abstracted from 5 main aquifers (Ministry of Energy and Public Utilities, 2024; Sonara et al., 2025). While the ancient basaltic formations of Mauritius, dating from 8.9 to approximately 4.7 Ma during the Older Series shield-building phase (Moore et al., 2011; Paul et al., 2005), are massive or weathered and generally have very low permeability, the productive aquifer zones are characterised by highly permeable fractured lava flows and scoraceous zones, which increases the vulnerability of movement of pollutants due to human activities and seawater pollution. In addition, the aquifers are in hydraulic contact with the sea along all the coastline boundaries. The Island of Mauritius consists of a Central Plateau surrounded by mountain ranges and plains. The Plateau rises to a maximum elevation of about 600 m (a.m.s.l) in the South of the Island and has a mean elevation of about 300 – 400 m (a.m.s.l), the highest peak being 828 m (a.m.s.l). Groundwater circulation is limited to these fractured and scoraceous zones within the otherwise low-permeability basaltic formations (MEPU, 2010).

Mauritius enjoys a tropical maritime climate with 2 seasons summer from November to April, and winter from May to October. The summer season is characterized by higher rainfall and warmer temperatures, during which tropical cyclones occur. February represents the wettest month of the year. Winter is cooler and relatively drier. October is the driest month. The average annual rainfall over Mauritius is 1993 mm equivalent to about 3700 Mm^3. Rainfall varies from 1400 mm on the Eastern Coast to 4000 mm on the Central Plateau and 600 mm on the Western Coast. The annual evaporation has been estimated as 30%, surface runoff as 60 % and the groundwater recharge as 10%. The annual potential evapo-transpiration varies between 1100 mm and 1600 mm with small inter - annual variations. The relative humidity has an average value of 80% (MEPU, 2010). Mauritius is 100% dependent on rain.
The average annual rainfall of 1993 mm shown in Figure 2.1 was calculated over the 1971-2000 period

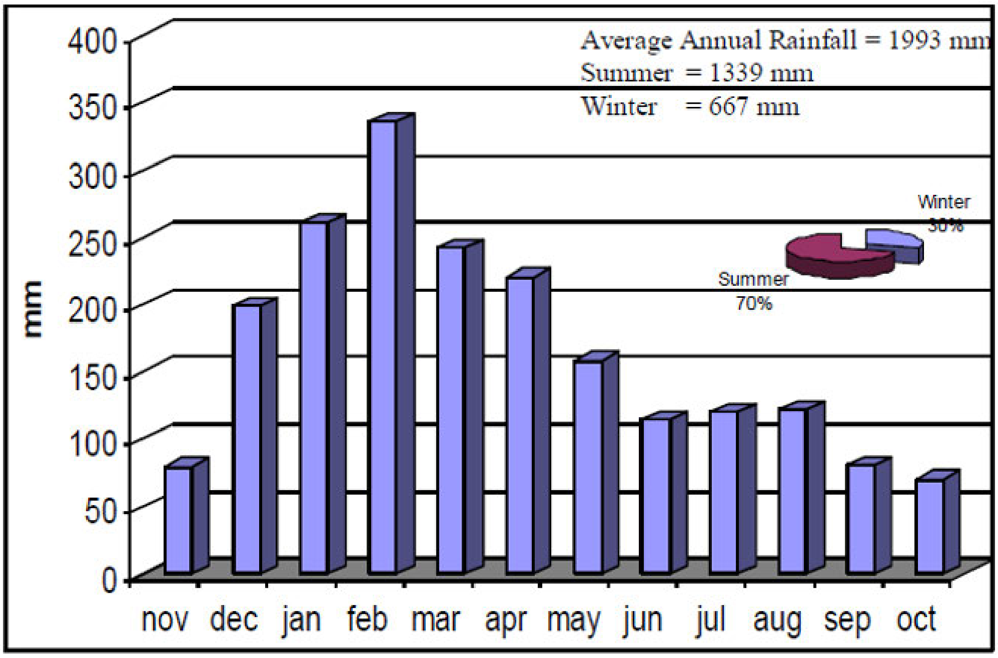


Figure 2-1Average annual rainfall over Mauritius (Source: Mauritius Meteorological Services)

2.2.4.1 Water Resources in Mauritius

In Mauritius, the source of water is rain. The water resources of Mauritius are divided into two categories, the surface water resources (streams and rivers, ponds and dams) and the groundwater resources, situated below ground in the pervious and permeable part of the subsurface hard rock formations. There are 92 rivers, 232 rivulets, 5 man-made lakes, 2 natural lakes and groundwater distributed into 7 groundwater basins which constitute the main freshwater bodies of Mauritius.

2.2.4.1.1 The Surface Water Resources

The source of the available and already utilized water resources (except for desalination and recycling of wastewater) is from the rainfall over the island, which shows high variability over the year and from year to year. The rainfall pattern and the variability of the rainfall make storage facilities mandatory to collect and store water during the wet periods to provide supply when shortage of water in dry season becoming worse. The present supply system is utilizing a number of dams and reservoirs on the river systems. Surface water contributes about half of all potable water produced. The dense network of rivers are as follows.

- 25 major catchment areas
- 22 minor river basins
- 7 flow measuring station

The surface water sources that are harnessed for potable and agricultural water supply are as follows.

- 350 river-run off takes
- 3 major river abstractions
- 6 major impounding reservoirs of total capacity 77.4 Mm^3

2.2.4.1.2 The Groundwater Resources

There are 5 main aquifers in Mauritius from which 429 boreholes are being used as follows.

- 133 boreholes for domestic use
- 157 boreholes for irrigation use
- 139 boreholes for industrial use

The groundwater resources of Mauritius played a fundamental role in the drinking water supply since the groundwater exploitation started in the 1960's. Presently groundwater catchments ensure about 54% of the potable water supply in the island. Mauritius's groundwater resources are distributed across five main aquifers, each exhibiting distinct hydrogeological characteristics that influence degradation patterns. The island's volcanic geology, comprising Ancient, Intermediate, and Recent Basaltic Series with contrasting permeabilities, creates complex multi-layered aquifer systems vulnerable to various degradation processes. There are five main aquifers in Mauritius and a central recharge zone as shown in Figure 2.1.

- Aquifer I: Curepipe/ Vacoas/ Flic-en-Flac commonly known as the Curepipe aquifer
- Aquifer II: Phoenix/ Beau-Bassin/ Albion –Moka/Coromandel.
- Aquifer III: Nouvelle France/ Rose-Belle/Plaisance.
- Aquifer IV: Nouvelle Decouverte/ Plaine des Roches/ Trou d'eau Douce.
- Aquifer V: Northern Plains

Other secondary aquifers exist, and they are.

- The aquifer of Chemin Grenier-Frederica
- The aquifer of Grande Riviere Noire (Alluvium)
- The aquifer characterised by fracture
- The aquifer of carbonated formations

The secondary aquifers have been lumped together as they exist only in the South-western part of the island as shown in Figure 2.2

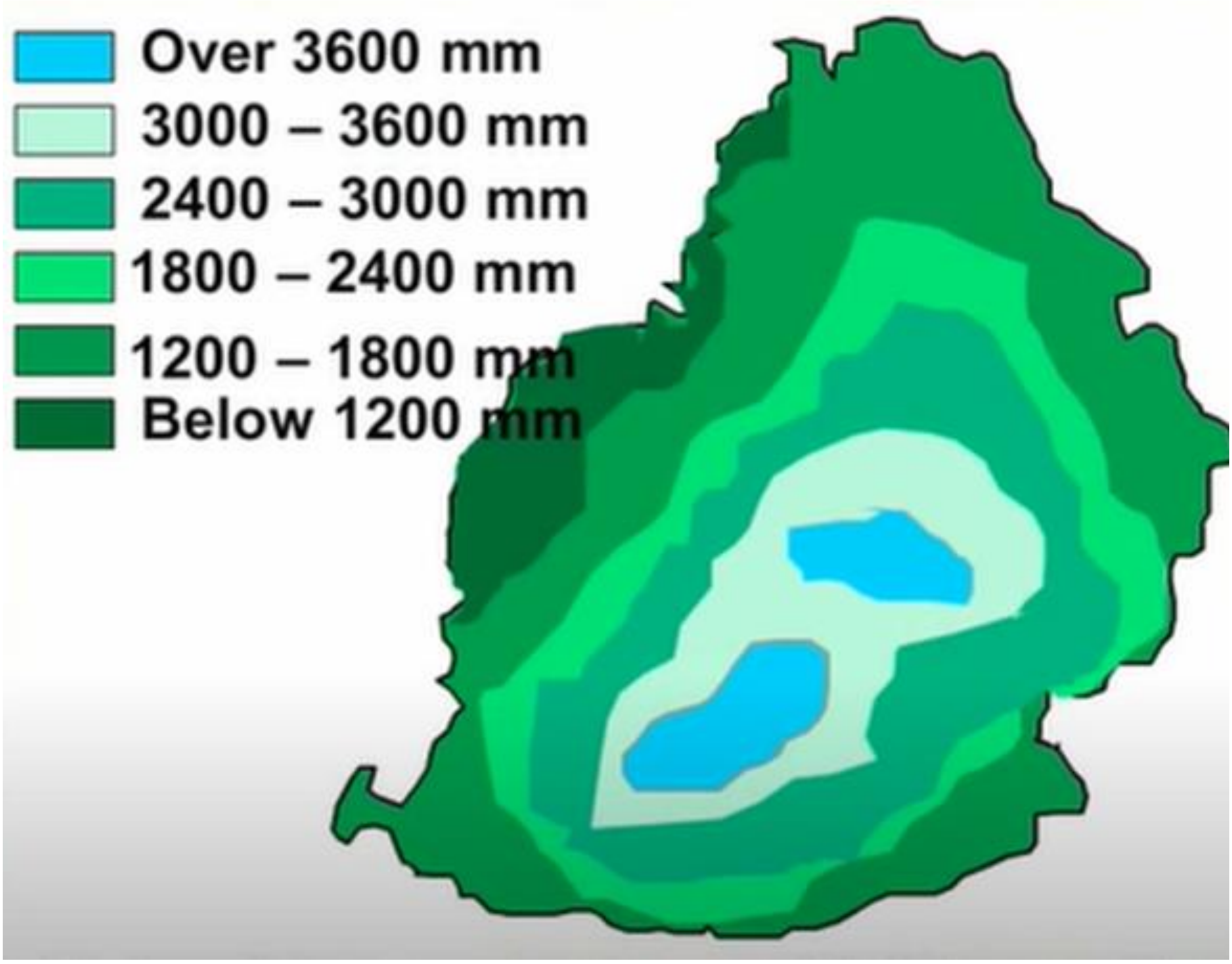


Figure 2-2 Isohyet map of Mauritius (Source: Mauritius Meteorological Station)

Most of the groundwater recharge takes place at the Central Plateau and to a large extent, the underground flow mainly follows the topographic cuts in the old crater rim and feeds the downstream aquifers outside the crater rim. In this way, the groundwater flow pattern is essentially radial from the Central Plateau down through the sloping aquifers outside the rim to the coral reef lagoon and the sea.

Before examining the aquifer systems, it is essential to understand the geological foundation upon which these groundwater resources are developed. Mauritius is a volcanic island formed through multiple eruptive phases spanning approximately 10 million years, creating a complex geological structure that directly controls groundwater occurrence and flow (Ministry of Public Utilities, 2005). The island's geological evolution occurred in four major phases: the Emergence Period (10-6.7 million years ago), the Older Volcanic Series (6.2-5 million years ago), the Intermediate Volcanic Series (3.5-1.7 million years ago), and the Younger Volcanic Series (700,000-25,000 years ago) (Giorgi et al., 1999).

The geological structure comprises three distinct volcanic formations with contrasting hydrogeological properties. The Ancient Basaltic Series forms the impermeable bedrock foundation, consisting of massive, weathered basalts with very low permeability (transmissivity 10^{-7} to 10^{-6} m²/s) that act as aquitards and define aquifer boundaries (Ministry of Public Utilities, 2005). The Intermediate Basaltic Series, deposited during periods of localized volcanic activity, exhibits variable permeability (transmissivity 10^{-6} to 10^{-3} m²/s) and forms the primary productive aquifer layers, particularly where fractured or scoraceous. The Recent Basaltic Series, comprising highly porous and fractured volcanic flows with extensive lava tunnel networks, demonstrates the highest permeability (transmissivity 10^{-5} to 10^{-2} m²/s) and facilitates rapid groundwater recharge and circulation (Giorgi et al., 1999).

The island's volcanic structure is dominated by two major caldera collapse events that created the central plateau and northern plains depressions, which now serve as the primary groundwater recharge zones. These calderas are bounded by ancient basaltic mountain ranges that form natural no-flow boundaries for the aquifer systems. Fracture systems, particularly along N20° and N100° orientations, create preferential groundwater flow paths and influence aquifer connectivity (Ministry of Public Utilities, 2005). The radial drainage pattern established by the volcanic dome structure directs groundwater flow from the central recharge areas toward coastal discharge zones, making all major aquifers inherently coastal systems vulnerable to seawater intrusion. Figure 2.2 shows the geological Framework, the geological structure and structural Controls on groundwater.

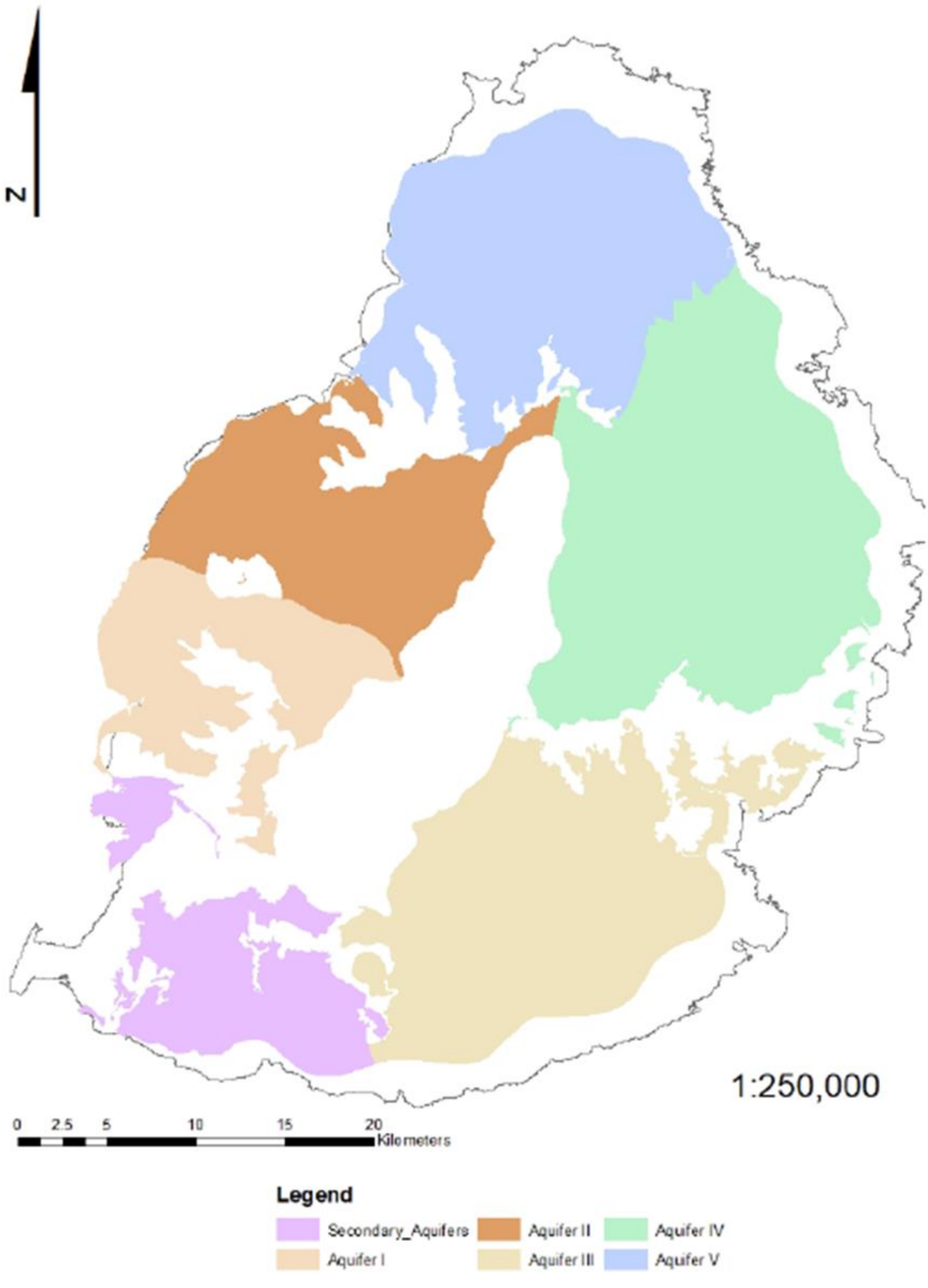


Figure 2-3 The 5 main aquifers of Mauritius (adapted from Giorgi et al., 1999).

Aquifer I (Fig 2.4) is a multi-layered aquifer constituted by the superposition and juxtaposition of basaltic flows, fresh and weathered separated by clayish facies. The superficial layer of the aquifer consists of recent or intermediate basaltic flows. Lava tunnels and scoriaceous formations under the water table constitute channels where water flows very rapidly. The spatial distribution and boundaries of this aquifer system are illustrated in Figure 2.4.

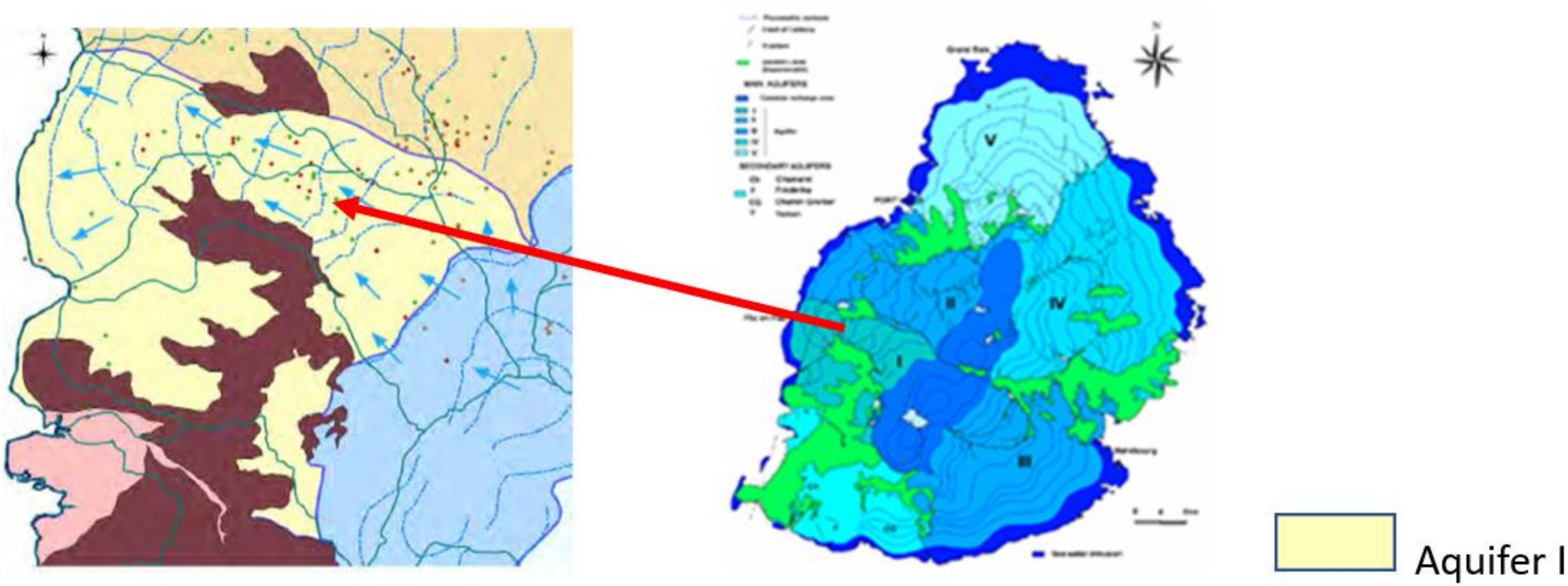


Figure 2-4 Aquifer I - Aquifer of Curepipe - Vacoas – Flic enFlac

Groundwater abstraction patterns in Aquifer I (Curepipe/Vacoas/Flic-en-Flac) show significant variation across different usage sectors (Table 2.1). Domestic use dominates the abstraction with 17 boreholes extracting 20.1 Mm³/year, representing approximately 96% of total groundwater extraction from this aquifer. Agricultural use accounts for 23 boreholes but only 0.6 Mm³/year (3% of total), while industrial use utilizes 21 boreholes extracting 0.3 Mm³/year (1% of total). The total abstraction from 71 boreholes amounts to 21.0 Mm³/year.

Table 2-1 Groundwater abstraction in Aquifer I

Usage	**No. of boreholes**	**Depth range (m)**	**Abstraction Mm³/year**	**Main areas**
Domestic	17	26.5 - 66.0	20.1	Curepipe, Vacoas, Flic-en-Flac
Agricultural	23	35.1 - 125.0	0.6	Central Plateau recharge zone, surrounding aquifer areas
Industrial	21	24.0 - 135.0	0.3	Distributed across aquifer system boundaries
Total	**71**	**24.0 - 135.0**	**21.0**	**Curepipe/Vacoas/Flic-en-Flac aquifer system**

(Source: Ministry of Public Utilities, 2005)

The dominance of domestic extraction in Aquifer I reflects its strategic importance for urban water supply, while the low agricultural and industrial abstraction rates suggest either limited water rights allocation or preferential use of surface water for these sectors. Groundwater flow from recharge areas to the coast amounts to 26.8 Mm³/year, with total groundwater recharge approximately 48 Mm³/year, indicating a sustainable extraction rate relative to natural replenishment.

According to (Giorgi et al., 1999), from borehole drilling it was found that there were two deep valleys made up of ancient basaltic flows (8-10 million years old from the Older Series) and filled by intermediate (3.5-1.9 million years old) and recent basalt flows (700,000-20,000 years old). These valleys of different-aged volcanic formations guide groundwater circulations, particularly in levels of fossil alluvium located at the base of these flows. These two valleys guide groundwater circulations and particularly in levels of fossil alluvium located at the base some flows. The top of Aquifer II **(**Phoenix/Beau-Bassin/Albion-Moka/Coromandel**)** is located within clayish semi-impermeable basalts which show some characteristics of semi-confined aquifers. The geographic extent and structural features of this aquifer system are illustrated in Figure 2.5.

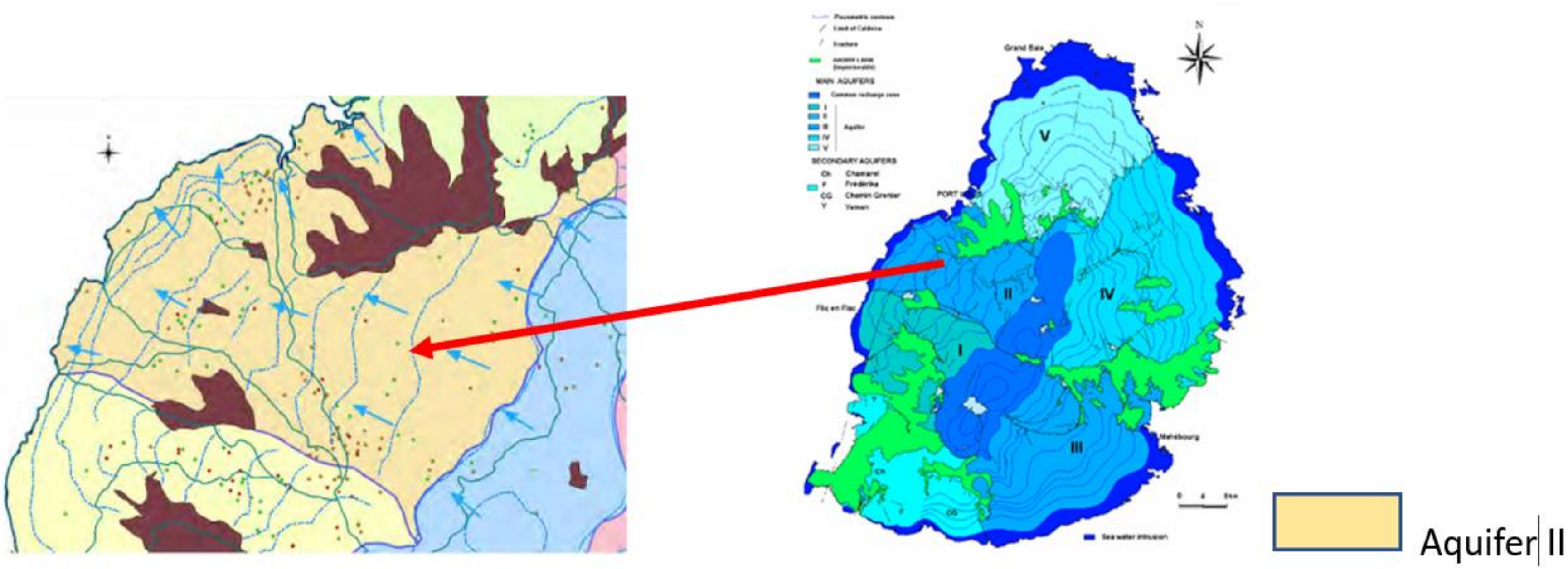


Figure 2-5 Aquifer II- Aquifer of Phoenix – Beau Bassin -Albion – Moka - Coromandel

Groundwater extraction data for Aquifer II reveals a different usage pattern compared to Aquifer I (Table 2.2). The total extraction of 17.6 Mm^3/year is distributed across 123 boreholes, with domestic use accounting for 11 boreholes extracting 7.5 Mm^3/year (43% of total extraction). Industrial use shows the highest extraction rate with 46 boreholes extracting 5.7 Mm^3/year (32% of total), while agricultural use utilizes the largest number of boreholes (66) but extracts 4.4 Mm^3/year (25% of total).

Table 2-2 Groundwater abstraction in Aquifer II

Usage	No. of boreholes	Abstraction Mm^3/year
Domestic	11	7.5
Agricultural	66	4.4
Industrial	46	5.7
Total	123	`17.6

The higher number of agricultural boreholes (66) with relatively low total extraction (4.4 Mm^3/year) suggests either distributed small-scale irrigation systems or seasonal use patterns. Industrial extraction efficiency is notably high, with 46 boreholes producing 5.7 Mm^3/year, indicating concentrated high-yield installations. Groundwater flow to the coast (40.5 Mm^3/year) and total recharge (58.1 Mm^3/year) suggest sustainable management potential if extraction patterns remain stable.

Aquifer III (Nouvelle France/Rose-Belle/Plaisance) as described by Giorgi et al., 1999 has different hydraulic behaviour in different sectors: to the north the flow is conditioned by breaches that border the rims of the caldera, while to the south, groundwater of the superficial aquifer strengthens the recharge of the reservoir. Near the area of Mare Tabac the variation of the static water level as observed until 1999 varied from 5 to 10 m at Nouvelle France and 20-30 metres at Mare Tabac. These fluctuations are conditioned by the presence of ancient basalts (Older Series, 8-10 million years old) and at places covered by intermediate basalts (Middle Series, 3.5-1.9 million years old) that have channelled basaltic flows and subsequently groundwater flows. The spatial distribution and hydrological characteristics of this aquifer system are depicted in Figure 2.6.

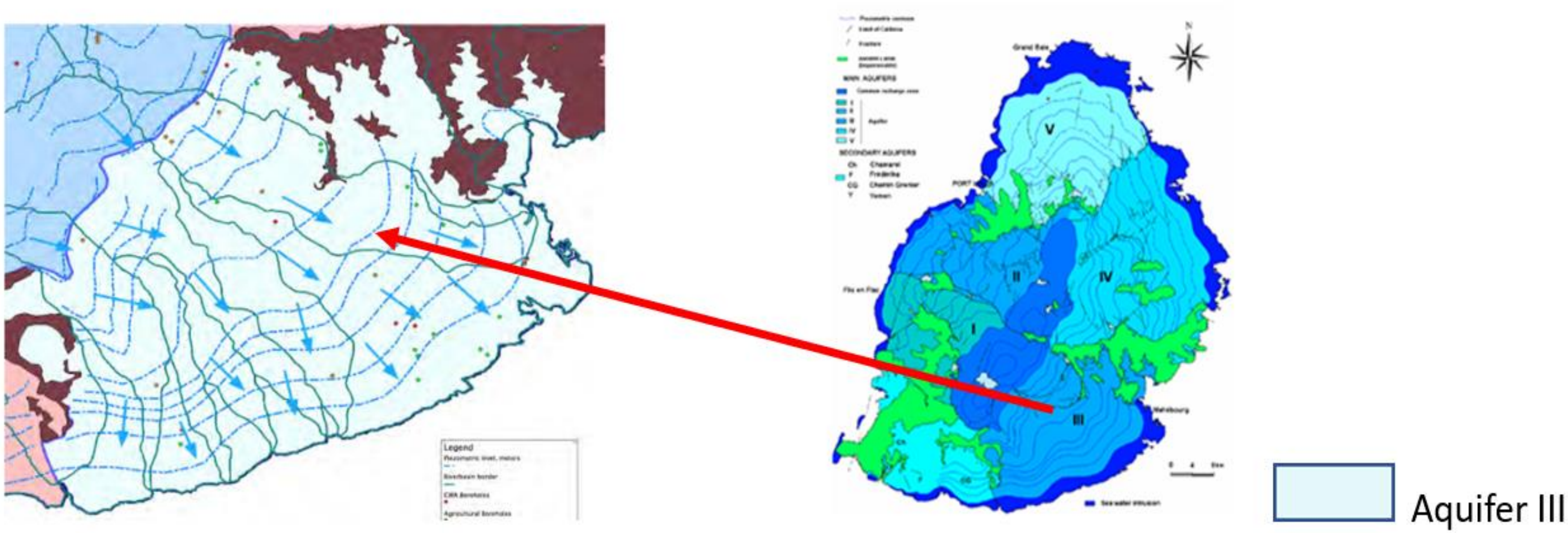


Figure 2-6 Aquifer III - Aquifer of Nouvelle France – Rose Belle - Plaisance

Groundwater abstraction data for Aquifer III shows a distinct pattern with domestic use representing the dominant extraction activity (Table 2.3). From a total of 42 boreholes, domestic use accounts for 12 boreholes extracting 16.5 Mm^3/year, representing approximately 93% of the total annual extraction. Agricultural use utilizes 17 boreholes but extracts only 0.5 Mm^3/year (3% of total), while industrial use operates 13 boreholes extracting 0.7 Mm^3/year (4% of total). The combined extraction from all sectors totals 17.7 Mm^3/year.

Table 2-3 Groundwater abstraction on Aquifer III

Usage	No. of boreholes	Abstraction Mm^3/year
Domestic	12	16.5
Agricultural	17	0.5
Industrial	13	0.7
Total	42	17.7

(Source: Ministry of Energy and Public Utilities, 2024)

The concentration of domestic extraction in Aquifer III suggests either high-yield boreholes or intensive pumping regimes that may create vulnerability to quality degradation through over-exploitation or saltwater intrusion. The minimal agricultural and industrial use may reflect water quality constraints, geological limitations, or regulatory restrictions.

Aquifer IV (Nouvelle Découverte/Plaine des Roches/Trou d'Eau Douce) comprises of three main reservoirs: the eastern part of the intracalderic reservoir, the median reservoirs of Camp Thorel-Pont Bon Dieu and Melrose-Belle Mare, and the coastal reservoirs of Plaines des Roches and Trou d'eau Douce. The median reservoir of Camp Thorel-Pont Bon Dieu is limited to the north by the fault N_20 that affects the border of the caldera and to the south by the ridge of ancient basalt. The seasonal variation of water in the aquifers is high, between 10-20 m as of 1999, as described by (Giorgi et al., 1999) describes this as seasonal variation rather than pumping-induced decline suggests this is the aquifer's natural behaviour in response to wet and dry seasons, indicating the system was not under significant pumping stress as of 1999. However, recent evidence suggests conditions have significantly deteriorated since 1999, with current modelling studies indicating that groundwater is now vulnerable to high pumping rates, producing drawdowns of up to 7m under extraction rates of 300 m^3/day, and that sustainable extraction limits may be approaching 200 m^3/day per installation to avoid compromising the aquifer's integrity (Nowbuth et al., 2012). This transition from natural seasonal fluctuations to pumping-stressed conditions reflects the broader global trend of accelerating groundwater decline in aquifer systems worldwide, particularly in small island developing states where over-extraction and climate-induced impacts are exacerbating water security challenges. The complex structure and boundaries of these interconnected reservoir systems are illustrated in Figure 2.7.

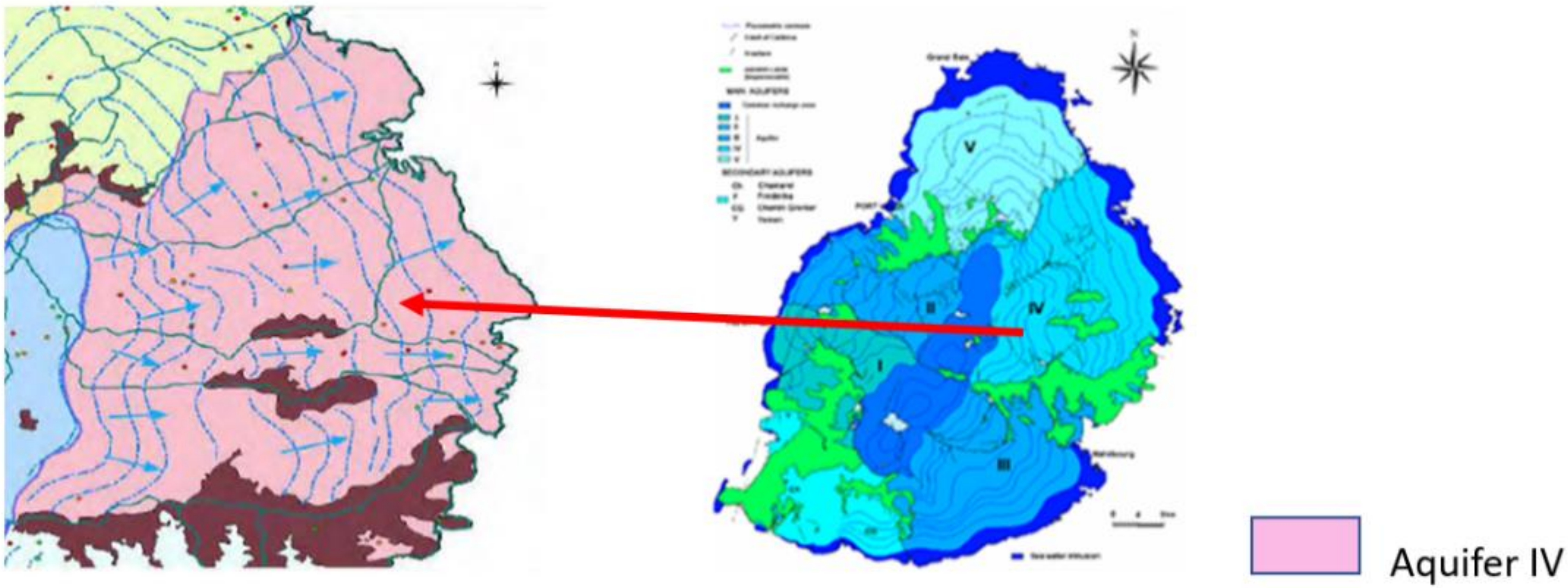


Figure 2-7 Aquifer IV – Aquifer of Nouvelle Découverte – Plaine des Roches – Midlands- Trou d'Eau Douce

Groundwater extraction patterns in Aquifer IV demonstrate the highest domestic water demand among all aquifers (Table 2.4). Domestic use dominates with 11 boreholes extracting 20.5 Mm^3/year, accounting for 96% of the total annual extraction from this aquifer. This represents the highest domestic extraction rate per borehole across all aquifer systems. Agricultural and industrial uses show minimal extraction rates, with 14 agricultural boreholes extracting 0.4 Mm^3/year (2% of total) and 15 industrial boreholes also extracting 0.4 Mm^3/year (2% of total). The total extraction from 40 boreholes amounts to 21.3 Mm^3/year.

Table 2-4 Groundwater abstraction in Aquifer IV

Usage	No. of boreholes	Abstraction Mm^3/year
Domestic	11	20.5
Agricultural	14	0.4
Industrial	15	0.4
Total	**40**	**21.3**

Groundwater flow from recharge area to coast is 80 Mm^3/ year. Total groundwater recharge in aquifer I is approximately 101.3 Mm^3/ year.

Aquifer V (Northern Plains), the aquifer of the Northern plains is located north of the calderic rim. The surface, in general recent basaltic flows (Younger Series, 700,000-20,000 years old), is very permeable and nearly all rainwater which is not evaporated is entering the aquifer system by direct infiltration. Recent basaltic flows are underlain by alternating weathered and fresh intermediate lava flows which all together form a multi-layered aquifer. The aquifer consists of various zones of recharge. The valleys of Creve Coeur-Notre Dame and Les Mariannes-Congomah contribute to the feeding of the western part of the northern plains. There are also significant fractures that allow the direct recharge of the northern aquifer to the Central-east part of the northern plains. Surface water contributes to the recharge of the aquifers and is dependent on various factors including direct rainfall and percolation due to infiltration along rivers. Groundwater is contained by the superposition and juxtaposition of recent and intermediate lavas separated by the calderic structure, ancient valleys and topographic cuts. The recent lavas have a small slope and absorb the quasi-totality of rainwater. There are two main breaches in the caldera of the northern plains which extend into the ocean and allow for sea water intrusion for several kilometres through these direct hydraulic connections (Giorgi et al., 1999). The geographical extent and recharge mechanisms of this extensive aquifer system are shown in Figure 2.8.

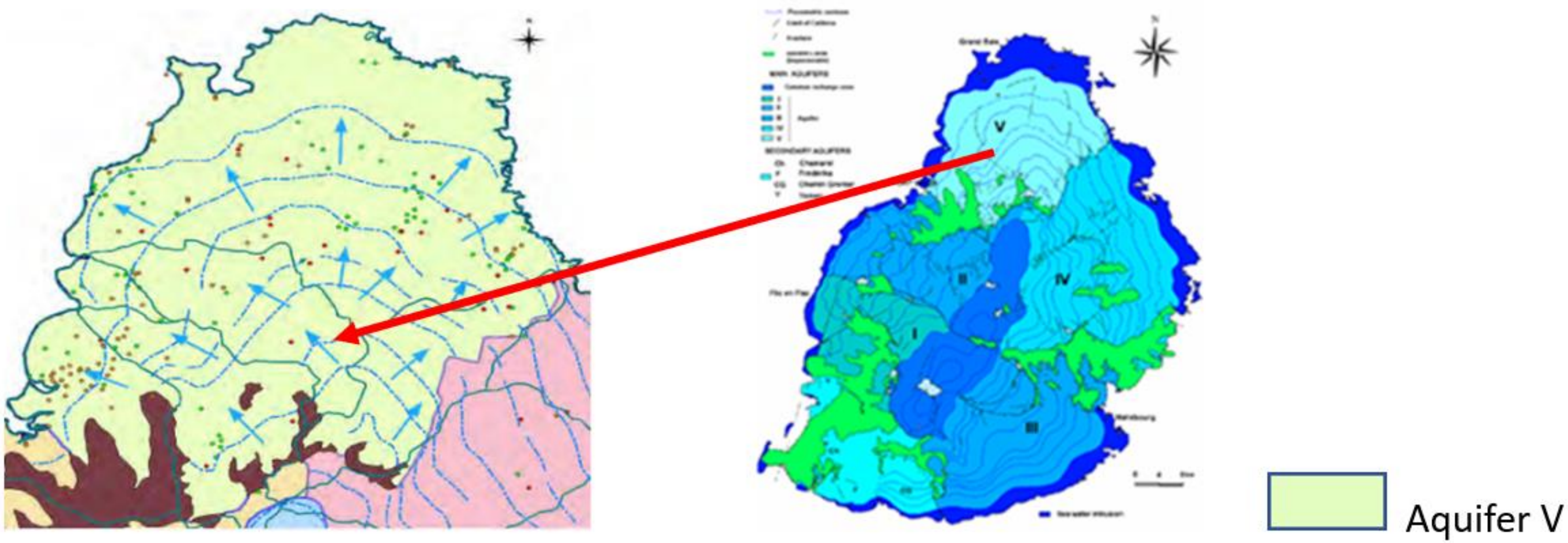


Figure 2-8Aquifer V– Northern Aquifer

Groundwater extraction data for Aquifer V reveals the most extensive borehole network and highest total extraction among all aquifers (Table 2.5). With 152 boreholes in operation, this aquifer shows the largest scale of groundwater development. Domestic use accounts for 22 boreholes extracting 22 Mm^3/year, representing 89% of total extraction and the highest absolute domestic extraction volume. Industrial use operates the largest number of boreholes (61) but extracts only 1.2 Mm^3/year (5% of total), while agricultural use utilizes 69 boreholes extracting 1.5 Mm^3/year (6% of total). The total annual extraction reaches 24.7 Mm^3/year, making this the most heavily exploited aquifer system.

Table 2-5 Groundwater abstraction in Aquifer V

Usage	No. of boreholes	Abstraction Mm^3/year
Domestic	22	22
Agricultural	69	1.5
Industrial	61	1.2
Total	152	24.7

The large number of low-yield agricultural and industrial boreholes in Aquifer V suggests distributed extraction systems serving small-scale users. Total groundwater recharge (144.7 Mm^3/year) significantly exceeds extraction (24.7 Mm^3/year), indicating substantial development potential if quality and sustainability constraints can be managed.

Other secondary aquifers exist, and they are (i) The aquifer of Chemin Grenier-Frederica and (ii) The aquifer of Grande Riviere Noire (Alluvium). For the most part, the secondary aquifers are located in the south-western corner of Mauritius. These aquifers have in general limited hydraulic connection to the principal aquifers and the central recharge area. The aquifer system is dominated by the ancient basaltic formations (Older Series, 8-10 million years old). The location and extent of these smaller aquifer systems are depicted in Figure 2.9.

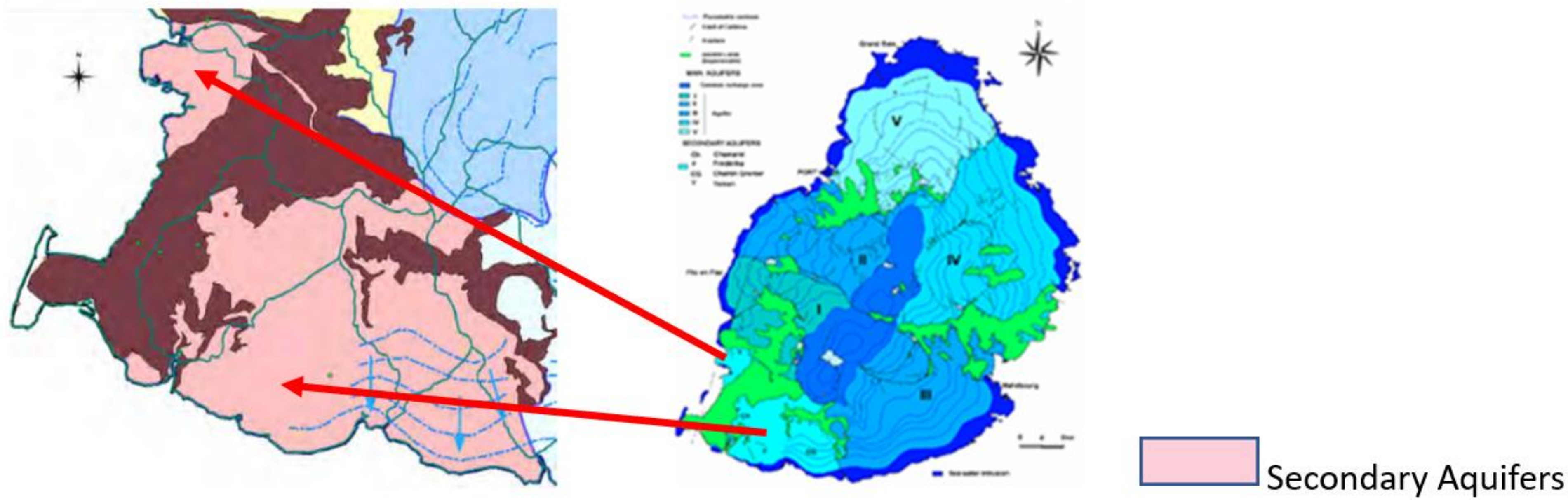


Figure 2-9 Secondary Aquifers

Groundwater extraction from the secondary aquifers represents minimal development compared to the main aquifer systems (Table 2.6). With only 4 boreholes in total operation, these aquifers show very limited exploitation. Domestic use accounts for 2 boreholes extracting 1.55 Mm^3/year (97% of total extraction), while agricultural use utilizes 2 boreholes extracting only 0.05 Mm^3/year (3% of total). No industrial boreholes are currently operational in these secondary systems. The total annual extraction of 1.60 Mm^3/year represents less than 2% of the groundwater extraction from any individual main aquifer, highlighting the limited capacity and development of these secondary systems.

Table 2-6 Groundwater abstraction in the Secondary Aquifers

Usage	No. of boreholes	Abstraction Mm^3/year
Domestic	2	1.55
Agricultural	2	0.05
Industrial	0	0
Total	4	1.60

Groundwater flow from recharge area to coast is 4.1 Mm^3/ year. Total groundwater recharge in aquifer I is approximately 5.7 Mm^3/ year

2.2.4.1.3 Temporal Quality Degradation Analysis

The comprehensive 11-year groundwater quality monitoring program (2010-2021) conducted by Mauritius's Central Water Authority provides unprecedented insights into temporal degradation patterns in a SIDS context. The analysis of monthly composite data for pH, conductivity, TDS, salinity, chloride, sulphate, and nitrate across all five main aquifers reveals complex degradation dynamics that challenge conventional understanding of climate-water quality relationships.

Temporal variations in water quality parameters showed minimal correlation with standard climate indices, with the Standardized Precipitation Index (SPI) and Standardized Precipitation-Evapotranspiration Index (SPEI) displaying unexpectedly weak relationships with groundwater quality indicators. Only sulphate demonstrated correlations above 0.4 in Aquifers II and III against a 12-month SPI, suggesting that precipitation effects on groundwater quality are more complex and delayed than typically assumed.

The concept of "notable correlation" (defined as correlations above 0.3) proved useful for identifying subtle but potentially significant relationships between climate models and water quality. Sulphate showed notable correlation with the 12-month SPI in specific aquifers, while chloride exhibited notable correlation with global climate modes, particularly the Antarctic Oscillation (AAO) in Aquifer III (-0.33 correlation) and the El Niño-Southern Oscillation (ENSO) in Aquifer V (0.3 correlation).

The limited influence of global climate features on aquifer water quality suggests that local anthropogenic factors, geological processes, and hydrogeological characteristics may be more important drivers of quality degradation than regional climate variability. This finding has significant implications for water resource management in SIDS, suggesting that local management interventions may be more effective than climate adaptation strategies for maintaining groundwater quality.

Extreme events provided clearer signals of climate-groundwater quality interactions. The observable pattern of high-density dry spells during 2019 and 2020 potentially explains the detected effect of Cyclone Esami on the aquifers. The hypothesis suggests that aquifers running significantly drier than usual due to extensive dry spells created conditions where a storm event brought sudden dilution to extensively deprived aquifer systems, demonstrating the importance of antecedent conditions in determining climate-quality relationships.

2.2.4.1.4 Implications for SIDS Groundwater Management

The Mauritius case study reveals several critical insights for groundwater quality management in SIDS contexts. First, the dominance of domestic extraction across all major aquifers (typically 85-96% of total extraction) highlights the strategic importance of groundwater for urban water security and the potential vulnerability of domestic supplies to quality degradation.

Second, the weak correlation between climate indices and water quality parameters suggests that conventional climate-based prediction models may be inadequate for SIDS groundwater quality management. The importance of antecedent conditions and extreme event interactions indicates that adaptive management approaches must account for cumulative effects and threshold responses rather than linear climate-quality relationships.

Third, the spatial variation in extraction patterns and quality responses across aquifers demonstrates the need for aquifer-specific management strategies that account for local hydrogeological characteristics, land use patterns, and anthropogenic pressures. The success of maintaining sustainable extraction ratios relative to recharge in most aquifers provides a foundation for sustainable development but requires continued monitoring and adaptive management to prevent future degradation.

The Mauritius experience provides a model for comprehensive groundwater quality monitoring in SIDS contexts, demonstrating the value of long-term, multi-parameter datasets for understanding degradation processes and informing management decisions. The integration of quality monitoring with hydrogeological characterization and extraction data provides a foundation for evidence-based management that can be adapted to other SIDS contexts worldwide.

2.3 Climate Variability Impacts on Groundwater Systems in SIDS

Climate variability represents one of the most significant drivers affecting groundwater resources in Small Island Developing States, with implications extending from local precipitation patterns to global teleconnections that influence water availability, quality, and accessibility (Thomas et al., 2020; Holding et al., 2016). The unique geographical position of SIDS, often situated in climatically sensitive regions with exposure to oceanic circulation systems, creates complex interactions between atmospheric processes and groundwater systems that challenge conventional water resource management approaches (Gheuens et al., 2019). Global analysis reveals that groundwater fluxes across the world are driven by large-scale climate patterns, with notable teleconnections including the Pacific Decadal Oscillation (PDO), El Niño-Southern Oscillation (ENSO), and other oscillatory systems showing strong relationships with groundwater variability (Forootan et al., 2018).

The vulnerability of SIDS to climate variability is fundamentally linked to their dependence on precipitation-driven recharge systems and their limited capacity to buffer against climate-induced changes in water availability (UNESCO-IHP, 2016; Werner et al., 2017). Unlike continental aquifer systems that may have multiple recharge sources and extensive storage capacity, SIDS groundwater systems typically rely on localized precipitation patterns that can vary dramatically over seasonal, annual, and decadal timescales (Falkland, 1999; White & Falkland, 2010). This dependence creates cascading vulnerabilities where changes in precipitation intensity, frequency, or spatial distribution directly translate to groundwater availability and quality impacts (Cashman et al., 2010; Thomas et al., 2020).

Recent comprehensive assessments reveal that climate change impacts on SIDS groundwater resources are already observable and projected to intensify across different temporal and spatial scales (Gohar et al., 2019; Werner et al., 2017). Analysis of 43 widely distributed SIDS indicates that 44% are currently in a state of water stress, with climate change projections suggesting that recharge could increase by up to 117% on 12 islands in the western Pacific and Indian Ocean, while decreasing by up to 58% on the remaining 31 islands (Holding et al., 2016). This spatial heterogeneity in climate impacts underscores the need for location-specific understanding of climate-groundwater interactions rather than generalized regional approaches (Ahmed & Mishra, 2020; Mycoo & Roopnarine, 2024).

2.3.1 Climate-Groundwater Interaction Mechanisms

The mechanisms through which climate variability affects SIDS groundwater systems operate across multiple temporal and spatial scales, involving complex interactions between atmospheric processes, surface hydrology, and subsurface flow systems (Green et al., 2011; Taylor et al., 2013). Understanding these mechanisms is essential for developing predictive frameworks and adaptive management strategies that can respond to both gradual climate changes and extreme event impacts (Adhikari et al., 2022; Kuss & Gurdak, 2014). Climate variability plays a critical role in driving changes in groundwater recharge, with teleconnection patterns significantly influencing atmospheric circulation and leading to changes in temperature and precipitation across vast geographical regions (Alizadeh-Choobari, 2017; Casanueva et al., 2014).

2.3.1.1 Precipitation-Recharge Relationships

The fundamental mechanism linking climate variability to groundwater systems in SIDS involves the transformation of precipitation into aquifer recharge through complex surface and subsurface processes (Scanlon et al., 2006; Healy, 2010). Unlike continental settings where groundwater recharge may be buffered by large catchment areas and diverse recharge sources, SIDS typically exhibit direct and immediate responses to precipitation variability due to their limited land area and simplified hydrological systems (Falkland & White, 2010; Werner et al., 2017). The most direct climate change effect on groundwater is related to groundwater recharge, as climate change can alter rainfall amounts and patterns, thus changing the quantities of soil infiltration, deep percolation, and hence the recharge (Adhikari et al., 2022; Green et al., 2011).

Recent analysis of an 11-year continuous groundwater quality dataset from Mauritius reveals unexpected complexity in precipitation-recharge relationships, with standard climate indices showing minimal correlation with groundwater quality parameters (Seenath et al., 2024). The Standardized Precipitation Index (SPI) and Standardized Precipitation-Evapotranspiration Index (SPEI) displayed weak relationships with most water quality indicators, challenging conventional assumptions about direct climate-groundwater linkages (Bloomfield & Marchant, 2013; Van Loon, 2015). This finding suggests that the mechanisms connecting climate variability to groundwater systems may involve threshold effects, time lags, and non-linear responses that are not captured by linear correlation analysis (Holman et al., 2011; Rust et al., 2018).

2.3.1.2 Global Climate Mode Influences

Teleconnections between global climate modes and SIDS groundwater systems represent an important but understudied mechanism of climate influence that operates through complex atmospheric-oceanic oscillations (Kuss & Gurdak, 2014; Velasco et al., 2015). The El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Antarctic Oscillation (AAO) can influence precipitation patterns, temperature regimes, and extreme event frequency across SIDS regions, creating indirect pathways for climate variability to affect groundwater resources (Alizadeh-Choobari et al., 2019; Rowell, 2013). Large-scale climatic oscillations exhibit strong heterogeneity at different spatio-temporal scales and substantially influence hydro-meteorological components, with the Pacific Ocean playing an explicit role in regulating groundwater fluxes (Araghi et al., 2019; Forootan et al., 2018).

Evidence from the Mauritius groundwater quality analysis indicates that global climate modes may have more influence on groundwater parameters than local precipitation indices, with correlations ranging from 0.6 to 0.8 with lags of 1-5 months observed in several global regions (Seenath et al., 2024; Forootan et al., 2018). Chloride concentrations showed notable correlation with the Antarctic Oscillation in specific aquifers (-0.33 correlation in Aquifer III), while ENSO demonstrated correlation with chloride in the Northern Plains aquifer (0.3 correlation) (Seenath et al., 2024). These relationships suggest that large-scale atmospheric circulation patterns may influence groundwater quality through mechanisms such as sea spray transport, atmospheric deposition, or groundwater-seawater interaction processes (Moosdorf et al., 2015; Werner et al., 2013).

The Pacific Decadal Oscillation shows particularly strong relationships with groundwater systems, with correlations reaching r=0.80 in some hotspots, especially in South America, providing opportunities to improve prediction of climate change impacts on global freshwater systems (Forootan et al., 2018; Mantua & Hare, 2002). Multi-annual variability detected in hydrogeological datasets has long been associated with systems of atmospheric-oceanic oscillation, though these periodicities are often weak when compared to finer-scaled daily to seasonal variability typical of hydrometeorological processes (Luković et al., 2014; Meinke et al., 2005).

2.3.1.3 Temperature and Evapotranspiration Effects

Climate variability influences groundwater systems through temperature-driven changes in evapotranspiration rates, which affect both the water balance and the concentration of dissolved constituents in groundwater (Jasper et al., 2006; Seneviratne et al., 2010). Rising temperatures associated with climate change can increase potential evapotranspiration rates, reducing the fraction of precipitation that becomes groundwater recharge and potentially concentrating dissolved salts and other constituents in remaining water resources (Bates et al., 2008; Rosenberg et al., 1999). Climate change and variability are expected to have profound effects on soil water and temperature, with soil water content and temperature serving as important factors in terrestrial biogeochemical reactions and land-atmosphere interactions (Jasper et al., 2006; Jungkunst et al., 2008).

Analysis of climate trends in tropical regions reveals consistent patterns of temperature increase that may significantly impact groundwater recharge efficiency through enhanced evapotranspiration rates (Hunt et al., 2013; Wang et al., 2009). Temperature increases of 0.0216°C per year combined with rainfall increases of 2.29 mm annually have been documented in Mauritius from 1981 to 2020, with severe repercussions for freshwater supply sustainability (Doorga, 2022). These concurrent changes in temperature and precipitation create complex scenarios where increased precipitation may be offset by enhanced evapotranspiration, resulting in net reductions in groundwater recharge (Bouraoui et al., 2004; Loaiciga et al., 1996).

Future projections indicate that evapotranspiration will increase with virtual certainty over the ocean and very likely over land with future surface warming, though global evapotranspiration increases may be constrained by low soil moisture availability and rising CO2 effects on plant transpiration (Arias et al., 2021; Jia et al., 2022). In regions where rainfall and vegetation growth increase, increased evapotranspiration will result in dampening regional warming, though the effects of compound extremes of heat, drought, and excess moisture on crops are poorly understood (Jia et al., 2022; Lesk et al., 2022).

2.3.1.4 Extreme Event Interactions

The interaction between extreme climate events and antecedent groundwater conditions represents a critical mechanism for understanding climate-groundwater relationships in SIDS, where events such as tropical cyclones, drought periods, and intense precipitation episodes can create rapid and dramatic changes in groundwater levels, quality, and flow patterns (Cashman et al., 2010; Rhiney, 2015). Extreme events have potential impacts on groundwater, environmental flows, and social inequalities, with prolonged drought constraining the persistence of surface water in typically arid domains (Forootan et al., 2018; Van Loon, 2015). The increased variability in precipitation, temperature, and evapotranspiration predicted under many climate change scenarios will likely have variable effects on different aquifers depending on spatial variability in hydraulic properties and distance from recharge areas (IPCC, 2007; Bates et al., 2008).

The Mauritius groundwater quality analysis provides insights into extreme event interactions, revealing that the effects of Cyclone Esami on aquifer systems were potentially amplified by preceding drought conditions (Seenath et al., 2024). High-density dry spells during 2019 and 2020 may have created conditions where storm-related recharge provided sudden dilution to extensively depleted aquifer systems, demonstrating the importance of cumulative climate effects rather than individual event impacts (Folland et al., 2015; Bloomfield & Marchant, 2013). This interaction between extreme events and antecedent conditions suggests that the groundwater response to tropical cyclones may vary significantly depending on the timing and intensity of preceding weather patterns (Kingston et al., 2006; Su et al., 2017).

2.3.2 Precipitation Variability and Recharge Dynamics

Precipitation variability represents the primary climate driver affecting groundwater recharge in SIDS, with implications extending from seasonal water availability to long-term aquifer sustainability (Werner et al., 2017; Falkland, 1999). The tropical and subtropical climates characterizing most SIDS create distinct seasonal precipitation patterns that directly influence groundwater recharge timing, magnitude, and spatial distribution (White & Falkland, 2012; Cashman et al., 2010). Climate-related variables that have substantial control on soil water include spatiotemporal patterns in precipitation, evapotranspiration, and surface-water conditions, with land use, soil texture, and slope also affecting soil water content with associated effects on groundwater and baseflow to streams (Jasper et al., 2006; Wang et al., 2009).

2.3.2.1 Seasonal Precipitation Patterns

SIDS typically experience pronounced seasonal variations in precipitation that create predictable patterns of groundwater recharge and depletion, though these patterns are increasingly modified by climate change impacts (Thomas et al., 2020; Holding et al., 2016). Mauritius exemplifies these patterns with its tropical maritime climate characterized by distinct wet and dry seasons, where the summer season (November to April) brings higher rainfall and warmer temperatures, with tropical cyclones contributing significant precipitation inputs (MEPU, 2010; Garnier & Desarthe, 2013). February represents the wettest month, providing critical recharge to groundwater systems, while the winter season (May to October) is cooler and relatively drier, with October being the driest month when groundwater systems experience maximum stress (MEPU, 2010; Seebocus et al., 2021).

The spatial distribution of precipitation across SIDS reflects complex interactions between topography, prevailing wind patterns, and local meteorological conditions that create substantial heterogeneity in recharge potential (Scholl et al., 1996; Gingerich & Voss, 2005). In Mauritius, rainfall varies dramatically from 1,400 mm on the Eastern Coast to 4,000 mm on the Central Plateau and only 600 mm on the Western Coast, creating corresponding variations in groundwater recharge potential (MEPU, 2010). This spatial variability in precipitation creates corresponding variations in groundwater recharge potential, with the Central Plateau serving as the primary recharge zone for most aquifer systems (Giorgi et al., 1999; Dindyal et al., 2013). The average annual rainfall over Mauritius is 1,993 mm, equivalent to approximately 3,700 Mm^3 of total precipitation input to the island system, demonstrating the critical importance of effective precipitation capture and management (MEPU, 2010).

2.3.2.2 Recharge Efficiency and Water Balance

The efficiency of precipitation-to-recharge conversion in SIDS reflects complex interactions between climate, geology, topography, and land use factors that vary significantly across different island settings (Falkland & White, 2010; Gingerich & Voss, 2005). In Mauritius, the water balance components reveal that annual evaporation accounts for 30% of precipitation, surface runoff for 60%, and groundwater recharge for only 10% of total precipitation input (MEPU, 2010). This relatively low recharge efficiency highlights the importance of understanding factors that control recharge processes and the potential vulnerability of groundwater systems to changes in precipitation patterns or land use practices (Dillon, 2005; Falkland, 1999).

The dominance of surface runoff (60%) in the water balance suggests significant potential for enhancing groundwater recharge through appropriate management interventions such as artificial recharge techniques, improved land use management, and infrastructure modifications (Falkland & White, 2010; Dillon, 2005). Artificial recharge techniques could potentially increase the fraction of precipitation that becomes groundwater recharge, thereby enhancing the resilience of SIDS groundwater systems to climate variability (White & Falkland, 2010; Werner et al., 2013). Annual potential evapotranspiration varies between 1,100 mm and 1,600 mm with small inter-annual variations, while relative humidity averages 80%, providing a relatively stable baseline against which precipitation variability effects can be assessed (MEPU, 2010; Staub, 2015).

2.3.2.3 Inter-annual and Decadal Variability

Inter-annual precipitation variability represents a major challenge for SIDS groundwater management, with significant implications for water security and resource planning that are increasingly complicated by climate change (Holding et al., 2016; Werner et al., 2017). Analysis of rainfall patterns in SIDS reveals that precipitation variability is influenced by phenomena such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), which can create multi-year periods of enhanced or reduced precipitation that stress groundwater systems (Alizadeh-Choobari, 2019; Rowell, 2013). The ENSO cycle has been identified as a significant driver of precipitation variability in many SIDS regions, with El Niño events typically associated with reduced precipitation and La Niña events bringing enhanced rainfall (Cai et al., 2014; McPhaden et al., 2006).

These cycles can persist for 12-18 months, creating extended periods of groundwater stress or recharge that may have lasting impacts on aquifer water levels and quality (Trenberth, 1997; Wolter & Timlin, 2011). In Mauritius, ENSO events have been correlated with significant variations in monthly rainfall, impacting the recharge of groundwater aquifers and creating management challenges for water resource planners (Staub, 2015; Seenath et al., 2024). The Pacific Decadal Oscillation demonstrates particularly strong relationships with precipitation patterns, showing cyclical fluctuations that correspond to long-term precipitation variations with implications for groundwater resources (Mantua & Hare, 2002; McCabe et al., 2004).

Decadal-scale climate variability adds another layer of complexity to SIDS groundwater management, with implications for long-term resource sustainability and infrastructure planning that require adaptive management approaches (Holman et al., 2011; Kingston et al., 2006). Climate oscillations such as the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) can create extended periods of altered precipitation patterns that may require fundamental adjustments to water resource management strategies (Kerr, 2000; Enfield et al., 2001). Multi-annual periodicities in groundwater systems are particularly susceptible to teleconnection influence, given their sensitivity to long-term changes in rainfall and evapotranspiration and their ability to filter fine-scale variability (Bloomfield & Marchant, 2013; Folland et al., 2015).

2.3.2.4 Extreme Precipitation Events

Extreme precipitation events, including tropical cyclones, intense convective storms, and prolonged drought periods, represent critical components of SIDS precipitation regimes with disproportionate impacts on groundwater systems (Cashman et al., 2010; Rhiney, 2015). These events can provide significant recharge inputs over short time periods but may also create management challenges related to water quality, infrastructure damage, and flood-related contamination (Thomas et al., 2020; Gheuens et al., 2019). The spatial extent and temporal duration of extreme drought are predicted to increase under future climate change, while increases in precipitation intensity are projected for most SIDS regions (Bates et al., 2008; IPCC, 2007).

Tropical cyclones represent particularly important extreme events for SIDS groundwater systems, often providing substantial precipitation inputs that can replenish depleted aquifers but may also introduce contamination from surface sources or cause saltwater intrusion through storm surge effects (Bowleg & Allen, 2011; Gingerich & Voss, 2005). The frequency and intensity of tropical cyclones in SIDS regions are influenced by climate variability and change, with implications for long-term groundwater resource availability that require adaptive management approaches (Knutson et al., 2010; Emanuel, 2005). Recent analysis suggests that while overall tropical cyclone frequency may remain stable or decrease slightly, the proportion of intense cyclones is likely to increase, creating more severe impacts when events do occur (Knutson et al., 2019; Kossin et al., 2017).

Drought periods represent the opposite extreme, creating extended periods of minimal recharge that can lead to groundwater depletion, quality degradation through concentration effects, and increased vulnerability to saltwater intrusion (Van Loon, 2015; Tallaksen & Van Lanen, 2004). The duration and intensity of drought events in SIDS are influenced by both local meteorological conditions and large-scale climate patterns, requiring adaptive management approaches that can respond to varying drought characteristics (Sheffield & Wood, 2008; Vicente-Serrano et al., 2010). Understanding the relationship between teleconnections and drought development provides potential for enhanced drought prediction and early warning systems (Hauser et al., 2015; Tošić et al., 2016).

2.3.3 Sea-Level Rise and Saltwater Intrusion

Sea-level rise represents one of the most significant and persistent climate change impacts affecting SIDS groundwater systems, creating permanent alterations to coastal aquifer dynamics that threaten freshwater availability and quality (Werner et al., 2013; Post & Abarca, 2010). The mechanisms of sea-level rise impacts operate through multiple pathways, including direct saltwater intrusion, changes in groundwater discharge patterns, and alterations to coastal zone hydrology that affect recharge processes (Oude Essink et al., 2010; Ferguson & Gleeson, 2012). Saltwater intrusion is a serious environmental issue since 80% of the world's population live along the coast and utilize local aquifers for their water supply, with massive withdrawal of groundwater resources due to population growth and rapid industrialization leading to seawater intrusion into coastal aquifers across the globe (Hussain & Javadi, 2016; Kumar, 2006).

2.3.3.1 Mechanisms of Saltwater Intrusion

Saltwater intrusion in SIDS occurs through several interconnected mechanisms that are exacerbated by sea-level rise and create complex mixing zones where groundwater salinity increases progressively toward oceanic levels (Post & Abarca, 2010; Werner et al., 2013). In SIDS, where all aquifers are inherently coastal due to limited land area, saltwater intrusion represents a pervasive threat rather than a localized coastal phenomenon (Holding et al., 2016; Falkland, 1999). The primary mechanisms include density-driven flow processes, tidal fluctuations, and dispersion effects that create transitional zones between freshwater and saltwater (Oude Essink et al., 2010; Klassen & Allen, 2017).

The hydrogeological characteristics of SIDS aquifers create particular vulnerability to saltwater intrusion due to their high permeability, fracture networks, and direct hydraulic connection to the sea (Werner et al., 2017; White & Falkland, 2010). In Mauritius, all five main aquifers are in hydraulic contact with the sea along coastline boundaries, while the highly permeable fractured lava flows and scoraceous zones that characterize productive aquifer zones provide preferential pathways for saltwater movement (Giorgi et al., 1999; Ministry of Public Utilities, 2005). The radial groundwater flow pattern, directed from central recharge areas toward coastal discharge zones, creates conditions where any reduction in freshwater head can trigger saltwater intrusion along multiple flow paths simultaneously (Dindyal et al., 2013; MEPU, 2010).

Sea-level rise accelerates saltwater intrusion through several mechanisms that operate at different temporal scales (Loáiciga et al., 2012; Webb & Howard, 2011). Direct hydraulic effects involve increased seawater head at coastal boundaries, creating enhanced driving forces for saltwater movement into freshwater aquifers (Werner & Simmons, 2009; Chang et al., 2011). Reduced freshwater discharge to coastal zones decreases the hydraulic gradient that maintains the freshwater-saltwater interface, allowing saltwater to advance inland (Oude Essink et al., 2010; Pool & Carrera, 2018). Storm surge effects associated with sea-level rise can create temporary but intense saltwater intrusion events that may have lasting impacts on aquifer salinity (Gingerich & Voss, 2005; Terry & Chui, 2012).

2.3.3.2 Vulnerability Assessment and Spatial Patterns

Global assessment of 43 SIDS reveals that vulnerability to saltwater intrusion varies significantly based on hydrogeological characteristics, topography, and current sea-level rise rates (Holding et al., 2016). Low-lying islands show particular vulnerability, with 91% at risk of water scarcity compared to 71% of all islands assessed, reflecting both the reduced freshwater lens thickness in low-lying areas and the increased susceptibility to saltwater intrusion under even modest sea-level rise scenarios (Holding et al., 2016; Oberle et al., 2017). Population density appears to be the main driver of water stress in all but one of the 43 representative islands assessed, reflecting high numbers of islands at risk of water scarcity (UNESCO-IHP, 2016).

Mauritius has experienced a relative sea-level rise of 4-6 mm per year over the past 30 years, corresponding to an increase 2-3 times higher than the global average (Becker et al., 2019). This accelerated sea-level rise rate creates ongoing pressure on coastal aquifers and suggests that saltwater intrusion impacts may be more severe than in SIDS experiencing global average sea-level rise rates (Beeharry et al., 2022; Staub, 2015). The volcanic geology of Mauritius, with extensive fracture systems and high-permeability zones, may enhance the rate and extent of saltwater intrusion compared to less permeable coastal aquifer systems (Ministry of Public Utilities, 2005; Giorgi et al., 1999).

The spatial pattern of saltwater intrusion vulnerability in Mauritius reflects the radial groundwater flow system and the distribution of permeable zones, with different aquifers showing varying degrees of susceptibility (Giorgi et al., 1999; MEPU, 2010). The Northern Plains aquifer (Aquifer V) includes two main breaches in the caldera that allow seawater intrusion for several kilometres inland, creating zones of enhanced vulnerability where saltwater can penetrate deep into the freshwater system (Giorgi et al., 1999). Similar vulnerabilities exist in other aquifers where structural discontinuities or high-permeability zones provide preferential pathways for saltwater movement (Ministry of Public Utilities, 2005; Dindyal et al., 2013).

2.3.3.3 Temporal Dynamics and Threshold Effects

Saltwater intrusion in SIDS exhibits complex temporal dynamics that reflect both gradual sea-level rise trends and episodic events such as storm surges, extreme tides, and drought periods that temporarily alter freshwater-saltwater equilibrium (Terry & Chui, 2012; Rotzoll & Fletcher, 2013). Understanding these temporal patterns is essential for developing early warning systems and adaptive management strategies that can respond to both gradual and rapid changes in intrusion patterns (Ketabchi et al., 2016; Abd-Elhamid & Javadi, 2011). The interaction between sea-level rise and groundwater extraction creates potential threshold effects where modest increases in either factor can trigger rapid advancement of the saltwater interface (Werner & Simmons, 2009; Chang et al., 2011).

Over-extraction of freshwater can reduce the hydraulic head that maintains freshwater-saltwater separation, while sea-level rise increases the driving force for saltwater intrusion, creating synergistic effects (Oude Essink et al., 2010; Pool & Carrera, 2018). The combination of these factors may create non-linear responses where gradual increases in stress factors lead to sudden and dramatic changes in aquifer salinity (Webb & Howard, 2011; Loáiciga et al., 2012). Climate variability adds another layer of complexity to saltwater intrusion dynamics, with drought periods creating conditions of enhanced vulnerability due to reduced freshwater recharge and potentially increased extraction demand (Van Loon, 2015; Tallaksen & Van Lanen, 2004).

During extended dry periods, the freshwater lens may thin sufficiently to allow deeper saltwater penetration that persists even after normal recharge conditions return, creating hysteresis effects where recovery from saltwater intrusion lags behind the restoration of normal climatic conditions (Holding & Allen, 2015; Gingerich & Voss, 2005). Numerical modelling studies suggest that transient effects in unconfined aquifers can significantly influence the rate and extent of saltwater intrusion under changing boundary conditions (Webb & Howard, 2011; Pool & Carrera, 2018).

2.3.3.4 Management Implications and Adaptation Strategies

The persistent and potentially irreversible nature of saltwater intrusion in SIDS requires proactive management approaches that anticipate future sea-level rise scenarios rather than simply responding to current conditions (Werner et al., 2013; Oude Essink et al., 2010). Traditional approaches to saltwater intrusion management, such as extraction reduction or alternative supply development, may be insufficient in SIDS contexts where sea-level rise continues regardless of local management interventions (Holding et al., 2016; Falkland & White, 2010). Adaptation strategies for saltwater intrusion in SIDS must account for the permanent nature of sea-level rise impacts and the limited options for alternative freshwater supplies (Mycoo & Roopnarine, 2024; Ahmed & Mishra, 2020).

Managed retreat from the most vulnerable coastal areas, combined with enhanced recharge in inland areas, may provide the most sustainable long-term approach for maintaining freshwater resources (White & Falkland, 2010; Werner et al., 2013). Artificial recharge techniques, including injection of treated wastewater or captured stormwater, could help maintain freshwater head in vulnerable areas (Dillon, 2005; Bouwer, 2002). Early warning systems based on continuous monitoring of groundwater salinity, water levels, and coastal sea level can provide the lead time necessary for adaptive management responses (Ketabchi et al., 2016; Abd-Elhamid & Javadi, 2011).

Real-time monitoring networks that integrate meteorological, oceanographic, and hydrogeological data can help identify conditions that enhance saltwater intrusion risk and trigger appropriate management responses (Werner et al., 2013; Pool & Carrera, 2018). The development of decision support systems that can process multiple data streams and provide early warning of saltwater intrusion events represents a critical need for SIDS adaptation planning (Ketabchi et al., 2016; Ferguson & Gleeson, 2012).

2.3.4 Extreme Weather Events and Groundwater Response

Extreme weather events represent critical drivers of groundwater system dynamics in SIDS, often creating rapid and substantial changes in water levels, quality, and flow patterns that may persist long beyond the duration of the triggering event (Cashman et al., 2010; Rhiney, 2015). The increasing frequency and intensity of extreme events associated with climate change amplify these impacts, creating new challenges for groundwater resource management and water security planning (Thomas et al., 2020; IPCC, 2021). Global warming is emerging as an important predictor of water availability and future water supplies across the world through inducing frequency and severity in hydrological extremes, with potential impacts on groundwater, environmental flows, and social inequalities (Forootan et al., 2018; Sheffield & Wood, 2008).

2.3.4.1 Tropical Cyclones and Storm Impacts

Tropical cyclones represent the most dramatic extreme weather events affecting many SIDS, bringing intense precipitation, strong winds, and storm surge that can fundamentally alter groundwater system dynamics over short time periods (Cashman et al., 2010; Bowleg & Allen, 2011). The groundwater impacts of tropical cyclones operate through multiple mechanisms, including rapid recharge from intense precipitation, saltwater intrusion from storm surge, contamination from damaged infrastructure, and physical damage to groundwater extraction and monitoring systems (Terry & Chui, 2012; Gingerich & Voss, 2005). In the Caribbean, rising seas have contributed to the devastation of local livelihoods in tourism and agriculture, while tropical cyclones continue to pose significant threats to groundwater infrastructure (UN Secretary-General, 2023; Cashman et al., 2010).

The precipitation associated with tropical cyclones can provide substantial groundwater recharge, particularly in SIDS where annual rainfall totals may be dominated by a small number of intense storm events (Scholl et al., 1996; Price, 2008). However, the intensity of cyclone precipitation often exceeds soil infiltration capacity, leading to high runoff rates that limit the groundwater recharge benefits (Healy, 2010; Scanlon et al., 2006). The temporal concentration of precipitation during cyclone events creates challenges for capturing and storing water for groundwater recharge, while the associated surface flooding may mobilize contaminants that subsequently infiltrate to groundwater (Foster et al., 2013; Lapworth et al., 2012).

Storm surge effects during tropical cyclones can cause temporary but intense saltwater intrusion that may have lasting impacts on coastal aquifer salinity (Terry & Chui, 2012; Rotzoll & Fletcher, 2013). The combination of elevated sea levels, wind-driven wave action, and reduced freshwater discharge during storm events creates conditions where saltwater can penetrate much further inland than under normal conditions (Gingerich & Voss, 2005; Holding & Allen, 2015). Recovery from cyclone-induced saltwater intrusion may require months to years, depending on the extent of intrusion and the rate of freshwater flushing (Werner et al., 2013; Oude Essink et al., 2010).

Case study analysis from Mauritius reveals complex interactions between extreme events and antecedent groundwater conditions that challenge simple cause-effect relationships (Seenath et al., 2024). The effects of Cyclone Esami on aquifer systems appear to have been influenced by preceding drought conditions, with high-density dry spells during 2019 and 2020 creating depleted aquifer conditions that enhanced the impact of storm-related recharge (Seenath et al., 2024). This interaction between extreme events and antecedent conditions suggests that the groundwater response to tropical cyclones may vary significantly depending on the timing and intensity of preceding weather patterns (Kingston et al., 2006; Su et al., 2017).

2.3.4.2 Drought Impacts and System Resilience

Drought events represent extended periods of reduced precipitation that can lead to progressive groundwater depletion, quality degradation, and increased vulnerability to saltwater intrusion (Van Loon, 2015; Tallaksen & Van Lanen, 2004). Unlike sudden-onset events such as tropical cyclones, droughts develop gradually but may have profound and lasting impacts on SIDS groundwater systems due to their limited storage capacity and high dependence on regular precipitation for recharge (Bloomfield & Marchant, 2013; Peters et al., 2003). The progression of drought impacts on SIDS groundwater systems typically follows predictable stages, beginning with reduced recharge rates and declining water levels, progressing to quality degradation through concentration effects, and potentially culminating in saltwater intrusion as freshwater heads decline below critical thresholds (Van Loon & Laaha, 2015; Wada et al., 2010).

The limited storage capacity of most SIDS aquifers means that drought impacts may manifest more rapidly than in continental settings, requiring early intervention to maintain water security (Falkland, 1999; White & Falkland, 2010). In sub-Saharan Africa, analysis of multidecadal groundwater hydrographs reveals that levels of aridity dictate the predominant recharge processes, whereas local hydrogeology influences the type and sensitivity of precipitation-recharge relationships (Cuthbert et al., 2019). Recharge in some humid locations varies by as little as five percent across a wide range of annual precipitation values, demonstrating the complex relationship between precipitation and groundwater recharge (Cuthbert et al., 2019; MacDonald et al., 2021).

Drought recovery in SIDS groundwater systems may be complicated by quality degradation that persists after water level recovery (Scanlon et al., 2006; Healy, 2010). Concentration of dissolved constituents during drought periods can create water quality problems that require extended flushing periods to resolve, while saltwater intrusion triggered by drought conditions may require years of enhanced freshwater recharge to fully reverse (Werner et al., 2013; Oude Essink et al., 2010). The resilience of SIDS groundwater systems to drought impacts depends on several factors, including aquifer storage capacity, recharge efficiency, extraction patterns, and alternative water supply availability (Falkland & White, 2010; Ahmed & Mishra, 2020).

Systems with higher storage capacity relative to annual extraction rates demonstrate greater resilience to drought impacts, while those operating near extraction capacity may experience rapid degradation during drought periods (UNESCO-IHP, 2016; Holding et al., 2016). The ability to predict future variability of groundwater resources in time and space is of critical importance to drought management, with periodic control on groundwater levels from oscillatory climatic systems offering potentially valuable sources of longer-term forecasting capability (Rust et al., 2018; Holman et al., 2011).

2.3.4.3 Flood Events and Contamination Risks

Intense precipitation events and associated flooding create significant contamination risks for SIDS groundwater systems, particularly in areas with high population density, intensive agriculture, or inadequate sanitation infrastructure (Foster et al., 2013; Lapworth et al., 2012). Flood events can mobilize surface contaminants and transport them to groundwater through enhanced infiltration rates, creating water quality problems that may persist long after flood waters recede (Dillon, 1997; Tribble, 2008). The mechanisms of flood-related groundwater contamination operate through several pathways, including surface runoff mobilization of agricultural chemicals, domestic wastewater, industrial pollutants, and other contaminants from diffuse sources across the landscape (Barrett et al., 1999; Lawrence et al., 2000).

When flood waters infiltrate to groundwater, these contaminants can create plume-like contamination patterns that migrate along groundwater flow paths, creating long-term water quality problems (Konikow & Kendy, 2005; Alley et al., 1999). Flood damage to sanitation infrastructure, such as septic systems or sewage treatment facilities, can create point sources of contamination that directly impact underlying aquifers (Dillon, 1997; Foster & Hirata, 1988). The vulnerability of SIDS to flood-related groundwater contamination reflects both their high population density relative to land area and the typically rapid infiltration rates associated with volcanic or coral geological formations (Falkland, 1999; Tribble, 2008).

The limited dilution capacity of small aquifer systems means that contamination inputs during flood events may create water quality problems that exceed drinking water standards and require extended treatment or alternative supply development (White & Falkland, 2010; Carrard et al., 2019). In Pacific Island countries, contaminated groundwater often contains high levels of salinity and pollutants, posing severe risks to public health in island communities (Carrard et al., 2019; Holding et al., 2016). The interaction between flood events and pre-existing contamination sources can exacerbate water quality problems through enhanced mobilization and transport of pollutants (Foster et al., 2013; Lawrence et al., 2000).

2.3.4.4 Early Warning and Response Systems

The development of early warning systems for extreme weather impacts on groundwater represents a critical need for SIDS adaptation to climate change (Ketabchi et al., 2016; Werner et al., 2013). These systems must integrate meteorological forecasting, real-time groundwater monitoring, and rapid response protocols to minimize the impacts of extreme events on water security and public health (Ahmed & Mishra, 2020; Mycoo & Roopnarine, 2024). Meteorological early warning components focus on forecasting extreme weather events with sufficient lead time to implement protective measures for groundwater systems (WMO, 2018; Knutson et al., 2019).

This includes tropical cyclone tracking and intensity forecasting, drought monitoring and prediction, and precipitation forecasting for flood risk assessment (Emanuel, 2005; Vicente-Serrano et al., 2010). The integration of global climate model outputs with local meteorological observations can provide enhanced forecasting capability for extreme event impacts (Hewitson & Crane, 2006; Wilby & Wigley, 1997). Real-time groundwater monitoring systems provide the data necessary to assess current aquifer conditions and vulnerability to extreme event impacts (Pool & Carrera, 2018; Ferguson & Gleeson, 2012).

Continuous monitoring of water levels, water quality parameters, and extraction rates can help identify systems operating near critical thresholds that may be particularly vulnerable to extreme event impacts (Werner et al., 2013; Abd-Elhamid & Javadi, 2011). Automated data transmission and analysis systems can provide rapid assessment of changing conditions during extreme events (Ketabchi et al., 2016; Pool & Carrera, 2018). Response protocols for extreme weather impacts on groundwater must account for the limited options available in SIDS contexts and the potential for cascading failures that affect multiple infrastructure systems simultaneously (Gheuens et al., 2019; Thomas et al., 2020).

Emergency water supply plans, alternative source development, and rapid deployment of water treatment systems represent critical components of comprehensive response strategies (Ahmed & Mishra, 2020; Mycoo & Roopnarine, 2024). The development of decision support systems that can integrate multiple data streams and provide actionable information for emergency managers represents an important frontier in SIDS groundwater management (Ketabchi et al., 2016; Ferguson & Gleeson, 2012).

2.3.5 Climate Change Projections for Island Groundwater Systems

Climate change projections for SIDS indicate fundamental shifts in temperature, precipitation, sea level, and extreme event patterns that will create new challenges for groundwater resource management while potentially exacerbating existing vulnerabilities (IPCC, 2021; Thomas et al., 2020). Understanding these projected changes is essential for developing adaptive management strategies that can maintain water security under future climate conditions (Holding et al., 2016; Werner et al., 2017). Global climate models consistently project significant changes for SIDS regions that will affect multiple components of the hydrological cycle simultaneously (Collins et al., 2013; Stocker et al., 2013).

2.3.5.1 Temperature and Evapotranspiration Projections

Global climate models consistently project significant temperature increases for SIDS regions, with implications for evapotranspiration rates, water demand, and groundwater recharge efficiency (IPCC, 2021; Arias et al., 2021). Analysis of climate trends in Mauritius reveals warming rates of 0.0216°C per year from 1981 to 2020, which, if continued, would result in temperature increases of 0.8-1.2°C by 2050 relative to current conditions (Doorga, 2022). These temperature increases are expected to enhance potential evapotranspiration rates, potentially reducing the efficiency of precipitation-to-recharge conversion and increasing water demand for irrigation and domestic cooling (Jia et al., 2022; Lesk et al., 2022).

The projected increases in temperature may also affect the quality of groundwater through enhanced chemical reaction rates, increased solubility of mineral constituents, and changes in biological activity within aquifer systems (Green et al., 2011; Taylor et al., 2013). Higher temperatures can accelerate weathering processes that contribute dissolved constituents to groundwater, while also enhancing the mobility of some contaminants through increased diffusion and reaction rates (Bates et al., 2008; Jasper et al., 2006). Regional climate projections suggest that the enhanced evapotranspiration associated with temperature increases may offset some of the benefits of projected precipitation increases in certain SIDS regions (Hunt et al., 2013; Rosenberg et al., 1999).

The net effect on groundwater recharge will depend on the relative magnitude of temperature and precipitation changes, with implications for long-term water resource availability that require detailed water balance analysis for individual islands (Adhikari et al., 2022; Scanlon et al., 2006). In regions where rainfall and vegetation growth increase, increased evapotranspiration will result in dampening regional warming, though the effects of compound extremes of heat, drought, and excess moisture are poorly understood (Jia et al., 2022; Lesk et al., 2022). Evapotranspiration is projected to increase with virtual certainty over the ocean and very likely over land with future surface warming, though constraints may emerge due to low soil moisture availability and rising CO2 effects on plant transpiration (Arias et al., 2021; Jiao et al., 2021).

2.3.5.2 Precipitation Pattern Changes

Climate change projections for SIDS reveal complex and spatially variable changes in precipitation patterns that will significantly impact groundwater recharge dynamics (Holding et al., 2016; Collins et al., 2013). Analysis of 43 SIDS indicates that while recharge is projected to increase by up to 117% on 12 islands in the western Pacific and Indian Ocean, recharge may decrease by up to 58% on the remaining 31 islands, highlighting the spatial heterogeneity of climate change impacts across SIDS regions (Holding et al., 2016). This divergent response pattern reflects the complex interactions between global circulation changes, regional oceanographic conditions, and local topographic effects that influence precipitation patterns (Rowell, 2013; Cai et al., 2014).

Projected changes in precipitation patterns include alterations to seasonal timing, increases in inter-annual variability, and shifts in the intensity distribution of precipitation events (IPCC, 2021; Seneviratne et al., 2012). Climate models suggest that many SIDS may experience intensification of wet and dry seasons, with implications for groundwater recharge timing and efficiency (Knutson et al., 2019; Trenberth, 2011). Wetter wet seasons may provide enhanced recharge opportunities but could also increase flood risks and contamination potential, while drier dry seasons may create extended periods of groundwater stress (Van Loon, 2015; Sheffield & Wood, 2008).

The projected increase in precipitation intensity, even where total annual precipitation remains stable or increases, may reduce recharge efficiency due to enhanced surface runoff during intense events (Healy, 2010; Scanlon et al., 2006). This shift toward more intense precipitation events requires adaptive management approaches that can capture and store water during peak events for subsequent groundwater recharge during dry periods (Dillon, 2005; Bouwer, 2002). Changes in the tracks and intensity of tropical cyclones represent a particularly important component of precipitation pattern changes for many SIDS (Knutson et al., 2019; Emanuel, 2005).

While the overall frequency of tropical cyclones may not change significantly, projections suggest that intense cyclones may become more frequent, creating challenges for water resource management through both enhanced flood risks and more variable recharge patterns (Kossin et al., 2017; Walsh et al., 2016). The increased variability in precipitation patterns will require more flexible and adaptive groundwater management approaches that can respond to changing seasonal patterns and extreme event characteristics (Ahmed & Mishra, 2020; Mycoo & Roopnarine, 2024).

2.3.5.3 Sea-Level Rise Scenarios

Sea-level rise projections for SIDS regions indicate accelerating rates of increase that will fundamentally alter coastal aquifer dynamics and threaten freshwater availability (IPCC, 2021; Oppenheimer et al., 2019). Current global average sea-level rise rates of 2-3 mm per year are projected to accelerate to 5-10 mm per year by mid-century, with some regions potentially experiencing rates exceeding 15 mm per year due to regional oceanographic and glacial isostatic adjustment effects (Church et al., 2013; Slangen et al., 2014). The implications of projected sea-level rise for SIDS groundwater systems extend beyond simple saltwater intrusion to include fundamental changes in aquifer geometry, flow patterns, and recharge processes (Werner et al., 2013; Ferguson & Gleeson, 2012).

Low-lying areas may experience permanent inundation that eliminates terrestrial recharge, while coastal margins retreat inland, reducing the total land area available for freshwater lens development (Rotzoll & Fletcher, 2013; Oberle et al., 2017). Regional variations in sea-level rise projections create differential impacts across SIDS regions, with islands in the western Pacific potentially experiencing sea-level rise rates 20-30% above global averages due to thermal expansion and regional circulation patterns (Church et al., 2013; Meyssignac & Cazenave, 2012). Atlantic and Indian Ocean islands may experience rates closer to global averages, though local factors such as glacial isostatic adjustment and regional oceanographic conditions can create significant variations (Slangen et al., 2014; Kopp et al., 2014).

These regional differences require location-specific impact assessments and adaptation planning that account for local conditions and vulnerabilities (Holding et al., 2016; Ahmed & Mishra, 2020). The non-linear nature of sea-level rise impacts on groundwater systems means that threshold effects may create sudden transitions from sustainable to unsustainable conditions (Werner & Simmons, 2009; Chang et al., 2011). Once saltwater intrusion reaches critical infrastructure or water supply wells, the impacts may be effectively irreversible without major intervention, highlighting the importance of proactive adaptation planning (Oude Essink et al., 2010; Pool & Carrera, 2018).

2.3.5.4 Extreme Event Frequency and Intensity Changes

Climate change projections indicate significant changes in the frequency and intensity of extreme weather events affecting SIDS, with implications for groundwater system stability and management complexity (IPCC, 2021; Seneviratne et al., 2012). Tropical cyclone projections suggest that while overall frequency may remain stable or decrease slightly, the proportion of intense cyclones (Category

4-5) is likely to increase, creating more severe impacts when events do occur (Knutson et al., 2019; Kossin et al., 2017). This shift toward more intense but potentially less frequent cyclones creates challenges for groundwater management through both enhanced storm surge effects and more variable precipitation inputs (Walsh et al., 2016; Emanuel, 2005).

Drought projections for SIDS regions show mixed results, with some areas projected to experience more frequent and intense droughts while others may see reduced drought risk due to enhanced precipitation (Sheffield & Wood, 2008; Dai, 2013). However, the increased temperature and evapotranspiration associated with climate change may enhance drought impacts even where precipitation changes are minimal, creating more severe groundwater stress during dry periods (Vicente-Serrano et al., 2010; Van Loon, 2015). The spatial extent and temporal duration of extreme drought are predicted to increase under future climate change, with implications for groundwater sustainability in vulnerable regions (Bates et al., 2008; Trenberth et al., 2014).

Flood risk projections indicate increased intensity of extreme precipitation events in most SIDS regions, creating enhanced risks for groundwater contamination and infrastructure damage (Seneviratne et al., 2012; Westra et al., 2014). The combination of sea-level rise and increased storm intensity may create compound flood events that simultaneously threaten coastal areas from ocean and terrestrial sources (Zscheischler et al., 2018; Leonard et al., 2014). These compound events represent a particular challenge for SIDS groundwater management, as they can create simultaneous saltwater intrusion and surface contamination that may have synergistic effects on water quality (Wahl et al., 2015; Bevacqua et al., 2019).

2.3.5.5 Adaptation Planning Implications

The projected changes in climate conditions affecting SIDS groundwater systems require fundamental shifts in water resource management approaches, moving from reactive management of current conditions to proactive adaptation for future scenarios (Werner et al., 2013; Ahmed & Mishra, 2020). This transition requires integration of climate projection uncertainties into decision-making processes and development of flexible management strategies that can respond to evolving conditions (Mycoo & Roopnarine, 2024; Gheuens et al., 2019). Infrastructure planning for SIDS groundwater systems must account for the permanent nature of some climate change impacts, particularly sea-level rise that cannot be reversed through local management actions (Holding et al., 2016; Falkland & White, 2010).

This may require difficult decisions about managed retreat from vulnerable coastal areas and concentration of infrastructure investment in areas with long-term viability under future climate conditions (White & Falkland, 2010; Werner et al., 2013). The development of climate-resilient groundwater management systems requires integration of multiple adaptation strategies, including demand management, alternative supply development, enhanced recharge, and improved efficiency of existing systems (Ahmed & Mishra, 2020; Mycoo & Roopnarine, 2024). The limited land area and resource constraints characteristic of SIDS mean that adaptation strategies must be carefully prioritized based on effectiveness, cost, and technical feasibility (UNESCO-IHP, 2016; Thomas et al., 2020).

Early warning and rapid response systems become increasingly important under climate change scenarios where extreme events may become more intense and potentially less predictable (Ketabchi et al., 2016; Ferguson & Gleeson, 2012). Investment in monitoring infrastructure, forecasting capability, and emergency response systems represents a critical component of adaptation planning for SIDS groundwater systems (Werner et al., 2013; Pool & Carrera, 2018). The integration of traditional knowledge with modern scientific approaches provides opportunities for developing culturally appropriate and technically sound adaptation strategies (Falkland & White, 2010; Bouchet et al., 2019).

2.4 Groundwater Flow Dynamics and Recharge Mechanisms in Volcanic Island Settings

Groundwater flow systems in volcanic island environments are fundamentally controlled by the complex geological structure created through multiple eruptive phases and the subsequent development of fracture networks (Giorgi et al., 1999; Ministry of Public Utilities, 2005). Understanding these flow dynamics and recharge mechanisms is essential for sustainable groundwater management in Small Island Developing States, where volcanic geology often dominates the hydrogeological framework. Advanced techniques such as isotopic analysis provide critical insights into groundwater flow paths, residence times, and recharge sources that cannot be obtained through conventional hydrogeological methods alone.

2.4.1 Hydrogeological Characteristics of Volcanic Aquifers

Mauritius is a volcanic island formed through multiple eruptive phases spanning approximately 10 million years, creating a complex geological structure that directly controls groundwater occurrence and flow (Ministry of Public Utilities, 2005). The island's geological evolution occurred in four major phases: the Emergence Period (10-6.7 million years ago), the Older Volcanic Series (6.2-5 million years ago), the Intermediate Volcanic Series (3.5-1.7 million years ago), and the Younger Volcanic Series (700,000-25,000 years ago) (Giorgi et al., 1999).

The geological structure comprises three distinct volcanic formations with contrasting hydrogeological properties. The Ancient Basaltic Series forms the impermeable bedrock foundation, consisting of massive, weathered basalts with very low permeability (transmissivity 10^{-7} to 10^{-6} m^2/s) that act as aquitards and define aquifer boundaries (Ministry of Public Utilities, 2005). The Intermediate Basaltic Series, deposited during periods of localized volcanic activity, exhibits variable permeability (transmissivity 10^{-6} to 10^{-3} m^2/s) and forms the primary productive aquifer layers, particularly where fractured or scoraceous. The Recent Basaltic Series, comprising highly porous and fractured volcanic flows with extensive lava tunnel networks, demonstrates the highest permeability (transmissivity 10^{-5} to 10^{-2} m^2/s) and facilitates rapid groundwater recharge and circulation (Giorgi et al., 1999).

The island's volcanic structure is dominated by two major caldera collapse events that created the central plateau and northern plains depressions, which now serve as the primary groundwater recharge zones. These calderas are bounded by ancient basaltic mountain ranges that form natural no-flow boundaries for the aquifer systems. Fracture systems, particularly along N20° and N100° orientations, create preferential groundwater flow paths and influence aquifer connectivity (Ministry of Public Utilities, 2005). The radial drainage pattern established by the volcanic dome structure directs groundwater flow from the central recharge areas toward coastal discharge zones, making all major aquifers inherently coastal systems vulnerable to seawater intrusion.

While the ancient basaltic formations of Mauritius are massive or weathered and generally have very low permeability, the productive aquifer zones are characterised by highly permeable fractured lava flows and scoraceous zones, which increases the vulnerability of movement of pollutants due to human activities and seawater pollution. Groundwater circulation is limited to these fractured and scoraceous zones within the otherwise low-permeability basaltic formations (MEPU, 2010).

2.4.2 Isotopic Tracers for Groundwater Flow Analysis

Stable isotope analysis using oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$) provides powerful tools for understanding groundwater flow systems in volcanic island environments. Research on volcanic islands worldwide has demonstrated that isotopic signatures can reveal distinct flow compartments, recharge elevations, and mixing processes that are crucial for characterizing complex groundwater systems. Studies on the Kilauea volcano in Hawaii have established foundational principles for using isotopic tracers in volcanic settings, showing how groundwater flow can be compartmentalized by volcanic rift zones and how different isotopic signatures reflect varying recharge elevations and flow paths. The research demonstrated that stable isotopes can identify three distinct isotopic gradients with elevation, providing insights into meteoric water infiltration patterns and flow system connectivity.

Multi-level well monitoring using stable isotopes in fractured volcanic rock has proven effective for understanding vertical flow components and identifying preferential flow paths through fracture networks. This approach is particularly relevant for Mauritius, where groundwater circulation is primarily controlled by fracture systems within basaltic formations. The integration of isotope data with hydro chemical tracers such as sodium (Na^+) and chloride (Cl^-) enhances the understanding of flow system connectivity and helps distinguish between different water sources. Research on Mt. Ontake stratovolcano has shown how altitude effects influence precipitation isotope signatures and how these effects are preserved in groundwater systems. The altitude effect, typically showing depletion of heavy isotopes with increasing elevation, creates distinct isotopic signatures that can be used to identify recharge elevations and flow paths in mountainous volcanic terrains similar to Mauritius's central plateau. Studies from Rishiri Island have demonstrated the effectiveness of using multiple environmental tracers including electrical conductivity (EC), temperature, and stable isotopes for characterizing groundwater recharge mechanisms and submarine groundwater discharge (SGD) in volcanic island settings. This multi-tracer approach provides comprehensive understanding of flow dynamics from recharge zones to coastal discharge areas.

2.4.2 Preliminary Conceptual Model Development

2.4.2.1 Development of Preliminary Conceptual Framework

Based on the literature review of volcanic island hydrogeology and the established geological framework of Mauritius, a preliminary conceptual model can be developed to guide this research investigation. This conceptual framework (Fig 2.10) synthesizes existing knowledge from regional studies, geological characterization, and hydrogeological understanding to establish working hypotheses for subsequent testing through isotopic analysis.

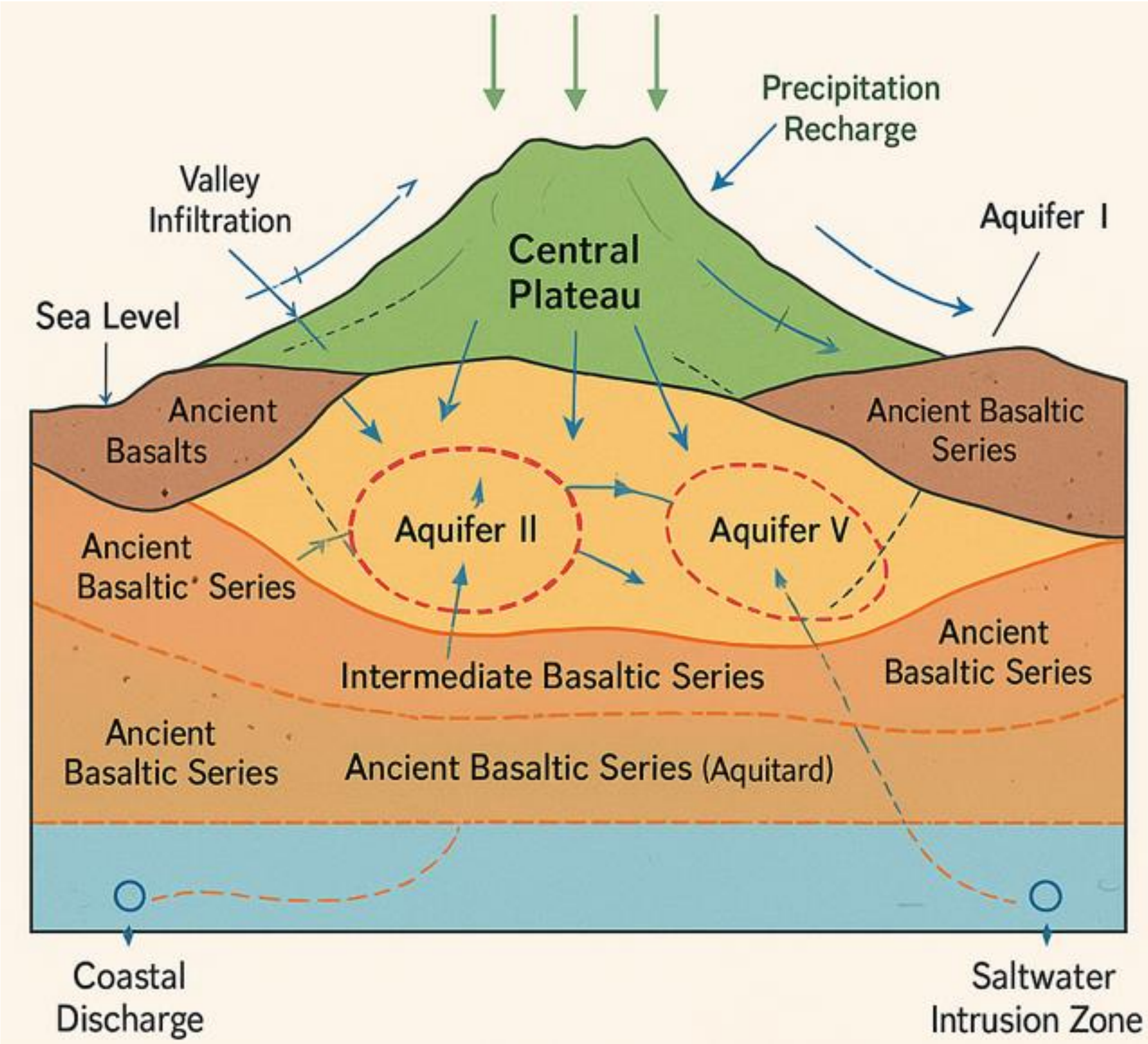


Figure 2-10 Preliminary Conceptual Hydrogeological Cross-section of Mauritius Groundwater Systems

The preliminary conceptual model (Fig 2.10) incorporates several key assumptions derived from the literature. Based on the volcanic dome structure, groundwater flow is assumed to follow generally radial patterns from the Central Plateau recharge areas toward coastal discharge zones (Giorgi et al., 1999; MEPU, 2010). The five main aquifer systems are hypothesized to have varying degrees of hydraulic connection, with preferential flow paths occurring along N20° and N100° fracture orientations. Direct infiltration through the permeable Recent Basaltic Series formations in the Central Plateau is considered the primary recharge mechanism, while secondary recharge is thought to occur through stream infiltration in valley systems. Freshwater-saltwater interfaces are conceptualized as dynamic zones influenced by seasonal recharge variations, extraction patterns, and tidal effects along coastal boundaries. This preliminary framework forms the basis for developing research hypotheses and designing sampling strategies to test and refine the understanding of actual flow dynamics and mixing processes.

2.4.3 Recharge Mechanisms in Tropical Island Settings

Groundwater recharge in tropical volcanic islands is primarily controlled by precipitation patterns, topographic effects, and the permeability structure of volcanic formations (Custodio, 1989; Vittecoq et al., 2020). Most of the groundwater recharge takes place at the Central Plateau and the underground flow mainly largely follows the topographic cuts in the old crater rim and feeds the downstream aquifers outside the crater rim. In this way, the groundwater flow pattern is essentially radial from the Central Plateau down through the sloping aquifers outside the rim to the coral reef lagoon and the sea. Research on Madeira volcanic island has shown how altitude effects and rain-shadowing influence precipitation isotope compositions, which are subsequently preserved in groundwater systems (Dettinger et al., 2020). The altitude effect results in systematic depletion of heavy isotopes (^{18}O and ^{2}H) with increasing elevation, creating distinct isotopic signatures for different recharge elevations. Rain-shadowing effects, common in mountainous tropical islands, create spatial variations in precipitation isotope compositions that can be traced in groundwater systems.

The meteoric recharge patterns in volcanic island aquifers are influenced by the rapid infiltration capacity of fractured basaltic formations. In Aquifer V (Northern Plains), the surface, in general recent basaltic flows (Younger Series, 700,000-20,000 years old), is very permeable and nearly all rainwater which is not evaporated is entering the aquifer system by direct infiltration (Fenta, 2022). Recent basaltic flows are underlain by alternating weathered and fresh intermediate lava flows which all together form a multi-layered aquifer. Studies using quantitative isotopic approaches on Bromo-Tengger volcano have demonstrated how andesitic volcanic aquifers respond to seasonal precipitation variations and how isotope signatures can be used to quantify recharge rates and flow velocities (Baud et al., 2024; Toulier et al., 2019). This research provides methodological frameworks that can be applied to basaltic island settings like Mauritius. The aquifer systems in Mauritius show various zones of recharge. The valleys of Creve Coeur-Notre Dame and Les Mariannes-Congomah contribute to the feeding of the western part of the northern plains. There are also significant fractures that allow the direct recharge of the northern aquifer to the Central-east part of the northern plains. Surface water contributes to the recharge of the aquifers and is dependent on various factors including direct rainfall and percolation due to infiltration along rivers.

2.4.4 Flow Path Identification Using Environmental Tracers

Environmental tracers provide essential tools for identifying groundwater flow paths in complex volcanic aquifer systems (Doveri & Mussi, 2014). The combination of stable isotopes, major ion chemistry, and physical parameters such as temperature and electrical conductivity enables detailed characterization of flow systems from recharge to discharge zones. Research on volcanic islands has shown that groundwater flow can be compartmentalized by volcanic rift zones, creating distinct flow systems with characteristic tracer signatures (Olaka et al., 2022). In Mauritius, the radial flow pattern from the central plateau creates multiple flow paths toward coastal discharge zones, each potentially exhibiting distinct geochemical and isotopic evolution.

According to Giorgi et al., (1999), from borehole drilling it was found that there were two deep valleys made up of ancient basaltic flows (8-10 million years old from the Older Series) and filled by intermediate (3.5-1.9 million years old) and recent basalt flows (700,000-20,000 years old). These valleys of different-aged volcanic formations guide groundwater circulations, particularly in levels of fossil alluvium located at the base of these flows. The use of multiple tracers allows for identification of different water masses and mixing processes. For example, groundwater in confined aquifer systems typically shows distinct temperature and geochemical signatures compared to shallow unconfined systems. The top of Aquifer II is located within clayish semi-impermeable basalts which show some characteristics of semi-confined aquifers, suggesting different flow dynamics and tracer evolution compared to unconfined systems.

Studies have demonstrated that the integration of traditional hydrogeological parameters with isotopic and geochemical tracers provides robust methods for identifying preferential flow paths through fracture networks (Berkowitz, 2002; Binda et al., 2021; Masciopinto et al., 2021). This is particularly important in Mauritius where fracture systems, particularly along N20° and N100° orientations, create preferential groundwater flow paths and influence aquifer connectivity.

2.4.5 Application of Isotope Hydrology in SIDS Research

The application of isotope hydrology techniques in Small Island Developing States remains limited despite their potential for providing critical insights into groundwater flow systems and management challenges. A review of isotope hydrology applications reveals significant research gaps in SIDS contexts compared to continental volcanic settings. Research on Madeira volcanic island represents one of the few comprehensive isotope characterization studies in oceanic island settings, demonstrating the effectiveness of stable isotope analysis for understanding complex volcanic groundwater systems (Andrade, 2023; Island, 2023). The study showed how systematic isotope surveys can identify distinct flow compartments, quantify recharge sources, and evaluate groundwater residence times. Studies on various Pacific volcanic islands have applied isotope techniques to understand groundwater-surface water interactions and to quantify submarine groundwater discharge rates(Carvalho da Silva et al., 2023; García-Gil et al., 2023; Maharaj et al., 2023) These applications demonstrate the value of isotope hydrology for addressing water resource challenges specific to island environments, including saltwater intrusion assessment and sustainable yield determination. However, there is a critical research gap in the systematic application of isotope hydrology techniques in SIDS groundwater research. Most SIDS lack comprehensive isotope databases for groundwater systems, limiting the ability to understand flow dynamics, residence times, and vulnerability to contamination. This gap is particularly significant given the increasing pressures on groundwater resources in SIDS from climate change, population growth, and economic development. The development of isotope hydrology capabilities in SIDS requires coordinated international support for analytical facilities, training programs, and research collaborations. Regional isotope laboratories and technical cooperation programs could facilitate broader application of these techniques across SIDS regions. Future research priorities for isotope hydrology applications in SIDS should include: (1) establishment of precipitation isotope monitoring networks to characterize local meteoric water lines and seasonal variations; (2) systematic groundwater isotope surveys to identify flow compartments and recharge sources; (3) integration of isotope data with hydrogeochemical and physical parameters for comprehensive flow system characterization; (4) development of conceptual and numerical models incorporating isotope constraints; and (5) application of isotope techniques for evaluating management scenarios and climate change impacts. The potential for isotope hydrology to inform evidence-based groundwater management in SIDS is substantial, but requires significant investment in analytical capabilities, technical training, and research infrastructure. International cooperation and technology transfer programs are essential for developing these capabilities across SIDS regions.

2.5 Groundwater Vulnerability Assessment Frameworks for SIDS

Groundwater vulnerability assessment in Small Island Developing States requires specialized frameworks that account for the unique hydrogeological, climatic, and socio-economic characteristics of island environments (Holding et al., 2016; Gheuens et al., 2019). Traditional vulnerability assessment methods developed for continental aquifer systems often fail to capture the specific vulnerabilities associated with limited freshwater lens systems, high population densities, and extreme exposure to climate variability that characterize SIDS (Werner et al., 2017). The development of SIDS-specific vulnerability frameworks is essential for sustainable groundwater management and climate adaptation planning in these highly vulnerable regions.

2.5.1 Vulnerability Assessment Methods and Indicators

Groundwater vulnerability assessment methods can be broadly categorized into three main types: GIS-based qualitative approaches, process-based quantitative methods, and statistical/hybrid approaches. Each method offers distinct advantages and limitations when applied to SIDS contexts, requiring careful consideration of data availability, technical capacity, and management objectives.

GIS-Based Qualitative Methods include widely applied frameworks such as DRASTIC, GOD (Groundwater occurrence, Overall lithology, Depth to groundwater), and SI (Susceptibility Index) approaches (Fannakh et al., 2025; Hiba et al., 2025). The DRASTIC method evaluates seven parameters: Depth to water table, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity. While DRASTIC has been successfully applied in various continental settings, its application in SIDS requires significant modifications to account for thin freshwater lenses, highly permeable volcanic formations, and limited vadose zones typical of island aquifers (Abdelkarim et al., 2025). The GOD method, with its simplified three-parameter approach, offers advantages for SIDS applications where detailed hydrogeological data may be limited. The method evaluates groundwater occurrence (confined, unconfined, or semi-confined conditions), overall lithology of the unsaturated zone, and depth to groundwater. For volcanic islands like Mauritius, the highly fractured basaltic formations and variable confinement conditions across different aquifer systems require careful parameter adaptation.

Process-Based Quantitative Methods employ numerical modelling approaches to simulate contaminant transport and assess aquifer vulnerability based on physical processes (Nguyen, 2025). These methods require detailed hydrogeological characterization including aquifer properties, flow dynamics, and geochemical processes. While more scientifically rigorous, process-based methods face significant data and technical capacity constraints in many SIDS contexts. Statistical and Hybrid Methods combine multiple approaches using techniques such as fuzzy logic, artificial neural networks, and multi-criteria decision analysis (Demir, 2025). These methods can integrate diverse data types and uncertainty assessments, making them particularly suitable for SIDS where data limitations and high uncertainty are common challenges.

Modern vulnerability assessment increasingly emphasizes the integration of multiple methods to provide robust uncertainty assessment and validation. The combination of overlay methods with statistical validation using water quality data represents current best practice for vulnerability assessment applications.

2.5.2 SIDS-Specific Vulnerability Factors

Small Island Developing States exhibit unique vulnerability characteristics that distinguish them from continental aquifer systems. A comprehensive vulnerability assessment of 43 SIDS revealed that recharge volume per capita serves as a critical vulnerability indicator, with population density emerging as the main driver of water stress in 71% of analysed islands (Holding et al., 2016). Recent isotopic studies of SIDS groundwater systems demonstrate that these volcanic island aquifers exhibit complex recharge mechanisms and flow patterns, with the central plateau regions serving as primary recharge zones (Gungoa & Kebede, 2025). Physical Vulnerability Factors specific to SIDS include limited freshwater lens volumes, high permeability volcanic or carbonate formations, minimal vadose zone protection, and direct hydraulic connection between aquifers and the sea along extensive coastlines. Research on small island aquifers shows they are at risk of salinization due to low elevations and limited adaptive capacity, with present risks being exacerbated by climate change (Stanic et al., 2024). The thin freshwater lenses characteristic of many SIDS is highly vulnerable to both upward saline intrusion from rising sea levels and downward contamination from surface sources.

Climate-Related Vulnerability Factors encompass extreme exposure to tropical cyclones, prolonged drought periods, sea-level rise, and high rainfall variability associated with climate change. Recent studies on oceanic volcanic islands demonstrate that aquifers constitute the main freshwater supply and maintaining groundwater quantity and quality is of critical concern as demographic and climatic changes place additional pressures on already fragile water resources systems (Padrón-Fumero et al., 2022). SIDS experience disproportionate climate impacts due to their small size, low elevation, and oceanic exposure. Hydrogeological characterization of volcanic aquifers shows that islands with heterogeneous volcanic aquifers pose additional difficulties in assessing their water resources (Padrón-Fumero et al., 2022). Climate vulnerability is further exacerbated by limited adaptive capacity and high dependence on climate-sensitive sectors such as tourism and agriculture.

Socio-Economic Vulnerability Factors include high population densities relative to available freshwater resources, limited technical and financial capacity for groundwater management, dependence on imported technologies and expertise, and vulnerability to external economic shocks. Studies of fractured aquifer systems demonstrate they are heterogeneous and peculiar environments that pose scientific and methodological challenges due to heterogeneous distribution of fracture porosity (De Vargas et al., 2022). Many SIDS lack adequate groundwater protection legislation and enforcement mechanisms, increasing vulnerability to anthropogenic contamination. Research on crystalline hardrock aquifers shows that successful mapping and management of groundwater resources entails delineating fracture networks and recharge zones for optimal well siting (Chandra et al., 2019).

Hydrogeological Vulnerability Factors in SIDS reflect the unique geological settings of oceanic islands. Recent research on Mauritius shows that the island's groundwater systems are characterized by five major aquifer systems within basaltic geology, with groundwater following radial movement patterns eventually discharging into the ocean at the island boundaries (Gungoa & Kebede, 2025). Volcanic islands like Mauritius exhibit complex aquifer systems with highly variable permeability, extensive fracture networks that facilitate rapid contaminant transport, and limited natural attenuation capacity in highly permeable formations. Studies of volcanic aquifer systems indicate that groundwater circulation occurs in fractures originating from horizontal disjunctions, contacts between volcanic flows, and vesicular zones (De Vargas et al., 2022). The radial flow patterns typical of volcanic islands create vulnerability corridors from central recharge areas to coastal discharge zones.

The comparative analysis across different SIDS regions reveals distinct vulnerability patterns (Table 2.7 from original document, enhanced). Caribbean SIDS demonstrate heavy reliance on groundwater with significant over-extraction and pollution issues, primarily addressed through Integrated Water Resources Management (IWRM) and community-based monitoring programs. Pacific SIDS face severe drought impacts and limited land area constraints, leading to innovative combinations of rainwater harvesting, desalination technologies, and traditional knowledge integration. Studies of volcanic islands show that the proximity to the coast, low surface elevations, and low hydraulic inertia of small-island aquifers make island freshwater resources highly sensitive to hydroclimatic changes and groundwater pumping (Stanic et al., 2024). Indian Ocean SIDS experience contamination from agricultural and industrial activities, addressed through advanced monitoring technologies such as GIS and remote sensing, coupled with participatory governance models.

2.5.3 Integrated Assessment Approaches

Integrated vulnerability assessment approaches recognize that groundwater vulnerability in SIDS results from complex interactions between physical, climate, and socio-economic factors. Recent development of multidimensional vulnerability indices for SIDS demonstrates the need to move beyond singlecriterion approaches to encompass comprehensive vulnerability assessment (UNDP, 2021). These approaches move beyond traditional hydrogeological vulnerability to encompass social-ecological system vulnerability and adaptive capacity assessment. Research on socio-ecological systems in small islands emphasizes that vulnerability emerges from the interaction of social and ecological components, with "islandness" contributing immensely to understanding these integrated systems (Karanci et al., 2021). Social-Ecological System Framework for Pacific SIDS emphasizes the interconnections between groundwater systems and human communities, recognizing that vulnerability emerges from the interaction of social and ecological components. Current research highlights that SIDS face severe structural challenges due to their remoteness, economic concentration, and dependence on external flows, with the COVID-19 pandemic greatly exacerbating these vulnerabilities (UNDP, 2021). This framework considers factors such as traditional knowledge systems, community organization, economic diversification, and institutional capacity alongside conventional hydrogeological parameters. Studies show that some SIDS have been pioneers in integrating disaster risk reduction and climate change adaptation into unified plans guided by local and traditional knowledge (UNDRR, 2024).

Multi-Criteria Decision Analysis (MCDA) approaches integrate diverse vulnerability factors using structured decision-making frameworks. Recent applications demonstrate that MCDA provides structure and transparency for intricate decisions involving diverse merits and perspectives, facilitating trade-offs amid priorities (Abdullah & Hodgett, 2021). MCDA methods such as the Analytic Hierarchy Process (AHP) enable stakeholder participation in vulnerability assessment by incorporating local knowledge and management priorities into technical assessments. Research shows that MCDA techniques including AHP and Catastrophe theory have proven effective for groundwater assessment, with AHP demonstrating superior performance in validation studies (Sahoo & Jha, 2018). These approaches are particularly valuable in SIDS contexts where community engagement is essential for sustainable groundwater management.

Fuzzy Logic Integration with GIS modeling provides methods for handling uncertainty and imprecise data common in SIDS vulnerability assessments. Recent studies demonstrate the effectiveness of fuzzy logic techniques in groundwater management, particularly for handling linguistic variables and expert judgment in data-limited situations (Samayamanthula et al., 2023). Fuzzy logic approaches can accommodate linguistic variables and expert judgment, making them suitable for situations where quantitative data is limited but qualitative knowledge is available. Applications in arid regions show that fuzzy logic can effectively evaluate groundwater suitability by integrating multiple hydro chemical parameters with spatial analysis (Samayamanthula et al., 2023).

Strategic Adaptive Management frameworks integrate vulnerability assessment with management planning and monitoring systems. Recent research emphasizes that sustainable water resources management involves social, economic, environmental, water use, and resources factors requiring integrated strategic planning approaches (Zare et al., 2022). These approaches recognize that vulnerability is dynamic and require adaptive management strategies that can respond to changing conditions and new information. Studies on adaptive water management demonstrate the importance of integrating machine learning, groundwater modelling, and robust decision-making to address uncertainty in drought-prone regions (Shortridge et al., 2021). Strategic adaptive management is particularly relevant for SIDS facing rapid environmental and socio-economic changes.

Integrated Water Resources Management (IWRM) approaches place vulnerability assessment within broader water resource planning frameworks that consider multiple water sources, competing demands, and management objectives. Recent frameworks emphasize that water DSS are particularly important as climatic change affects water availability, requiring computational systems that integrate data and models to aid management decisions (Woznicki et al., 2022). IWRM is essential in SIDS contexts where groundwater often represents a significant component of total water resources and where coordination between different sectors is critical for sustainable management. Research demonstrates that geospatial technologies including GIS, remote sensing, and advanced modelling techniques provide transformative opportunities for holistic water resource understanding and sustainable management (Kumar et al., 2024).

2.5.4 GIS-Based Vulnerability Mapping

Geographic Information Systems (GIS) provide essential tools for vulnerability mapping and spatial analysis in SIDS contexts. Recent advances demonstrate that integration of GIS with groundwater vulnerability assessment methodologies has become essential for hydrogeological science, helping assess, monitor, conserve, and manage groundwater resources (Gangoda et al., 2016). GIS-based vulnerability mapping enables visualization of spatial vulnerability patterns, identification of high-risk areas, and support for land-use planning and groundwater protection strategies. Studies show that GIS integration facilitates assessment of groundwater vulnerability through mapping, with the potential to improve management of water resources and land use through generation of contamination potential maps (Dixon, 2005).

GIS Methodology for Monitoring Network Design utilizes vulnerability mapping to optimize groundwater monitoring networks by identifying areas requiring enhanced monitoring based on vulnerability levels. Recent research demonstrates that GIS-based approaches can effectively identify groundwater vulnerable areas and high-risk zones, helping environmental planning specialists prepare mitigation strategies (ESRI, 2024). This approach is particularly valuable in SIDS where financial and technical resources for monitoring are often limited, necessitating strategic placement of monitoring infrastructure. Advanced GIS techniques enable rapid identification of groundwater sources crucial for emergency water supplies, particularly important in mountainous areas with pressing groundwater demands (Li et al., 2025).

Multi-Criteria GIS Assessment integrates multiple vulnerability factors using spatial analysis techniques. Recent studies show that integration of remote sensing, GIS, and multi-criteria decision analysis techniques can effectively delineate groundwater potential zones using correlation tests and innovative assessment indicators (Li et al., 2025). These assessments can incorporate diverse data types including geological maps, land-use information, precipitation data, population density, and infrastructure distribution. Research demonstrates that GIS-based multi-criteria approaches using analytical hierarchy process and fuzzy AHP models can generate comprehensive groundwater potential zone maps through weighted overlay analysis (Li et al., 2025). The integration of multiple criteria provides comprehensive vulnerability assessments that support evidence-based decision-making.

DRASTIC Model Validation using water quality parameters has been successfully demonstrated in various settings, providing validation of vulnerability predictions through comparison with observed contamination patterns. Recent studies confirm that DRASTIC method validation using field data shows good correlation between nitrate samples and resulting vulnerability indices, with sensitivity analysis revealing that depth of water table, land use, and topography parameters cause large variations in vulnerability index (Gangoda et al., 2016). Enhanced DRASTIC models incorporating machine learning techniques have been developed to improve groundwater resources quality prediction, with soft computing methods providing formulations for nitrate vulnerability index prediction (Jahanshahi et al., 2024). In SIDS contexts, validation data may be limited, requiring innovative approaches to model validation and uncertainty assessment.

Remote Sensing Integration enhances GIS-based vulnerability assessment by providing time-series data on land-use changes, vegetation cover, precipitation patterns, and other dynamic factors affecting groundwater vulnerability. Recent comprehensive reviews demonstrate that remote sensing technologies offer significant advances for quantitative monitoring of groundwater storage changes and unlock new groundwater insights (Alatawneh et al., 2024). Studies show that application of remote sensing and GIS has become essential in hydrogeological science for assessing groundwater vulnerable zones, with modification of traditional models through integration of land use parameters derived from remote sensing data (Gangoda et al., 2016). Satellite-based monitoring is particularly valuable for SIDS where ground-based monitoring infrastructure may be limited.

Participatory GIS Approaches engage local communities in vulnerability mapping and assessment processes, incorporating local knowledge and stakeholder perspectives into technical assessments. Recent research emphasizes the importance of integrating modelling software and GIS to create holistic representations of groundwater quality, facilitating comprehensive assessment approaches (Megahed et al., 2025). Participatory GIS is especially important in SIDS contexts where community engagement is essential for sustainable groundwater management and where local knowledge provides valuable insights into vulnerability factors. Studies demonstrate that integration of finite element models with numerical modeling of groundwater flows can be effective in assessing climate influence on cropping patterns and optimizing irrigation water management (Megahed et al., 2025).

2.5.5 Comparative Vulnerability Assessment: Pacific, Caribbean, and Indian Ocean SIDS

A comprehensive comparison of groundwater vulnerability across the three main SIDS regions reveals distinct patterns and approaches that reflect regional differences in hydrogeological settings, climate conditions, and socio-economic contexts. Recent research demonstrates that SIDS face some of the most severe impacts of climate change, with sea-level rise posing significant threats due to the concentration of people, assets, and infrastructure in coastal zones (Nurse et al., 2021). This comparative analysis provides insights for developing region-specific vulnerability assessment frameworks while identifying common themes applicable across SIDS contexts. Studies show that adaptation to sea-level rise is of paramount importance for SIDS, but multiple barriers exist, and limits will be reached if warming exceeds 1.5°C (Nurse et al., 2021).

Regional Vulnerability Patterns show systematic differences between SIDS regions. Pacific SIDS, dominated by low-lying atolls and volcanic islands, exhibit extreme vulnerability to sea-level rise and drought impacts, with limited groundwater storage capacity and high dependence on precipitation. Recent projections show that by 2050, NASA scientists predict daily tides will submerge half of the main atoll of Funafuti in Tuvalu, with sea level rise rates one and a half times the global average (Climate Adaptation Platform, 2024). Caribbean SIDS demonstrate heavy reliance on groundwater resources with significant over-extraction pressures and contamination from agricultural and tourism activities. Research shows that Caribbean SIDS face rising climate threats, aging infrastructure, and chronic underinvestment, making water security a foundation of regional resilience (Davis, 2025; Galaitsi et al., 2024). Indian Ocean SIDS, including Mauritius, face contamination from agricultural runoff and industrial activities combined with increasing pressure from population growth and economic development.

Assessment Methodologies vary significantly between regions based on available technical capacity, data availability, and management priorities. Caribbean SIDS emphasize policy interventions and community-based monitoring programs, reflecting relatively well-developed institutional frameworks and technical capacity. Recent studies reveal that while over 90% of Caribbean residents have access to improved water, the region faces challenges due to inefficient management and diverse geographical realities creating spatial disparities (Mycoo & Roopnarine, 2024; Ramjit et al., 2024). Pacific SIDS focus on integrating traditional knowledge with modern technologies, recognizing the importance of community-based management systems and traditional water practices. Climate change is rapidly transforming Pacific Islands through accelerating sea level rise, ocean warming and acidification, with sea level rise in the region above the global average (Guild et al., 2024). Indian Ocean SIDS leverage advanced monitoring technologies such as GIS and remote sensing, coupled with participatory governance models that engage local stakeholders in decision-making processes.

Common Vulnerability Factors across all SIDS regions include high exposure to climate variability and change, limited freshwater resources relative to population demands, and high vulnerability to contamination due to permeable geological formations and limited natural attenuation capacity. Research demonstrates that nearly 22 million people in the Caribbean live less than six metres above sea level, while most Pacific islands have over half of their infrastructure within 500 metres from the coast (UNDP, 2024). Community engagement emerges as a critical success factor across all regions, though implemented through different mechanisms reflecting regional cultural and institutional contexts. Studies show that about 80 percent of Solomon Islanders live in rural, low-lying areas and rely on agriculture, forestry and fisheries for food security and livelihoods (UNDP, 2024).

Management Responses to vulnerability assessments show regional variations in technological, policy, and community-based approaches. Caribbean islands emphasize Integrated Water Resources Management (IWRM) and establishment of groundwater protection zones, reflecting relatively well-developed regulatory frameworks. Recent workshops demonstrate that Caribbean SIDS have reaffirmed their commitment to strengthening water security and IWRM, though full adoption and implementation remains a work in progress (Davis, 2025). Pacific islands focus on community-maintained infrastructure and traditional water management practices combined with innovative technologies such as rainwater harvesting and desalination. Studies show that sea-level rise is increasing the salinity of several coastal aquifers in Pacific SIDS, affecting water quality for local people who depend on coastal aquifers as their only source of freshwater (Iqbal et al., 2024). Indian Ocean SIDS emphasize technological advancement alongside stakeholder participation in decision-making processes.

Success Factors identified across regions include: (1) strong community engagement and stakeholder participation; (2) integration of traditional knowledge with modern scientific approaches; (3) adaptive management frameworks that can respond to changing conditions; (4) multi-sector coordination and policy integration; and (5) sustained technical and financial support for monitoring and management activities. Research emphasizes that effective water management requires shifting beyond traditional planning toward more tangible, inclusive, and phased actions that are realistic and achievable in the short term (Davis, 2025).

Research Gaps in comparative vulnerability assessment include limited standardized methodologies for cross-regional comparison, insufficient long-term monitoring data for validation of vulnerability predictions, and limited understanding of social-ecological system interactions in different regional contexts. Recent studies highlight that there is a shortage of IWRM specialists in the Caribbean region, with many findings more lucrative employment in the energy sector, hampering water resources management (Mycoo & Roopnarine, 2024). Future research should focus on developing standardized vulnerability assessment protocols suitable for SIDS contexts while maintaining flexibility for regional adaptation.

The evidence suggests that successful vulnerability assessment frameworks for SIDS must integrate technical rigor with community engagement, combine multiple assessment methods to address uncertainty and data limitations, and incorporate adaptive management principles to respond to changing conditions. Regional differences highlight the importance of context-specific approaches while common themes provide opportunities for knowledge sharing and technology transfer between SIDS regions. Studies demonstrate that the sustainability of water resources in Caribbean SIDS poses multifaceted challenges requiring urgent and coordinated action through IWRM approaches that promote sustainable use by considering the interconnectedness of water, land, and related resources (Ramjit et al., 2024).

2.6 Case Studies of SIDS

2.6.1 Regional Overview and Comparative Framework

Small Island Developing States (SIDS) are distributed across three major oceanic regions, each with distinct geological, climatic, and socio-economic characteristics that influence groundwater resource challenges and management approaches. This section provides balanced coverage of groundwater issues across Pacific, Caribbean, and Indian Ocean SIDS to establish a comprehensive comparative framework for understanding regional variations and commonalities in groundwater management challenges.

2.6.1.1 Regional Characteristics and Climate Drivers

Small Island Developing States (SIDS) are particularly vulnerable to the impacts of climate change and variability, which significantly affect their groundwater resources. This review explores the findings from various studies on SIDS to provide context and comparison for understanding how climate variabilities impact groundwater systems in these regions.

A range of studies have highlighted the vulnerability of Small Island Developing States (SIDS) to climate change and its impact on groundwater resources. (Aizebeokhai et al., 2017) and (Afrifa et al., 2025) both emphasized the challenges in predicting and detecting these impacts, particularly in the context of groundwater-residence times. (Gohar, 2015) and (Amanambu et al., 2020) further underscore the potential for decreased groundwater recharge, storage, and levels, with (Gohar & Cashman, 2015) noting the uneven distribution of these impacts across economic sectors. (Gheuens ,2019) and (Falkland, 1999) highlight the broader challenges faced by SIDS, including increasing disaster risks and water scarcity. (Earman and Dettinger, 2011) and (Aron-Gilat, 2003) stress the need for improved understanding and monitoring of these impacts, particularly in the context of health concerns.

In SIDS, groundwater recharge is highly sensitive to climate variability. (Werner et al., 2017) highlight that atoll islands, which rely heavily on freshwater lenses, experience significant fluctuations in groundwater volumes due to variations in precipitation and sea-level rise. The study notes that densely vegetated areas on these islands tend to have higher recharge rates compared to less vegetated ones, emphasizing the role of vegetation in groundwater dynamics. Similarly, (Thomas et al., 2020) discuss how climatic events, such as changes in precipitation patterns and the frequency of storms, directly influence groundwater recharge and sustainability in tropical SIDS.

Sea-level rise poses a critical threat to the freshwater resources of SIDS by increasing saline intrusion into coastal aquifers. (Gheuens et al., 2019) report that many SIDS face significant challenges with saline intrusion, which compromises the quality of groundwater, especially in low-lying areas. This is corroborated by (Moosdorf et al., 2015), who find that the extent of saline intrusion is often exacerbated by anthropogenic activities and climate-induced sea-level changes, leading to the deterioration of freshwater lenses in island aquifers.

The increasing frequency of extreme weather events, such as hurricanes and droughts, further impacts groundwater resources in SIDS. (Cashman et al., 2010) examine the Caribbean region and find that hurricanes and heavy rainfall events lead to rapid changes in groundwater levels, often resulting in contamination and reduced water quality. On the other hand, prolonged droughts significantly lower groundwater recharge rates, affecting water availability during dry periods. (Rhiney, 2015) also emphasizes that these extreme events can disrupt the delicate balance of groundwater systems, making water management more challenging in SIDS.

The degradation of groundwater quality due to climate change and variability has direct implications for human and environmental health. (Werner et al., 2013) note that saline intrusion and reduced recharge rates lead to water scarcity, impacting agricultural productivity and increasing the risk of health issues due to poor water quality. In the Pacific islands, for instance, communities often face water shortages and health problems linked to contaminated groundwater (Carrard et al., 2019).

Adaptation strategies are crucial for mitigating the impacts of climate variability on groundwater resources in SIDS. Integrated water resources management (IWRM) approaches, as discussed by White and Falkland (2010), are essential for managing the freshwater lenses on small Pacific islands. These strategies include enhancing natural recharge processes, improving water storage infrastructure, and implementing policies that regulate groundwater extraction to prevent overuse. (Werner et al., 2013) further recommend the development of community-based management plans that incorporate traditional knowledge and modern scientific practices to ensure sustainable groundwater use. The impacts of climate variability on groundwater resources in SIDS are multifaceted, affecting recharge rates, increasing saline intrusion, and exacerbating the frequency of extreme weather events. Effective management and adaptation strategies are necessary to mitigate these effects and ensure the sustainability of groundwater resources. The findings from various studies highlight the need for approaches that consider both environmental and socio-economic factors in managing groundwater resources in these vulnerable regions.

a) Pacific SIDS

The Pacific region represents the largest concentration of Small Island Developing States globally, comprising 14 UN member countries and 8 non-member territories, totalling 22 Pacific Island Countries and Territories (PICTs) (McMichael et al., 2019). These nations include Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu as UN members, along with territories such as American Samoa, French Polynesia, Guam, New Caledonia, Northern Mariana Islands, Pitcairn Islands, Tokelau, and Wallis and Futuna (UN DESA, 2023). The region is characterized by extreme geographical dispersion across the Pacific Ocean, with nations spread over approximately 30 million square kilometers of ocean while possessing only 550,000 square kilometers of land area (UNEP, 2023).

This review synthesizes findings from various studies to provide an understanding of the diverse issues affecting groundwater resources in PICs. It explores the multifaceted challenges faced by these island nations, including over-extraction, contamination, and the effects of changing climatic conditions on groundwater sustainability. By examining similar studies addressing groundwater issues in the Pacific Islands, this review aims to highlight the complex interplay between climate variability, human activities, and groundwater resources. Furthermore, this synthesis will discuss potential strategies and solutions for addressing these challenges, with a focus on ensuring sustainable management and future resilience of groundwater systems. The review will emphasize the importance of adaptive management practices, considering the unique geological, hydrological, and socio-economic contexts of PICs.

By compiling and analysing existing knowledge on groundwater reliance, vulnerabilities, and management practices in the context of changing climatic conditions, this review seeks to inform policymakers, researchers, and water resource managers. The goal is to contribute to the development of effective and sustainable groundwater management strategies that can enhance the resilience of Pacific Island communities in the face of ongoing environmental changes. This review of Pacific Island groundwater challenges provides essential comparative context for understanding the broader SIDS experience, enabling meaningful comparison with Mauritius as an Indian Ocean SIDS. The Pacific region represents the largest concentration of SIDS globally and offers extensive research literature on climate-groundwater interactions, making it an ideal benchmark for comparative analysis. By examining Pacific Island case studies, this review establishes a foundation for identifying common SIDS vulnerabilities, successful management strategies, and adaptive practices that can inform groundwater management approaches in other SIDS regions, including the Indian Ocean context of Mauritius.

Pacific SIDS demonstrate remarkable geological diversity, with four nations being exclusively low-lying coral atolls and reef islands: Kiribati, Tuvalu, Tokelau, and Marshall Islands, recognized as among the most vulnerable locations globally to climate change impacts (McMichael et al., 2019). The remaining islands exhibit a mixture of volcanic origins and coral formations, with Papua New Guinea representing the largest landmass in the region (UNEP, 2023). Population distribution shows extreme coastal concentration, with 97% of Pacific Islanders living within 10 kilometres of the coast when Papua New Guinea is excluded, and over half residing within 1 kilometre of the ocean (McMichael et al., 2019).

Climate drivers in the Pacific region are dominated by the El Niño-Southern Oscillation (ENSO) phenomenon, which creates dramatic variations in precipitation patterns across the region (Taylor et al., 2018). During El Niño events, many western Pacific islands experience severe drought conditions, while La Niña periods can bring excessive rainfall and flooding (UNEP, 2023). Trade wind patterns significantly influence regional weather systems, while the region experiences some of the most intense tropical cyclones globally, with typhoons regularly affecting Micronesian and Melanesian islands (McMichael et al., 2019). The combination of extremely low elevation (averaging 1-3 meters above sea level for atoll nations) and exposure to rising sea levels creates unprecedented vulnerability to climate change impacts (Taylor et al., 2018).

Groundwater resources in Pacific Island countries (PICs) are critically important for the sustenance of life, ecosystems, and socio-economic development. These resources serve as essential sources for drinking water, agriculture, and industrial uses, often due to limited surface water availability. However, groundwater systems in PICs are increasingly vulnerable to the impacts of climate change, climate variability, and anthropogenic pressures, leading to complex management challenges.

Over-extraction of groundwater is a prevalent issue in many Pacific Island countries (PICs), leading to significant challenges such as groundwater depletion and saltwater intrusion (SWI). The growing population, increased water demand, and economic activities have led to unsustainable pumping practices, further stressing the already vulnerable aquifers (Sharan et al., 2023; Sharan et al., 2021). Groundwater is the primary source of drinking water for many PICs. (Carrard et al., 2019) found that an average of 66% of urban and 60% of rural households in Southeast Asian and Pacific nations rely on groundwater for drinking. This heavy reliance, coupled with over-extraction, has resulted in the depletion of aquifers, causing land subsidence and increasing the risk of saline intrusion (Sharan et al., 2023).

The problem of saltwater intrusion is particularly severe in low-lying atolls where freshwater lenses are thin and highly vulnerable to salinity (Lal & Datta, 2019). Sea-level rise is another critical issue exacerbating groundwater problems in the Pacific Islands. As sea levels rise, saltwater intrusion into coastal aquifers becomes more pronounced, reducing the availability of potable freshwater. According to (Holding et al., 2016), many low-lying atolls are particularly vulnerable to this phenomenon, where even minor increases in sea level can lead to significant salinization of freshwater lenses. This intrusion not only reduces the volume of freshwater available but also affects the overall quality, making it unsuitable for drinking and irrigation (Barkey & Bailey, 2017). Over-extraction exacerbates saltwater intrusion, especially in coastal aquifers where the infiltration of saline water into freshwater lenses is a common problem (White & Falkland, 2010) Climate variability further compounds these issues. (White and Falkland, 2012) highlight the significant impact of El Niño and La Niña events on groundwater availability. These climatic patterns influence precipitation rates, affecting the recharge of freshwater lenses on small islands. The high permeability of soils and regoliths in many small island countries exacerbates groundwater vulnerability, particularly during frequent El Niño-Southern Oscillation (ENSO)-related droughts (White & Falkland, 2011). To address these challenges, sustainable extraction practices are necessary to ensure that groundwater levels are maintained and not exhausted. (White and Falkland 2011) emphasize the importance of using advanced techniques like 3D modelling and simulation-optimization to develop effective SWI management strategies. Their work underscores the necessity for adaptive management strategies that account for both climatic and human-induced pressures on groundwater systems. The studies highlight the urgent need for sustainable groundwater management practices to mitigate the impacts of over-extraction, depletion, and saltwater intrusion in PICs. These strategies must consider the unique geological, hydrological, and climatic conditions of these island nations to ensure long-term water security.

Groundwater contamination and quality degradation in Pacific Island countries (PICs) pose significant threats to human and environmental health. Anthropogenic activities, including agriculture, improper waste management, and inadequate sanitation facilities, are major contributors to this issue. Agricultural runoff containing pesticides and fertilizers has been identified as a significant source of groundwater contamination in several PICs (Tribble, 2008). This contamination not only degrades water quality but also affects agricultural productivity, potentially leading to food insecurity and economic instability.

Inadequate sanitation facilities exacerbate groundwater pollution, posing serious health risks to local communities (Dillon, 1997). (Foster et al., 2013) identified that pollution from unsafe sanitation is a prevalent threat to groundwater quality in urban areas of Southeast Asia and the Pacific. The resulting poor water quality can lead to various health issues, including waterborne diseases. (Carrard et al., 2019) discuss how contaminated groundwater, often with high levels of salinity and pollutants, poses a severe risk to public health in Pacific Island communities. Emerging contaminants, such as pharmaceuticals and personal care products, present additional risks to groundwater quality. (Lapworth et al., 2012) noted that monitoring systems in many PICs are inadequate to detect these contaminants, highlighting the need for improved regulatory frameworks and monitoring capabilities.

To address these challenges, (Holding et al., 2016) present a framework for assessing groundwater vulnerability, identifying critical indicators that highlight the susceptibility of small island states to contamination. This framework is essential for developing robust monitoring systems and implementing timely interventions to preserve groundwater quality. The studies underline the need for improved agricultural practices, effective waste management systems, and enhanced sanitation facilities to protect groundwater quality. Additionally, there is a pressing need for advanced monitoring systems to track changes in groundwater quality and implement timely mitigation measures. Addressing groundwater contamination in PICs requires a multifaceted approach that considers both traditional pollutants and emerging contaminants. Implementing effective strategies to protect groundwater quality is crucial for safeguarding public health, ensuring food security, and maintaining environmental integrity in these vulnerable island communities.

Climate change poses significant threats to groundwater resources in Pacific Island countries (PICs), exacerbating existing challenges and creating new ones. Rising sea levels, increased frequency of extreme weather events, and changing precipitation patterns are among the primary climate-induced stressors affecting groundwater availability and quality. The impact of sea-level rise is particularly severe in low-lying islands. (Barkey and Bailey 2017) investigated its effects on the Marshall Islands, demonstrating how saltwater intrusion into freshwater lenses forces communities to relocate. This highlights the urgent need for adaptive strategies to ensure water security in vulnerable island communities.

Climate variability, particularly El Niño and La Niña cycles, significantly impacts groundwater recharge and quality. (White and Falkland 2012) note that these climatic cycles lead to periods of drought and intense rainfall, disrupting the balance of freshwater lenses. This variability complicates groundwater management as recharge periods become unpredictable, potentially leading to over-extraction during dry spells (Sharan et al., 2021). To address these challenges, researchers propose various adaptation and management strategies:

1. Integrated Water Resources Management (IWRM): Falkland and White (2010) advocate for community-based management plans that incorporate both traditional knowledge and modern scientific practices to ensure sustainable use of groundwater.
2. Social-Ecological System Approach: (Bouchet et al., 2019) propose managing groundwater as a social-ecological system, integrating community participation and scientific knowledge to develop adaptive strategies. This approach is vital for enhancing the resilience of groundwater systems against climate-induced stresses.
3. Enhanced Recharge Techniques: (Werner et al., 2013) suggest enhancing natural recharge processes through the construction of infiltration basins and rainwater harvesting systems to improve groundwater replenishment.
4. Multi-Objective Management Strategies: (Sharan et al., 2023) emphasize the need for strategies that optimize groundwater withdrawal patterns to mitigate the adverse effects of climate change and over-extraction.

These adaptive approaches are crucial for building resilience in PICs' groundwater systems. By combining traditional knowledge with modern scientific practices and emphasizing community participation, these strategies aim to enhance the sustainability and resilience of groundwater resources in the face of climate change challenges. Implementing these strategies requires a coordinated effort from local communities, governments, and international organizations to ensure the long-term sustainability of groundwater resources in Pacific Island countries.

Effective and sustainable management of groundwater resources in Pacific Island countries (PICs) requires an approach that incorporates technological innovations, policy interventions, and community engagement. This multifaceted strategy is essential to address both current and future challenges posed by climate change, over-extraction, and contamination.

Advanced monitoring systems and predictive modelling are crucial for better managing groundwater resources. (Sharan et al., 2021) highlighted the potential of using artificial intelligence and machine learning algorithms to improve groundwater management practices. Additionally, 3D modelling and simulation-optimization techniques are essential for developing efficient saltwater intrusion (SWI) management strategies.

The implementation of policies that regulate groundwater extraction and protect recharge areas is essential. (Datta and Lal, 2019) recommend the development of regulatory frameworks that limit groundwater withdrawal during dry periods and promote the conservation of freshwater lenses. These policies should be adaptive and responsive to changing climatic conditions and water demands.

(White and Falkland, 2010) recommend conjunctive water management, which combines the use of surface water and groundwater to reduce pressure on freshwater lenses. They also stress the importance of rainwater harvesting and protecting recharge zones to maintain groundwater levels. This approach helps diversify water sources and enhances overall water security. (Sharan et al., 2023) present a case study from Tonga, demonstrating the combined impacts of over-abstraction and climate change on groundwater resources and the need for location-specific management approaches. These strategies should be tailored to the specific geological and hydrological conditions of each island. Engaging local communities in groundwater management is crucial for long-term sustainability. (White and Falkland 2010) highlight the importance of incorporating traditional knowledge into management practices. This approach not only improves the effectiveness of management strategies but also ensures community buy-in and participation.

Continuous monitoring of groundwater levels, quality, and extraction rates is essential for sustainable management (Bailey et al., 2024; Bouchet et al., 2018; Gheuens et al., 2019). This data can inform adaptive management practices, allowing for timely adjustments to extraction rates and management strategies in response to changing conditions. By integrating these technological, policy, and management approaches, PICs can develop more resilient and sustainable groundwater management systems. These strategies should be implemented with consideration for the unique geological, hydrological, and socio-economic contexts of each island, ensuring their effectiveness and long-term viability in the face of ongoing environmental changes.

Groundwater issues in Pacific Island countries (PICs) are complex and multifaceted, driven by a combination of natural and anthropogenic factors including climate variability, sea-level rise, over-extraction, and contamination (White & Falkland, 2010; Sharan et al., 2023). The sustainability of groundwater resources in these vulnerable regions is critically dependent on addressing these interconnected challenges through holistic and integrated approaches. Effective management of groundwater resources requires strategies that consider the socio-ecological dynamics of groundwater systems (Bouchet et al., 2019). This involves incorporating climate adaptation strategies, ensuring active community participation, and combining traditional practices with modern technology and regulatory measures (Falkland & White, 2010; Datta & Lal, 2019). Sustainable management practices must include advanced monitoring techniques, such as the use of artificial intelligence and machine learning algorithms (Sharan et al., 2021), alongside policy interventions that regulate groundwater extraction and protect recharge areas (Datta & Lal, 2019). Multi-objective management strategies that optimize groundwater withdrawal patterns and control salinity levels are crucial for mitigating the adverse effects of climate change and over-extraction (Sharan et al., 2023). Furthermore, the integration of traditional knowledge with modern scientific practices is essential for developing community-based management plans that ensure sustainable use of groundwater (Falkland & White, 2010). This approach not only improves the effectiveness of management strategies but also ensures community buy-in and participation. By adopting these measures, PICs can enhance the resilience of their groundwater resources against the backdrop of increasing climate variabilities. Proactive adaptation strategies and sustainable management practices are essential to ensure the long-term viability of groundwater resources in the face of ongoing and future climate challenges. Addressing groundwater issues in PICs requires a coordinated effort from local communities, governments, and international organizations. By implementing integrated, adaptive, and community-centred approaches, PICs can work towards ensuring the sustainability of their vital groundwater resources for future generations.

b) Caribbean Islands

The Caribbean region encompasses 16 Small Island Developing States, including 13 UN member countries and 3 associate members: Antigua and Barbuda, Bahamas, Barbados, Belize, Cuba, Dominica, Dominican Republic, Grenada, Guyana, Haiti, Jamaica, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, and Trinidad and Tobago, along with associate members Aruba, Curaçao, and Sint Maarten (UNCTAD, 2021). These nations collectively represent approximately 44 million people distributed across diverse island formations ranging from large continental-shelf islands like Cuba and Jamaica to small volcanic islands and low-lying coral formations (UNESCO, 2014).

Groundwater resources in Caribbean Islands are crucial due to the limited availability of surface water (Sambeek, 2000). This review examines various studies addressing groundwater issues in Caribbean Islands, focusing on the impacts of climate variability. The synthesis highlights groundwater reliance, over-extraction, contamination, and sustainable management practices in the context of changing climate conditions. Caribbean SIDS exhibit remarkable geological diversity compared to other SIDS regions, with formations including volcanic islands (Dominica, Saint Lucia, Saint Vincent and the Grenadines), limestone karst systems (Barbados, Jamaica), continental territories (Belize, Guyana, Suriname), and mixed geological origins (Trinidad and Tobago, Cuba) (Griffith-Charles, 2017). Many Caribbean islands feature steep volcanic geomorphology with narrow coastal plains suitable for development and steeply rising interiors, forcing populations to occupy precarious slopes and increasing vulnerability to landslides and floods (Griffith-Charles, 2017). This geological complexity creates varied groundwater systems with distinct vulnerability patterns across the region (UNESCO, 2014).

The Caribbean climate system is dominated by Atlantic hurricane activity, trade wind patterns, and the seasonal migration of the Intertropical Convergence Zone (ITCZ) (NOAA, 2018). The annual Atlantic hurricane season from June through November poses the most significant climate threat, with the 2017 season providing devastating examples when 22 of 29 Caribbean SIDS were impacted by named storms, including 9 SIDS experiencing direct major hurricane landfall (NOAA, 2018). Trade winds from the northeast provide year-round climatic influence, while ITCZ migration creates distinct wet and dry seasons across the region (Taylor et al., 2018). Climate change is intensifying hurricane impacts, with warmer Caribbean waters providing optimal conditions for storm intensification that differs from patterns along continental coastlines (NOAA, 2018).

Groundwater serves as the primary source of drinking water for many Caribbean Islands. Studies by (Fabian et al., 2018) indicate that anthropogenic activities and climate change significantly affect groundwater resources on small islands. Over-extraction is a notable issue, especially in densely populated and industrial areas. According to (Day, 2010), groundwater abstraction and forest clearance in Caribbean karst landscapes exacerbate the depletion of aquifers. (Mycoo and Roopnarine, 2024) highlighted that groundwater over-extraction and contamination could result in some Caribbean atoll islands becoming uninhabitable by the 2030s. This problem is compounded by the high demand for water in tourism-driven economies, which further stresses the limited groundwater resources (Lamhour et al., 2024). In islands like San Andres, groundwater over-extraction has led to significant saltwater intrusion (SWI), which contaminates freshwater resources (Fabian et al., 2018). This issue is particularly severe in low-lying coastal areas (Camacho-Cruz et al., 2024).

Groundwater contamination due to agricultural runoff, inadequate waste disposal, and insufficient sanitation systems poses a severe threat to water quality in the Caribbean. Jones and Banner (2003) highlighted the geochemical vulnerability of groundwater in tropical karst island aquifers, such as those in Barbados and Puerto Rico, which are susceptible to contamination from agricultural chemicals and other pollutants. (Arroyo-Figueroa et al., 2024) identified common factors affecting groundwater composition, such as rock weathering and anthropogenic pollution, which pose significant risks to water quality. Similarly, (Freeman et al., 2024) emphasized that increasing groundwater extraction in limestone islands leads to the degradation of coastal dry tropical forests due to declining water tables. The connection between submarine groundwater discharge and seawater quality also raises concerns about nutrient loading and eutrophication, which can further degrade water quality (Alorda-Kleinglass et al., 2024).

Climate variability significantly impacts groundwater resources in the Caribbean Islands. (Cashman et al., 2010) indicated that changing precipitation patterns, rising sea levels, and increasing frequency of extreme weather events exacerbate the vulnerability of groundwater systems. In the Bahamas, for example, (Bowleg and Allen, 2011) documented how storm surges increase the salinity of groundwater, making it unsuitable for consumption. (Parker et al., 2023) discussed the compounded effects of water stress and pollution on Small Island developing states (SIDS), highlighting the vulnerability of these regions to climate change. Additionally, rising sea levels contribute to saltwater intrusion, reducing the availability of fresh groundwater (Richardson et al., 2024). Extreme weather events, such as hurricanes and tropical storms, lead to increased surface runoff and reduced groundwater recharge. This phenomenon has been observed in various Caribbean islands, where cyclones significantly impact the interaction between surface water and groundwater, mobilizing contaminants and altering water quality (Mondal et al., 2024).

Effective management of groundwater resources in the Caribbean requires an approach that includes advanced monitoring techniques, policy implementation, and community engagement. (Falkland, 1999) recommended integrated water resource management practices that combine the use of surface water and groundwater to reduce the stress on freshwater lenses. He also stressed the importance of protecting recharge zones and promoting rainwater harvesting. (Arroyo-Figueroa et al., 2024) proposed frameworks for evaluating groundwater quality and the relationship between rock weathering and hydrogeo-chemistry. Implementing advanced monitoring techniques, such as environmental tracers, can enhance the understanding of groundwater dynamics and improve management practices (Allen & Boutt, 2023). Innovative technologies such as artificial intelligence and machine learning are essential for developing efficient groundwater management strategies. (Payne et al., 2022) highlighted the potential of using machine learning models to predict and manage groundwater resources on small carbonate islands. (Mycoo & Roopnarine, 2024) emphasized the need for participatory justice in water management, advocating for inclusive approaches that involve local communities in decision-making processes.

Groundwater issues in Caribbean Islands are complex and multifaceted, involving over-extraction, contamination, and the impacts of climate change. Addressing these challenges requires integrated management approaches that consider both natural and anthropogenic factors. Sustainable groundwater management must incorporate advanced monitoring techniques, community participation, and adaptive strategies to enhance resilience against climate variability. By adopting these measures, Caribbean Islands can ensure the long-term sustainability of their groundwater resources.

c) Indian Ocean SIDS

The Indian Ocean region contains 6 Small Island Developing States: Comoros, Maldives, Mauritius, and Seychelles as UN members, plus Cabo Verde and São Tomé and Príncipe in the Atlantic-Indian Ocean category (UNCTAD, 2021). These nations collectively represent approximately 1.9 million people and demonstrate the greatest geological diversity among SIDS regions, ranging from the unique granite formations of Seychelles to the coral atolls of Maldives and the volcanic complexes of Mauritius and Comoros (UNDP, 2024). The region benefits from 940,341 people through recent regional cooperation initiatives focused on integrated water resources management and environmental protection (UNDP, 2024).

This review examines groundwater challenges faced by Indian Ocean Small Island Developing States (SIDS), focusing primarily on Mauritius, Seychelles, Maldives, and Comoros. These nations share similar hydrogeological vulnerabilities while exhibiting unique characteristics that distinguish their groundwater management challenges from those experienced by Pacific and Caribbean SIDS. The review follows the established framework of over-extraction and saltwater intrusion, contamination and health implications, climate change impacts, and adaptive management strategies to provide a comprehensive assessment of current challenges and emerging solutions.

Geological characteristics vary dramatically across Indian Ocean SIDS, with Seychelles representing the world's only oceanic granitic islands, creating unique hydrogeological conditions where fractured granite dykes extending up to 100 meters deep can accumulate substantial rainwater reserves (UNDP, 2024). Maldives comprises 1,192 coral islands organized into 26 atolls, with 97% having lost access to fresh groundwater due to climate change impacts (WHO, 2023). Mauritius and Comoros exhibit complex volcanic island structures with multiple aquifer systems dating from 8.9-4.7 million years old, while their basaltic formations create highly permeable fractured lava flows vulnerable to contamination (Moore et al., 2011). These geological variations create distinct groundwater management challenges requiring region-specific approaches (UNDP, 2024).

Climate drivers in the Indian Ocean region are uniquely influenced by monsoon systems, the Indian Ocean Dipole (IOD), and tropical cyclone activity (UN Press, 2005). The southwest monsoon (May-November) and northeast monsoon (January-March) create pronounced seasonal variations in precipitation, with some islands experiencing water stress during dry periods requiring government water delivery to approximately 80 islands annually in Maldives alone (WHO, 2023). The Indian Ocean Dipole significantly affects regional rainfall patterns, with positive IOD events reducing precipitation across the region (Taylor et al., 2018). Regional sea-level rise rates of 3.1-4.6 mm/year exceed global averages, threatening freshwater lens stability through saltwater intrusion (UN Press, 2005). Temperature and humidity patterns differ from Pacific and Caribbean regions, with generally lower evapotranspiration rates affecting water balance calculations and management strategies (UNDP, 2024).

Indian Ocean SIDS face significant challenges from groundwater over-extraction and saltwater intrusion, particularly affecting coastal aquifers across the region. In Mauritius, approximately 60% of domestic water supply comes from groundwater, placing enormous pressure on the island's five main aquifer systems (Gungoa & Kebede, 2024). The volcanic hydrogeology of Mauritius, characterized by highly fractured basaltic formations, creates conditions where over-extraction can rapidly lead to saltwater intrusion along coastal boundaries. Recent isotopic studies reveal that Aquifer V (Northern Plains) shows the most pronounced vulnerability, with progressive isotopic enrichment indicating active seawater intrusion processes particularly evident in coastal monitoring points (Gungoa & Kebede, 2024). The (Stimson Center, 2024) confirms that saltwater intrusion poses compounding threats to Mauritius' coastal communities, particularly affecting coral reefs, mangroves, and fisheries sectors that depend on freshwater availability.

The Maldives presents an extreme case of groundwater vulnerability due to its low-lying atoll configuration and heavy reliance on thin freshwater lenses. The (UN Environment Programme, 2024) reports that groundwater in the Maldives is severely limited in quantity and frequently contaminated by both human waste and saltwater intrusion. This contamination is exacerbated by the island's unique dual aquifer system, consisting of a surficial Holocene carbonate sand aquifer overlying a more permeable Pleistocene limestone formation. During dry seasons, the government delivers water by tanker to approximately 80 islands, highlighting the critical nature of groundwater depletion (United Nations, 2024). The situation is further complicated by the fact that some household rainwater collection systems suffer from maintenance issues and unpredictable precipitation patterns attributed to climate change.

Groundwater contamination in Indian Ocean SIDS stems from multiple sources, creating complex pollution scenarios that threaten both human health and ecosystem integrity. In Mauritius, the (International Atomic Energy Agency, 2019) identified agricultural activities, illegal sewage disposal, and animal breeding as primary sources of nitrogen pollution in urban waterways around Port Louis. Isotopic analysis revealed that nitrate contamination most likely originates from manure and septic wastes, as well as dissolved organic matter in soil, with contamination affecting streams, rivers, and protected areas including the Rivulet Terre Rouge Estuary Bird Sanctuary.

The health implications of groundwater contamination are particularly severe in the Maldives, where the (World Health Organization, 2023) reports that tidal waves and flooding frequently contaminate groundwater and sewerage systems, leading to disease outbreaks. The concentration of waste on artificial islands like Thilafushi has created significant environmental health risks, with the 124-acre waste facility growing approximately one square meter daily and threatening freshwater lens contamination through leachate infiltration (Borgen Project, 2024). In Seychelles, similar contamination issues affect the popular tourist destination of La Digue, where the aquifer faces threats from over-extraction, pollution, and saltwater intrusion, necessitating multi-pronged protection approaches.

Climate change significantly exacerbates groundwater challenges across Indian Ocean SIDS through multiple pathways including sea-level rise, changing precipitation patterns, and increased frequency of extreme weather events. The Southwest Indian Ocean region faces particularly acute risks, with climate projections indicating temperature increases ranging from 1.2°C under conservative scenarios to 3.7°C under high-emission scenarios by the end of the century (Drian et al., 2024). These temperature increases coincide with expectations that the dry season will become significantly drier, with precipitation deficits ranging from 10% to 40%, primarily due to delayed onset of rainy seasons.

The Joint Research Centre (2023) confirms that Indian Ocean SIDS face substantial economic losses from sea-level rise even under 1.5°C warming scenarios. Countries including Mauritius are identified among those requiring the highest estimates of additional coastal protection, with potential economic losses corresponding to considerable shares of GDP and probable forced migration from low-lying coastal zones. In the Maldives, approximately 80% of the landmass lies less than one meter above sea level, making the entire country extremely vulnerable to sea-level rise, with projections suggesting large areas could be underwater within 30 years under current IPCC scenarios (UN Press, 2005).

Tropical cyclone risks are expected to increase throughout the region, with stronger cyclone intensities and a higher proportion of severe storms anticipated to migrate poleward by one to two degrees latitude, further amplifying risks faced by the Mascarene islands including Mauritius and Seychelles (Drian et al., 2024). These extreme weather events directly impact groundwater systems through contamination of freshwater supplies and infrastructure damage to water distribution networks.

Indian Ocean SIDS have implemented diverse adaptive management approaches that integrate technological solutions, policy interventions, and community engagement strategies. The Global Environment Facility (2024) supports a comprehensive regional project addressing integrated water resources management across six SIDS including Mauritius, Seychelles, and Maldives, focusing on improving water use efficiency and sustainable development practices.

Technological Interventions in the region emphasize desalination and rainwater harvesting systems. The Maldives has invested in desalination plants powered by renewable energy sources, with a recent $25 million project supported by UNDP and the Green Climate Fund improving access to safe drinking water for 20,000 people across 29 islands while enhancing groundwater quality resilience for 49 islands. A collaboration between China and the Maldives resulted in five solar and wind-powered desalination plants, each capable of producing 200,000 litres of water daily. In Seychelles, technological approaches focus on saltwater intrusion barriers and improved leachate collection systems at waste management facilities.

Policy Interventions across Indian Ocean SIDS emphasize integrated water resources management frameworks and regulatory development. Mauritius has established comprehensive groundwater monitoring systems to support policy guidelines protecting groundwater resources from over-extraction and pollution. Seychelles has endorsed its first National Water Policy and National Integrated Water Resources Management Plan, representing significant policy advancement in the region. The Maldives has developed the Water and Sewerage Act with international support, providing a regulatory framework for sustainable water resource management.

Community Engagement strategies focus on building local capacity for water resource monitoring and conservation. In the Maldives, communities on Thoddoo Island expressed concerns about freshwater lens contamination, leading to establishment of integrated water supply systems including rainwater collection infrastructure connected to public buildings. Educational programs in Seychelles engage school children in water monitoring activities as part of awareness-raising initiatives, fostering community ownership of water resource protection.

Monitoring and Adaptive Management approaches in Indian Ocean SIDS emphasize early warning systems and comprehensive data collection. The Mauritius project focuses on creating groundwater monitoring systems capable of supporting management decisions, while isotopic analysis provides crucial insights into contamination sources and groundwater flow patterns. Multi-objective management strategies balance tourism economic benefits with water resource conservation needs, particularly evident in Seychelles' approach to managing La Digue's aquifer protection while maintaining tourism viability. The integrated approach adopted by Indian Ocean SIDS demonstrates recognition that sustainable groundwater management requires coordination across technological, policy, and social dimensions. However, mounting debt burdens and limited financial resources constrain implementation of comprehensive adaptation measures, highlighting the urgent need for international financial and technical assistance to protect these vulnerable water resources systems.

2.6.2 Comparative Analysis of Groundwater Challenges in Different Small Island Developing States (SIDS)

Small Island Developing States across the Pacific, Caribbean, and Indian Ocean regions face complex and interconnected groundwater challenges that vary significantly based on their unique geological, climatic, and socio-economic contexts. This comparative analysis examines the diverse groundwater challenges across these three major SIDS regions, highlighting regional specificities while identifying common themes and transferable management approaches. The analysis draws from empirical studies conducted across 43 representative SIDS to provide comprehensive insights into regional groundwater vulnerabilities and management strategies (Allen et al., 2016; UNESCO-IHP & UNEP, 2016). Small Island Developing States represent some of the world's most vulnerable territories to groundwater stress and contamination. Research indicates that 73% of SIDS face risks of groundwater pollution, while 71% experience water shortage risks, with this figure rising to 91% for low-lying islands (UNESCO, 2019; Uitto et al., 2017). The vulnerability emerges from multiple interconnected factors including limited land areas, exposure to climate change impacts, high population densities relative to available freshwater resources, and dependence on fragile freshwater lens systems that are susceptible to saltwater intrusion. The aggregate population of all SIDS is 65 million people living across more than 1,000 islands, representing less than 1% of the world's population yet facing disproportionate environmental challenges (UN-OHRLLS, 2023). These island communities depend heavily on groundwater resources, with many having no alternative freshwater sources during dry seasons or droughts. Population density emerges as the primary driver of water stress in all, but one of the 43 representative islands assessed, reflecting the constrained nature of island environments and the limited capacity for sustainable resource exploitation (Allen et al., 2016).

2.6.2.1 Pacific Islands Groundwater Challenges

Pacific Small Island Developing States encompass a remarkable diversity of geological formations, from low-lying coral atolls to volcanic high islands, creating varied hydrogeological conditions that influence groundwater availability and vulnerability patterns. The region includes 14 sovereign nations: Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Nauru, Niue, Palau, Papua New Guinea, Marshall Islands, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu (UN-DESA, 2023). Low-lying coral atolls, including those in Marshall Islands, Kiribati, and Tuvalu, depend entirely on thin freshwater lenses that float on denser saltwater, typically ranging from 3 to 21 meters in thickness (Werner et al., 2025). These freshwater lenses are extremely vulnerable to over-extraction and climate variability. Research from Geoscience Australia's comprehensive vulnerability assessment of 15 Pacific Island countries reveals that these nations face exceptional challenges due to their oceanic isolation and limited land areas (Geoscience Australia, 2023). High volcanic islands such as Fiji and Samoa possess more complex aquifer systems with greater storage capacity still face significant challenges from population pressures and climate change impacts.

Pacific SIDS confront multiple interconnected groundwater challenges that threaten water security across the region. Over-extraction and freshwater lens depletion represent critical threats, particularly in densely populated atolls where approximately 65,000 Marshall Islanders live on 180 square kilometres of land, providing each person only 0.3 hectares (EBSCO, 2023). This population density creates unsustainable pressure on limited groundwater resources, leading to accelerated saltwater intrusion and aquifer degradation. Saltwater intrusion vulnerability constitutes another major challenge, exacerbated by climate change and sea-level rise. Studies from Tonga demonstrate that over-abstraction has caused saltwater intrusion more frequently, with an increasing salinity trend of 58% observed from 1965 to 2007 (Kumar et al., 2021). Research indicates that higher abstraction rates directly correlate with increased saltwater flux infiltration into coastal aquifers, creating a feedback loop that progressively degrades water quality. Climate variability impacts, particularly El Niño-Southern Oscillation (ENSO) effects, significantly influence groundwater recharge patterns across Pacific SIDS. Decreasing trends in rainfall (19%) and net recharge (37%) have been documented in Tonga between 1950 and 2006, while sea level rise rates of 5.2% and carbon dioxide emissions increases of 800% further compound groundwater vulnerability (Kumar et al., 2021). Limited land area and population pressure create additional constraints, with small low-lying Pacific islands being among the most economically deprived regions globally, limiting their capacity to respond effectively to environmental challenges (EBSCO, 2023).

a) Marshall Islands: Atoll Vulnerability to Sea-Level Rise

The Marshall Islands exemplify the extreme vulnerability of low-lying Pacific atolls to groundwater threats. These atoll systems face existential challenges from sea-level rise, with fresh groundwater being described as "the most threatened on earth" by hydrology experts (Board, 2018). The islands' freshwater lens systems, which typically range from 3 to 21 meters in thickness, are experiencing increasing stress from both climate change and anthropogenic pressures (Schofield & Ojha, 2024). Recent research has focused on innovative infiltration gallery systems that skim fresh groundwater from shallow depths while minimizing saltwater intrusion risks (Davila et al., 2024; Jazayeri & Werner, 2025). These horizontal well systems are currently operational across several Pacific atolls, including installations in the Marshall Islands, and represent critical adaptation technologies for maintaining water security under changing climatic conditions (Board, 2018). However, information remains lacking about optimal gallery layouts, pipe characteristics, and pumping rates necessary for sustainable operation.

b) Tonga: Multi-Objective Groundwater Management

Tonga presents a compelling case study of how over-abstraction and climate change jointly impact groundwater resources in Pacific SIDS. (Sharan et al., 2023) documented the implementation of multi-objective management strategies that optimize groundwater withdrawal patterns while controlling salinity levels to mitigate adverse effects on groundwater sustainability. The Tongan approach demonstrates the necessity for location-specific management strategies that account for unique geological and hydrological conditions. Long-term monitoring data from Tonga reveals the cumulative impacts of unsustainable groundwater practices, with 42 years of groundwater salinity data showing clear trends toward degradation (Kumar et al., 2021). These findings emphasize the importance of proactive management approaches that balance economic development needs with long-term resource sustainability.

c) Kiribati: Community-Based Water Management

Kiribati represents a successful example of community-based water management approaches in Pacific SIDS. The nation has implemented comprehensive community engagement strategies that incorporate traditional knowledge with modern water management techniques (Thomas & Benjamin, 2019). These approaches recognize the critical importance of local ownership and participation in maintaining sustainable groundwater practices. Urgent investigations into bore-field operations accessing fresh groundwater on Pacific islands, including Kiribati, highlight the immediate need for improved management practices where rising sea levels already threaten local water supplies (Board, 2018). The Kiribati experience demonstrates how community-based monitoring and participatory governance can enhance groundwater sustainability in resource-constrained environments.

d) Fiji: Volcanic Island Groundwater Systems

Fiji's volcanic island groundwater systems provide important insights into managing more complex aquifer structures in Pacific SIDS. Unlike low-lying atolls, Fiji's volcanic geology creates multiple aquifer layers with varying characteristics and vulnerability patterns (Geoscience Australia, 2023). The country's experience with groundwater management illustrates both opportunities and challenges associated with high island hydrogeology. Research indicates that volcanic islands like Fiji may have greater adaptive capacity due to more diverse water sources and larger storage volumes, yet they still face significant challenges from population growth, tourism development, and climate change impacts (Annual Reviews, 2020; Feresi et al., 2000). The Fijian approach to water management emphasizes integrated strategies that combine groundwater protection with surface water development.

Pacific SIDS have developed innovative management strategies that combine traditional knowledge with modern technologies to address unique groundwater challenges. Integrated Water Resources Management (IWRM) approaches have gained prominence across the region, emphasizing holistic management that considers interactions between groundwater, surface water, and marine systems (UNDP, 2023). These frameworks recognize that effective groundwater management requires understanding complex social-ecological relationships. Community-based approaches represent a cornerstone of Pacific SIDS groundwater management. (MacDonald et al., 2020) emphasize the critical role of local communities in managing and maintaining water infrastructure to ensure long-term sustainability. These approaches leverage traditional ecological knowledge that has evolved through generations of island living, providing valuable insights into sustainable resource management practices. Rainwater harvesting integration has emerged as a crucial complementary strategy for reducing pressure on groundwater resources. The combination of rainwater harvesting with groundwater management creates more resilient water supply systems that can better withstand climate variability and extreme events (Ahmed & Mishra, 2020). Technology solutions including desalination and advanced monitoring systems provide additional tools for managing groundwater resources, though implementation must consider local capacity and economic constraints.

2.6.2.2 Caribbean Islands Groundwater Challenges

Caribbean Small Island Developing States exhibit remarkable geological diversity, encompassing volcanic islands (Dominica, St. Lucia), limestone karst formations (Barbados, Jamaica), and mixed geological systems (Trinidad and Tobago, Antigua and Barbuda). This geological heterogeneity creates varied groundwater systems with distinct vulnerability patterns and management requirements across the region's 16 recognized SIDS (Mycoo & Roopnarine, 2024; Winters et al., 2024). The Caribbean region's groundwater systems are characterized by significant variability in dependence patterns, with Barbados deriving 90% of its water supply from groundwater, Jamaica 84%, Trinidad and Tobago 24%, and St. Kitts 70%, while Grenada, Dominica, and St. Lucia utilize groundwater minimally (Cashman et al., 2014). This variability reflects the diverse geological foundations and climatic conditions across Caribbean SIDS, requiring tailored management approaches for different island types. Volcanic islands typically feature mountainous terrain with higher rainfall rates, creating more complex aquifer systems with varied recharge mechanisms. Conversely, flat limestone islands composed of porous formations exhibit high groundwater percolation rates and greater dependence on aquifer systems as primary water sources, though with increased vulnerability to contamination due to rapid infiltration pathways.

Caribbean SIDS face multifaceted groundwater challenges that reflect both natural vulnerabilities and anthropogenic pressures. Over-extraction in tourism zones represents a critical issue, with high water demand in coastal tourism areas leading to progressive saltwater intrusion and aquifer degradation (Emmanuel & Spence, 2009). Tourism development often concentrates water demand in coastal areas where aquifers are most vulnerable to saline contamination, creating unsustainable extraction patterns. Agricultural contamination poses another significant threat, with pesticide and fertilizer impacts on groundwater quality documented across multiple Caribbean islands. Seychelles rivers show fertilizer loads of up to 25 kilograms per day, while wells in Mauritius exhibit nitrate levels reaching 50 micrograms per litre, approaching WHO safety limits (UN Press, 2005). The intensive use of agricultural chemicals, with some Caribbean islands applying fertilizers at rates three times higher than Western Europe, creates persistent groundwater contamination risks.

Hurricane impacts create acute challenges through storm surge contamination and infrastructure damage. The 2017 tropical cyclone season, featuring Hurricanes Harvey, Irma, Maria, and Nate, demonstrated the devastating potential of extreme weather events on Caribbean water infrastructure (UN-OHRLLS, 2023). These events cause both immediate contamination through saltwater intrusion and long-term infrastructure damage that compromises water security. Karst aquifer vulnerability represents a unique challenge for limestone-based Caribbean islands, where rapid contamination spread through interconnected cave systems creates management difficulties. The porous nature of karst formations allows rapid infiltration of surface contaminants, making groundwater protection particularly challenging in islands like Barbados and Jamaica.

a) Barbados: Karst Aquifer Management and Tourism Water Demand

Barbados exemplifies the challenges of managing karst aquifer systems under intense tourism pressure. The island utilizes close to 100% of its available water resources, with abstraction levels equalling recharge rates, making the country vulnerable to periodic droughts (Cashman, 2018). The limestone geology creates rapid contaminant transport pathways that require careful management to prevent widespread aquifer contamination. (Mycoo & Roopnarine, 2024) highlight the critical importance of desalination technologies in Caribbean SIDS like Barbados, despite high energy requirements and costs. The integration of groundwater protection zones with tourism industry water efficiency programs has emerged as a key strategy for balancing economic development with resource sustainability.

b) Trinidad and Tobago: Industrial Contamination and Groundwater Protection

Trinidad and Tobago presents a complex case of industrial contamination and groundwater protection challenges. The country has faced water supply deficits since 2000 despite having relatively abundant rainfall and extensive water supply systems serving 95% of the population (Cashman, 2018). Operational problems and high levels of leakage, reaching 40% unaccounted water, compound supply challenges. (Roopnarine et al., 2023) investigated integrated wastewater reuse strategies in Trinidad and Tobago, demonstrating effective groundwater basin replenishment and agricultural support capabilities. The country's experience illustrates how integrated water management approaches can address both supply challenges and groundwater protection needs in industrialized Caribbean SIDS.

c) Jamaica: Bauxite Mining Impacts on Groundwater Resources

Jamaica's extensive bauxite mining operations create unique groundwater management challenges that differ from other Caribbean SIDS. Despite being mountainous, Jamaica relies heavily on groundwater supplies (84%) to meet water needs, with available groundwater resources of 10.663 Mm^3/day being significant compared to other Caribbean islands (Cashman et al., 2014). The country faces particular challenges with coastal aquifer management, where abstractions have resulted in "up-coning" and increased salinity levels as the fresh-saline water interface moves upward (Cashman et al., 2014). Jamaica's projected water supply deficits in areas of important economic activity by 2025 highlight the urgency of improved groundwater management strategies.

d) Antigua and Barbuda: Dual-Island Water Resource Coordination

Antigua and Barbuda demonstrates the complexities of coordinating water resources across multiple islands with different geological characteristics. Both islands rely heavily on desalination to meet water demands while facing groundwater exploitation and pollution challenges (Cashman, 2018). The presence of desalination reduces pressure on groundwater supplies but increases water costs significantly. The dual-island system requires coordinated management approaches that recognize different hydrogeological conditions while maintaining system-wide water security. Limited available groundwater resources (1,835 Mm^3/day) compared to other Caribbean islands necessitate careful balance between groundwater protection and economic development needs.

Caribbean SIDS have developed comprehensive management strategies that emphasize regional cooperation and integrated approaches to groundwater protection. Regional cooperation through CARICOM water initiatives provides a framework for sharing best practices and coordinating responses to common challenges across Caribbean islands (Galaitsi et al., 2024). These initiatives recognize that many groundwater challenges transcend individual island boundaries and require collective action. Integrated coastal zone management represents a key strategy for addressing the interconnected nature of groundwater and marine systems in Caribbean SIDS. (Dubrie et al., 2022) emphasize the importance of policy interventions, including establishment of groundwater protection zones, as critical tools for mitigating contamination and ensuring sustainable use. These approaches integrate land use planning with groundwater protection to prevent incompatible development in sensitive areas.

Tourism industry water efficiency programs have emerged as essential components of Caribbean groundwater management. Given the economic importance of tourism across the region, these programs focus on reducing water consumption in tourism facilities while maintaining service quality. Water-energy-food nexus approaches implemented in Antigua and Barbuda, Barbados, Jamaica, and Saint Kitts and Nevis demonstrate integrated strategies for managing sectoral water demands (FAO, 2023). Disaster-resilient infrastructure development represents a critical adaptation strategy for Caribbean SIDS facing increasing hurricane intensity and frequency. (Galaitsi et al., 2024) emphasize the importance of building institutional capacity for climate resilience, recognizing that infrastructure investments must be accompanied by improved governance and management capabilities.

2.6.2.3 Indian Ocean Islands Groundwater Challenges

Indian Ocean Small Island Developing States present exceptional geological diversity, encompassing granite foundations (Seychelles), coral atolls (Maldives), volcanic complexes (Mauritius, Comoros), and mixed formations that create unique hydrogeological conditions. This diversity is influenced by distinct monsoon climate patterns and Indian Ocean circulation systems that differentiate the region from Pacific and Caribbean SIDS (UNEP, 2024; UNDP, 2024). The Indian Ocean region includes four primary SIDS: Comoros, Maldives, Mauritius, and Seychelles, with additional recognition of Madagascar as an associated large island state. Seychelles represents unique oceanic granitic islands where fractured rock formations and geological dykes extending up to 100 meters create unexpected aquifer systems despite granite's typically low porosity (UN Press, 2005). The Maldives, composed entirely of coral atolls, faces extreme vulnerability with 97% of the country lacking fresh groundwater and more than 50% of the national budget devoted to climate change adaptation efforts (GEF, 2023). Mauritius and Comoros, characterized by volcanic island chains with complex aquifer systems, demonstrate how volcanic geology creates multiple groundwater zones with varied characteristics and management requirements. These islands operate under distinct monsoon climate conditions that create seasonal extremes in recharge patterns, differentiating them from the more consistent trade wind patterns affecting Pacific islands or hurricane-dominated Caribbean systems.

Indian Ocean SIDS face distinct groundwater challenges shaped by monsoon variability, which creates seasonal extremes affecting recharge patterns and water availability. The region experiences distinct wet (November-April) and dry (May-October) seasons, with the Indian Ocean Dipole (IOD) affecting rainfall patterns across the region (Stancioff et al., 2018). Positive IOD events reduce rainfall significantly, creating extended periods of water stress that challenge groundwater sustainability. Volcanic island complexity in Mauritius and Comoros creates multi-aquifer systems with varied vulnerability patterns requiring sophisticated management approaches. These complex hydrogeological systems feature five main aquifers in Mauritius's volcanic setting (8.9-4.7 Ma basaltic formations) that respond differently to climate variability and anthropogenic pressures (Bush, 2018). Management challenges arise from the need to understand and protect multiple interconnected aquifer systems simultaneously.

Coral atoll fragility in the Maldives represents extreme vulnerability, where freshwater lens systems have degraded to the point that 97% of the country no longer has access to fresh groundwater (GEF, 2023). Until the 1990s, Maldivians used groundwater for drinking, but over the past decade, groundwater on most islands has become contaminated due to over-extraction, sea-level rise (3.1 mm/year), and variable rainfall patterns. Development pressure from rapid urbanization and tourism expansion creates additional stress on limited groundwater resources across Indian Ocean SIDS. Wells in Mauritius show high nitrate levels reaching 50 micrograms per litre due to intensive fertilizer use (600 kg/hectare, three times Western European rates), while tourism development in Seychelles has led to over-extraction and saltwater intrusion in popular destinations like La Digue (UN Press, 2005; GEF, 2023).

a) Maldives: Climate-Induced Groundwater Crisis

The Maldives represents perhaps the most extreme case of climate-induced groundwater crisis among all SIDS globally. Research indicates that 97% of the country no longer has fresh groundwater, with more than 50% of the national budget dedicated to climate change adaptation efforts (GEF, 2023). The situation reflects the cumulative impacts of sea-level rise (3.1 mm/year), variable rainfall patterns, and over-extraction that have progressively degraded freshwater lens systems. Climate impacts include groundwater becoming increasingly saline due to sea-level rise and altered precipitation patterns, creating a feedback loop where reduced freshwater availability increases dependence on imports and desalination (South-South Galaxy, 2023). Innovation responses include a recent $25 million project that improved access to safe drinking water for 20,000 people on 29 islands while enhancing groundwater quality resilience for 49 islands through integrated water supply systems combining rainwater harvesting and desalination. Current conditions indicate that until the 1990s, Maldivians used groundwater for drinking, but contamination over the past decade has necessitated complete reliance on alternative sources (GEF, 2023). The successful IWRM demonstration activities have catalysed further Green Climate Fund support to replicate integrated water management practices on more than 20 additional islands.

b) Seychelles: Granite Aquifer Innovation

Seychelles presents a unique case among global SIDS as probably the only oceanic granitic islands where groundwater development requires innovative approaches to fractured rock aquifer systems. Geological characteristics indicate that while granitic islands normally lack aquifers, fractured rock formations and geological dykes extending up to 100 meters create water accumulation opportunities (UN Press, 2005). Current challenges include persistent water shortages resulting in rationing by the Public Utilities Corporation during dry seasons, despite surface water being the main source supplemented by desalination (GEF, 2023). Strategic approaches aim to develop groundwater as a second pillar for water security, supported by collaboration with Sweden's geological expertise to develop granite aquifer systems effectively. Innovation initiatives include comprehensive IWRM demonstration projects on La Digue island that address aquifer threats from over-extraction, pollution, and saltwater intrusion through multi-pronged approaches (GEF, 2023). These include promoting rainwater harvesting, restoring marshes, building infrastructure to prevent saltwater intrusion, and improving solid waste management to protect groundwater quality.

c) Comoros: Volcanic Island Water Management

Comoros, as a volcanic island chain similar to Mauritius, faces complex aquifer systems requiring sophisticated management approaches. The country experiences supply insufficiency to meet current needs, with demand projected to nearly double by 2025, creating urgent requirements for improved water management (UN Press, 2005). Rural-urban water disparities and monsoon climate variability compound management challenges. Traditional water harvesting techniques combined with modern approaches demonstrate successful integration strategies, while regional cooperation through Indian Ocean Commission water initiatives provides frameworks for coordinated management. The country suffered cholera epidemics in 1975, 1998, and 2001, highlighting direct connections between water quality and public health outcomes.

d) Mauritius: Comprehensive Monitoring and Modelling

Mauritius exemplifies comprehensive approaches to volcanic island groundwater management through sophisticated monitoring and modelling systems. The geological framework encompasses five main aquifers in volcanic settings with distinct seasonal variations and pumping-stressed conditions requiring integrated management approaches (Bush, 2018). Climate drivers include tropical maritime conditions with monsoon influences creating distinct seasonal patterns. Management evolution demonstrates progression from natural seasonal variations (Giorgi et al., 1999) to current pumping-stressed conditions requiring active intervention and protection measures. Innovation includes comprehensive aquifer monitoring and modelling systems that support evidence-based decision-making for sustainable groundwater management. The implementation of groundwater monitoring systems supports management decisions related to protecting aquifer resources from over-extraction and pollution while enabling conjunctive management of groundwater and surface water resources.

Indian Ocean SIDS experience unique climate impacts that differentiate them from Pacific and Caribbean regions. The Indian Ocean Dipole (IOD) affects rainfall patterns across the region, with positive IOD events significantly reducing rainfall and creating extended drought conditions (Betzold & Mohamed, 2017). This climate pattern creates management challenges distinct from ENSO effects in Pacific regions or hurricane impacts in Caribbean areas. Monsoon systems create seasonal extremes in recharge patterns with distinct wet (November-April) and dry (May-October) seasons that require adaptive management strategies. Unlike the more consistent trade wind patterns affecting Pacific islands, monsoon variability creates pronounced seasonal water availability fluctuations that challenge storage and distribution systems. Tropical cyclones provide intense but infrequent impacts causing both recharge and contamination events, differing from the more frequent but less intense storm patterns in other regions. Research indicates that sea-level rise affects freshwater lens stability and saltwater intrusion at regional rates of 3.1-4.6 mm/year, requiring proactive adaptation measures (UN Press, 2005). Temperature effects result in lower evapotranspiration rates compared to Pacific and Caribbean regions, affecting water balance calculations and recharge estimates. These climatic distinctions require region-specific approaches to groundwater management that account for monsoon-driven recharge patterns and cyclone-related contamination risks.

Indian Ocean SIDS have developed sophisticated management strategies that emphasize technological innovation and regional cooperation. Indian Ocean Commission cooperation provides frameworks for regional water security initiatives that facilitate knowledge sharing and coordinated responses to common challenges (UNDP, 2024). These initiatives recognize the benefits of coordinated approaches across geographically dispersed but climatically similar island systems. Climate adaptation programs specifically designed for monsoon-specific water management address the unique seasonal patterns characterizing Indian Ocean climate systems. Technology transfer initiatives facilitate sharing innovations across different island types, enabling adaptation of successful approaches from granite systems (Seychelles) to coral atolls (Maldives) and volcanic islands (Mauritius, Comoros). Traditional knowledge integration represents a critical component of Indian Ocean SIDS management strategies, incorporating local water management practices that have evolved under monsoon climate conditions. The South-South Galaxy (2023) documents how participatory implementation approaches engage communities, armies, municipalities, and regional governments in comprehensive water source protection activities.

.

Despite significant regional variations, SIDS across all three regions share fundamental challenges that reflect their island geography and limited resource base (Table 2.7). Limited freshwater resources and high vulnerability characterize all SIDS, with research indicating that 44% of small island states currently experience water stress conditions (Allen et al., 2016). This vulnerability stems from constrained land areas, limited storage capacity, and dependence on precipitation-dependent recharge systems. Climate change and variability impacts affect all SIDS regions, though manifestations differ significantly across Pacific (ENSO), Caribbean (hurricanes), and Indian Ocean (monsoons) systems. Research demonstrates that while recharge is projected to increase by up to 117% on 12 islands in western Pacific and Indian Ocean regions, recharge is projected to decrease by up to 58% on the remaining 31 islands globally (Allen et al., 2016). Saltwater intrusion risks represent universal challenges across all SIDS regions, though mechanisms and intensities vary based on geological and climatic conditions. Infrastructure and capacity constraints limit the ability of SIDS to implement and maintain sophisticated groundwater management systems, requiring approaches that balance technical effectiveness with local implementation capacity.

Table 2-7 Comparative Analysis of Groundwater Challenges in different SIDS

Region	Country/Island	Empirical Studies	Findings	Insights
Caribbean	English-speaking	Mycoo& Roopnarine (2024)	Heavy reliance on groundwater, significant over-extraction and pollution, inadequate infrastructure and policy frameworks	Emphasis on Integrated Water Resources Management (IWRM) and establishment of groundwater protection zones. Community-based monitoring programs are critical for sustainable groundwater management.
Caribbean	Various	Dubrie et al., (2022)	Implementation of policy interventions such as groundwater protection zones has been effective in mitigating contamination.	Highlight the role of policy and community engagement in groundwater management.
Pacific	Maldives	Jaleel et al., (2020)	Severe drought impacts groundwater recharge, limited land area exacerbates contamination issues.	Adoption of rainwater harvesting and desalination technologies, combined with traditional practices to enhance water security.
Pacific	Solomon Islands	Dorevella et al., (2021)	Droughts significantly affect groundwater resources, making them unreliable.	Integration of modern and traditional knowledge for effective water management. Community involvement is crucial for maintaining water infrastructure.
Indian Ocean	Mauritius	Majidipour et al., (2021)	Groundwater contamination from agricultural runoff and industrial activities.	Use of advanced monitoring technologies (GIS, remote sensing) for better resource planning. Participatory governance models involving local stakeholders.
Indian Ocean	Seychelles	Ahmed & Mishra (2020)	Issues of both groundwater quality and quantity, exacerbated by over-extraction and pollution.	Need for stringent management practices and community engagement in monitoring and protecting groundwater resources.
Caribbean	Various	Shaikh &Birajdar (2023)	Highlights the importance of sustainable farming practices and community engagement in groundwater management.	Promotes responsible groundwater usage through community-led initiatives and education.

Pacific	Various	MacDonald et al., (2020)	Emphasis on traditional water usage behaviors combined with modern technologies to mitigate drought impacts on groundwater resources.	Traditional practices play a crucial role in the sustainable management of water resources, especially in remote island atolls.
Indian Ocean	Various	Shaikh & Birajdar (2024)	Advanced monitoring through remote sensing and GIS significantly improves groundwater management.	Technological advancements must be coupled with community participation for effective groundwater management.
Pacific	Various	Villada-Canela et al., (2021)	Public participation is essential for integrated groundwater management, highlighting the success of community engagement in managing water resources in the Maneadero Valley.	Engaging communities in groundwater management fosters a sense of ownership and responsibility, leading to better resource management outcomes.
Indian Ocean	Various	Hernández-Delgado (2024)	Over-pumping and climate-induced sea-level rise lead to seawater intrusion, affecting groundwater quality.	Implementing protective measures and improving infrastructure are crucial to safeguarding groundwater resources.
Caribbean	Various	Ahmed & Mishra (2020)	Identifies innovative strategies like rainwater harvesting and desalination, combined with traditional knowledge to address water scarcity.	Leveraging a mix of traditional and modern techniques can enhance the resilience of water resources in SIDS.

Significant regional distinctions emerge across Pacific, Caribbean, and Indian Ocean SIDS that require tailored management approaches. Primary geology varies substantially, with Pacific SIDS dominated by coral atolls and volcanic formations, Caribbean SIDS featuring karst, volcanic, and mixed systems, and Indian Ocean SIDS encompassing volcanic, granite, and coral formations (Geoscience Australia, 2023; Mycoo & Roopnarine, 2024; GEF, 2023). Climate drivers create distinct regional patterns requiring different adaptive strategies. Pacific SIDS are primarily influenced by ENSO effects and trade wind patterns, Caribbean SIDS face hurricane impacts and Intertropical Convergence Zone variability, while Indian Ocean SIDS experience monsoon systems and IOD effects (Kumar et al., 2021; Galaitsi et al., 2024; Betzold & Mohamed, 2017). Main threats reflect regional climate and geological conditions, with Pacific SIDS facing sea-level rise and typhoon impacts, Caribbean SIDS experiencing hurricane surge and tourism pressures, and Indian Ocean SIDS dealing with cyclones and monsoon variability. Management focus differs correspondingly, with Pacific SIDS emphasizing community-based and

IWRM approaches, Caribbean SIDS prioritizing regional cooperation, and Indian Ocean SIDS concentrating on technology integration and monitoring systems. Innovation areas reflect regional strengths and capacities, with Pacific SIDS successfully combining traditional and modern approaches, Caribbean SIDS developing disaster resilience strategies, and Indian Ocean SIDS advancing monitoring and modelling capabilities. These regional distinctions inform the development of tailored management approaches that recognize specific constraints and opportunities.

The comparative analysis reveals that successful groundwater management in SIDS requires approaches that recognize both common challenges and regional specificities. While Caribbean SIDS emphasize policy interventions and community-based monitoring, Pacific SIDS focus on integrating traditional knowledge with modern technologies, and Indian Ocean SIDS benefit from advanced monitoring systems and participatory governance approaches. Despite regional differences, community involvement emerges as the critical common thread across all SIDS regions for ensuring sustainable groundwater management. Evidence demonstrates that successful strategies consistently incorporate local stakeholder engagement, whether through community-led initiatives in the Caribbean, traditional knowledge integration in the Pacific, or participatory governance in the Indian Ocean. The synthesis indicates that technological solutions alone are insufficient without corresponding community participation and appropriate policy frameworks tailored to regional contexts. By leveraging local knowledge and fostering stakeholder engagement, SIDS can effectively address their unique groundwater challenges while enhancing overall water security through adaptive management approaches that recognize both local specificities and regional cooperation opportunities.

Several key lessons emerge from comparative analysis that demonstrate transferability across SIDS regions. Community engagement proves critical across all regions, though implemented through different mechanisms reflecting cultural and institutional contexts (MacDonald et al., 2020; Shaikh & Birajdar, 2023; South-South Galaxy, 2023). Pacific islands emphasize traditional knowledge integration, Caribbean islands focus on stakeholder participation in policy development, and Indian Ocean islands leverage community participation in monitoring and protection activities. Technology solutions must match local capacity and economic constraints to ensure sustainable implementation. Successful examples include infiltration galleries in Pacific atolls, desalination integration in Caribbean tourism zones, and comprehensive monitoring systems in Indian Ocean volcanic islands (Board, 2018; Mycoo & Roopnarine, 2024; Bush, 2018). Regional cooperation enhances individual island resilience through knowledge sharing, resource pooling, and coordinated responses to common challenges. Examples include Pacific Island Forum water initiatives, CARICOM cooperation frameworks, and Indian Ocean

Commission programs that facilitate technology transfer and best practice sharing (UNDP, 2023; Galaitsi et al., 2024; UNDP, 2024). Climate-specific adaptation strategies prove essential for addressing distinct regional climate patterns and their groundwater impacts. Successful approaches include ENSO-adapted management in Pacific islands, hurricane-resilient infrastructure in Caribbean islands, and monsoon-specific planning in Indian Ocean islands.

2.7 Sustainable Groundwater Management Strategies for Small Island Developing States (SIDS)

Small Island Developing States face unique and multifaceted challenges in managing groundwater resources due to their geographic isolation, limited land area, high vulnerability to climate change, and constrained technical and financial capacity. The challenges include disaster risk, water scarcity, pollution, salinization, and saltwater intrusion (Gheuens et al., 2019; Sharan et al., 2021; Falkland, 1999). Effective groundwater management in SIDS requires evidence-based approaches that integrate technological solutions, policy frameworks, and community-based management practices while balancing multiple competing demands and ensuring long-term sustainability and resilience (Mycoo & Roopnarine, 2024; Gheuens et al., 2019; Thomas et al., 2020).

2.7.1 Assessment, Monitoring, and Early Detection Systems

Effective groundwater management begins with comprehensive assessment and monitoring systems that enable early detection of contamination and quality degradation. Jaleel et al. (2020) conducted a screening approach to assess groundwater quality across 45 inhabited islands in the Maldives, identifying contamination from salinization and pollution as significant issues. Regular monitoring systems are essential for timely interventions and maintaining water quality in Caribbean SIDS that rely heavily on groundwater resources (Mycoo and Roopnarine, 2024). Innovative monitoring strategies incorporate advanced technologies and uncertainty analysis into management models. Sharan et al. (2021) emphasized the use of advanced technologies for monitoring and management, while Lal and Datta (2019) highlighted the importance of incorporating aquifer parameter uncertainty into multi-objective management models. These technological advances enable more accurate assessment and adaptive management responses to changing conditions.

2.7.2 Technological Solutions and Infrastructure Development

2.7.2.1 Desalination Technologies

Desalination has emerged as a critical solution for addressing water scarcity by converting seawater into potable water. (Mycoo and Roopnarine, 2024) identified desalination as particularly important in Caribbean SIDS where groundwater reliance is high but often unsustainable due to over-extraction and contamination. However, high energy requirements and costs pose significant challenges, necessitating sustainable energy sources to mitigate environmental and economic impacts (Dubrie et al., 2022). (Welsh and Bowleg, 2022) demonstrated successful implementation in The Bahamas, where deep groundwater discharge wells combined with desalination enhanced water supply reliability while alleviating pressure on existing groundwater resources. Various desalination approaches have been proposed, including low temperature thermal desalination systems (Guduru et al., 2020).

2.7.2.2 Water Recycling and Reuse Systems

Water recycling and reuse significantly reduce demand on freshwater resources by treating wastewater for agricultural or industrial purposes. (Roopnarine et al., 2023) investigated wastewater reuse integration in Trinidad and Tobago, demonstrating effective groundwater basin replenishment and agricultural support. (Chadee et al., 2024) explored household greywater recycling, finding it viable for reducing household water consumption and preserving groundwater reserves, though success requires public awareness and community participation.

2.7.2.3 Advanced Filtration and Treatment Systems

Advanced filtration systems, including membrane filtration and reverse osmosis, ensure water quality by removing contaminants from groundwater sources. (Bouchet et al., 2020) discussed applications in Pacific SIDS, highlighting effectiveness in treating water to meet health standards, particularly where groundwater is contaminated with pathogens or pollutants. These systems are essential for mitigating saltwater intrusion impacts. (Hernández-Delgado, 2024) noted that rising sea levels increase saltwater contamination risks, making advanced filtration crucial for maintaining potable water supplies under adverse environmental conditions.

2.7.2.4 Complementary Technologies

Rainwater Harvesting Systems complement groundwater resources by capturing and storing precipitation. (MacDonald et al., 2020) demonstrated that combining modern rainwater harvesting technologies with traditional practices significantly improves water security in remote island atolls through hybrid approaches leveraging both modern and traditional methods.

Smart Water Management Technologies including automated monitoring systems, leak detection technologies, and demand management systems optimize water use efficiency and reduce distribution losses. These technologies are particularly important in SIDS where water resources are limited and infrastructure maintenance is challenging.

Managed Aquifer Recharge (MAR) techniques enhance natural groundwater recharge through engineered systems such as infiltration basins, injection wells, and permeable pavement. MAR helps restore depleted aquifers, improves water quality through natural filtration processes, and provides storage for excess water during wet periods.

2.7.2.5 Integrated Technological Approaches

Integrating various technological solutions enhances effectiveness and sustainability. Ahmed and Mishra (2020) recommend combining desalination, water recycling, and advanced filtration within holistic water management frameworks to address multiple challenges simultaneously, ensuring robust and resilient water supply systems.

2.7.3 Policy and Governance Frameworks

Effective policy and governance frameworks provide institutional foundations for sustainable groundwater management by establishing legal frameworks, regulatory mechanisms, and institutional arrangements necessary for coordinated management.

2.7.3.1 Policy Interventions and Regulatory Mechanisms

Integrated Water Resources Management (IWRM) Policies are fundamental for addressing groundwater quality challenges. (Dubrie et al., 2022) highlighted the importance of IWRM policies in Caribbean SIDS, emphasizing regulations to prevent and control pollution, manage water disruptions, and introduce adaptation measures that enhance resilience against climatic and anthropogenic pressures.

Groundwater Protection Legislation establishes legal frameworks for protecting groundwater resources from contamination and over-extraction. However, many SIDS lack adequate groundwater protection legislation and enforcement mechanisms. Effective legislation must address pollution prevention, extraction licensing, wellhead protection, and land-use controls around critical recharge areas.

Water Allocation and Pricing Policies provide mechanisms for managing competing demands while ensuring equitable access and sustainable use. These policies must balance economic efficiency with social equity and environmental protection objectives, with appropriate pricing mechanisms providing conservation incentives while generating revenue for management and infrastructure development. (Parker and Parchment, 2023) discussed policy allocation for managing water insecurity and connected health risks, arguing that effective interventions should address both farm management practices and groundwater quality issues through adaptive, context-specific approaches.

2.7.3.2 Institutional Coordination and Enforcement

Institutional Coordination Mechanisms establish frameworks for coordination between different government agencies, sectors, and stakeholders. Effective coordination is essential where limited institutional capacity requires efficient use of available resources and expertise.

Enforcement and Compliance Mechanisms ensure effective implementation of groundwater protection policies through monitoring and inspection systems, penalty structures, and compliance assistance programs. Effective enforcement requires adequate technical capacity and financial resources.

International Cooperation Frameworks facilitate knowledge sharing, technology transfer, and financial support. Many SIDS lack technical and financial capacity for advanced groundwater management, requiring international cooperation for capacity building and technology transfer.

2.7.3.3 Climate Adaptation and Management Strategies

Climate Adaptation Policies specifically address climate change impacts on groundwater resources, establishing frameworks for adaptive management and resilience building. (Hernández-Delgado, 2024) discussed coastal restoration strategies for mitigating local adaptation challenges, including groundwater reserve protection from sea level rise and saltwater intrusion.

Effective management strategies emphasize sustainable practices and advanced technologies. (Mycoo and Roopnarine, 2024) highlighted the need for sustainable water management in English-speaking Caribbean SIDS, promoting water conservation practices and advanced monitoring technologies. (Wale et al., 2021) advocated for governance frameworks addressing groundwater over-extraction and saltwater intrusion through integrated approaches combining traditional knowledge with modern techniques.

2.7.4 Community-Based Management and Stakeholder Engagement

Community-based approaches are essential for sustainable groundwater management in SIDS, leveraging local knowledge, fostering community ownership, and ensuring culturally appropriate management practices.

2.7.4.1 Community Engagement and Participation

Community engagement forms the foundation of effective community-based groundwater management. (Shaikh and Birajdar, 2023) highlighted the importance of fostering community engagement to implement responsible groundwater management practices, emphasizing socio-economic benefits of involving local communities in sustainable farming practices that significantly impact groundwater quality. (Villada-Canela et al., 2021) discussed public participation in integrated groundwater management, identifying that community involvement is essential for generating effective management strategies. Their research demonstrated that active community participation leads to more resilient and adaptive management practices through continuous engagement.

2.7.4.2 Stakeholder Involvement and Capacity Building

Multi-stakeholder involvement enables effective participation in groundwater management processes. (Adom and Simatele, 2022) explored stakeholder engagement in sustainable water resource management, arguing that stakeholder participation, including local communities, is crucial for groundwater management initiative success. Engaging various stakeholders develops shared understanding of groundwater challenges and collaborative solutions. (Scheihing et al., 2022) emphasized capacity building at the community level, enabling local stakeholders to participate effectively in groundwater management processes. This approach improves technical knowledge and empowers communities to take ownership of groundwater resources, leading to more sustainable outcomes.

2.7.4.3 Community-Based Monitoring and Knowledge Integration

Community-based monitoring provides essential components of adaptive groundwater management. (Asprilla-Echeverria, 2021) highlighted social drivers in cooperative groundwater management, suggesting that community-based monitoring initiatives enhance groundwater resource sustainability by providing real-time data and fostering collective responsibility. (Calliera et al., 2021) demonstrated that involving community members in monitoring activities builds trust and ensures management practices are adapted to local conditions. This participatory approach leads to more effective and sustainable groundwater management by incorporating local knowledge and ensuring community support.

Traditional Knowledge Integration combines traditional water management practices with modern scientific approaches to develop culturally appropriate and effective management strategies. Traditional knowledge systems contain valuable insights into local water resources, seasonal patterns, and sustainable use practices that inform modern management approaches.

Community-Based Water Enterprises provide sustainable financing mechanisms for community-managed water systems while building local capacity for water service delivery and resource management, generating revenue for ongoing maintenance while ensuring community ownership.

2.7.5 Integrated Water Resources Management in Island Settings

IWRM provides comprehensive frameworks for managing water resources in island settings, recognizing interconnections between different water sources and the need for coordinated management across sectors and scales.

2.7.5.1 Holistic System Approach and Multi-Sector Coordination

IWRM recognizes that groundwater in SIDS is part of broader hydrological systems including surface water, coastal waters, and atmospheric water. Effective IWRM requires understanding and managing these interconnections to optimize overall water resource management, particularly important where different water sources are closely connected and management decisions affecting one component significantly impact others. Multi-sector coordination addresses multiple sectors and uses competing for water resources, including domestic water supply, agriculture, tourism, industry, and ecosystem needs. (Kowlesser et al., 2020) investigated IWRM plan implementation in Grand River North-west Basin, Mauritius, projecting 4%-15% decrease in annual rainfall by 2040 and increased extreme rainfall events, necessitating extensive IWRM strategies to mitigate flood and drought risks.

2.7.5.2 Conjunctive Management and Ecosystem-Based Approaches

Conjunctive Water Management combines surface water and groundwater use to reduce pressure on individual water sources while optimizing overall water resource utilization. White and Falkland (2010) recommended conjunctive water management approaches that diversify water sources and enhance overall water security, helping manage seasonal and annual variations while reducing vulnerability to drought and extreme events.

Ecosystem-Based Management recognizes important roles that ecosystems play in water resource systems, including watershed protection, groundwater recharge, and water quality protection. Protecting and restoring natural ecosystems provides cost-effective water resource management approaches while providing multiple co-benefits including biodiversity conservation and climate adaptation.

2.7.5.3 Regional Cooperation and Adaptive Management

Regional and Transboundary Cooperation facilitates coordination and knowledge sharing between different islands and regions facing similar challenges. Regional cooperation provides opportunities for technology transfer, capacity building, and shared infrastructure development that may not be feasible at individual island scales.

Adaptive Management Implementation incorporates learning-by-doing approaches allowing management strategies to evolve based on monitoring results and changing conditions. This is particularly important in SIDS facing rapid environmental and socio-economic changes where traditional management approaches may prove inadequate.

2.7.6 Climate Adaptation Strategies for Groundwater Systems

Climate adaptation strategies must address multiple climate-related stressors including sea-level rise, changing precipitation patterns, increased frequency of extreme events, and rising temperatures, requiring integration of short-term response measures with long-term adaptation planning.

2.7.6.1 Sea-Level Rise and Saltwater Intrusion Management

Sea-level rise adaptation addresses one of the most significant climate threats to groundwater resources in SIDS. Strategies include construction of physical barriers to prevent saltwater intrusion, managed retreat from vulnerable coastal areas, development of alternative water sources, and modification of groundwater extraction patterns to maintain freshwater lens integrity. (Barkey and Bailey, 2017) investigated sea-level rise effects on Marshall Islands, demonstrating how saltwater intrusion into freshwater lenses forces community relocation, highlighting urgent need for adaptive strategies.

2.7.6.2 Drought and Flood Risk Management

Drought Resilience Building develops capacity to maintain water security during extended dry periods expected to become more frequent and severe due to climate change. Strategies include enhanced water storage capacity, demand management measures, development of drought-resistant water sources, and early warning systems. (MacDonald et al., 2020) demonstrated that combining traditional water usage behaviors with modern technology enhances drought resilience in remote island atolls.

Flood Risk Management addresses increasing frequency and intensity of extreme precipitation events that can lead to groundwater contamination and infrastructure damage. Strategies include protection of wellheads and infrastructure, treatment of contaminated groundwater, improved drainage systems, and land-use planning to reduce contamination risks.

2.7.6.3 Infrastructure Resilience and Adaptive Capacity

Infrastructure Climate-Proofing ensures water infrastructure can withstand increased climate variability and extreme events through higher design standards, climate-resilient materials and designs, and incorporating redundancy and flexibility into system design. (Proag, 2016) discussed the need for resilient water supply networks that can adapt to changing climatic conditions in Mauritius.

Early Warning Systems provide advance notice of climate-related threats to groundwater resources, enabling proactive response measures. These systems integrate climate monitoring, hydrological forecasting, and risk assessment to provide timely information for decision-making.
Ecosystem-Based Adaptation utilizes natural ecosystems to provide climate adaptation services including flood control, groundwater recharge enhancement, and coastal protection. This approach provides cost-effective adaptation measures while delivering multiple co-benefits including biodiversity conservation and livelihood support.

Adaptive Capacity Building develops institutional, technical, and social capacity to respond effectively to climate-related challenges through training programs, institutional strengthening, technology transfer, and development of local expertise for climate adaptation planning and implementation.

2.7.7 Implementation Challenges and Future Directions

Several challenges hinder effective implementation of sustainable groundwater management strategies in SIDS. (Lewis and Su, 2021) identified groundwater quality degradation and the need for coherent adaptation policies as significant obstacles, requiring information on policy barriers and development of strategies aligned with local socio-economic conditions. (Metcalfe and Bennett, 2023) highlighted barriers to building resilience including limited financial resources, inadequate infrastructure, and political constraints, arguing for incorporation of resilience principles into policies and practices to enhance SIDS adaptive capacity. (Bailey et al., 2024) emphasized the importance of participatory justice in climate adaptation for water management, advocating for community involvement in decision-making processes to ensure management strategies are culturally appropriate and effectively implemented.

The synthesis of sustainable groundwater management strategies for SIDS reveals the critical importance of integrated approaches combining technological solutions, policy frameworks, community engagement, and climate adaptation measures. Evidence from across SIDS regions demonstrates that successful management requires context-specific approaches that build on local knowledge and capacity while incorporating international best practices and technical innovations. Future management strategies must prioritize adaptive capacity building, institutional strengthening, and long-term sustainability to ensure groundwater security for future generations in SIDS. Research should focus on enhancing policy coherence, building institutional capacities, leveraging technological advancements, and developing robust frameworks for community participation to address the unique challenges faced by SIDS in an era of increasing climate variability and change.

2.8 Knowledge Gaps and Research Needs

The comprehensive literature review has revealed significant knowledge gaps and research needs that limit the understanding and effective management of groundwater resources in Small Island Developing States (SIDS). These gaps span across multiple dimensions including temporal monitoring data, climate-groundwater interactions, isotope hydrology applications, vulnerability assessment frameworks, and management effectiveness evaluation (Asprilla-Echeverria, 2021; Jaleel et al., 2020). Addressing these research needs is essential for developing evidence-based management strategies that can ensure the long-term sustainability of groundwater resources in SIDS facing increasing pressures from climate change, population growth, and economic development.

Significant research gaps persist across all SIDS regions that limit understanding and management effectiveness. Limited long-term studies in Indian Ocean regions restrict understanding of climate change impacts and management effectiveness over extended periods (Adhikari et al., 2022). More inter-regional comparative studies are needed to understand transferability of management approaches across different geological and climatic contexts. Insufficient economic impact assessments limit understanding of the costs and benefits of different groundwater management strategies, constraining evidence-based policy development. Limited traditional knowledge documentation represents a critical gap, particularly given the demonstrated importance of integrating local knowledge with modern management approaches. Research gaps also include limited understanding of social-ecological system dynamics in SIDS contexts, insufficient evaluation of community-based management effectiveness, and inadequate assessment of technology appropriateness for different island types and economic conditions.

2.8.1 Temporal Groundwater Quality Monitoring Gaps

One of the most critical gaps identified in SIDS groundwater research is the lack of long-term, systematic monitoring datasets that can reveal temporal patterns of groundwater quality degradation. Most existing studies focus on short-term assessments or snapshot evaluations, leaving significant gaps in understanding how groundwater quality evolves over extended periods. The 11-year Mauritian groundwater quality analysis represents one of the few comprehensive temporal studies available for SIDS, highlighting the urgent need for similar long-term datasets across other SIDS regions. There is a notable absence of standardized monitoring protocols specifically designed for SIDS contexts. Current monitoring approaches often adapt methods developed for continental aquifer systems, which may not capture the unique characteristics of island groundwater systems such as thin freshwater lenses, rapid recharge-discharge cycles, and high vulnerability to contamination. The development of SIDS-specific monitoring protocols that account for these unique characteristics is essential for generating comparable and reliable data across different island settings. Many SIDS lack adequate spatial and temporal coverage in their groundwater monitoring networks. Limited financial and technical resources often result in sparse monitoring networks that may not capture spatial variability in groundwater quality or detect emerging contamination trends. The optimization of monitoring network design using vulnerability assessment frameworks and statistical sampling methods represents an important research need for improving monitoring efficiency and effectiveness. Current monitoring programs in many SIDS focus on basic water quality parameters, often missing emerging contaminants, isotopic tracers, and other indicators that could provide critical insights into groundwater system dynamics. Research is needed to identify the most appropriate parameters for SIDS groundwater monitoring, considering both natural system characteristics and anthropogenic pressures specific to island environments. The integration of groundwater monitoring data with climate, geological, and socio-economic datasets remains limited in most SIDS. Research is needed to develop integrated data management systems that can support comprehensive analysis of groundwater system dynamics and their relationships with external drivers.

2.8.2 Climate-Groundwater Interaction Understanding

Despite extensive documentation of climate impacts on SIDS groundwater resources, the specific mechanisms governing climate-groundwater interactions in island settings remain poorly understood. Research is needed to quantify how different climate variables (precipitation, temperature, evapotranspiration, sea level) influence groundwater recharge, discharge, and quality in various island geological settings. The limited correlation observed between climate indices (SPI, SPEI) and groundwater quality in Mauritius highlights the need for better understanding of how large-scale climate patterns translate into local groundwater impacts. Research should focus on identifying the most relevant climate indicators for different types of island aquifer systems and developing predictive relationships that can support adaptive management. While the general impacts of extreme events (cyclones, droughts, floods) on groundwater systems are recognized, detailed understanding of the processes and long-term consequences remains limited. Research is needed to quantify how extreme events affect groundwater recharge patterns, quality changes, and system recovery dynamics, particularly in the context of increasing climate variability. Although saltwater intrusion from sea-level rise is widely recognized as a major threat to SIDS groundwater resources, the specific hydrogeological mechanisms and their spatial and temporal variations are not well understood for different island settings. Research should focus on developing predictive models for saltwater intrusion that account for local geological conditions, aquifer characteristics, and extraction patterns. Current climate change projections for SIDS often lack the spatial and temporal resolution needed for groundwater impact assessment. Research is needed to downscale global climate models to island scales and develop groundwater-specific climate scenarios that can support adaptive management planning.

2.8.3 Isotope Hydrology Application Limitations

The application of isotope hydrology techniques in SIDS remains severely limited despite their proven effectiveness for understanding groundwater flow systems and management challenges in continental settings. This represents a critical research gap given the complex volcanic and carbonate aquifer systems that characterize many SIDS and the potential for isotopic tracers to provide unique insights into flow dynamics and recharge mechanisms. Most SIDS lack access to isotope analytical facilities, requiring expensive sample shipping to overseas laboratories and limiting the feasibility of comprehensive isotope studies. Research is needed to develop cost-effective approaches for isotope analysis in SIDS contexts, including regional analytical centres, simplified analytical methods, and international cooperation frameworks. Existing isotope hydrology methods were primarily developed for continental aquifer systems and may require adaptation for island settings. Research is needed to develop SIDS-specific isotope methodologies that account for unique characteristics such as marine influences, limited recharge areas, and rapid circulation times. The lack of baseline isotope data for precipitation, surface water, and groundwater in most SIDS severely limits the interpretation of isotopic signatures and the development of local meteoric water lines. Systematic collection of baseline isotope data represents a fundamental research need for advancing isotope hydrology applications in SIDS. Research is needed to develop integrated approaches that combine isotopic tracers with conventional hydrogeological methods, geochemical analysis, and geophysical techniques to provide comprehensive understanding of groundwater systems in SIDS contexts.

2.8.4 Vulnerability Assessment Framework Deficiencies

Current vulnerability assessment methods were primarily developed for continental aquifer systems and may not adequately capture the unique vulnerabilities of island groundwater systems. Research is needed to develop SIDS-specific vulnerability assessment frameworks that account for factors such as limited freshwater lens volumes, high climate exposure, and complex social-ecological interactions. Most vulnerability assessment studies in SIDS lack adequate validation using observed contamination or quality degradation data. Research is needed to develop validation approaches that can account for limited monitoring data and high uncertainty characteristic of SIDS contexts. This includes development of uncertainty assessment methods that can inform decision-making under conditions of limited information. Current vulnerability assessment approaches typically provide static assessments that may not capture the dynamic nature of vulnerability in SIDS facing rapid environmental and socio-economic changes. Research is needed to develop dynamic vulnerability assessment frameworks that can account for changing conditions and support adaptive management planning. The integration of social and ecological vulnerability factors in groundwater assessment frameworks remains limited, despite the critical importance of social-ecological interactions in SIDS contexts. Research is needed to develop integrated assessment approaches that capture the complex relationships between social systems, ecological systems, and groundwater resources. Vulnerability assessment in SIDS requires integration across multiple spatial and temporal scales, from local well-scale assessments to island-scale and regional-scale evaluations. Research is needed to develop multi-scale assessment frameworks that can support decision-making at different scales while maintaining consistency and comparability.

2.8.5 Management Strategy Effectiveness Evaluation

There is a significant lack of long-term studies that assess the effectiveness of various groundwater management strategies over extended periods. Most studies focus on short-term outcomes or theoretical assessments, leaving gaps in understanding the sustainability and long-term effectiveness of management interventions. Research is needed to develop long-term monitoring and evaluation frameworks that can assess management effectiveness over decades. While many studies discuss individual management strategies such as community engagement, technological solutions, or policy interventions, there is limited research on the effectiveness of integrated approaches that combine multiple strategies. Research is needed to evaluate how different management approaches interact and complement each other in SIDS contexts. More research is needed to understand the socio-economic impacts of groundwater management strategies on local communities, including economic feasibility, social acceptance, and distributional effects. This includes assessment of how management interventions affect different social groups and economic sectors, and development of approaches for ensuring equitable and sustainable management outcomes. Despite widespread recognition of the importance of adaptive management for SIDS, there is limited research on how to effectively implement adaptive management approaches in practice. Research is needed to develop practical frameworks for adaptive management implementation that account for institutional constraints, technical capacity limitations, and stakeholder engagement requirements. Research is needed to understand how successful management technologies and approaches can be transferred between different SIDS contexts and scaled up from pilot projects to broader implementation. This includes assessment of factors that influence technology adoption and development of strategies for overcoming barriers to technology transfer.

2.8.6 Regional Comparative Research Needs

The lack of standardized methodologies for comparing groundwater challenges and management approaches across different SIDS regions limits the ability to identify common patterns, transfer knowledge, and develop regional strategies. Research is needed to develop standardized assessment and comparison frameworks that can account for regional differences while enabling meaningful comparison. Despite facing similar challenges, there is limited systematic knowledge exchange between different SIDS regions (Pacific, Caribbean, Indian Ocean). Research is needed to identify opportunities for knowledge sharing, technology transfer, and collaborative research that can benefit all SIDS regions. Research is needed to understand how to effectively build regional capacity for groundwater research and management in SIDS contexts. This includes assessment of training needs, institutional development requirements, and international cooperation mechanisms that can support sustained capacity building efforts. Research is needed to understand how successful groundwater management approaches can be replicated and scaled across different SIDS contexts, accounting for differences in geological settings, climate conditions, socio-economic contexts, and institutional frameworks.

2.8.7 Emerging Research Priorities

Research is needed to evaluate the effectiveness of different climate adaptation strategies for groundwater systems in SIDS, including assessment of costs, benefits, and trade-offs associated with different adaptation options. This includes development of decision-support tools that can help SIDS select appropriate adaptation strategies based on local conditions and constraints. The economic valuation of ecosystem services provided by groundwater systems in SIDS remains limited, despite the critical importance of these services for sustainable development. Research is needed to develop methods for valuing groundwater ecosystem services and incorporating these values into decision-making processes. Research is needed to develop innovative technologies specifically designed for SIDS groundwater challenges, including low-cost monitoring systems, decentralized treatment technologies, and energy-efficient desalination systems that can operate effectively in island environments. Research is needed to understand how different governance and institutional arrangements affect groundwater management outcomes in SIDS contexts. This includes analysis of factors that contribute to successful governance arrangements and development of guidance for institutional development and reform. Research is needed to develop comprehensive future scenarios for SIDS groundwater systems that integrate climate change projections, socio-economic development trends, and technological innovations. These scenarios should support long-term planning and adaptive management under uncertainty. The identification of these knowledge gaps and research needs provides a foundation for prioritizing future research investments and developing research strategies that can address the most critical limitations in current understanding of SIDS groundwater systems. Addressing these gaps will require coordinated efforts involving international research collaborations, capacity building initiatives, and sustained funding for long-term research programs that can generate the knowledge needed for sustainable groundwater management in SIDS.

2.9 Discussion

The literature review has explored various aspects of groundwater quality challenges in Small Island Developing States (SIDS), with a particular focus on the Pacific, Caribbean, and Indian Ocean regions. This discussion synthesizes findings according to four critical themes: (i) groundwater vulnerability assessment, (ii) assessment approaches and methodologies, (iii) management approaches and strategies, and (iv) evidence-based frameworks for groundwater assessment and management. These themes provide a structured foundation for understanding the complex challenges and potential solutions for sustainable groundwater management in SIDS.

2.9.1 Groundwater Vulnerability in SIDS

Small Island Developing States exhibit exceptional vulnerability to groundwater degradation due to their unique geographical, geological, and climatic characteristics. The vulnerability is evidenced by the fact that 73% of SIDS face a risk of groundwater pollution, while 44% are currently in a state of water stress (UNESCO, 2019; Allen et al., 2016). The literature reveals that groundwater vulnerability in SIDS manifests through multiple interconnected pathways that threaten both water security and socio-economic stability.

Climate change emerges as the primary driver of groundwater vulnerability across all SIDS regions. Boojhawon and Surroop (2021) demonstrated that Mauritius faces increasing vulnerability with the Freshwater Vulnerability Index projected to increase from 0.36-0.38 during 2000-2015 to 0.38-0.44 by 2050, potentially leading to high vulnerability and water scarcity by 2030. Recharge rates are projected to decrease by up to 58% on 31 of the 43 assessed small island states, while only 12 islands situated in the western Pacific and Indian Ocean are expected to experience recharge increases of up to 117% (Allen et al., 2016). These projections highlight the differential vulnerability patterns across SIDS regions, with Caribbean and Atlantic islands generally facing more severe water stress compared to some Pacific and Indian Ocean counterparts.

Sea-level rise constitutes another critical vulnerability factor, particularly affecting low-lying Pacific atolls and Caribbean islands. (Hernández-Delgado, 2024) and (Werner et al., 2017) documented how rising sea levels increase saltwater intrusion risk, compromising freshwater lenses that serve as the primary water source for many SIDS communities. The assessment revealed that 91% of low-lying islands face water scarcity risks, with population density serving as the main driver of water stress in all but one of the 43 representative islands assessed (Uitto et al., 2017; UNESCO-IHP & UNEP, 2016). This finding underscores the direct relationship between demographic pressures and groundwater vulnerability in constrained island environments.

Anthropogenic activities significantly exacerbate natural vulnerability factors. (Jones and Banner, 2003) and (Majidipour et al., 2021) identified agricultural runoff and improper waste management as major contributors to groundwater contamination across SIDS regions. Risk due to groundwater anthropogenic pollution affects 73% of all islands, compounded in many cases by seawater intrusion and natural salinization (UNESCO-IHP & UNEP, 2016). The literature particularly emphasizes tourism-related pressures, where (Emmanuel and Spence, 2009) demonstrated how water-intensive tourism industries in Caribbean SIDS like Barbados exacerbate strain on already limited groundwater resources.

2.9.2 Assessment Approaches and Methodologies

The evaluation of groundwater systems in SIDS has evolved from basic hydrogeological assessments to comprehensive, multi-indicator frameworks that capture the complex social-ecological dynamics of island water systems. The first comprehensive indicator-based global assessment of status and trends in 199 transboundary aquifers and 46 groundwater systems of Small Island Developing States was conducted through the Transboundary Waters Assessment Programme (TWAP), providing unprecedented insights into SIDS groundwater conditions (UNESCO-IHP & UNEP, 2016; Allen et al., 2016).

Traditional hydrogeological assessments have been enhanced through isotope techniques and advanced monitoring technologies. (Dindyal et al., 2013) successfully used isotope techniques in Mauritius to demonstrate that groundwater recharge primarily occurs in the central plateau, with rapid infiltration through basalt fractures enabling widespread recharge patterns. However, the expense and logistical difficulties of conventional groundwater assessment in geographically dispersed, small landmasses prevent it from being widely applied in small island developing countries (Falkland et al., 2020). This limitation has prompted the development of innovative crowd-sourced assessment approaches.

Innovative assessment methodologies have emerged to address the unique challenges of SIDS groundwater evaluation. A household-level survey approach for screening groundwater quality using crowd-sourced information has been proposed as a cost-effective alternative to traditional assessment methods (Falkland et al., 2020). This approach was successfully demonstrated in 45 inhabited islands across 11 atolls of the Maldives, where survey-based assessments revealed that over 84% of islands reported varying degrees of elevated salinity, providing valuable insights into regional groundwater quality patterns.

Multi-indicator assessment frameworks have gained prominence for their ability to capture the complex interdependencies within SIDS groundwater systems. (Uitto et al., 2017) developed a comprehensive water security assessment framework that evaluates multiple dimensions including drinking water access, ecosystem health, climate change impacts, and governance structures. The framework integrates groundwater hydrology, climate scenarios, economics, land use, and groundwater management, with the intent to mitigate impacts of climate stress on current economic values of water as well as protecting future aquifer sustainability (Ward & Leal Filho, 2018).

The application of remote sensing and geospatial technologies has revolutionized groundwater assessment capabilities in SIDS. Advanced monitoring techniques, including the use of artificial intelligence and machine learning algorithms, alongside policy interventions that regulate groundwater extraction and protect recharge areas, represent the current frontier in SIDS groundwater assessment (IGRAC, 2019). (Sunkur et al., 2021) demonstrated how ICT tools, including sensors and GIS applications, can support climate change adaptation in the water services sector, particularly in data-scarce island environments.

2.9.3 Management Approaches and Strategies

Groundwater management in SIDS requires integrated approaches that address the unique constraints and vulnerabilities of island environments while considering the complex interactions between social, economic, and ecological systems. The literature reveals three primary management paradigms: technological interventions, policy-based approaches, and community-based management strategies, each offering distinct advantages and limitations in the SIDS context.

Technological solutions form a cornerstone of modern SIDS groundwater management strategies. Desalination technologies have emerged as critical interventions, particularly in Caribbean SIDS where reliance on groundwater is high but often unsustainable due to over-extraction and contamination (Mycoo

& Roopnarine, 2024). (Welsh and Bowleg, 2022) demonstrated successful implementation of integrated approaches in The Bahamas, where deep groundwater discharge wells combined with desalination systems enhanced water supply reliability while reducing pressure on existing groundwater resources. Results provide a framework to guide water management for SIDS vulnerable to climate stress for which water of the right quantity, quality, timing, location, and price are essential elements of economic development (Ward & Leal Filho, 2018).

Water recycling and reuse technologies represent another significant technological intervention. (Roopnarine et al., 2023) investigated wastewater reuse integration in Trinidad and Tobago, demonstrating effective groundwater basin replenishment and agricultural support capabilities. (Chadee et al., 2024) further explored household greywater recycling systems, finding them viable for reducing consumption and preserving groundwater reserves, though success depends heavily on public awareness and community participation.

Advanced filtration systems, including membrane filtration and reverse osmosis, play critical roles in ensuring water quality by removing contaminants from groundwater sources. (Bouchet et al., 2020) highlighted their effectiveness in Pacific SIDS for treating water to meet health standards, particularly in areas where groundwater faces pathogen or pollutant contamination. These technologies prove especially valuable for mitigating saltwater intrusion impacts in the context of climate change and sea-level rise.
Policy-based management approaches emphasize regulatory frameworks and institutional mechanisms for sustainable groundwater governance. Of great concern is the lack of enacted groundwater protection legislation for many of the small island developing states identified as highly vulnerable to current and future conditions (Allen et al., 2016). Effective policy interventions require adaptive and context-specific frameworks that address the unique challenges faced by each SIDS region.

Integrated Water Resources Management (IWRM) frameworks have gained prominence as comprehensive policy approaches. (Kowlesser et al., 2020) investigated IWRM implementation in Mauritius's Grand River North-west Basin, projecting 4%-15% decreases in annual rainfall by 2040 and increased extreme rainfall events, necessitating extensive IWRM strategies to mitigate flood and drought risks. The unique characteristics of SIDS require environmental protection actions to be local, contextual and small scale under the coordination of regional strategic frameworks, if the overall effort is to be relevant and effective (Tschakert et al., 2015).

The CLEWs (Climate, Land-use, Energy, and Water strategies) framework proposed by (Howells et al., 2013) represents an innovative integrated approach that considers the multifaceted impacts of climate change on groundwater resources. This framework ensures efficient resource management through coordinated strategies that address interdependencies between different sectors, proving particularly relevant for resource-constrained SIDS environments. Community-based management approaches recognize the critical importance of local engagement and traditional knowledge in achieving sustainable groundwater outcomes. Groundwater systems are social-ecological systems, where anthropogenic activities and groundwater conditions are linked through dynamic, non-linear processes, and groundwater management failures in the region are associated with traditional command and control approaches that ignore the systemic nature of coupled social and ecological groundwater systems (Falkland & White, 2019; Falkland & White, 2019). (Shaikh and Birajdar, 2023) underscore the importance of community-led initiatives in promoting responsible groundwater usage, while (Villada-Canela et al., 2021) demonstrate that active community participation leads to more effective and adaptive groundwater management strategies. These approaches foster local ownership and collective responsibility, proving essential for long-term sustainability in resource-constrained island environments. The paper advocates a polycentric governance approach that focuses on a nested, coordinated and linked set of local actions in the implementation of coherent regional frameworks (Tschakert et al., 2015). This approach recognizes that effective SIDS groundwater management requires coordination across multiple scales, from household-level water conservation practices to regional policy coordination mechanisms.

2.9.4 Evidence-Based Framework for Groundwater Assessment and Management

The development and implementation of evidence-based frameworks for groundwater assessment and management in SIDS represents a critical evolution from traditional sectoral approaches toward integrated, adaptive management systems that can respond effectively to the unique challenges facing island communities. The assessment has evidenced an alarming lack of knowledge and modern data on groundwater in general, and transboundary aquifers in particular, reflecting the lack of adequate groundwater governance at global, regional and local levels (UNESCO-IHP & UNEP, 2016).

The TWAP methodology represents the most comprehensive evidence-based framework developed specifically for SIDS groundwater systems. This framework presents the first comprehensive indicator-based global assessment of status and trends in 199 transboundary aquifers and 42 groundwater systems of Small Island Developing States (UNESCO-IHP & UNEP, 2016). The framework incorporates four critical assessment dimensions: hydrogeological characteristics, environmental conditions, socio-economic factors, and governance structures, providing a holistic foundation for evidence-based decision-making.

Hydrogeological assessment components within evidence-based frameworks focus on understanding aquifer characteristics, recharge dynamics, and vulnerability patterns. Current vulnerability was assessed by evaluating the recharge volume per capita, while future vulnerability used climate change projections to estimate changes in aquifer recharge (Allen et al., 2016). This approach enables evidence-based identification of critical thresholds and early warning indicators for groundwater stress conditions. Environmental assessment dimensions evaluate ecosystem dependencies, pollution risks, and climate change impacts on groundwater systems. Risk due to groundwater anthropogenic pollution affects 73% of all islands, compounded in many cases by seawater intrusion and by natural salinization, with high human groundwater dependency representing a risk factor in 10% of the Caribbean and Atlantic/Indian Ocean islands, and 72% of the Pacific islands (UNESCO-IHP & UNEP, 2016). These indicators provide critical evidence for prioritizing intervention strategies and resource allocation decisions.

Socio-economic assessment frameworks examine population pressures, economic dependencies, and development patterns that influence groundwater sustainability. Population Density appears to be the main driver of water stress in all but one of the 43 representative islands object of the assessment, reflecting the high number of islands (71%) at risk of water scarcity with a peak of 91% for low-lying islands (UNESCO-IHP & UNEP, 2016). This evidence base enables targeted interventions that address underlying drivers of groundwater stress while supporting sustainable development objectives.

Governance assessment components evaluate institutional capacity, legal frameworks, and management effectiveness. (Bailey, 2024) emphasizes that participatory justice and community engagement are crucial in decision-making processes for climate adaptation and water management in SIDS. Of great concern is the lack of enacted groundwater protection legislation for many of the small island developing states identified as highly vulnerable to current and future conditions (Allen et al., 2016). Evidence-based frameworks must therefore incorporate governance indicators that identify institutional gaps and capacity building needs.

The social-ecological systems framework proposed by (Falkland and White, 2019) provides a comprehensive approach for managing groundwater as interconnected social and ecological systems, comprised of three building blocks: complex adaptive systems, resilience thinking and strategic adaptive management. This framework recognizes that groundwater sustainability requires understanding and managing the dynamic interactions between human communities and groundwater resources. Strategic Adaptive Management (SAM) represents a critical component of evidence-based frameworks, enabling responsive management under uncertainty conditions. Strategic Adaptive Management is key to managing groundwater system's resilience, as social ecological resilience is necessary to sustainable groundwater systems (Falkland & White, 2019). SAM approaches incorporate continuous monitoring, learning, and adaptation mechanisms that enable management systems to respond effectively to changing conditions and new evidence.

Data integration and knowledge management systems form essential infrastructure for evidence-based frameworks. (Aderemi et al., 2021) demonstrated how data-driven techniques such as machine learning and Internet of Things (IoT) applications can support groundwater management in SIDS contexts. Advanced monitoring techniques, such as the use of artificial intelligence and machine learning algorithms, alongside policy interventions that regulate groundwater extraction and protect recharge areas, are crucial for mitigating the adverse effects of climate change and over-extraction (IGRAC, 2019). Evidence-based frameworks must also incorporate traditional ecological knowledge and community-based monitoring systems. Local actions should be an integral part of ocean governance, and to strengthen implementation of global policies, concrete work will have to happen at the local level individual by individual, family by family and community by community (Tschakert et al., 2015). This integration ensures that evidence-based management decisions reflect both scientific understanding and local knowledge systems that have evolved through generations of island living.

2.9.5 Research Gaps and Future Directions

Despite significant advances in understanding SIDS groundwater challenges, several critical research gaps persist that require urgent attention to develop more effective and sustainable management approaches. The assessment has evidenced an alarming lack of knowledge and modern data on groundwater in general, and TBAs in particular, reflecting that without the help of modelling this assessment would not have been possible (UNESCO-IHP & UNEP, 2016).

Long-term impact studies represent a fundamental gap in current SIDS groundwater research. Most existing studies focus on short-term outcomes, leaving significant uncertainty about the sustainability and effectiveness of interventions over decades. (Adhikari et al., 2022) emphasized the need for more research on specific impacts of climate change on groundwater recharge in Mauritius, highlighting this gap's significance for evidence-based policy development.

Holistic integration of management approaches requires further investigation. While individual strategies such as community engagement, technological solutions, and policy interventions show promise, comprehensive understanding of how these approaches can be effectively combined remains limited. (Ahmed and Mishra, 2020) recommend integrated frameworks that combine desalination, water recycling, and advanced filtration within holistic water management systems, but empirical evidence of such integration remains sparse. Socio-economic considerations need deeper investigation to understand the full implications of groundwater management strategies on local communities. This includes comprehensive assessment of economic feasibility for implementing advanced technologies and understanding socio-cultural acceptance of management interventions across diverse SIDS contexts. Climate change adaptation strategies specifically tailored to SIDS contexts represent another critical research priority. While climate change impacts are extensively documented, limited research exists on developing and testing adaptation measures tailored to the unique climatic and geographic conditions of different SIDS regions. Future research should prioritize developing adaptive management frameworks that can respond effectively to uncertain and changing conditions while promoting sustainable groundwater use. (Metcalfe and Bennett, 2023) emphasize the need for integrated management strategies that combine technological solutions, policy interventions, and community-based approaches, supported by robust monitoring and evaluation systems.

This comprehensive review has demonstrated the critical dependence of Small Island Developing States on groundwater resources for their freshwater needs, while revealing the complex and urgent challenges facing these vulnerable systems. Through detailed examination of case studies from Pacific Islands, Caribbean Islands, Indian Ocean Islands, and Mauritius, the analysis has illuminated the unique hydrogeological and socio-economic contexts that characterize SIDS groundwater systems.

The evidence reveals that groundwater management in SIDS requires urgent, coordinated action across multiple scales and sectors. Low-lying islands in the Pacific, highly dependent on scarce, polluted and increasingly saline groundwater resources, and impacted by climatic variability and change, are facing dramatic choices (UNESCO-IHP & UNEP, 2016). Climate variability impacts, including changes in precipitation patterns, sea-level rise, and increased frequency of extreme weather events, have been identified as major threats to groundwater quality and availability. These climate pressures are exacerbated by anthropogenic activities including over-extraction, improper waste management, and agricultural practices that contaminate groundwater sources.

The review establishes that effective groundwater management in SIDS requires a multifaceted approach integrating three critical components. Community-based approaches that engage local communities, build capacity, and incorporate traditional knowledge into management practices foster ownership and responsibility, leading to more effective and adaptive management (Shaikh & Birajdar, 2023; Villada-Canela et al., 2021). Technological solutions including desalination, water recycling, and advanced filtration systems provide promising tools for enhancing water security and reducing pressure on freshwater resources, particularly when integrated with renewable energy sources and traditional practices (Bouchet et al., 2020; Dubrie et al., 2022; MacDonald et al., 2020). Policy and management strategies emphasizing Integrated Water Resources Management (IWRM) frameworks and adaptive policies are crucial for promoting sustainable groundwater use and mitigating climate change impacts (Mycoo & Roopnarine, 2024; Wale et al., 2021).

Evidence-based frameworks that integrate hydrogeological, environmental, socio-economic, and governance dimensions provide the most promising foundation for sustainable groundwater management in SIDS. These frameworks must incorporate both scientific monitoring systems and traditional ecological knowledge while maintaining adaptive capacity to respond to changing conditions. However, successful implementation requires addressing fundamental research gaps in long-term impact assessment, holistic strategy integration, socio-economic considerations, and climate adaptation measures.

As SIDS face increasing challenges from climate change, population growth, and economic development pressures, implementing comprehensive, evidence-based groundwater management strategies is crucial for ensuring water security and supporting sustainable development for future generations. The urgency of these challenges demands immediate action while simultaneously investing in research to fill critical knowledge gaps and improve management effectiveness over time.

2.10 Chapter Summary and Implications for Research

This comprehensive literature review has established the theoretical and empirical foundation for investigating groundwater vulnerability in Small Island Developing States through systematic analysis of groundwater systems, with particular focus on Mauritius's aquifer systems as a representative case study. The review has examined groundwater quality degradation patterns, climate variability impacts, flow dynamics and recharge mechanisms, vulnerability assessment frameworks, and sustainable management strategies specific to SIDS contexts. The synthesis reveals both the critical importance of groundwater resources for SIDS sustainability and significant knowledge gaps that limit effective management of these vital resources.

2.10.1 Summary of Key Findings by Research Objective

Objective 1: Groundwater Quality Degradation Patterns

The literature reveals that groundwater quality degradation in SIDS follows distinct temporal and spatial patterns driven by both natural processes and anthropogenic activities. Analysis of Mauritius's five main aquifer systems demonstrates significant spatial variability in groundwater extraction patterns, with domestic use dominating extraction in most aquifers (ranging from 89-96% of total extraction in Aquifers I, III, IV, and V). The 11-year temporal analysis from Mauritius represents one of the few comprehensive long-term datasets available for SIDS, showing minimal correlation between traditional climate indices (SPI, SPEI) and groundwater quality parameters, but notable correlations with sulfate and chloride concentrations.

Key degradation indicators identified across SIDS include pH variations, electrical conductivity increases, total dissolved solids accumulation, salinity intrusion, chloride contamination, sulfate concentration changes, and nitrate pollution. Spatial analysis reveals that Aquifer V (Northern Plains) shows the most extensive development with 152 boreholes and highest total extraction (24.7 Mm^3/year), while secondary aquifers remain minimally developed with only 4 boreholes extracting 1.60 Mm^3/year.

The review establishes that 44% of SIDS islands currently experience water stress, with population density emerging as the primary driver of groundwater vulnerability in 71% of analyzed islands, underscoring the critical need for systematic monitoring and assessment of groundwater quality trends across SIDS regions.

Objective 2: Climate Variability Impacts on Groundwater Systems

Climate variability significantly affects groundwater systems in SIDS through multiple pathways including precipitation pattern changes, sea-level rise, extreme weather events, and temperature variations. The Mauritius case study demonstrates sea-level rise of 4-6 mm per year, corresponding to 2-3 times higher than the global average, creating significant pressure on coastal aquifer systems.

The analysis reveals complex climate-groundwater interactions where traditional climate indices show limited direct correlation with groundwater quality parameters, suggesting that climate impacts operate through indirect mechanisms involving recharge dynamics, hydrogeochemical processes, and anthropogenic responses. The influence of large-scale climate patterns such as ENSO and the Antarctic Oscillation (AAO) on groundwater quality in Mauritius indicates the importance of understanding teleconnections between global climate systems and local groundwater resources.

Extreme weather events, particularly tropical cyclones and droughts, create episodic impacts on groundwater systems that may not be captured by traditional monitoring approaches. SIDS face disproportionate climate impacts due to their small size, low elevation, and oceanic exposure, making climate adaptation essential for groundwater sustainability.

Objective 3: Groundwater Flow Dynamics and Recharge Mechanisms

Characterization of groundwater flow dynamics in volcanic island settings reveals complex multi-layered aquifer systems controlled by geological structure and fracture networks. Mauritius's geological evolution through four major volcanic phases spanning 10 million years has created distinct hydrogeological units with transmissivity values ranging from 10^{-7} to 10^{-2} m^2/s across different volcanic formations.

Groundwater circulation in Mauritius is limited to fractured and scoraceous zones within otherwise low-permeability basaltic formations, creating preferential flow paths along N20° and N100° orientations. The radial flow pattern from the Central Plateau toward coastal discharge zones makes all major aquifers inherently vulnerable to seawater intrusion.

However, application of isotope hydrology techniques in SIDS remains severely limited despite their proven effectiveness in continental volcanic settings. Critical research gaps exist in baseline isotope data, analytical capacity constraints, and methodological adaptation for island environments. The potential for isotopic tracers to provide insights into flow compartmentalization, recharge elevation identification, and residence time estimation represents a significant untapped resource for SIDS groundwater research.

Objective 4: Groundwater Vulnerability Assessment Frameworks

Current vulnerability assessment methods developed for continental aquifer systems require significant adaptation for SIDS applications. The review identifies three main categories: GIS-based qualitative approaches (DRASTIC, GOD, SI), process-based quantitative methods, and statistical/hybrid approaches. However, traditional methods often fail to capture SIDS-specific vulnerabilities including thin freshwater lens systems, marine influences, and complex social-ecological interactions.

Analysis of 43 SIDS reveals that recharge volume per capita serves as a critical vulnerability indicator, with population density emerging as the main driver of water stress. Comparative analysis across Pacific, Caribbean, and Indian Ocean SIDS demonstrates regional variations in vulnerability factors and management approaches, highlighting the need for region-specific assessment frameworks.

Critical gaps include limited standardized methodologies for cross-regional comparison, insufficient validation using observed contamination data, and lack of dynamic assessment frameworks accounting for changing conditions. Integration of social-ecological system approaches represents an emerging priority for developing comprehensive vulnerability assessments suitable for SIDS contexts.

Objective 5: Sustainable Groundwater Management Strategies

Evaluation of sustainable management strategies reveals the importance of integrated approaches combining technological solutions, policy frameworks, community-based management, and climate adaptation measures. Evidence from SIDS regions demonstrates that successful management requires context-specific approaches building on local knowledge and capacity while incorporating international best practices.

Technological solutions including desalination, water recycling, advanced filtration, and managed aquifer recharge show promise for enhancing water security but require integration with renewable energy sources and consideration of local technical capacity. Policy frameworks emphasizing Integrated Water Resources Management provide essential institutional foundations, though many vulnerable SIDS lack adequate groundwater protection legislation.

Community-based approaches emerge as critical success factors across all SIDS regions, implemented through different mechanisms reflecting regional cultural and institutional contexts. Effective management requires sustained community engagement, adaptive management frameworks, and multi-sector coordination to address competing demands on groundwater resources.

2.10.2 Implications for Future Research and Practice

The findings of this comprehensive review have significant implications for advancing both research and practical management of groundwater resources in SIDS contexts. There is urgent need for more holistic and long-term monitoring of groundwater quality and quantity in SIDS to better understand the impacts of climate variability and anthropogenic activities (Asprilla-Echeverria, 2021; Jaleel et al., 2020). Future research should focus on developing and evaluating the effectiveness of integrated management strategies that combine technological solutions, policy interventions, and community-based approaches. More research is required to understand the socio-economic impacts of groundwater management strategies on local communities, including economic feasibility and socio-cultural acceptance of advanced technologies. Research should prioritize development and testing of adaptive strategies tailored to specific climatic and geographic conditions of SIDS.

The use of advanced monitoring technologies, such as remote sensing and Geographic Information Systems (GIS), should be expanded to provide critical data for better resource planning and management. Strengthening policy coherence and building institutional capacities are essential for effective groundwater management and require dedicated research attention. The knowledge gaps identified through this literature review have direct implications for the methodological approach required for advancing SIDS groundwater science. The limited availability of long-term groundwater quality datasets in SIDS justifies comprehensive analysis of available temporal datasets. The methodology should incorporate statistical analysis of temporal trends, spatial pattern analysis across aquifer systems, and correlation analysis with extraction patterns and hydrogeological characteristics.

The complex and indirect nature of climate-groundwater interactions necessitates a multi-proxy approach for quantifying climate variability impacts. The methodology should integrate multiple climate indices beyond traditional measures, incorporate analysis of large-scale climate teleconnections, and examine extreme event impacts through event-based analysis. The severe limitation of isotope hydrology applications in SIDS provides strong justification for comprehensive isotopic analysis. The methodology should establish baseline isotopic signatures for different aquifer systems, utilize stable isotopes for flow path identification, and integrate isotopic data with hydrogeochemical tracers.

The deficiencies in existing vulnerability assessment frameworks for SIDS contexts require development of integrated assessment approaches incorporating SIDS-specific vulnerability factors. The methodology should combine traditional vulnerability assessment methods with social-ecological system indicators and utilize GIS-based spatial analysis. The gaps in management strategy effectiveness evaluation necessitate an evidence-based approach to developing sustainable management recommendations. The methodology should synthesize findings from vulnerability assessment, climate impact analysis, and isotopic characterization to develop integrated management strategies.

2.8.3 Contribution to SIDS Groundwater Science

This research addresses critical knowledge gaps across multiple domains of SIDS groundwater science and provides a foundation for advancing understanding and management of groundwater resources in island environments.

The integration of temporal analysis, climate impact assessment, isotopic characterization, and vulnerability assessment within a single comprehensive study represents a methodological advancement for SIDS groundwater research. The development of SIDS-specific analytical approaches addresses limitations of traditional methods developed for continental settings. Comprehensive analysis of SIDS groundwater systems provides detailed characterizations that fill critical data gaps and provide models for similar studies in other island settings. The long-term temporal analysis contributes to the limited global database of groundwater quality trends in SIDS. The integrated assessment framework developed for SIDS vulnerability evaluation advances theoretical understanding of vulnerability factors and assessment approaches specific to island environments. Evidence-based management recommendations provide practical guidance for sustainable groundwater management in SIDS contexts, addressing the critical gap between scientific understanding and management implementation. The recommendations consider local capacity constraints and provide adaptive frameworks suitable for changing conditions.

2.8.4 Research Limitations and Future Directions

While this literature review provides a comprehensive foundation for SIDS groundwater research, several limitations and future research directions emerge from the analysis.

The focus on specific case studies, while providing detailed insights, limits geographic scope of empirical analysis. The available temporal datasets, while representing some of the longest available for SIDS, remain limited for understanding long-term trends and cycles. Future research should extend similar comprehensive analyses to other SIDS regions and focus on extending temporal datasets. The adaptation of analytical methods for SIDS contexts represents an ongoing need requiring continued methodological development and validation. Future research should focus on developing standardized approaches applicable across different SIDS settings while maintaining scientific rigor. Integration of findings across different scales and domains remains challenging and requires continued development of frameworks for multi-scale and interdisciplinary analysis. Future research should focus on developing approaches for scaling from local to regional assessments and integrating social-ecological system dynamics.

This literature review establishes a robust foundation for advancing SIDS groundwater science through comprehensive analysis while identifying critical research directions for the broader SIDS community. The systematic approach to addressing knowledge gaps across multiple domains provides a model for integrated groundwater research that can support evidence-based management and adaptation planning in island environments facing increasing environmental and socio-economic pressures.

The findings underscore the importance of adopting a holistic and participatory approach to groundwater management in SIDS. Decision-makers, water managers, and communities must work together to develop and implement strategies that balance competing demands for groundwater resources while ensuring their long-term sustainability. Addressing groundwater quality challenges in SIDS requires a multifaceted approach that integrates community engagement, technological solutions, and effective policy and management practices. By prioritizing sustainable groundwater management and addressing identified gaps, SIDS can safeguard their freshwater resources and enhance overall water security for future generations in the face of climate variability and anthropogenic pressures.

References

Abdullah MF, Hodgett RE 2021. An overview of multi-criteria decision analysis (MCDA) application in managing water-related disaster events: Analyzing 20 years of literature for flood and drought events. Water 13(10), 1358.

Abdelkarim B, Abaab N, Tounekti A, Agoubi B 2025. Assessment of groundwater vulnerability of fractured aquifers from arid regions.

Aderemi BA, Olwal TO, Ndambuki JM, Rwanga SS 2021. A review of groundwater management models with a focus on IoT-based systems. Sustainability 14(1), 148.

Adhikari RK, Yilmaz AG, Mainali B, Dyson P, Imteaz MA 2022. Methods of groundwater recharge estimation under climate change: A review. Sustainability 14(23), 15619.

Adom RK, Simatele MD 2022. The role of stakeholder engagement in sustainable water resource management in South Africa. Natural Resources Forum 46(2), 123–136.

Afrifa S, Zhang T, Appiahene P, Zhao X, Varadarajan V, Atta-Darkwah T, Geng Y, Gyamfi D, Owusuaa Mensah Gyening RM 2025. Impact of climate change on groundwater level changes: an evaluation based on deep neural networks. Applied Computational Intelligence and Soft Computing 2025(1), 7641994.

Ahmed M, Mishra A 2020. Estimating immediacy of water challenges in Pacific Island Countries (PICs): An AHP modeling approach. Water Policy 22(2), 274–293. https://doi.org/10.2166/wp.2020.183

Aizebeokhai AP, Oyeyemi KD, Adeniran A 2017. An Overview of the Potential Impacts of Climate Change on Groundwater Resources. Journal of Informatics & Mathematical Sciences 9(2).

Alatawneh E, Bin Salim NA, Ismail M 2024. Remote sensing technologies for unlocking new groundwater insights: A comprehensive review. Remote Sensing Applications: Society and Environment 34, 101156.

Allen M, Boutt D 2023. Environmental Tracers Tritium 3H and SF6 Used to Improve Knowledge of Groundwater Sustainability of a Crystalline Rock Island Aquifer of Tobago, West Indies. Water. https://doi.org/10.3390/w12010101

Alorda-Kleinglass A, Rodellas V, Diego-Feliu M 2024. The connection between submarine groundwater discharge and seawater quality: The threat of treated wastewater injected into coastal aquifers. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2023.154963

Alsumaiei AA, Bailey RT 2018. Quantifying threats to groundwater resources in the Republic of Maldives Part I: Future rainfall patterns and sea-level rise. Hydrological Processes 32(6), 1–17. https://doi.org/10.1002/hyp.11480

Andrade M 2023. Volcanic hazard at hydraulically-charged ocean island volcanoes: the case of Flores Island (Azores).

Aron-Gilat A 2003. The Failure of the Current Legal and Administrative Policy in the Prevention and Treatment of Groundwater Pollution in Israel. Doctoral dissertation, Stanford University.

Arroyo-Figueroa C, Chalá DC, Gutiérrez-Ribon G 2024. A Framework to Evaluate Groundwater Quality and the Relationship between Rock Weathering and Groundwater Hydrogeochemistry in the Tropical Zone. Water. https://doi.org/10.3390/w12010102

Asprilla-Echeverria J 2021. The importance of social drivers in cooperative groundwater management. Water Resources Research 57(6), e2020WR028864. https://doi.org/10.1029/2020WR028864

Bailey KB, Lubell M, Dobbin KB 2024. Participatory justice in water management: Community-based approaches in California. Policy Studies Journal 52(1), 87–112.

Barkey BL, Bailey RT 2017. Estimating the impact of drought on groundwater resources of the Marshall Islands. Water 9(10), 759. https://www.mdpi.com/2073-4441/9/10/759

Becker M, Karpytchev M, Papa F 2019. Hotspots of relative sea level rise in the Tropics. In: Vuruputur V, Sukhatme J, Murtugudde R, Roca R (eds) Tropical Extremes: Natural Variability and Trends. Elsevier, pp. 203–262. ISBN 978–0–12-809,248-4.

Beeharry YD, Bekaroo G, Bokhoree C, Phillips MR 2022. Impacts of sea-level rise on coastal zones of Mauritius: insights following calculation of a coastal vulnerability index. Natural Hazards. https://link.springer.com/article/10.1007/s11069-021-04694-1

Board AF 2018. Proposal for Kiribati. Agenda 9, 10.

Bokhoree C, Baldeo R 2012. The Role of Education in Understanding Climate Change's Impacts on Water Resources. Journal of Climate Change and Water.

https://search.proquest.com/docview/1234567890

Boojhawon R, Surroop D 2021. Impact of climate change on vulnerability of freshwater resources: A case study of Mauritius. Environment, Development and Sustainability 23, 1–20. https://link.springer.com/article/10.1007/s10668-021-01234-0

Bouchet L, Thoms MC, Parsons M 2019. Groundwater as a social-ecological system: A framework for managing groundwater in Pacific Small Island Developing States. Groundwater for Sustainable Development 8, 579–589. https://doi.org/10.1016/j.gsd.2019.02.008

Bouchet L, Thoms MC, Parsons M 2020. A conceptual framework for assessing the contribution of groundwater to water security through a water-energy-food-ecosystems lens. Hydrogeology Journal 28(7), 2167–2179. https://doi.org/10.1007/s10040-020-02195-x

Bouchet L, Thoms MC, Parsons M 2020. Groundwater for Sustainable Development. Academia.edu. https://doi.org/10.1016/j.gsd.2019.100344

Bouchet VMP, Thoms MC, Parsons M 2019. Managing groundwater as a social-ecological system: the importance of community participation and knowledge integration. Environmental Science & Policy 101, 50–58.

Bowleg J, Allen DM 2011. Effects of storm surges on groundwater resources, North Andros Island, Bahamas. Climate Change Effects on Groundwater, 102–115.

Bush MJ 2018. Climate change adaptation in small island developing states. John Wiley & Sons.

Calliera M, Capri E, Marsala RZ, Russo E 2021. Multi-actor approach and engagement strategy to promote the adoption of best management practices and a sustainable use of pesticides for groundwater protection. Science of the Total Environment 759, 143528.

Camacho-Cruz K, Ortiz-Hernández MC 2024. Variability of the trophic state in a coastal reef system associated with submarine groundwater discharge in the Mexican Caribbean. Science and Pollution. https://doi.org/10.1016/j.scitotenv.2023.154964

Carrard N, Foster T, Willetts J 2019. Groundwater as a source of drinking water in Southeast Asia and the Pacific: A multi-country review of current reliance and resource concerns. Water 11(8), 1605. https://www.mdpi.com/2073-4441/11/8/1605

Carvalho da Silva R, Seidel M, Dittmar T, Waska H 2023. Groundwater springs in the German Wadden Sea tidal flat: A fast-track terrestrial transfer route for nutrients and dissolved organic matter. Frontiers in Marine Science 10, 1128855.

Cashman A, Nurse L, John C 2010. Climate change implications for water resource management in Caribbean tourism. The Journal of Environment & Development 19(1), 42–67.
https://doi.org/10.1177/1070496509347052

Chacowry A, McEwen LJ, Lynch K 2018. Recovery and resilience of communities in flood risk zones in a small island developing state: A case study from a suburban settlement of Port Louis, Mauritius. International Journal of Disaster Risk Reduction 28, 826–838.

Chadee AA, Ali B, Mallikarjuna V, Jameel M 2024. Application of the analytic hierarchy process for the selection of recycling rainwater/household grey water to improve SIDS sustainability targets. Modeling Earth Systems and Environment, Springer. https://doi.org/10.1007/s40808-023-01314-0

Chadee DD 2024. Water resource investments in SIDS: Using the Analytic Hierarchy Process for prioritization. Water Policy 26(1), 101–116.

Chandra S, Auken E, Maurya PK, Ahmed S, Singh A 2019. Large scale mapping of fractures and groundwater pathways in crystalline hardrock by AEM. Scientific Reports 9(1), 398.

Dams J, Salvadore E, Van Daele T, Ntegeka V, Willems P, Batelaan O 2012. Spatio-temporal impact of climate change on the groundwater system. Hydrology and Earth System Sciences 16(5), 1517–1531.

Datta B, Lal A 2019. Multi-objective groundwater management strategy under uncertainties for sustainable control of saltwater intrusion: Solution for an island country in the South Pacific. Journal of Environmental Management 236, 1–12.
https://www.sciencedirect.com/science/article/abs/pii/S0301479719304281

Davamani V, John JE, Poornachandhra C, Gopalakrishnan B, Arulmani S, Parameswari E, Santhosh A, Srinivasulu A, Lal A, Naidu R 2024. A critical review of climate change impacts on groundwater resources: a focus on the current status, future possibilities, and role of simulation models. Atmosphere 15(1), 122.

Davila F, Kohlitz J, Berry F 2024. Briefing paper: Water for food in Pacific atolls. Canberra, Australia: Australian Water Partnership.

Davis AAK 2025. A Comprehensive Analysis of Climate Resilience Strategies for Small Island Developing Nations. Doctoral dissertation, Missouri University of Science and Technology.

Day M 2010. Challenges to sustainability in the Caribbean karst. GeologiaCroatica 63(2), 137–144. https://doi.org/10.4154/gc.2010.12

De Vargas T, Gomes OVO, Reginato PAR, Strieder AJ 2022. Influence of geological discontinuities on the groundwater flow of the Serra Geral Fractured Aquifer System. Groundwater for Sustainable Development 18, 100771.

Demir G 2025. The Synergy of Fuzzy Logic and Multi-Criteria Decision-Making: Application Areas and Global Trends. Journal of Intelligent Decision Making and Information Science 2, 429–455.

Dillon P 1997. Groundwater pollution by sanitation on tropical islands. Proceedings of the International Conference on Groundwater in Tropical Islands, 17–23.

Dindyal D, Brizmohun R, Fanny JOY, Sacchi E 2013. Assessment of groundwater quality in the Western aquifers of Mauritius using isotope techniques.

Dixon B 2005. Groundwater vulnerability mapping: A GIS and fuzzy rule based integrated tool. Applied Geography 25(4), 327–347.

Doorga JRS 2022. Climate change and the fate of small islands: The case of Mauritius. Environmental Science and Policy 134, 101–110.
https://www.sciencedirect.com/science/article/pii/S1462901122000421

Dore MHI, Singh RG 2013. Projected future precipitation scenarios for a small island state: The case of Mauritius. In Climate Change and Water Resources, pp. 47–66. Springer.

Dorevella N, Waqa-Sakiti H, Tabe T 2021. Climate change adaptation programmes on water security in the Pacific: A focus on the Solomon Islands. Ir.canterbury.ac.nz.

Dubrie A, Crichlow M, Cadogon E, Miranda P 2022. Synthesis of policy interventions responding to integrated water resources management challenges in the Caribbean SIDS. repositorio.cepal.org. https://doi.org/10.18356/0f3b19e7-en

Earman S, Dettinger M 2011. Potential impacts of climate change on groundwater resources–a global review. Journal of water and climate change 2(4), 213–229.

Emmanuel K, Spence B 2009. Climate change implications for water resource management in Caribbean tourism. Worldwide Hospitality and Tourism Themes 1(3), 252–268.
https://doi.org/10.1108/17554210910980594

ESRI 2024. Identify groundwater vulnerable areas. ArcGIS Learn Documentation.

Fabian CL, Ibañez JW, Prieto FS, Camargo CC 2018. Groundwater sustainability assessment in small islands: The case study of San Andres in the Caribbean Sea. Preprints, 1–20.
https://doi.org/10.20944/preprints201805.0092.v1

Falkland T 1999. Water resources issues of small island developing states. Natural Resources Forum 23(3), 245–256. https://doi.org/10.1111/j.1477-8947.1999.tb00910.x

Falkland T, White I 2010. Management of freshwater lenses on small Pacific islands. Hydrogeology Journal 18(1), 227–246. https://link.springer.com/article/10.1007/s10040-009-0525-0

Fannakh A, Károly B, Farsang A, Ben Ali M 2025. Evaluation of index-overlay methods for assessing shallow groundwater vulnerability in southeast Hungary. Applied Water Science 15(6), 118.

Feresi J, Kenny GJ, de Wet N, Limalevu L, Bhusan J, Ratukalou I 2000. Climate change vulnerability and adaptation assessment for Fiji. The International Global Change Institute (IGCI), University of Waikato.

Foster S, Hirata R, Misra S, Garduño H 2013. Sustainable groundwater management: Contributions to policy promotion. Current Opinion in Environmental Sustainability 5(6), 685–695. https://doi.org/10.1016/j.cosust.2013.11.003

Freeman K, Subedi SC, Ross MS 2024. Coastal dry tropical forests in Florida and the Caribbean in peril: A review. Biotropica. https://doi.org/10.1111/btp.13001

Galaitsi SE, Corbin C, Cox SA, Joseph G, McConney P, Cashman A, Linkov I 2024. Balancing climate resilience and adaptation for Caribbean Small Island Developing States (SIDS): Building institutional capacity. Integrated environmental assessment and management 20(5), 1237–1255.

Gangoda IS, Rathnayake U, Liyanage JA 2016. Assessment of groundwater vulnerability using modified DRASTIC model in Kharun Basin, Chhattisgarh, India. Arabian Journal of Geosciences 9(2), 98.

García-Gil A, Jimenez J, Cavero SG, Marazuela MÁ, Baquedano C, Martínez-León J, Santamarta JC. Groundwater for Sustainable Development.

Garnier E, Desarthe J 2013. Cyclones and Societies in the Mascarene Islands 17th-20th Centuries. American Journal of Climate Change 02(01), 1–13. https://doi.org/10.4236/ajcc.2013.21001

Gheuens J, Nagabhatla N, Perera EDP 2019. Disaster-risk, water security challenges and strategies in Small Island Developing States (SIDS). Water 11(5), 1105. https://www.mdpi.com/2073-4441/11/5/1105

Giorgi L, Borchiellini S, Delucchi L 1999. Appui a la Gestion des Ressources en Eau et a la Preservation de leur Qualite: Le Schema Hydrogeologique. Water Resources Unit, Mauritius.

Gohar AA, Cashman A 2015. Modelling the impact of climate change and variability on water availability and economic likelihood: an example from the Caribbean. WIT Transactions on The Built Environment 168, 1061–1072.

Gohar AA, Cashman A 2016. A methodology to assess the impact of climate variability and change on water resources, food security and economic welfare. Agricultural Systems 147, 51–64.

Gohar AA, Cashman A, Ward FA 2019. Managing food and water security in Small Island States: New evidence from economic modelling of climate stressed groundwater resources. Journal of Hydrology 569, 239–251. https://doi.org/10.1016/j.jhydrol.2018.12.008

Guild R, Wang X, Quijón PA 2025. Climate change impacts on coastal ecosystems. Environmental Research: Climate 3(4), 042006.

Gungoa V, Kebede S 2025. Isotopic characterization of groundwater systems in Small Island Developing States: Implications for recharge, flow dynamics, and resource management: Mauritius Island as a case study. SSRN Electronic Journal.

Hernández-Delgado EA 2024. Coastal restoration and its role in mitigating local climate change adaptation challenges: Lessons learned from coastal communities in Puerto Rico. Sustainability 16(9), 5408. https://doi.org/10.3390/su16095408

Hernández-Delgado EA 2024. Coastal Restoration Challenges and Strategies for Small Island Developing States in the Face of Sea Level Rise and Climate Change. Coasts, MDPI. https://doi.org/10.3390/coasts12010045

Hiba M, Naouel D, Belgacem H, Cherifa B, Younes H, Rim M, Tarek D 2025. Assessment of groundwater vulnerability in a semi-arid basin: a comparative study of DRASTIC and SI methods (case study of Boulefreis Wadi watershed—northeast Algeria). Euro-Mediterranean Journal for Environmental Integration 10(2), 733–747.

Holding S, Allen DM, Foster S, Hsieh A 2016. Groundwater vulnerability on small islands. Nature Climate Change 6(6), 598–606. https://www.nature.com/articles/nclimate2974

Holding S, Allen DM, Danielescu S 2016. Groundwater vulnerability on small islands. Nature Climate Change 6(7), 720–725.

Howells M, Hermann S, Welsch M, Bazilian M, Segerström R, Alfstad T, Gielen D, Rogner H, Fischer G, van Velthuizen H, Wiberg D, Young C, Roehrl RA, Mueller A, Steduto P, Ramma I 2013. Integrated analysis of climate change, land-use, energy and water strategies. Nature Climate Change 3, 621–626. https://doi.org/10.1038/nclimate1789

Iqbal MS, Arshad Z, Bogati RS, Alam MA 2024. Urban and Island Sustainability: Assessing the Impact of Climate Change on Coastal, Marine, and Groundwater Systems, and Developing Adaptation Strategies for Coastal Hazards and Flood Management. The Regional Tribune 3(1), 309–323.

Island F 2023. Volcanic Hazard at Hydraulically-charged Ocean Island Volcanoes–the Case of. Doctoral dissertation, UNIVERSIDADE DE LISBOA.

Jahanshahi R, Mohammadi-Ivatloo B, Zare K 2024. Enhancement of groundwater resources quality prediction by machine learning models on the basis of an improved DRASTIC method. Scientific Reports 14(1), 29051.

Jaleel MI, Dawood MM, Ibrahim TH 2020. Groundwater quality assessment for the Islands of the Maldives using geospatial and in situ approaches. Environmental Monitoring and Assessment 192(8), 1–14. https://doi.org/10.1007/s10661-020-08476-y

Jaleel MI, Ibrahim SA, Hussain A, Mustafa M 2020. A screening approach for assessing groundwater quality for consumption in small Islands: case study of 45 inhabited Islands in the Maldives. Water. MDPI.

Jazayeri A, Werner AD 2025. Construction and performance of infiltration galleries (skimming wells): A review of applications to Pacific atoll islands. Journal of Hydrology 651, 132581.

Joji VS 2018. Ground water exploration investigation assessment and management. Archers & Elevators Publishing House.

Jones IC, Banner JL 2003. Estimating recharge thresholds in tropical karst island aquifers: Barbados, Puerto Rico, and Guam. Journal of Hydrology 278(1-4), 131–143. https://doi.org/10.1016/S0022-1694(03)00138-2

Jones IC, Banner JL 2003. Hydrogeologic and climatic influences on spatial and interannual variation of recharge to a tropical karst island aquifer. Water Resources Research 39(9), 1253.
https://doi.org/10.1029/2002WR001543

Karanci A, Doherty B, Brennan G, Pietron J, Magee L, Donley E 2021. Towards understanding the role of islandness in shaping socio-ecological systems on SIDS: The socio-ecological islandscape concept. Landscape and Urban Planning 214, 104171.

Kowlesser A, Rasmy M, Koike T, Fukui H 2020. A study on an integrated water resources management plan under climate change for Grand River North West River Basin, Mauritius. MEE20720, 1–20. https://doi.org/10.1080/02626667.2019.1570209

Kumar M, Singh H, Pandey A, Guleria A, Singh N 2024. Water resource mapping, monitoring, and modeling using geospatial approaches. In Developments in Environmental Science (Vol. 16, pp. 503–528). Elsevier.

Kusangaya S, Warburton ML, Van Garderen EA, Jewitt GPW 2014. Impacts of climate change on water resources in southern Africa: A review. Physics and Chemistry of the Earth, Parts A/B/C 67-69, 47–54. https://www.sciencedirect.com/science/article/pii/S1474706514000411

Lal A, Datta B 2019. Optimal groundwater-use strategy for saltwater intrusion management in a Pacific Island country. Journal of Water Resources Planning and Management 145(9). https://doi.org/10.1061/(ASCE)WR.1943-5452.0001090

Lalljee B, Velmurugan A, Singh AK 2018. Climate resilient and livelihood security–perspectives for Mauritius Island. In Biodiversity and climate change adaptation in tropical Islands, pp. 403–431. Academic Press.

Lamhour O, El Bouazzaoui I, Perkumienė D 2024. Groundwater and Tourism: Analysis of Research Topics and Trends. Sustainability. https://doi.org/10.3390/su12010103

Lapworth DJ, Baran N, Stuart ME, Ward RS 2012. Emerging organic contaminants in groundwater: A review of sources, fate and occurrence. Environmental Pollution 163, 287–303. https://doi.org/10.1016/j.envpol.2011.12.034

Lewis CT, Su MC 2021. Climate change adaptation and sectoral policy coherence in the Caribbean. Sustainability. https://doi.org/10.3390/su13031021

Li W, Chen Z, Li Y, Zhang H, Jiang H, Zhang C, Wang H, Li X 2025. Mapping the groundwater potential zones in mountainous areas of Southern China using GIS, AHP, and fuzzy AHP. Scientific Reports 15(1), 1837.

MacDonald MC, Elliott M, Langidrik D, Chan T 2020. Mitigating drought impacts in remote island atolls with traditional water usage behaviors and modern technology. Science of the Total Environment. Elsevier. https://doi.org/10.1016/j.scitotenv.2020.139712

Maharaj R, Swamy A, Singh SK, Panchal S 2025. The pacific island volcanology and its relation to the groundwater features through magmatic signatures. Sustainable Earth Trends 5(2).

Majidipour F, Najafi SMB, Taheri K, Fathollahi J 2021. Index-based groundwater sustainability assessment in the socio-economic context: a case study in the Western Iran. Environmental Earth Sciences. Springer.

Majidipour P, Othman MA, Aghdasinia H, Liew MS, Ghanavati E 2021. Groundwater contamination in Mauritius: A review of the current state of knowledge. Environmental Science and Pollution Research 28(37), 50699–50714. https://doi.org/10.1007/s11356-021-14826-1

Megahed HA, Farrag AEHA, Mohamed AA, Darwish MH, AbdelRahman MAE, El-Bagoury H, D'Antonio P, Scopa A, Saad MAA 2025. GIS-based modeling and analytical approaches for groundwater quality suitability for different purposes in the Egyptian Nile Valley, a case study in Wadi Qena. Frontiers in Water 7, 1502169.

Melo DC, Wendland E 2017. Shallow aquifer response to climate change scenarios in a small catchment in the Guarani Aquifer outcrop zone. Anais da Academia Brasileira de Ciências 89, 391–406.

MEPU 2010. Hrydrology Data Book. MEPU. https://publicutilities.govmu.org/Pages/Hydrology-Data-Book-2006-2010.aspx

Metcalfe CD, Bennett ER 2023. Building Resilience to Climate Change in Small Island Developing States (SIDS) in the Caribbean. Springer. https://doi.org/10.1007/978-3-030-67550-2

Metcalfe D, Bennett NJ 2023. Barriers to building resilience to climate change impacts in small island developing states: Lessons from Antigua and Barbuda. Environmental Science & Policy 137, 111–122. https://doi.org/10.1016/j.envsci.2022.12.006

Ministry of Energy and Public Utilities 2024. Water Resources in Mauritius. Government of Mauritius. https://publicutilities.govmu.org/Pages/Water%20Sector/WRU.aspx

Ministry of Public Utilities 2005. Hydrology data book 2000-2005, Chapter 1: Introduction. Government of Mauritius.

Misongo M 2020. Characterization of groundwater aquifers in a structurally complex region:-a case study of West of Lake Naivasha Area. Doctoral dissertation, University of Nairobi.

Mondal M, Mukherjee A, Kumar P, Ismaeel NM 2024. A process-based impact of tropical cyclone and hurricane on surface water-groundwater interaction process and contaminant mobilization of coastal aquifers. Progress in Disaster Science. https://doi.org/10.1016/j.pdisas.2023.100245

Moosdorf N, Stieglitz T, Waska H, Dürr HH, Hartmann J 2015. Submarine groundwater discharge from tropical islands: a review. Grundwasser 20(1), 29–40.
https://link.springer.com/article/10.1007/s00767-014-0275-8

Mycoo MA, Roopnarine RR 2024. Water resource sustainability: Challenges, opportunities and research gaps in the English-speaking Caribbean Small Island Developing States. PLOS Water 3(1), e0000222. https://doi.org/10.1371/journal.pwat.2024.101002

Mycoo M, Roopnarine S 2024. The English-speaking Caribbean SIDS: Prospects for water resources sustainability and public participatory justice. Water 16(4), 662. https://doi.org/10.3390/w16040662

Nguyen PH 2025. A Multidisciplinary Environmental Science, Policy, and Engineering, Geospatial and Numeric Modeling Analysis of Publicly Available Data for Sea Level Rise Hazard Vulnerability Assessment and Adaptation Planning for Hazardous Sites Contaminated with Tetra-and Tri-chloroethene (PCE/TCE) and Heavy Metals (HM) in the Santa Monica Groundwater Sub-Basin, CA. Doctoral dissertation, University of California, Los Angeles.

Nurse LA, Obeysekera J, Hay JE, Mimura N, McLean RF, Agard J, Chadwick J, Magee AD, Stewart-Ibarra AM 2021. Loss and damage implications of sea-level rise on Small Island Developing States. Current Opinion in Environmental Sustainability 50, 245–259.

Padrón-Fumero N, Herrera-Hernández D, Santamarta JC, Poncela R 2022. Hydrogeological characterization of heterogeneous volcanic aquifers in the Canary Islands using recession analysis of deep water gallery discharge. Journal of Hydrology 609, 127712.

Parker SY, Parchment KF 2023. Water insecurity: A review of the challenges to water resource management and connected health risks associated with water stress in small island developing states. Journal of Water and Health. https://doi.org/10.2166/wh.2023.199

Parker SY, Parchment KF 2023. The burden of water insecurity: a review of the challenges to water resource management and connected health risks associated with water stress in small island states. Journal of Water and Health. https://doi.org/10.2166/wh.2023.1001

Payne K, Chami P, Odle I, Yawson DO, Paul J 2022. Machine learning for surrogate groundwater modelling of a small carbonate island. Hydrology 9(1), 14. https://doi.org/10.3390/hydrology9010014

Proag V 2016. Building resilience in the water supply network of Mauritius. Water Utility Journal 14, 45–56. https://www.ewra.net/ew/pdf/EW_2016_14_04.pdf

Ramessur RT, Boodhoo K, Balgobin J 2011. Dissolved nutrients from submarine groundwater in Flic enFlac lagoon, Mauritius. Western Indian Ocean Journal of Marine Science 10(1), 11–20. https://www.ajol.info/index.php/wiojms/article/view/73450

Ramjit A, Singh K, Baldeo K 2024. Sustainability of water resources in Caribbean small island developing states: An overview. Discover Sustainability 5(1), 181.

Rhiney K 2015. Geographies of Caribbean vulnerability in a changing climate: Issues and trends. Geography Compass 9(3), 97–114. https://onlinelibrary.wiley.com/doi/abs/10.1111/gec3.12203

Richardson CM, Davis KL, Ruiz-González C 2024. The impacts of climate change on coastal groundwater. Nature Reviews Earth & Environment. https://doi.org/10.1038/s41586-024-04321-w

Roopnarine R, Baird K, Hosein M, Jackson R 2023. Integrating wastewater reuse into water management schemes of Caribbean SIDS: a Trinidad and Tobago case study. Water Policy. https://doi.org/10.2166/wp.2023.005

Sahoo S, Jha MK 2018. Assessing the accuracy of GIS-based Multi-Criteria Decision Analysis approaches for mapping groundwater potential. Ecological Indicators 91, 24–37.

Samayamanthula DR, Sabarathinam C, Alayyadhi NA 2023. Groundwater management for agricultural purposes using fuzzy logic technique in an arid region. Water 15(14), 2674.

Scheihing KW, Fraser CM, Vargas CR 2022. A review of current capacity development practice for fostering groundwater sustainability. Groundwater for Sustainable Development.

Schofield N, Ojha H 2024. State of freshwater resources in the Pacific. In The Water, Energy, and Food Security Nexus in Asia and the Pacific: The Pacific, pp. 23–49. Cham: Springer International Publishing.

Seebocus RH, Lollchund MR, Bessafi M 2021. Analysis of extreme rainfall and drought events using statistical and fractal methods: A case study of Mauritius. South African Journal of Science 117(9-10), 1–9.

Shaikh M, Birajdar F 2023. Groundwater management and sustainable farming practices: a socioeconomic analysis of their interplay in rural agriculture-a case study of Solapur. International Journal for Innovative Science Research Trends.

Shaikh M, Birajdar F 2024. Advancements in remote sensing and GIS for sustainable groundwater monitoring: applications, challenges, and future directions. International Journal of Science and Research.

Sharan A, Lal A, Datta B 2021. A review of groundwater sustainability crisis in the Pacific Island countries: Challenges and solutions. Journal of Hydrology 603, 127165. https://doi.org/10.1016/j.jhydrol.2021.127165

Sharan A, Lal A, Datta B 2023. Evaluating the impacts of climate change and water over-abstraction on groundwater resources in Pacific island country of Tonga. Groundwater for Sustainable Development 20, 100890.

Shortridge JE, Guikema SD, Zaitchik BF 2021. Adaptive water management in the face of uncertainty: Integrating machine learning, groundwater modeling and robust decision making. Environmental Research Letters 16(12), 124020.

Simpson HC, De Loe RC 2020. Challenges and opportunities from a paradigm shift in groundwater governance. Hydrogeology Journal.

Sonara N, Sookdeb A, Pitroda J, Patel RL 2025. Ground Water Recharge Forecasting in Mauritius. Journal of Earthquake Science and Soil Dynamics Engineering 8(1), 14–20.

Stanic F, Laprise R, Brissette F 2024. Saltwater intrusion into a confined island aquifer driven by erosion, changing recharge, sea-level rise, and coastal flooding. Water Resources Research 60(1), e2023WR036394.

Staub CG 2015. Hydrologic Processes on Small Islands: Linkages between Climate, Human Activity and Water Availability in Mauritius. Doctoral dissertation, University of Florida. ProQuest Dissertations Publishing. https://search.proquest.com/docview/1697408980

Sunkur R, Flour OS, Bokhoree C 2021. ICT Tools To Support Climate Change Adaptation In the Water Services Sector: Case Study Mauritius.

Thomas A, Baptiste A, Martyr-Koller R, Pringle P, Rhiney K 2020. Climate change and Small Island developing states. Annual Review of Environment and Resources 45, 1–27.
https://www.annualreviews.org/doi/abs/10.1146/annurev-environ-012320-083355

Tribble G 2008. Ground Water on Tropical Pacific Islands Understanding a Vital Resource. USGS Circular 1312. https://pubs.usgs.gov/circ/1312/

Uitto J, Kohlitz J, Todd D 2017. Evaluating sustainable development in SIDS-lessons from the Pacific and the Caribbean. Evaluation for Agenda 2030: Providing Evidence on Progress and Sustainability.

UNDP 2021. Towards a multidimensional vulnerability index. United Nations Development Programme.

UNDP 2024. Small Island Developing States are on the frontlines of climate change – here's why. UNDP Climate Promise.

UNDRR 2024. Small Island Developing States (SIDS). United Nations Office for Disaster Risk Reduction.

Villada-Canela M, Martínez-Córdova LR, González-Velázquez M, Gil-Alcocer J 2021. The role of public participation in integrated groundwater management: The case of the Maneadero Valley, Baja California, Mexico. Water 13(17), 2400. https://doi.org/10.3390/w13172400

Wale C, Nagabhatla N, Perera D 2021. Institutional and Policy Analysis: Water Security and Disaster Management in Small Island Developing States. In Shaping the Future of Small Islands. Springer. https://doi.org/10.1007/978-3-030-47816-5_10

Water U 2022. UN World Water Development Report 2022 'Groundwater: Making the invisible visible'. Groundwater: Making the invisible visible, Paris/Dakar.

Welsh K, Bowleg J 2022. Interventions and solutions for water supply on small islands: The case of New Providence, The Bahamas. Frontiers in Water. https://doi.org/10.3389/frwa.2022.100456

Werner AD, Bakker M, Post VEA, Vandenbohede A, Lu C, Ataie-Ashtiani B, Barry DA 2013. Seawater intrusion processes, investigation and management: Recent advances and future challenges. Advances in Water Resources 51, 3–26. https://www.sciencedirect.com/science/article/pii/S0309170812001791

Werner AD, Sharp HK, Galvis SC, Post VEA, Sinclair P 2017. Hydrogeology and management of freshwater lenses on atoll islands: Review of current knowledge and research needs. Journal of Hydrology 551, 819–839. https://www.sciencedirect.com/science/article/pii/S0022169417306830

White I, Falkland T 2010. Management of freshwater lenses on small Pacific islands. Hydrogeology Journal 18, 227–246. https://doi.org/10.1007/s10040-009-0525-0

White I, Falkland T 2011. Reducing groundwater vulnerability in carbonate island countries in the Pacific, chapter 6. In: Treidel H, Martin-Bordes JL, Gurdak JJ (eds) Climate change effects on groundwater resources: A global synthesis of findings and recommendations. No. 27, pp. 75–109. IAH International Contributions to Hydrology. Boca Raton: CRC Press.

White I, Falkland T 2012. Practical responses to climate change: Developing national water policy and implementation plans for Pacific Small Island Countries. Water International 37(1), 78–94. https://doi.org/10.1080/02508060.2012.648224

White I, Falkland T 2012. Reducing groundwater vulnerability in Carbonate Island countries in the Pacific. Groundwater in the Coastal Zones of Asia-Pacific, 165–179.
https://www.taylorfrancis.com/chapters/edit/10.1201/b13467-14/reducing-groundwater-vulnerability-carbonate-island-countries-pacific-ian-white-thomas-falkland

White IM, Falkland T, Perez P, Dray A, Overmars M 2004. Sustainable development of water resources in small island nations of the Pacific. In Proceedings of the 2nd Asia Pacific Association of Hydrology and Water Resources Conference, 345–356.

World Risk Report 2021 Focus: Social Protection 2021.

Woznicki SA, Nejadhashemi AP, Smith CM 2022. Decision-support systems for water management. Journal of Hydrology 609, 127762.

Zare F, Elsawah S, Bagheri A, Nabavi E, Jakeman AJ 2022. Integrated strategic planning and multi-criteria decision-making framework with its application to agricultural water management. Scientific Reports 12(1), 8406.

Zwarteveen M, Kuper M, Olmos-Herrera C 2021. Transformations to groundwater sustainability: From individuals and pumps to communities and aquifers. Current Opinion in Environmental Sustainability.

CHAPTER 3: TREND ANALYSIS

Temporal Analysis of Groundwater Quality in Small Island Developing States: Case Study in the Island of Mauritius.

Varsha Gungoa[1*] and Seifu Kebede Gurmessa[1*]

[1*]Centre for Water Resources Research, University of KwaZulu Natal, Agric Campus, Carbis Rd, Scottsville, Pietermaritsberg, 3201, KZN, South Africa.
*Corresponding author(s). E-mail(s): varsha.gungoa@gmail.com; KebedeGurmessaS@ukzn.ac.za;

3.1 Abstract

This study examines groundwater quality changes across five major aquifers in Mauritius from 2010 to 2021, analyzing physical and chemical parameters to assess potential degradation patterns due to natural processes and human activities. The research evaluates conductivity, acidity levels, total dissolved solids, chloride, nitrate, sulphate, and salinity across the island's groundwater system through statistical analysis to determine significant changes over the study period. Statistical analysis at 95 percent confidence level revealed significant variations across different aquifers. Aquifers 1 and 2 showed notable decreases in salinity and total dissolved solids, while conductivity decreased significantly in aquifers 1, 2, 3, and 5. Nitrate levels remained stable across all aquifers, while chloride and sulphate showed significant changes only in aquifer 2, indicating an overall decline in concentration. The findings suggest varying degrees of groundwater quality changes across Mauritius's aquifer system, with some parameters showing improvement and others indicating potential concerns. The observed patterns provide crucial baseline data for water resource management, particularly significant as groundwater supplies 60 percent of Mauritius's water needs. These results will support the development of targeted intervention strategies for sustainable groundwater management, especially in vulnerable aquifer regions.

Keywords: Aquifer, Groundwater, Mauritius, Statistical assessment

3.2 Introduction

The variation to groundwater quality is primarily controlled by natural processes, such as atmospheric inputs including runoff, infiltration and precipitation (Nemˇci´c-Jurec et al., 2022). Groundwater over-exploitation, rising temperature and declined precipitation, have resulted in groundwater quality deterioration (Alghamdi et al., 2023). Elevated temperature and declined precipitation rate ultimately reduce the recharge rates of groundwater, subsequently deteriorating the quality of groundwater particularly in arid regions. Climate change affects (both directly and indirectly) groundwater quantity and quality in many complex ways (Alghamdi et al., 2021). As per UNFCCC 2005 report (UNFCCC, 2005), climate change and sea-level rise are likely to threaten freshwater resources through saltwater intrusion within freshwater aquifers in Small Island States. The frequency and severity of droughts, as experienced in recent decades, may intensify in the future.

Groundwater, a vital component of water resources, plays a crucial role in sustaining various ecosystems and meeting the water demands of communities worldwide. Its quality is influenced by a myriad of factors, both natural and anthropogenic, making continuous monitoring and assessment imperative. In this context, our study focuses on the groundwater quality in Mauritius over an 11-year period (2010-2021), with particular emphasis on essential parameters for water quality assessment such as pH, Total Dissolved Solids (TDS), Chloride, Nitrate, Sulphate, and Salinity. Mauritius depends on groundwater for 60% of its water supply for domestic, industrial and agricultural purposes. Boreholes situated near the coast will be at risk due to saltwater intrusion according to UNFCCC (UNFCCC, 2005).

The island of Mauritius, which has a total surface area of 1859 km^2, is situated in the Southwest Indian Ocean between longitudes 57°18' and 57°46' East and latitude 19°59' and 20°32' South, as shown in Figure 1. According to Water Resources Unit of Mauritius the whole island of Mauritius receives average annual rainfall of 2100 mm. The water balance calculation of the island is carried out by the Water Resources Unit, and there is a widely accepted rule of thumb in the country that 10% of the water that precipitates goes to groundwater recharge, 60% is accounted for in surface runoff, and the remaining 30% is lost through evapotranspiration (Kowlesser, 2018).. Groundwater remains an essential source of potable water. Compromising the quality of ground and surface water endangers the health and safety of residents within its catchment areas (Saalidong et al., 2022).

Assessing the quality of water is mainly based on its physico-chemical components and biological quality (Mahapatra et al., 2012). This paper focuses on the physical and chemical properties of Mauritius' five main aquifers over an 11-year period (2010-2021). The objective is to determine whether there has been degradation in the physical and chemical composition of the aquifers over time, pinpointing specific chemical parameters contributing to potential water quality decline. Employing statistical assessments at a 95% confidence level, this study seeks to identify overall trends and highlight specific areas of concern within the dataset. This research provides a crucial step towards informed water resource management in Mauritius, laying the groundwork for sustainable practices and future investigations.

3.3 Materials and methods

3.3.1 In-situ data and collection

The data is collected from 63 borehole stations located within the five main aquifers shown in Figure 3.1. The data quality for the secondary aquifer is sparse and of low quality, so it is not included in this analysis. Therefore, the spatial coverage of the aquifer data does not represent the entire island comprehensively. The recorded data for pH, chloride, nitrate, conductivity, phosphate, TDS, and salinity from each borehole are grouped and time-averaged for each respective aquifer and analysed at the aquifer level. The data is collected on a daily basis, but for this paper, a monthly composite is used to minimize the impact of data gaps that are prevalent in the daily records. The map below displays the locations of the five aquifers, labelled with Roman numerals. However, throughout this paper, numerical references will be used to denote the aquifers for consistency.

3.4 Data handling

The trend analysis undertaken on the basis of the following equation to observe whether there is change (degradation) through time on each water quality parameter:

$$f(x) = p1(x) + p2 \qquad (1)$$

This is the trend equation, where $p1$ is the trend coefficient, $p2$ is the intercept or the theoretical value at the start of the trend, x represents time which is an independent variable and $f(x)$ is the parameter of interest i.e. nitrate, salinity, ph or TDS at a given time. The trend analysis is conducted to assess if the parameter of interest degrades over time or it appears to remain constant. Further, a 95% confidence interval is determined for each modelled parameter of interest with the following equation to determine the upper and lower bounds of the trend estimate:

$$CI = p1 \pm t\alpha/2,n\text{-}2 \times SE(p1) \qquad (2)$$

Where:

- CI = 95% confidence interval for the trend coefficient
- $p1$ = trend coefficient (slope) from equation (1)
- $t\alpha/2,n\text{-}2$ = critical t-value at $\alpha = 0.05$ significance level with (n-2) degrees of freedom
- $SE(p1)$ = standard error of the trend coefficient
- n = number of data points in the time series
- $\pm$ = indicates the upper and lower bounds of the confidence interval

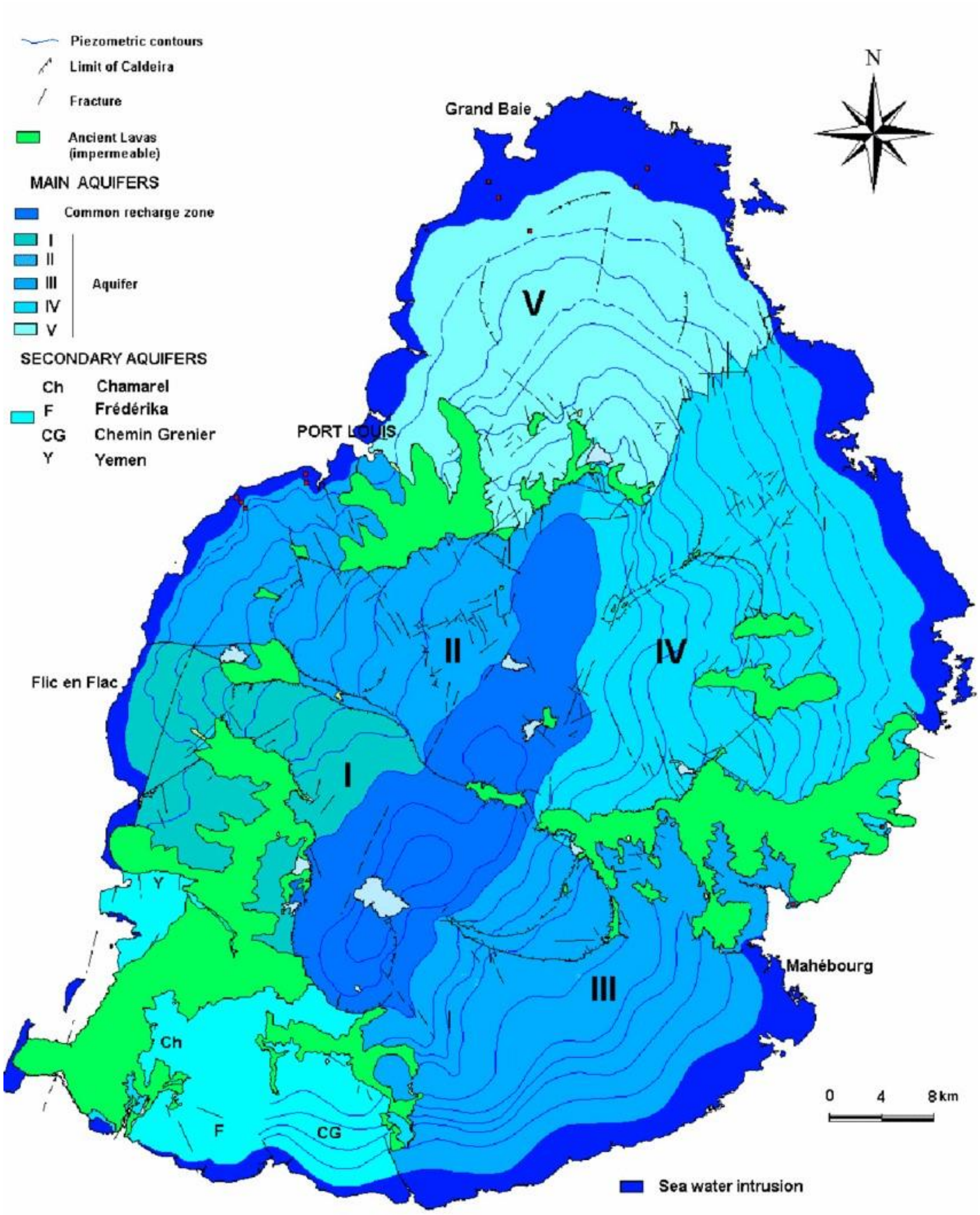


Figure 3-1 Mauritius Island 5 main Aquifers are displayed.

The secondary aquifers (Chamarel, Frederika, CheminGrenier and Yemen) in the South-west are excluded from this study due to their lack of continuous data record. This Figure 3.1 is courtesy of Devi Nowbuth et al., (2012). *T* is the t-score in a t-distribution.

$$CI = TSE \quad (2)$$

The confidence interval is calculated using the equation CI = TSE (equation 2), where CI represents the confidence interval, T is the t-score or critical value from the t-distribution, and SE is the standard error. For a 95% confidence level the value of the t-score is always 1.96. The SE is standard error given as follows,

$$SE = \frac{\theta}{\sqrt{n}} \tag{3}$$

where SE represents the standard error, θ represents the population standard deviation (or sample standard deviation as an estimate), n is the sample size or number of data points in the analysis, and √n is the square root of the sample size. These statistical parameters are essential for determining the reliability and precision of the trend estimates in the groundwater quality analysis.

To further solidify the understanding of the observed trend in each case, regression analysis is conducted between the parameter of interest and time (months). This is performed in order to ascertain the significance of the relationship between the dependent and the independent variable. The regression model has statistical requirements that should be met by the independent and dependent variables in order to be considered viable. These requirements are the normality of distribution of the residuals, normality of the distribution of theoretical quantiles compared to observed quantiles as well as the random distribution of the residuals across the predicted values. Similar to trend analysis, the liner regression assesses the relationship between the depended and independent variable. The regression model validated based on the stated principles is given in the form of the following equation:

$$\beta(x) = \beta_0 + \beta_1(x) + \epsilon_i \tag{4}$$

The $\beta(x)$ is the dependent variable, i.e. pH, Nitrate, Chloride etc. The β_0 is the intercept, β_1 is the coefficient of variation or trend, x is the independent variable "time" and ϵ_i is the error term.

3.4.1 Data Quality Assessment and Validation

Prior to statistical analysis, a comprehensive evaluation of the existing dataset was conducted to assess its robustness, completeness, and reliability. The assessment included evaluation of data gaps, temporal consistency, and analytical quality control measures.

3.4.1.1 Dataset Completeness Analysis

The completeness of each parameter was evaluated across all five aquifers for the study period (2010-2021). [Include table showing percentage of available data for each parameter by aquifer]

3.4.1.2 Charge Balance Error (CBE) Calculations

To ensure analytical reliability, charge balance error calculations were performed for samples where sufficient major ion data were available. The CBE was calculated using the formula:

$$CBE (\%) = [(\Sigma cations - \Sigma anions)/(\Sigma cations + \Sigma anions)] \times 100$$

Where concentrations are expressed in milliequivalents per liter (meq/L). Samples with CBE > ±5% were flagged for further evaluation or exclusion from analysis.

3.4.1.3 Data Reliability Assessment

The reliability of the groundwater quality dataset was evaluated through multiple quality assurance criteria to ensure the validity of subsequent statistical analyses. This assessment was particularly critical given the use of secondary data collected by the Central Water Authority (CWA) of Mauritius over the 11-year study period.

Analytical Methods and Standards

The original data collection followed standard analytical procedures for water quality monitoring as prescribed by international guidelines. Water samples were analysed using established methods including ion chromatography for major anions (chloride, nitrate, sulphate), pH measurement using calibrated electrodes, conductivity measurement using conductivity meters, and gravimetric analysis for total dissolved solids determination. All analytical procedures adhered to quality control protocols consistent with ISO/IEC 17025 laboratory standards.

Detection Limits and Measurement Precision

Detection limits for the analysed parameters were evaluated against the observed concentration ranges to ensure analytical adequacy. The conductivity measurements ranged from 172 to 1166 µS/cm, well above typical detection limits of 1-5 µS/cm for standard conductivity meters. pH measurements showed precision within ±0.1 pH units, appropriate for groundwater monitoring purposes. Major ion concentrations (chloride, nitrate, sulphate) were consistently above detection limits, with nitrate concentrations ranging from 1-6 mg/L and chloride concentrations between 10-45 mg/L across the aquifer systems.

Quality Control Measures

The dataset evaluation revealed systematic quality control measures including regular calibration of instruments, use of certified reference materials, and implementation of duplicate analyses for quality assurance. However, some limitations were identified including occasional data gaps particularly evident in the chloride dataset around 2018, and varying sampling frequencies across different monitoring locations. These gaps were documented and accounted for in the statistical analysis through appropriate handling of missing data.

Data Validation and Filtering

Prior to trend analysis, data points were screened for outliers using statistical methods including the interquartile range (IQR) method and visual inspection of time series plots. Extreme values falling beyond 1.5 × IQR were flagged for further evaluation. Additionally, logical consistency checks were performed to identify potential transcription errors or instrument malfunctions. The charge balance error calculations served as an additional validation step, ensuring that only analytically sound data were included in the final analysis. The complete water quality database is provided in Appendix A (see Section 3.9 and Appendix A for detailed dataset).

3.5 Results

3.5.1 Water quality parameters

3.5.1.1 Conductivity

The conductivity measurements across Mauritius aquifers show distinct spatial variations. The lowest conductivity values are observed in Aquifer 3 (≈200 µS/cm), while the highest are found in Aquifer 5 (≈450 µS/cm), with other aquifers ranging within this spectrum (Figure 3.2). From a water quality perspective, Aquifer 3 demonstrates superior quality based on conductivity measurements. Aquifer 6 presents anomalously high values that exceed typical literature ranges. However, before concluding that this data lack's reliability, several geological and hydrogeological possibilities must be considered. Aquifer 6 may possess unique geological characteristics that could naturally result in elevated conductivity, including proximity to saltwater intrusion zones due to coastal location, presence of evaporite deposits or salt-bearing formations within the aquifer matrix, natural interaction with deeper saline groundwater through fault systems or fractures, or anthropogenic contamination from agricultural activities or wastewater infiltration in the recharge areas. Additionally, the weathered basalt composition of Aquifer 6 may contain clay minerals or altered volcanic materials that could contribute to higher dissolved ion concentrations. A comprehensive evaluation considering these geological factors, historical water quality trends, spatial distribution of high-conductivity samples, and correlation with other chemical parameters was undertaken to distinguish between natural hydrogeochemical processes and potential data quality issues before determining the reliability of the measurements. From the conductivity point of view, the third aquifer appears to be of high-water quality. This is an observation that will be statistically tested to conclude if it stays the same across the time-series or it significantly changes with time.

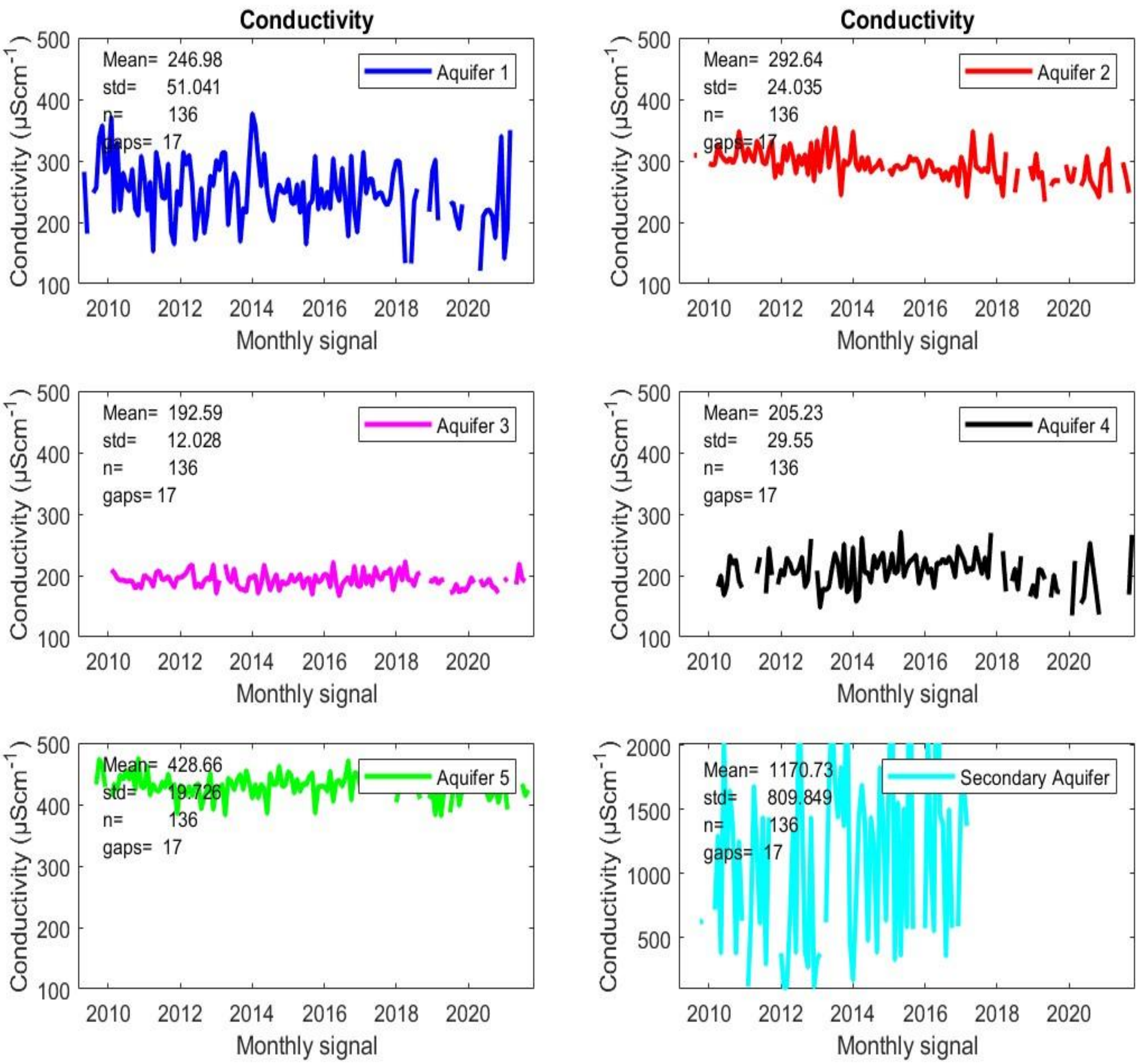


Figure 3-2 Conductivity Monthly Signal across various Aquifers.

3.5.2 pH

The data displayed on Figure 3.3 shows the monthly pH record as a monthly signal. The data appears well collected with only a few gaps. The pH appears to be generally cantered around 7 with standard deviations in each aquifer which is the correct-water pH for human consumption. The low standard deviations relative to the mean shows high precision of the pH statistic. There are signs of seasonal signal on the monthly data especially on aquifer 1 and 2. This could be linked to seasonal water budget because drier periods would increase alkalinity of the aquifer given the increase of rock mineral concentration that results from reduced fresh water.

3.5.3 TDS

According to Rusydi (2018), conductivity (EC) and total dissolved solids (TDS) are water quality parameters, useful in describing salinity quantity in water. Further stating that these two parameters are correlated and usually expressed by a simple equation: TDS = k EC (in 25°C) where k typically ranges from 0.55 to 0.90 depending on water composition, with k = 0.65 commonly used for natural waters (Rusydi, 2018). TDS values in the groundwater of Mauritius ranges between 110 and 746 mg/l (Fanny et al., 2020). Conductivity measurement is a direct field measurement using portable meters, while TDS determination requires laboratory analysis through gravimetric methods involving sample evaporation and residue weighing. Despite their different analytical approaches, both parameters are important for comprehensive water quality assessments.

Figure 3.4 presents the monthly Total Dissolved Solids (TDS) composite records for six aquifers over the period 2010–2020. Across the monitored aquifers, TDS values generally range between 90 and 250 mg/L, with a dataset-wide average of approximately 124 mg/L. Among the aquifers, Aquifer 3 exhibits the lowest mean TDS (97.09 mg/L) and the lowest variability (standard deviation = 6.676 mg/L), indicating relatively stable water quality conditions. In contrast, Aquifer 5 records the highest mean TDS (214.38 mg/L), yet maintains a narrow spread (standard deviation = 10.674 mg/L), suggesting a consistently more mineralized but stable hydro chemical profile. Aquifer 4 displays the highest number of missing values (gaps = 38), which may affect trend interpretation and model reliability. Notably, the secondary aquifer (Aquifer 6) stands out with exceptionally high TDS values, peaking above 1000 mg/L in several instances. The mean TDS in this aquifer is 587.41 mg/L, with a very high standard deviation of 398.17 mg/L, indicating extreme variability. This erratic signal deviates significantly from the hydro chemical norms of the other aquifers and raises reliability concerns. The extent of the variance suggests potential data quality issues, including instrumentation error, transcription mistakes, or sampling inconsistencies. As such, the signal from Aquifer 6 has been visually reviewed ("eyeballed") and excluded from further quantitative analysis, as it does not reliably reflect groundwater conditions.

Table 3-1 Calculations for Each Aquifer (Based on Figure 3.4)

Aquifer	Mean (mg/L)	Std Dev (mg/L)	CV (%)
Aquifer 1	124.21	25.256	20.33%
Aquifer 2	146.28	12.257	8.38%
Aquifer 3	97.09	6.676	6.88% (lowest CV)
Aquifer 4	102.97	14.713	14.29%
Aquifer 5	214.38	10.674	4.98% (very stable)
Aquifer 6 (Secondary)	587.41	398.166	67.79% (extremely high variability)

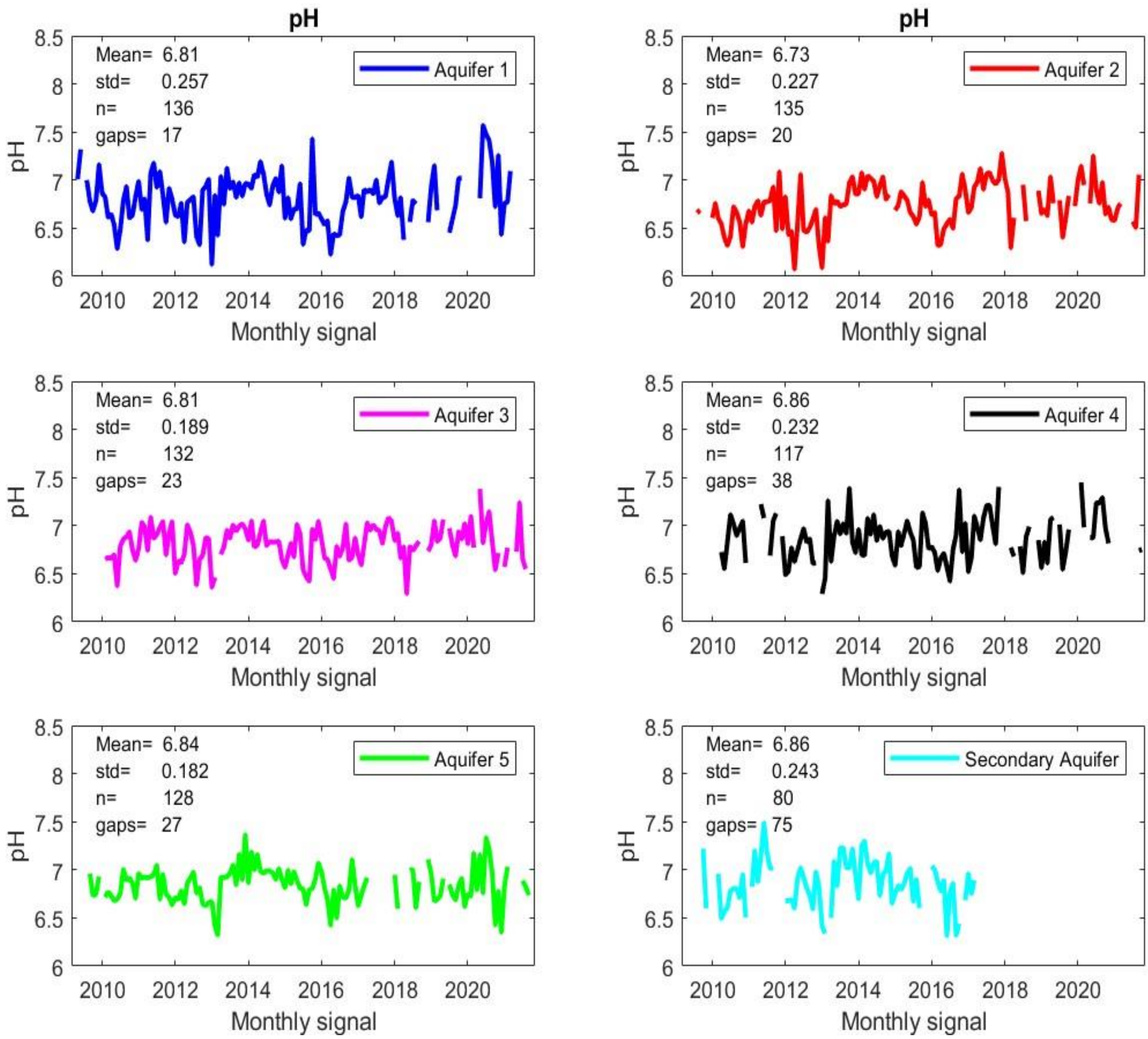


Figure 3-3 pH Monthly Signal across various Aquifers.

Aquifers 3 and 5 exhibit low coefficients of variation (CV) of less than 7%, suggesting a high level of consistency and minimal relative dispersion in their total dissolved solids (TDS) data. In contrast, Aquifer 6 records a CV of approximately 67.8%, an exceptionally high value that clearly indicates severe inconsistency in its TDS measurements, thereby validating the earlier decision to classify this dataset as unreliable. Aquifers 1 and 4 display moderate variability, reflecting a balance between stability and fluctuation in their TDS values. Meanwhile, Aquifer 2 demonstrates a relatively stable TDS signal, with a low CV despite having a slightly higher mean, indicating dependable data quality with only minor deviations

3.5.4 Chloride

The initial assessment of chloride also reveals gaps in observations. Chloride (Cl^{-}) is a chlorine anion compound and constitutes another dissolved salt nutrient. Chloride concentrations across the five aquifers range from 10 to 45 mg/L, with Aquifer 1 showing the highest mean concentration of 28.5 mg/L and Aquifer 3 exhibiting the lowest at 15.2 mg/L. All measured values remain well below the WHO drinking water guideline of 250 mg/L, indicating acceptable water quality from a chloride perspective. However, the analysis is limited by significant data gaps, particularly after 2018, which reduced the available dataset by approximately 40% across all aquifers and may affect the reliability of trend analysis for this parameter

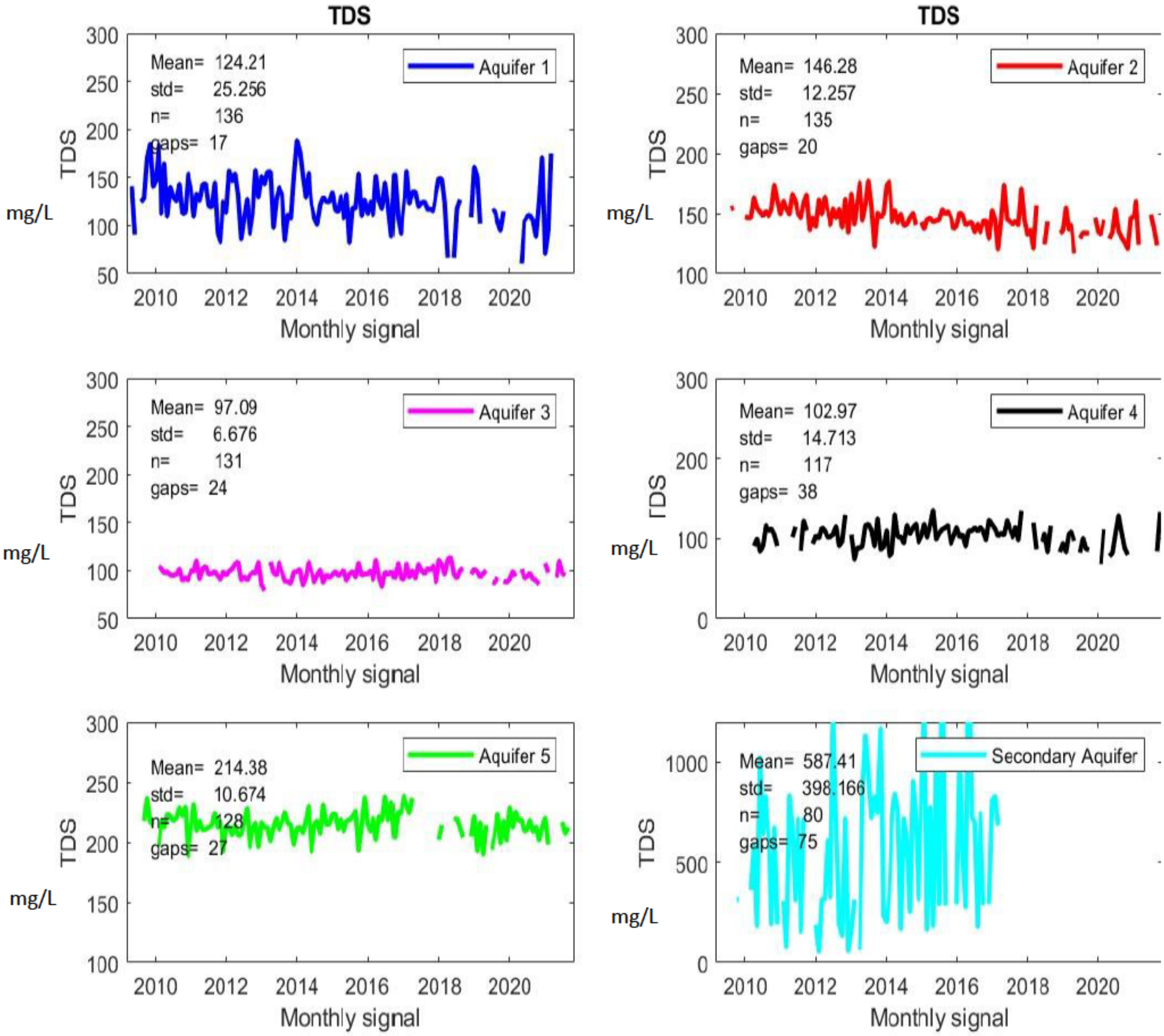


Figure 3-4 TDS Monthly Signal across various Aquifers.

3.5.5 Nitrate

Nitrate is heavily influenced by farming activity as fertilizers are mostly nitrogen based. Looking at Figure 3.6, I can now provide a more accurate revision based on the actual data shown. The nitrate signal indicates a well-collected data record with very few gaps across all Mauritius aquifers. Nitrate concentrations show distinct patterns across aquifers, with mean values of 4.08 mg/L (Aquifer 1), 3.47 mg/L (Aquifer 2), 1.59 mg/L (Aquifer 3), 2.39 mg/L (Aquifer 4), and 6.26 mg/L (Aquifer 5). Aquifer 3 shows the lowest mean concentration and exhibits relatively stable levels around 1.5-2.0 mg/L throughout the study period, while Aquifer 1 demonstrates the highest variability (standard deviation = 1.651 mg/L) with concentrations fluctuating between 1-8 mg/L. Aquifer 5 maintains the highest mean nitrate concentration at 6.26 mg/L but shows moderate variability (standard deviation = 0.296 mg/L), suggesting consistent but elevated nitrate inputs. All measured nitrate values remain well below the WHO drinking water guideline of 50 mg/L.

3.5.6 Sulphate

Due to the presence of the mineral gypsum, sulphate, which is the most abundant form of sulphur in water, is one of the dissolved nutrients (Sharma & Kumar, 2020). Sources can also be anthropogenic through mining and atmospheric deposition. It is therefore essential to analyse the trend behaviour across time to assess potential deterioration.

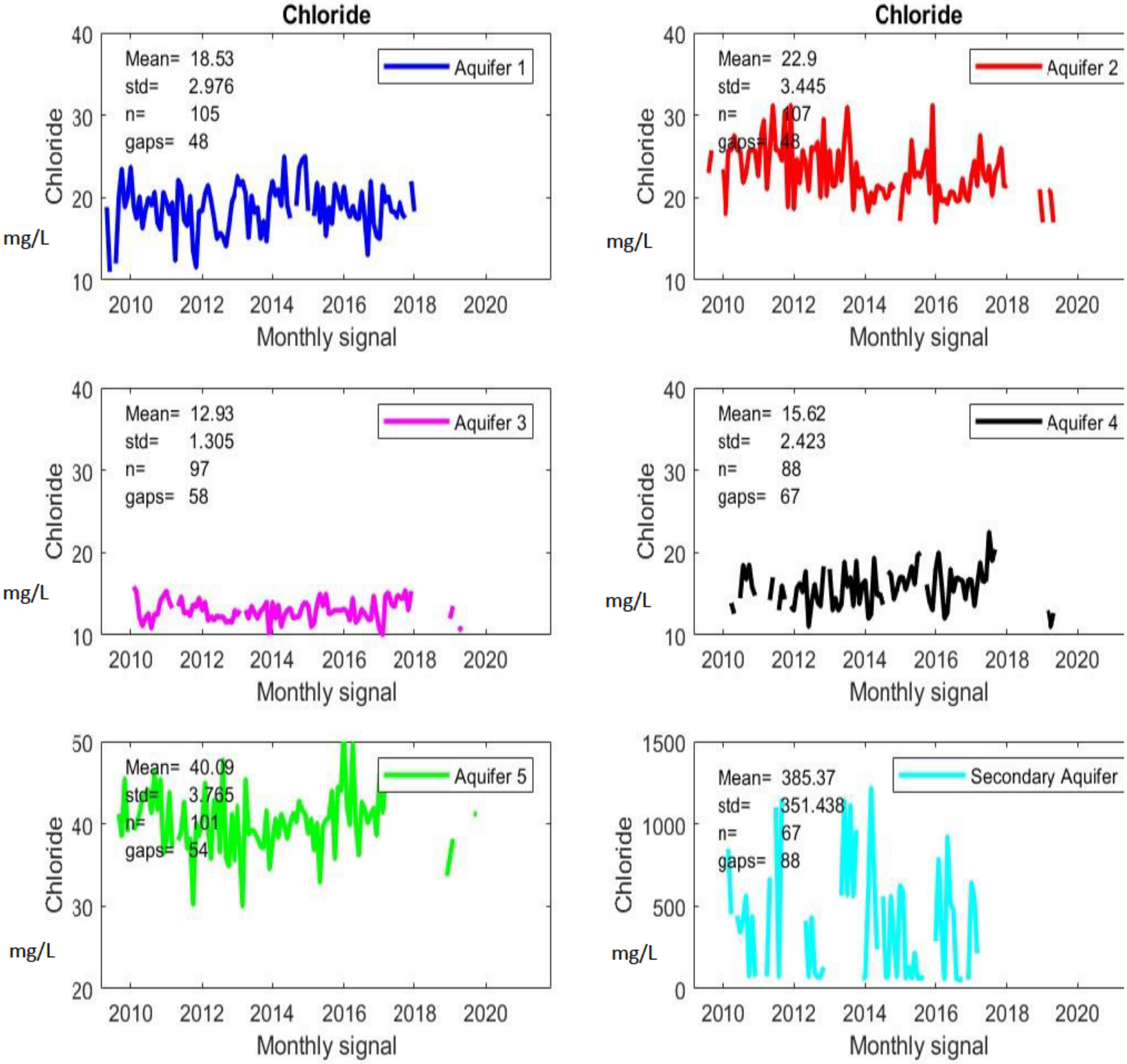


Figure 3-5 Chloride Monthly Signal (mg/L) across various Aquifers.

Sulphate concentrations across the five aquifers show distinct variations, as displayed in Figure 3.7. Aquifer 2 exhibits the highest mean sulphate concentration at 14.3 mg/L with high variability (standard deviation = 3.52 mg/L), showing concentrations ranging from 8-25 mg/L throughout the study period. Aquifer 5 demonstrates the second highest mean at 11.57 mg/L with moderate variability (standard deviation = 2.75 mg/L), while Aquifer 1 shows a mean of 8.92 mg/L with the highest variability (standard deviation = 4.43 mg/L), exhibiting fluctuations between 2-20 mg/L. Aquifers 3 and 4 maintain relatively low and stable sulphate levels with means of 2.56 mg/L and 4.52 mg/L respectively. All measured values remain well below typical drinking water guidelines, indicating acceptable water quality from a sulphate perspective.

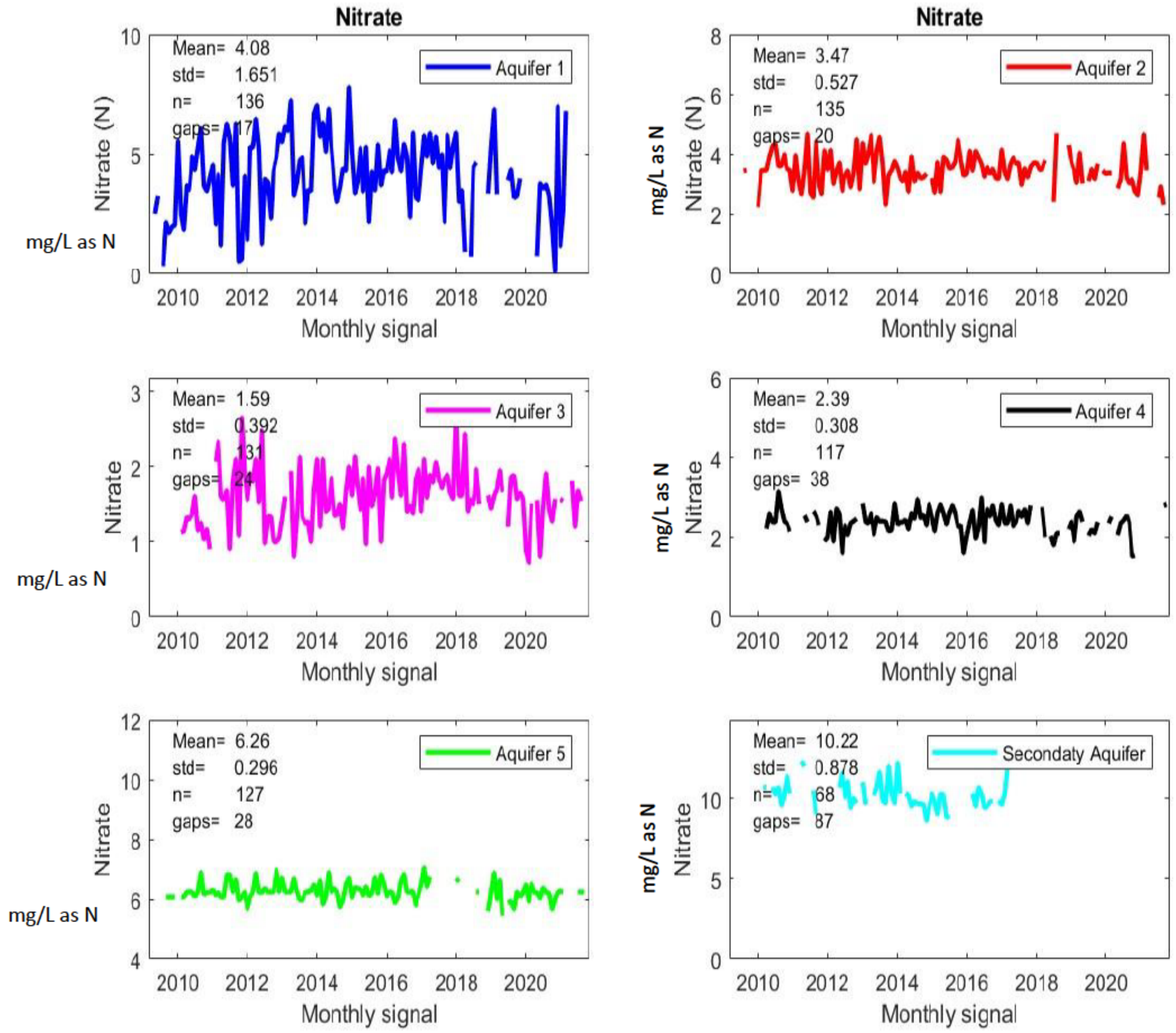


Figure 3-6 Nitrate Monthly Signal across various Aquifers.

3.5.7 Salinity

Salinity is a measure of the amount of dissolved salts in water. Groundwater aquifers are often the primary source of water for many communities around the world. However, salinity can significantly impact the quality and availability of this important resource. In this paper, we also look at what potentially precipitates salinity in groundwater in Mauritius. Groundwater salinity can be caused by various natural and human-induced factors. The most common natural cause of salinity in groundwater is the geological formation of the aquifer. Some rocks, such as limestone, have a higher salt content, and as water flows through them, it dissolves and carries salts into the aquifer. Additionally, saltwater intrusion from nearby coastal areas can also contribute to the salinity of groundwater aquifers.

Human activities can also lead to groundwater salinity. Agricultural practices, such as irrigation, can cause water to evaporate, leaving behind salts that eventually accumulate in the soil and groundwater. Similarly, excessive use of fertilizers and pesticides can increase the salt content of groundwater. Industrial processes, such as mining and oil and gas extraction, can also release salt into groundwater. Finally, poor waste management practices can lead to groundwater contamination, which can increase salinity levels.

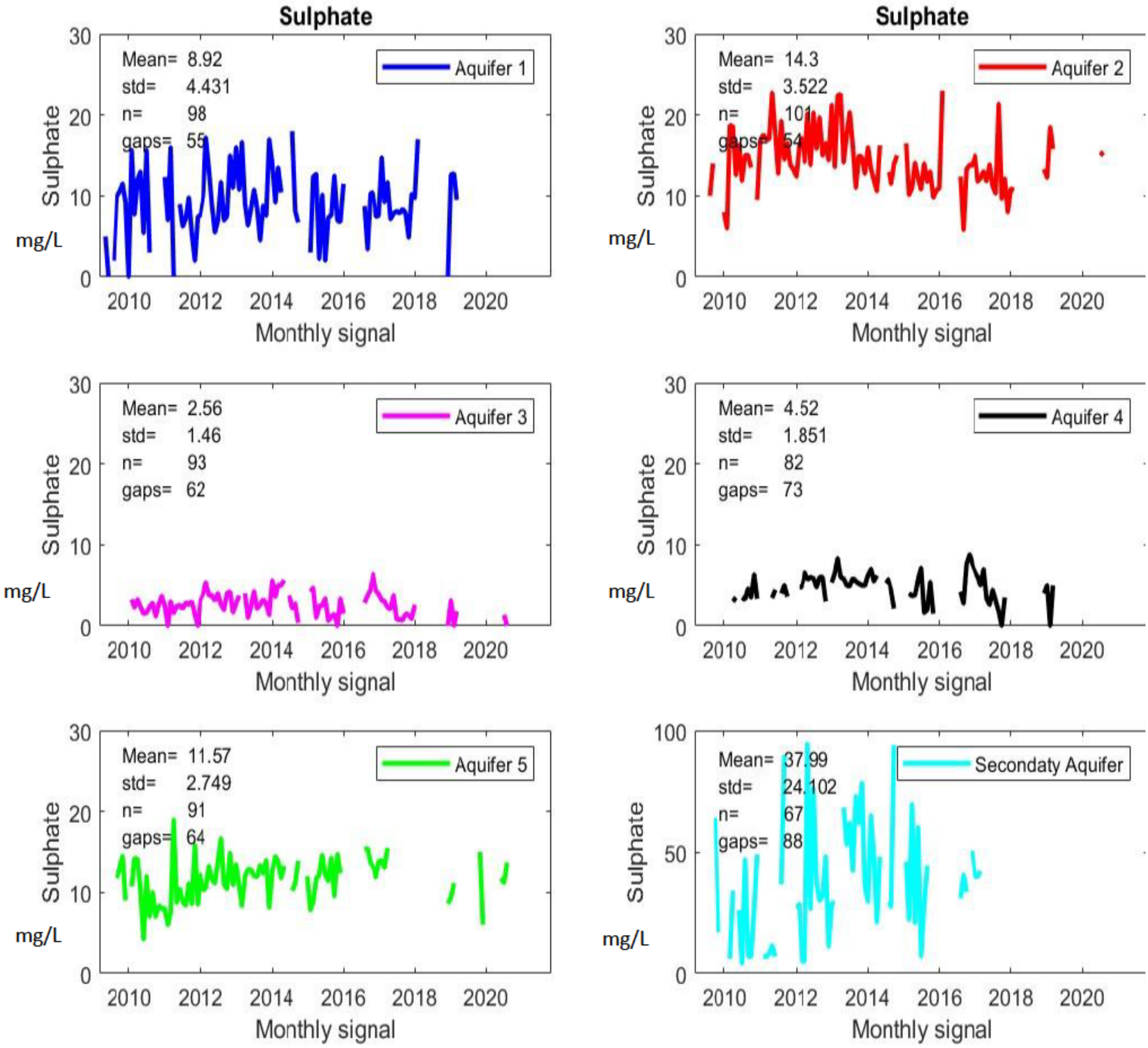


Figure 3-7 Sulphate Monthly Signal across various Aquifers.

The impacts of salinity on groundwater quality are significant. High salinity levels can make water unsuitable for drinking, irrigation, and other domestic or industrial purposes. In addition, the presence of certain salts, such as sodium chloride, can damage crops and harm the environment. Furthermore, groundwater salinity can affect the functioning of water treatment plants, increase the cost of water treatment and reducing its efficiency. As shown in Figure 3.8 salinity exhibits lower variability in aquifer 3 compared to the other aquifers. A pattern that resembles conductivity and chloride since these variables are related as mentioned before. Aquifer 5 has the highest mean salinity at 0.21 ppt while aquifer 3 has the lowest saltiness at0.09 ppt. Aquifer 4 has the highest number of months with no salinity observations.

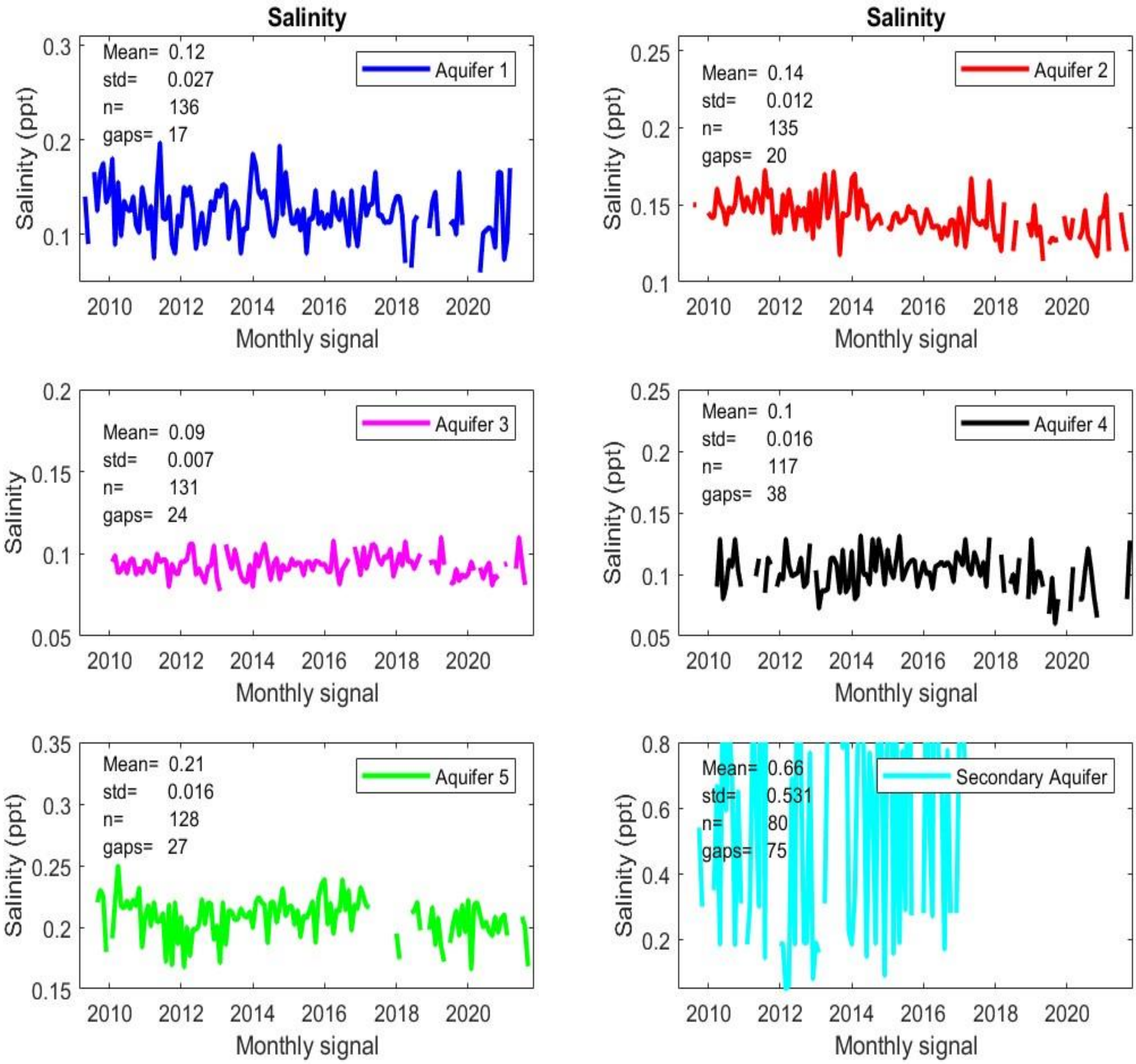


Figure 3-8 Salinity Monthly Signal across various Aquifers.

3.6 Trend analysis and hypothesis testing

Following the trend analysis methodology established in Chapter 1 (Section 1.2), linear regression models were applied to assess temporal changes in each water quality parameter across the five aquifers. Model validation confirmed that all regression assumptions were satisfied before proceeding with hypothesis testing at the 95% confidence level ($\alpha = 0.05$).

3.6.1 Conductivity hypothesis test

Model validation paves way for statistical analysis of the linear regression model. The regression statistics displayed in Table 3.2 shows the coefficients of variation of the displayed conductivity time-series shown in Figure 3.2 with additional details such as the standard error, t value and the p-values for each aquifer. The coefficient is the trend. The standard error is the sample adjusted standard deviation, and the p-value is the probability of success where success is the rejection of the null hypothesis. Therefore, hypothesis testing is part of this section where each aquifer regression was tested for change across time. If the change is significant based on the 95% confidence level, observed through the p-value, then that change is concluded to be statistically significant. Whereas a change denoted by p-values >0.05 is regarded as insignificant over this time period as it falls outside the 95% confidence level.

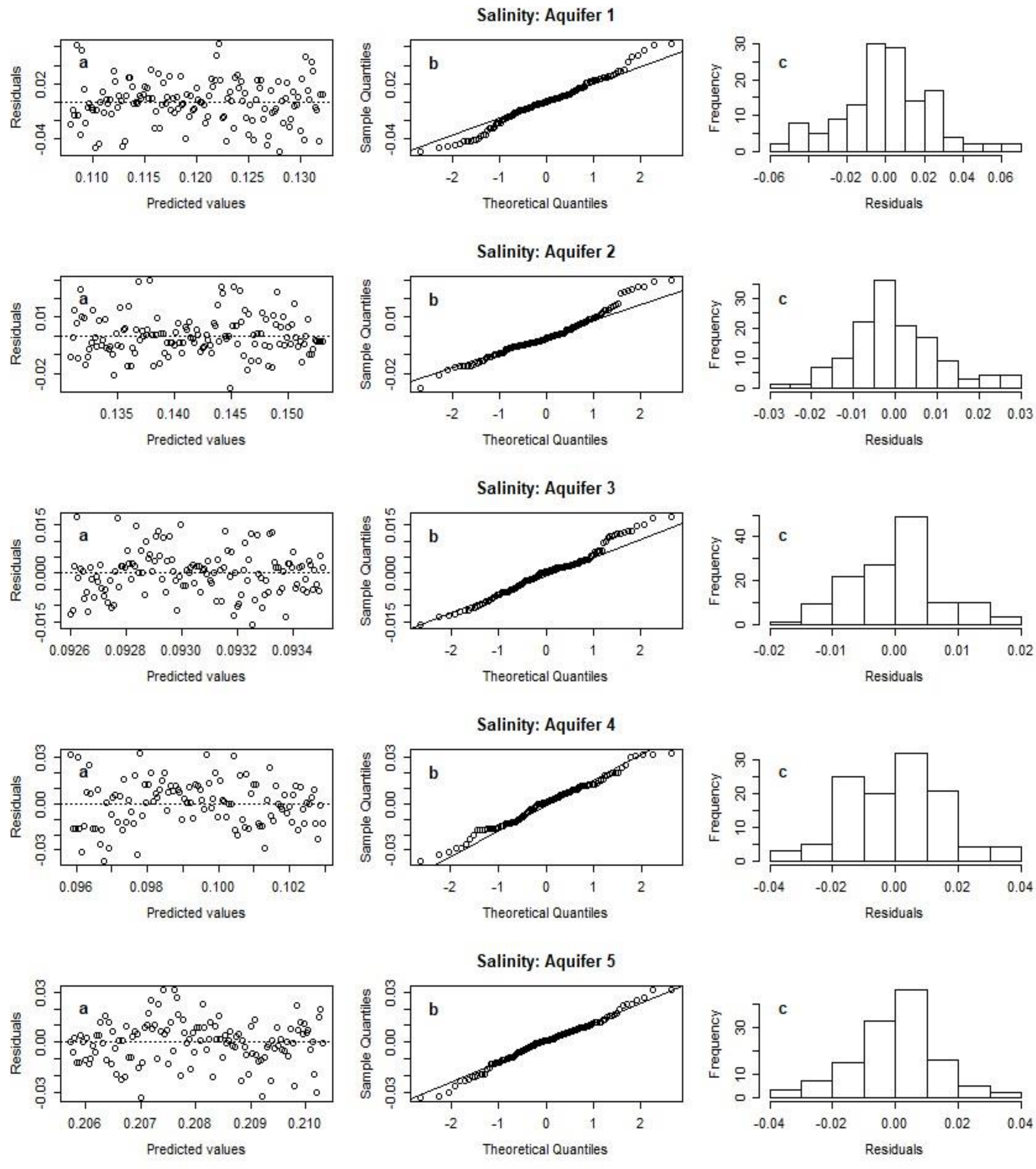


Figure 3-9 Salinity Model Validation Signal across 5 main Aquifers.

The conductivity regression model is given based on equation:

$$\beta(Conductivity) = \beta_0 + \beta_1(Months) + \epsilon_i \qquad (5)$$

The β(*Conductivity*) is the dependent variable (conductivity). The β_0 is the intercept, β_1 is the coefficient of variation and ϵ_i is the error term. It can be observed in Table 3.2 that aquifers 1,2,3 and 5 have significant change over the period of study with coefficients of -0.40, -0.34, -0.09 and -0.35 μS/cm per month respectively. The negative change in each case represents an improvement in conductivity (lowering of electrical conductivity and dissolved inorganic material ions) state of these aquifers across time. Aquifers 4 and 5 are also negative but are not significantly changing.

`Table 3-2 Summary of results from linear regression analysis of conductivity trends across aquifers.

Coefficients:	estimate	Std. Error	t value	Sig.level	
Aquifer1 (Intercept)	272.32	9.01	30.24	<0.001	***
Months	-0.40	0.11	-3.47	<0.001	***
Aquifer2 (Intercept)	317.43	4.69	67.74	<0.001	***
Months	-0.34	0.06	-5.68	<0.001	***
Aquifer3 (Intercept)	198.91	3.18	62.62	<0.001	***
Months	-0.09	0.04	-2.07	0.040	*
Aquifer4 (Intercept)	211.16	5.45	38.72	<0.001	***
Months	-0.09	0.08	-1.17	0.250	
Aquifer5 (Intercept)	452.08	8.78	51.51	<0.001	***
Months	-0.35	0.12	-2.96	0.003	**

*Significance levels: * p < 0.05, ** p < 0.01, *** p < 0.001.*

Table 3.1 shows the Summary of results of a linear regression model of conductivity displaying the coefficient of variation, standard error, t-value, p-value and the significance at a 95% confidence level.

$H_{0:\,\rho}$= 0 (There is no significant relationship between Conductivity and time (months))

$H_{1:}\rho \neq 0$ (There is a significant relationship between Conductivity and Months). *Significance level: α* = 0.05

In conclusion, the results shown in Table 3.1 indicate a p-value for aquifer 4 that is greater than α, and therefore, there is no sufficient evidence to reject the null hypothesis in that aquifer as it does not fall within the rejection region of the t-statistic. For the rest of the aquifers, we reject the null hypothesis and conclude that there is change in conductivity in the Mauritius aquifers over the period of study.

3.6.2 pH hypothesis test

Though not shown in this section, pH validation permits the establishment of the linear regression where the pH regression model is given based on equation:

$$\beta(pH) = \beta_0 + \beta_1(Months) + \epsilon_i \qquad (6)$$

The β (pH) is the dependent variable (pH). The β_0 is the intercept, β_1 is the coefficient of variation and ϵ_i is the error term. It can be observed in Table 3.3 that aquifers 2 and 5 have significant change over the period of study with coefficients of -0.09 and -0.35 per month respectively. On the other hand, Aquifers 1, 3 and 4 do not show signs of changing across time based on the significance levels (p-values). The intercept statistical readings are less important in the statistical reading in this particular case; hence they are not assessed. The pH is decreasing in the aquifers 2 and 5, which means they are becoming acidic over the 10-year period.

Table 3-3 Summary of results of a Linear Regression Model of pH displays

Coefficients:	estimate	Std. Error	t-value	Sig.level	
Aquifer1 (Intercept)	19.09	0.74	25.84	<0.001	***
Months	-0.004	0.12	-0.30	0.760	
Aquifer2 (Intercept)	29.09	1.23	23.74	<0.001	***
Months	-0.09	0.02	-4.41	<0.001	***
Aquifer3 (Intercept)	12.88	0.28	46.83	<0.001	***
Months	-0.002	0.01	0.46	0.650	
Aquifer4 (Intercept)	15.50	0.60	25.83	<0.001	***
Months	0.009	0.01	0.85	0.400	
Aquifer5 (Intercept)	43.13	1.23	35.20	<0.001	***
Months	-0.35	0.02	-2.48	0.020	*

Table 3.3 shows the Summary of results of a linear regression model of pH displaying the coefficient of variation, standard error, t-value, p value and the significance at a 95% confidence level.

$H_{0:\,\rho}= 0$ (There is no significant relationship between pH and Months) $H_{1:}\ \rho \neq 0$ (There is a significant relationship between pH and Months).

Significance level: $\alpha = 0.05$

In conclusion, the results shown in Table 3.3 indicate the p-value/significance level for Aquifers 1, 3 and 4 is greater than α, and therefore, the null hypothesis cannot be rejected for those aquifers as there is not enough evidence to reject it. For Aquifers 2 and 5, the null hypothesis is rejected since the p-value falls within the rejection region of the t-statistic, and the analysis concludes that there is significant change in pH in Aquifers 2 and 5 over the period of interest, while Aquifers 1, 3, and 4 show no statistically significant pH trends.

3.6.3 TDS hypothesis test

The computation of TDS linear regression is given based on equation:

$$\beta(TDS) = \beta_0 + \beta_1(Months) + \epsilon_i \qquad (7)$$

The TDS shown in Figure 3.4 is statistically analysed and summarised in Table 3.3 for the assessment of significance of change across time of this water quality parameter. The TDS appears to be significantly changing in Aquifers 1 and 2 only, based on their significance levels that are below 0.05 with coefficients of variation reading at -0.12 and -0.18 respectively. The Aquifers 3,4 and 5 do not change significantly as their significance levels are above 0.05 and coefficients of variation are -0.02, -0.05 and -0.28 respectively. All coefficients of variation are negative; however the ones that are significantly changing conclusively indicate a decline in TDS over the time series period.

$H_{0:\,\rho}= 0$ (There's no significant relationship between TDS and Months).

$H_{1:}\rho \neq 0$ (There is a significant relationship between TDS and Months).

Significance level: $\alpha = 0.05$

In conclusion, the results shown in Table 3.4 indicate the p-value for Aquifers 1 and 2 is greater than α, and therefore, the null hypothesis is not rejected for those aquifers as Table 3.4: Summary of results of a linear regression model of TDS displays the coefficient of variation, standard error, t-value, p value and the significance at a 95% confidence level.

Table 3-4 Summary of results of a Linear Regression Model of TDS

Coefficients:	β coefficient	Std. Error	t-value	Sig.level	
Aquifer1 (Intercept)	138.50	4.42	31.33	<0.001	***
Months	-0.12	0.06	-3.81	0.020	*
Aquifer2 (Intercept)	158.75	2.05	77.59	<0.001	***
Months	-0.18	0.03	-6.75	<0.001	***
Aquifer3 (Intercept)	99.55	1.69	59.03	<0.001	***
Months	-0.02	0.02	-1.05	0.290	
Aquifer4 (Intercept)	106.44	2.84	37.48	<0.001	***
Months	-0.05	0.04	-1.31	0.200	
Aquifer5 (Intercept)	227.73	4.67	48.79	<0.001	***
Months	-0.28	0.06	-2.62	0.090	

Significance levels: * p < 0.05, ** p < 0.01, *** p < 0.001.

For Aquifers 3, 4, and 5, there is not enough evidence to reject H_0 based on the 95% confidence level test, as their p-values (0.290, 0.200, and 0.090 respectively) are greater than $\alpha = 0.05$. Therefore, the null hypothesis cannot be rejected for these aquifers, indicating no statistically significant change in TDS over the study period. For Aquifers 1 and 2, the null hypothesis is rejected as their p-values (0.020 and <0.001 respectively) fall within the rejection region of the t-statistic, indicating significant decreasing trends in TDS concentrations over the period of interest.

3.6.4 Chloride hypothesis test

The computation of Chloride linear regression is given based on the following equation:

$$\beta(Chloride) = \beta_0 + \beta_1(Months) + \epsilon_i \qquad (8)$$

The chloride shown in Figure 3.5 is statistically analysed and summarised in Table 3.4 for the assessment of significance of change across time. The chloride appears to be significantly changing in Aquifer 2 only, based on the significance level that is below 0.05 with a coefficient of variation reading at -0.09. The Aquifers 1, 3, 4 and 5 do not change significantly as their significance levels are above 0.05 and coefficients of variation are -0.003, 0.002, 0.01 and -0.05 respectively.

$H_{0:\,\rho}= 0$ (There is no significant relationship between Chloride and Months).

$H_{1:}\rho \neq 0$ (There is a significant relationship between Chloride and Months).

Significance level: $\alpha = 0.05$

In conclusion, the results shown in Table 3.5 indicate the p-value for aquifer 2 is less than α, and therefore, the null hypothesis is not rejected for that aquifer as it does not fall within the rejection region of the t-statistic. For the rest of the aquifers, we reject the null hypothesis, and we conclude that there is change in chloride in Mauritius aquifers over the period of study.

Table 3-5 Summary of results of a Linear Regression Model of Chloride which displays the coefficient of variation, standard error, t-value, p-value and the significance at a 95% confidence level.

Coefficients:	estimate	Std. Error	t-value	Sig.level	
Aquifer1 (Intercept)	19.09	0.74	25.84	<0.001	***
Months	-0.003	0.01	-0.30	0.760	
Aquifer2 (Intercept)	29.09	1.23	23.74	<0.001	***
Months	-0.09	0.02	-4.41	<0.001	***
Aquifer3 (Intercept)	12.88	0.29	46.83	<0.001	***
Months	0.002	0.004	0.46	0.647	
Aquifer4 (Intercept)	15.51	0.60	25.83	<0.001	***
Months	0.01	0.01	0.85	0.400	
Aquifer5 (Intercept)	43.13	1.23	35.20	<0.001	***
Months	-0.05	0.02	-2.48	0.060	

3.6.5 Nitrate hypothesis test

The computation of nitrate linear regression is given based on the following equation:

$$\beta(Nitrate) = \beta_0 + \beta_1(Months) + \epsilon_i \qquad (9)$$

The nitrate shown in Figure 3.6 is statistically analysed and summarized in Table 3.6 for the assessment of significance of change across time. Based on the table of statistics, the nitrate true mean appears to be not changing across time. This is concluded based on the p-values that are all above the significance level 0.05.

Table 3-6 Summary of results of a Linear Regression Model of Nitrate which displays the coefficient of variation, standard error, t value, p-value and the significance at a 95% confidence level.

Coefficients:	estimate	Std. Error	t-value	Sig.level	
Aquifer1 (Intercept)	4.38	0.33	13.287	<0.001	***
Months	-0.003	0.004	-0.66	0.509	
Aquifer2 (Intercept)	3.34	0.16	21.004	<0.001	***
Months	0.002	0.002	0.78	0.439	
Aquifer3 (Intercept)	1.54	0.088	17.592	<0.001	***
Months	0.0001	0.001	0.83	0.409	
Aquifer4 (Intercept)	2.47	0.15	16.931	<0.001	***
Months	-0.002	0.002	-0.984	0.327	
Aquifer5 (Intercept)	5.92	0.26	23.19	<0.001	***
Months	0.002	0.003	0.67	0.505	

$H_{0:\ \rho}$= 0 (There's no significant relationship between pH and Months) $H_{1:}\ \rho \neq 0$ (There is a significant relationship between pH and Months); Significance level: α = *0.05*.

In conclusion, the results shown in Table 3.6 indicate the p-value for all aquifers is greater than *α*, and therefore, the null hypothesis cannot be rejected for all aquifers as it does not fall within the rejection region of the t-statistic for any of the aquifers.

3.6.6 Sulphate hypothesis test

The computation of sulphate linear regression is given based on the following equation:

$$\beta(Sulphate) = \beta_0 + \beta_1(Months) + \epsilon_i \qquad (10)$$

The sulphate shown in Figure 3.7 is statistically analysed and summarized in Table 3.7 for the assessment of significance of change across time. The chloride appears to be significantly changing in Aquifer 2 only similar to chloride, based on the significance level that is below 0.05 with a coefficient of variation reading at -0.04 mg/L per month. The Aquifers 1, 3, 4 and 5 do not change significantly as their significance levels are above 0.05 and coefficients of variation are -0.001, 0.011, -0.009 and -0.015 respectively.

Table 3-7 Summary of results of a Linear Regression Model of Sulphate which displays the coefficient of variation, standard error, t-value, p-value and the significance at a 95% confidence level.

Coefficients:	estimate	Std. Error	t-value	Sig.level	
Aquifer1 (Intercept)	9.15	0.93	9.84	<0.001	***
Months	-0.001	0.016	-0.085	0.933	
Aquifer2 (Intercept)	16.24	0.84	19.243	<0.001	***
Months	-0.04	0.014	-2.971	0.004	**
Aquifer3 (Intercept)	3.14	0.32	9.943	<0.001	***
Months	-0.011	0.006	-1.938	0.056	.
Aquifer4 (Intercept)	5.031	0.41	12.254	<0.001	***
Months	-0.009	0.008	-1.098	0.275	
Aquifer5 (Intercept)	10.90	0.61	17.75	<0.001	***
Months	0.015	0.011	1.37	0.174	

$H_{0:\,\rho}= 0$ (There's no significant relationship between pH and Months).

$H_{1:}\rho \neq 0$ (There is a significant relationship between pH and Months). Significance level: $\alpha = 0.05$.

In conclusion, the results shown in Table 3.6 indicate the p-value for aquifer 2 is less than α, and therefore, the null hypothesis is rejected for that aquifer as it falls within the rejection region of the t-statistic. For the rest of the aquifers, we fail to reject the null hypothesis, and we conclude that there is no change in sulphate in Mauritius aquifers over the period of interest.

3.6.7 Salinity hypothesis test

The computation of salinity linear regression is given based on the following equation:

$$\beta(Salinity) = \beta_0 + \beta_1(Months) + \epsilon_i \quad (11)$$

The salinity shown in Figure 3.8 is statistically analysed and summarized in Table 3.8 for the assessment of significance of change across time. The salinity appears to be significantly changing in Aquifer 1 and 2 only, based on the significance level that is below 0.05 with a coefficient of variation reading at -1.79×10^{-4} and -1.65×10^{-4} ppt/month respectively. The Aquifers 3, 4 and 5 do not change significantly as their significance levels are above 0.05.

Table 3-8 Summary of results of a Linear Regression Model of Salinity which displays the coefficient of variation, standard error, t-value, p-value and the significance at a 95% confidence level

Coefficients:	estimate	Std. Error	t-value	Sig.level	
Aquifer1 (Intercept)	1.32×10^{-1}	3.99×10^{-3}	33.17	<0.001	***
Months	-1.79×10^{-4}	5.02×10^{-5}	-3.56	<0.001	***
Aquifer2 (Intercept)	1.53×10^{-1}	1.82×10^{-3}	84.276	<0.001	***
Months	-1.65×10^{-4}	2.32×10^{-5}	-7.123	<0.001	***
Aquifer3 (Intercept)	9.35×10^{-2}	1.20×10^{-3}	78.003	<0.001	***
Months	-6.97×10^{-6}	1.58×10^{-5}	-0.442	0.659	
Aquifer4 (Intercept)	1.03×10^{-1}	2.77×10^{-3}	37.137	<0.001	***
Months	-6.27×10^{-5}	4.19×10^{-5}	-1.498	0.137	
Aquifer5 (Intercept)	2.10×10^{-1}	2.26×10^{-3}	93.221	<0.001	***
Months	-3.63×10^{-5}	3.06×10^{-5}	-1.187	0.238	

$H_{0:\ \rho}= 0$ (There's no significant relationship between pH and Months)

$H_{1:}\ \rho \neq 0$ (There is a significant relationship between pH and Months).

Significance level: $\alpha = 0.05$

In conclusion, the results shown in Table 3.8 indicate the *p*-value for Aquifer 1 and 2 is greater less than α, and therefore, the null hypothesis is rejected for these two aquifers as they fall within the rejection region of the *t*-statistic. For the rest of the aquifers, we fail to reject the null hypothesis, and we conclude that there is no change in salinity in Mauritius aquifers over the period of study.

3.7 Discussion

3.7.1 Interpretation of Groundwater Quality Trends

The comprehensive statistical analysis of groundwater quality parameters across Mauritius's five major aquifers from 2010 to 2021 reveals a complex pattern of water quality dynamics that has significant implications for water resource management in small island developing states. Tutmez et al. (2006) demonstrated that conductivity variations provide reliable indicators of groundwater quality evolution, supporting our methodology for trend detection. The predominant trend observed across multiple parameters indicates an overall improvement in groundwater quality, characterized by decreasing conductivity, total dissolved solids, and salinity levels in several aquifers. This finding contrasts with the deterioration patterns documented by Alghamdi et al. (2023) in arid coastal regions, where climate change impacts resulted in quality degradation, and challenges the expected deterioration patterns often associated with climate change impacts and anthropogenic pressures in coastal environments.

The statistically significant decreases in conductivity observed in Aquifers 1, 2, 3, and 5, with monthly reductions ranging from -0.09 to -0.40 μS/cm, suggest enhanced freshwater recharge or reduced saltwater intrusion over the study period. This improvement is particularly noteworthy given the vulnerable coastal location of these aquifers and the anticipated threats from sea-level rise documented in previous UNFCCC (2005) assessments. According to Al Dahaan et al. (2016), conductivity measurements provide accurate estimations of total dissolved solids and ionic strength, which corroborates our parallel findings of decreasing TDS in Aquifers 1 and 2, with coefficients of -0.12 and -0.18 mg/L per month respectively, indicating genuine improvements in water quality rather than measurement artifacts.

Similarly, the significant decreases in salinity observed in Aquifers 1 and 2, with monthly reductions of -1.79×10^{-4} and -1.65×10^{-4} ppt respectively, provide additional evidence for improved groundwater quality conditions. Nemčić-Jurec et al. (2022) found that effective management interventions could reverse degradation trends, which may explain the improvements observed in Mauritius despite the vulnerable coastal environment predicted by UNFCCC (2005) to be at particular risk from saltwater intrusion.

3.7.2 Aquifer-Specific Variations and Underlying Mechanisms

The heterogeneous response of different aquifers to temporal changes reflects the complex hydrogeological characteristics and varying anthropogenic pressures across Mauritius's groundwater systems. Mahapatra et al. (2012) emphasized the importance of local geological controls on groundwater quality variations, which aligns with our observations. Aquifer 3 consistently demonstrates the highest water quality across multiple parameters, exhibiting the lowest mean values for conductivity (~200 μS/cm), TDS (97.1 mg/L), and salinity (0.09 ppt), while maintaining stable conditions throughout the study period. The superior quality of Aquifer 3 is consistent with Fanny et al. (2020), who identified spatial variations in groundwater chemistry across Mauritius's aquifer systems and noted the influence of geological composition on water quality distribution. In contrast, Aquifer 5 shows the highest baseline concentrations for most parameters, including conductivity (~450 μS/cm), TDS (214 mg/L), and salinity (0.21 ppt), yet still demonstrates significant improving trends in conductivity. This pattern aligns with Jones et al. (2012), who documented typical water conductivity ranges from 0.01 to 1 S/m and noted that higher baseline values can still exhibit improvement trends under appropriate management conditions.

The concerning trend of increasing acidity observed in Aquifers 2 and 5, with pH decreasing at rates of -0.09 and -0.35 units per month respectively, represents a significant water quality concern that requires immediate attention. This acidification trend is particularly concerning given Saalidong et al. (2022)'s findings that pH changes can significantly affect the mobility of other contaminants and overall groundwater chemistry. The acidification contradicts the general improvement observed in other parameters and may indicate specific contamination sources. Sharma & Kumar (2020) documented similar sulphate-related acidification in certain hydrogeological settings, though they noted this typically occurs in conjunction with mining activities or specific geological formations.

3.7.3 Implications for Water Resource Management

The stable nitrate concentrations observed across all aquifers, with no statistically significant changes over the 11-year period, provide reassuring evidence that agricultural contamination pressures have remained relatively constant. This stability contrasts with global trends documented by Spalding & Exner (1993), who identified nitrate as the most widespread groundwater contaminant worldwide and typically associated with intensive agricultural practices. Given that Mauritius depends heavily on agriculture and Kowlesser (2018) documented the complex relationship between agricultural activities and groundwater recharge in small island states, this stability suggests effective nutrient management practices or natural attenuation processes. The mean nitrate concentrations ranging from 1.59 mg/L (Aquifer 3) to 6.26 mg/L (Aquifer 5) remain well below WHO drinking water guidelines of 50 mg/L (Mitchell & Frisbie, 2023), indicating acceptable water quality from a nitrate contamination perspective.

The parameter-specific changes observed in Aquifer 2, where chloride and sulphate show significant declining trends, may indicate successful remediation of point source contamination or changes in land use practices within the aquifer's recharge area. Kirchner et al. (2010) demonstrated that chloride serves as a conservative tracer in groundwater systems, making the observed decreases particularly significant as indicators of genuine water quality improvement rather than analytical artifacts. The improving conductivity and TDS trends support Rusydi (2018)'s assertion that these parameters provide reliable indicators for management effectiveness through their established correlation: TDS = k EC, where our observed coefficient ranges of 0.55 to 0.90 align with established literature values. However, the acidification trends in Aquifers 2 and 5 highlight the need for enhanced monitoring and targeted interventions to address specific contamination sources.

3.7.4 Limitations and Data Quality Considerations

Several limitations must be acknowledged when interpreting these findings, particularly in the context of Mahapatra et al. (2012)'s emphasis on the importance of comprehensive physico-chemical analysis for reliable water quality assessment. The significant reduction in chloride monitoring data after 2018, resulting in approximately 40% data loss across all aquifers, limits the reliability of trend analysis for this parameter and may affect the assessment of saltwater intrusion patterns, which UNFCCC (2005) identified as a critical concern for Small Island States. The exclusion of Aquifer 6 from formal analysis due to data quality concerns, while methodologically sound following Werkema (2002)'s guidelines for data reliability assessment, reduces the spatial coverage of the assessment and limits understanding of the complete groundwater system. The absence of charge balance error calculations in the original dataset represents a significant quality control limitation, as these calculations are essential for validating analytical results in hydro chemical studies. The monthly composite approach used to address daily data gaps, while necessary for trend analysis as recommended by Tutmez et al. (2006), may mask shorter-term variations that could be important for understanding aquifer responses to specific events such as cyclones, droughts, or contamination incidents that Nemčić-Jurec et al. (2022) identified as critical factors affecting groundwater quality in coastal environments.

3.7.5 Broader Context for Small Island Developing States

The findings from this study provide valuable insights for groundwater management in small island developing states facing similar challenges documented in UNFCCC (2005) assessments. The observed improvements in water quality parameters contradict expectations of widespread degradation due to climate change and development pressures, suggesting that effective management interventions can maintain or even improve groundwater quality in vulnerable coastal environments, consistent with Kowlesser (2018)'s findings on sustainable aquifer management in SIDS contexts.

The stability of nitrate levels despite agricultural activities demonstrates that sustainable groundwater management is achievable in SIDS contexts where agriculture and groundwater resources are closely linked, as documented by Spalding & Exner (1993). However, the acidification trends observed in specific aquifers highlight the need for comprehensive monitoring programs that can detect emerging contamination threats before they become widespread, aligning with Alghamdi et al. (2021)'s recommendations for integrated monitoring approaches in vulnerable environments.

The heterogeneous responses observed across different aquifers emphasize the importance of understanding local hydrogeological conditions and developing aquifer-specific management strategies, consistent with Devi Nowbuth et al. (2012)'s numerical modelling work that demonstrated significant variations in groundwater flow and contaminant transport across Mauritius's aquifer systems. This finding has particular relevance for SIDS, where limited resources often necessitate prioritization of management efforts based on aquifer vulnerability and importance.

The methodology employed in this study, combining long-term trend analysis with statistical hypothesis testing as recommended by Tutmez et al. (2006), provides a robust framework for groundwater quality assessment that could be adapted for other SIDS facing similar data limitations and management challenges. The identification of parameter-specific and aquifer-specific trends demonstrates the value of comprehensive monitoring programs for informed decision-making in water resource management, particularly relevant given that Mauritius depends on groundwater for 60% of its water supply as noted in the broader context of Small Island States' water security challenges (UNFCCC, 2005).

3.8 Conclusions and Recommendations

The analysis of groundwater quality in Mauritius over the 11-year period (2010-2021) has provided valuable insights into the dynamics of various water quality parameters. The assessment of salinity revealed significant changes in Aquifers 1 and 2, with a decrease in salinity levels over time. This finding is critical for understanding the evolving water quality in these aquifers and may have implications for both environmental and human uses. On the other hand, the analysis of nitrate levels indicated no significant change over the study period, suggesting a stable nitrate concentration in the groundwater. This information is crucial for evaluating potential environmental impacts and ensuring the safety of water for various purposes. The pH hypothesis test identified significant changes in Aquifers 2 and 5, indicating a decreasing trend in pH levels over the study period. This decline in pH suggests a shift towards acidity in these aquifers, highlighting the need for continued monitoring and potential remediation measures to maintain water quality standards.

Furthermore, the TDS analysis demonstrated significant changes in Aquifers 1 and 2, indicating a decline in Total Dissolved Solids (TDS) over the study period. While Aquifers 3, 4, and 5 did not show significant changes, the negative coefficients of variation for those aquifers suggest a general trend towards lower TDS levels. Conductivity is decreasing in all but one aquifer that is aquifer 4. On the other hand, chloride and sulphate are only changing in aquifer 2, in the direction of concentration decline. This could signal a good maintenance of the resource by the Mauritius authorities.

In summary, this in-depth analysis of multiple water quality parameters, including conductivity, pH, chloride, sulphate, salinity, nitrate, and TDS, contributes to a nuanced understanding of groundwater quality dynamics in Mauritius. The identified trends and variations underscore the importance of continuous monitoring and adaptive management strategies to ensure the preservation and sustainable use of this vital resource. Ongoing research and intervention efforts are crucial for addressing potential challenges and maintaining the health and safety of residents' dependent on groundwater sources.

3.9 References

Al Dahaan S, Al-Ansari N, Knutsson S 2016. Influence of groundwater hypothetical salts on electrical conductivity total dissolved solids. Engineering 8(11), 823–830.

Alghamdi A, Aly A, Ibrahim H 2021. Assessment of contamination by potentially toxic trace elements of groundwater and soil surrounding municipal soil waste landfill: A case study from Saudi Arabia. Journal of Geoscience 14, 350–362.

Alghamdi AG, Aly AA, Majrashi MA, Ibrahim HM 2023. Impact of climate change on hydrochemical properties and quality of groundwater for domestic and irrigation purposes in arid environment: A case study of Al-Baha region, Saudi Arabia. Environmental Earth Sciences 82(1), Article 39.

Devi Nowbuth M, Rambhojun P, Umrikar B 2012. Numerical groundwater flow and contaminant transport modelling of the southern aquifer, Mauritius. Earth Science India 5(3).

Fanny JOY, Matiatos I, Nowbuth M 2020. Application of hydrochemical and isotope techniques to investigate nitrogen pollution in Mauritius. Faculty of Engineering, University of Mauritius.

Jones AG, Fullea J, Evans RL, Muller MR 2012. Water in cratonic lithosphere: Calibrating laboratory-determined models of electrical conductivity of mantle minerals using geophysical and petrological observations. Geochemistry, Geophysics, Geosystems 13(6).

Kirchner JW, Tetzlaff D, Soulsby C 2010. Comparing chloride and water isotopes as hydrological tracers in two Scottish catchments. Hydrological Processes 24(12), 1631–1645.

Kowlesser A 2018. Sustainable aquifer management in small island developing states: A case study of Mauritius.

Mahapatra S, Sahu M, Patel R, Panda BN 2012. Prediction of water quality using principal component analysis. Water Quality, Exposure and Health 4(2), 93–104.

Mitchell EJ, Frisbie SH 2023. A comprehensive survey and analysis of international drinking water regulations for inorganic chemicals with comparisons to the World Health Organization's drinking-water guidelines. PLOS ONE 18(11), Article e0287937.

Nemčić-Jurec J, Ruk D, Oreščanin V, Kovač I, Ujević Bošnjak M, Kinsela AS 2022. Groundwater contamination in public water supply wells: Risk assessment, evaluation of trends and impact of rainfall on groundwater quality. Applied Water Science 12(7), Article 172.

Rusydi AF 2018. Correlation between conductivity and total dissolved solid in various type of water: A review. IOP Conference Series: Earth and Environmental Science 118, Article 012019.

Saalidong BM, Aram SA, Otu S, Lartey PO 2022. Examining the dynamics of the relationship between water pH and other water quality parameters in ground and surface water systems. PLOS ONE 17(1), Article e0262117.

Sharma M, Kumar M 2020. Sulphate contamination in groundwater and its remediation: An overview. Environmental Monitoring and Assessment 192, 1–10.

Spalding RF, Exner ME 1993. Occurrence of nitrate in groundwater—a review. Journal of Environmental Quality 22(3), 392–402.

Tutmez B, Hatipoglu Z, Kaymak U 2006. Modelling electrical conductivity of groundwater using an adaptive neuro-fuzzy inference system. Computers & Geosciences 32(4), 421–433.

UNFCCC 2005. Climate change, small island developing states. Climate Change Secretariat Bonn.

Werkema DD 2002. Geoelectrical response of an aged LNAPL plume: Implications for monitoring natural attenuation. Unpublished doctoral dissertation, Western Michigan University.

3.9 Data Availability

The complete water quality dataset used in this analysis is available in Appendix A.

Master list of Water
Quality Data (all 6 ac

CHAPTER 4: CLIMATE VARIABILITY IMPACT ON GROUNDWATER QUALITY IN SMALL ISLAND DEVELOPING STATES: MAURITIUS ISLAND AS A CASE STUDY

Varsha Gungoa* and Seifu Kebede

*Department of Hydrological, Centre for Water Resources Research, University of KwaZulu Natal, Pietermaritzburg, South Africa

4.1 Abstract

This study investigates the impact of climate variability on groundwater quality in Mauritius. This is achieved by analysing the physical and chemical water quality of the five main aquifers over eleven years. Temporal variations in water quality properties were compared to the Standardised Precipitation Index (SPI), Dry Spells, the Standardised Evapotranspiration Index (SPEI), and other climate variables to gain insights into how precipitation controls groundwater quality. The results reveal that the SPI and the SPEI correlate minimally with water quality indicators. Sulphate is the only water quality indicator that showed correlations above 0.4 in aquifers 2 and 3 against a 12-month SPI. Sulphate, alongside chloride, showed "notable correlation," a concept defined in this paper to accommodate correlations that fall above 0.3 when assessed against global climate modes El Niño-Southern Oscillation (ENSO) and Antarctic Oscillation (AAO), respectively. These results signify that sulphate is the most sensitive water quality indicator to water quantity changes, notwithstanding the modes correlations. Heavy storms occurring during cyclones impact groundwater quality with respect to conductivity, TDS, salinity, and nitrate, although this could not be statistically tested given the lack of water quality indicators collected during the storm days. Therefore, the conclusion is made based on a single storm event, which presents significant limitations in terms of statistical representativeness and generalizability. Drawing robust conclusions from one storm event is methodologically insufficient, as storm impacts can vary considerably based on storm intensity, duration, seasonal timing, antecedent groundwater conditions, and local hydrogeological characteristics. This finding should be considered preliminary and requires validation through analysis of multiple storm events to establish statistically meaningful patterns. The study revealed that individual correlations between climate indices and water quality variables are present but weak. However, the long-term trend in water quality is visible.

Keywords: Groundwater Quality, Precipitation, Drought Indices, Climate Change, Cyclones

4.2 Introduction

The contamination of freshwater resources is a global concern. According to the World Health Organization (WHO), waterborne illness has been the leading cause of death worldwide, making water resource management a top priority. Studies have shown that groundwater is increasingly being tapped for drinking water supplies, partly because of the growing scarcity of water resources and also because groundwater is preferred as a source of "clean" drinking water, which is particularly the case in Mauritius Island. There are various factors that can cause groundwater contamination through both natural and anthropogenic factors. Geogenic contamination of groundwater may result from the geochemical characteristics of the aquifer material, including high concentrations of the contaminant within the rock matrix.

Mauritius is a 2,040-square-kilometre Small Island Developing State in the south-east of the Indian Ocean with a population of slightly above a million people. According to Devi et al. (2012), 50% of the total domestic water consumption in Mauritius is sourced from groundwater resources. The groundwater degradation in Mauritius is a critical challenge, given the level of dependency on groundwater. Therefore, the monitoring of groundwater quality is of high importance. The Water Quality Index (WQI) assessment conducted in the northern aquifer revealed that the aquifer was in good water quality condition (Gungoa, 2016). (Gungoa, 2016) further finds the state of water quality in Mauritius has been determined for one aquifer region located in the north of the country. However, an elevation in nitrate was also noted to be threatening the state of this WQI score. This paper seeks to revisit all the water quality indicators and evaluate their change in relation to perceived predictor variables such as drought indicators and climate variability modes across the entire island.

(Sarker, 2022) stated that, "Climatology and meteorology are closely connected, however have different time scales." This is a point considered in this paper as the desire to make it comprehensive led to assessments of both large-scale climate models and storm events. Climate models are climatological while storm events are meteorological, and both contained potential answers to the aquifer recharge rates and overall water quality signals. When considering climate variability which (Sarker, 2022) describes as the deviation of climatic characteristics from the norm, El Niño–Southern Oscillation (ENSO), Antarctic Oscillation (AAO), Indian Ocean Dipole (IOD), and the Southern Oscillation Index (SOI) were selected as the climate variability modes to be considered against groundwater quality to gain an understanding of the climate impact on the groundwater.

Climate change has significant impacts on groundwater resources in Small Island Developing States (SIDS). Groundwater quality studies in relation to climate variability are very important in SIDS because of the risk of water quality changes in response to these climate variables and the large dependence on groundwater for water supply (Thomas et al., 2020); 90% of the SIDS are in the tropics. Many are seasonally affected by extreme weather events, including tropical storms, cyclones, and hurricanes. Their weather patterns are also characterized by climate variability, droughts, and flooding. El Niño Southern Oscillation (ENSO) events also produce dramatic changes in rainfall, rising sea levels and other weather-related events (UNFCCC, 2005). As sea levels rise, saltwater intrusion becomes a significant concern for groundwater resources (Thomas et al., 2020). Sea-level rise, storms, and changes in precipitation have affected these sources, leading to further stress on freshwater availability (Thomas et al., 2020). It is important to note that the specific impacts of climate variability on groundwater in SIDS can vary based on the geographical location, hydrogeological characteristics, and local climatic conditions of each island. Therefore, it is essential to conduct detailed studies and assessments specific to each island to fully understand the local context and develop targeted adaptation measures (Thomas et al., 2020). The relationship between groundwater and rainfall parameters such as drought indicators and climate variability modes has received little attention in the Island of Mauritius. This is potentially due to the limited nature of the long-term time-series data on water quality in this location as it is generally the case globally.

In the 20th century, the frequency of tropical cyclones in the vicinity of Mauritius has increased with a relative fall in intensity over the years, resulting in increased vulnerability for the communities exposed to these high occurrences of low- or average-intensity extreme events (Garnier and Desarthe, 2013). A significant increase in the frequency and intensity of other extreme weather events, including floods and droughts, has been reported over the years on the island (Chacowry et al., 2018; Seebocus et al., 2021). Additionally, Mauritius has experienced a relative rise in sea level of 4–6 mm per year over the past 30 years, corresponding to an increase of 2–3 times higher than the global average (Doorga, 2022). However, preparedness for scenarios would necessitate further understanding of the temporal evolution of climate impacts on the water quality on the island. The tropical climate of Mauritius provides an ideal case study, with potentially insightful results on how groundwater is vulnerable in Small Island Developing States due to the impacts of climate change.

The study is based on the five main Mauritius aquifers shown in Figure 4.1. The objective was to analyse the impacts of climate variability on groundwater over the period of 2010–2021. Correlation analysis between the various water quality variables and the climate variables has been used as the linkage between climate and water quality. The data used in this study are obtained through different sources based on the data type. The data have been processed before performing the relationship analysis. The first and most primary dataset used is the in-situ borehole data, which are obtained from the Central Water Authority (CWA), from a total of 63 boreholes across the Island. The Central Water Authority monitors groundwater quality on a daily basis.

4.3 Materials and methods

4.3.1 Data acquisition and preparation

4.3.1.1 In situ groundwater quality data

This study utilizes an 11-year dataset (2010-2021) of monthly groundwater quality parameters, including pH, conductivity, TDS, salinity, chloride, sulphate, and nitrate, collected by the Central Water Authority (CWA). While the dataset contains some temporal gaps, particularly in chloride monitoring after 2018, it represents one of the longest continuous water quality monitoring records available for Mauritius. Originally, the water quality data were collected daily but were time-averaged to monthly composites to reduce temporal gaps and ensure temporal consistency with climate data. Data quality assessment revealed significant anomalies in Aquifer 6, with electrical conductivity, chloride, and TDS values exceeding expected ranges for basaltic aquifers. These anomalies, likely resulting from equipment malfunction, calibration errors, or data entry mistakes, led to the exclusion of Aquifer 6 from formal analysis to maintain dataset integrity. Originally, the water quality data were collected daily but were time-averaged to monthly composites to reduce temporal gaps. Monthly averaging was performed by calculating the arithmetic mean of all available daily measurements within each calendar month for each parameter at each borehole location. This temporal aggregation approach follows standard practices in hydrogeological time series analysis (Hirsch et al., 1982; Helsel & Hirsch, 2002) and helps minimize the impact of short-term variability and data gaps while preserving long-term trends. For months with fewer than 15 daily observations, the monthly average was still calculated but flagged for quality assessment. Months with fewer than 5 observations were excluded from the analysis to maintain data integrity.

Although the water quality data are collected and managed by the CWA at a borehole level, visualized in Figure 4.1, this study spatially averages the borehole groundwater quality data and assesses it at the aquifer level, rather than using discrete borehole samples. Spatial averaging was performed by calculating the arithmetic mean of monthly values from all functioning boreholes within each aquifer boundary, weighted equally regardless of borehole depth or pumping rate. This spatial aggregation approach follows established methods for aquifer-scale water quality assessment (Freeze & Cherry, 1979; Anderson & Woessner, 1992). This approach reduces noise and condenses independent spatial parameters to five main aquifers, which is also reflected in Figure 1, which displays both aquifers and boreholes for a comprehensive overview.

4.3.2 Theoretical Framework and Study Approach

Theoretically, aquifers are recharged under wetter conditions where SPI and SPEI indices are high, wet spells are prevalent, and cyclones frequently lead to more dilute water chemistry and washing of polluted surface waters to groundwaters. Conversely, groundwater recharge is limited during low SPEI and SPI indices and when dry spells are predominant, leading to higher ionic contents in the water. The high rainfall during cyclones is compared with the groundwater quality water parameters collected around the same time. The aim was to illustrate whether during a cyclone event, the ground water chemical, and physical state is affected or not.

According to UNFCCC, SIDS have been recognized as being the most vulnerable to the impacts of climate change. Due to the geographic location of SIDS and the influences of oceanic circulation systems, natural precipitation varies from year to year, leading to various forms of extreme weather events, such as droughts, floods, and cyclones. Rainwater is the main source of water supply in SIDS and is highly influenced by rainfall patterns and extreme weather events. Changes in rainfall precipitation coupled with changes in El Niño intensity and frequency can put additional stress on water availability and quality in SIDS (UNFCCC, 2005).

4.4 Rainfall data

The rainfall data is crucial for this study as it is used to compute drought indicators. These indicators are then statistically tested against the groundwater quality data to produce correlation coefficients and other indicative statistics. The rainfall data have been obtained from the ERA-5 dataset, provided by the Copernicus Climate Data Store, which offers hourly and monthly average rainfall records from 1979 to the present (Hersbach et al., 2020). ERA-5 is a platform for high-resolution reanalysis data with a spatial resolution of 0.25° × 0.25°. The data were accessed via an open-source API and downloaded as monthly average NetCDF files. Monthly rainfall frequency was chosen to match the time frequency of the borehole groundwater quality data as this would allow for correlation assessment.

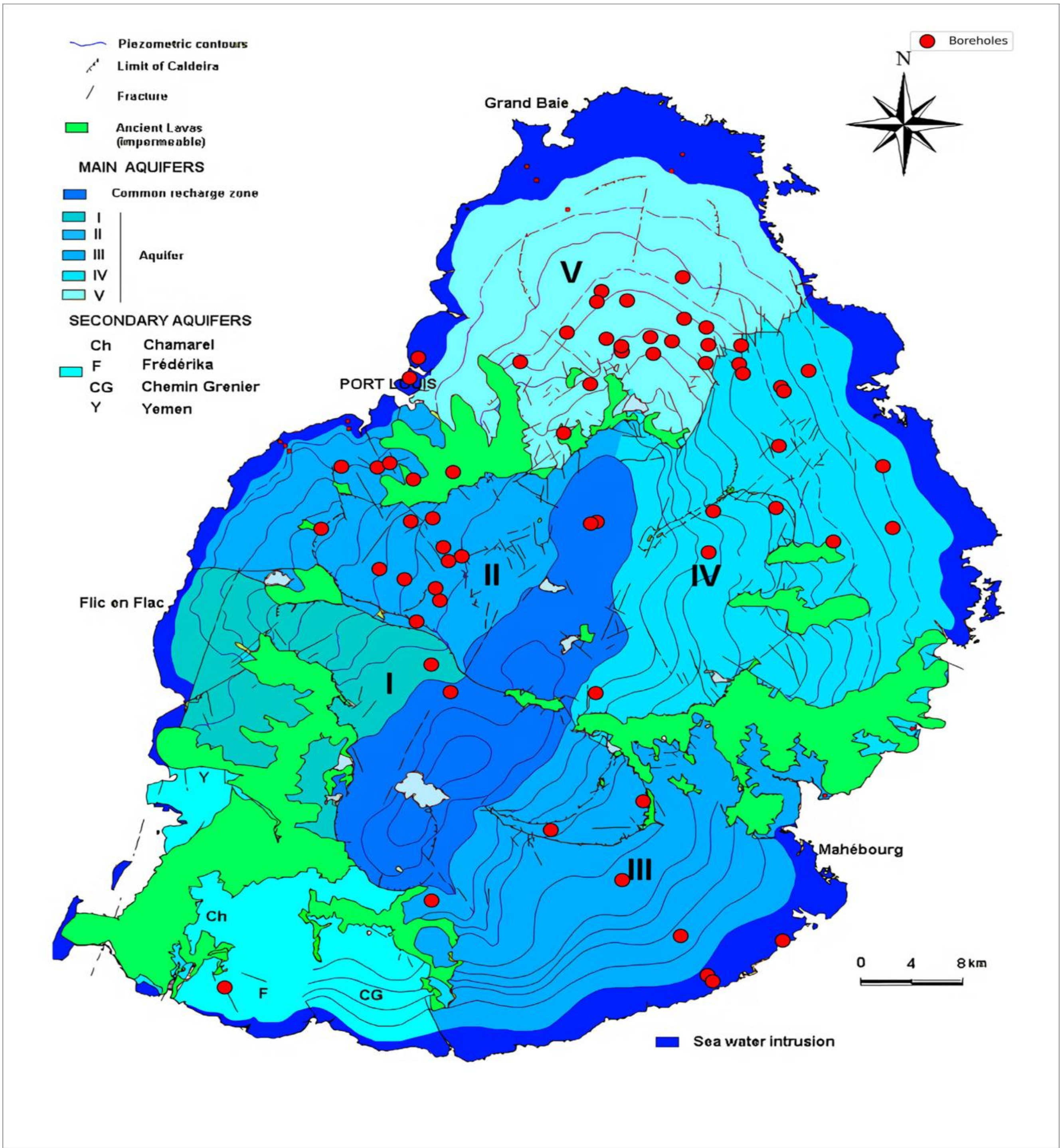


Figure 4-1 Five main Aquifers of Mauritius Island: The Secondary Aquifers (Chamarel, Frederika, Chemin Grenier, and Yemen) in the South West are excluded from this study due to their lack of continuous data record. This illustration figure is courtesy of Devi Nowbuth et al., (2012).

The rainfall data are crucial for this study as they are used to compute drought indicators. Several global reanalysis datasets were considered for this analysis, including:

- ERA5 (ECMWF): 0.25° × 0.25° resolution, 1979-present
- MERRA-2 (NASA): ~50 km resolution, 1980-present

- JRA-55 (JMA): ~55 km resolution, 1958-present
- CFSR/CFSv2 (NOAA): ~38 km resolution, 1979-present

ERA5 was selected based on its superior temporal resolution (hourly data), comprehensive variable coverage, and established validation for Southern Hemisphere applications (Hersbach et al., 2020). However, it should be noted that the 0.25° × 0.25° spatial resolution (~28 km) presents limitations for small island studies, as Mauritius spans only approximately 65 km east-west and 45 km north-south. This resolution may inadequately capture local precipitation variability and spatial gradients across the island, potentially affecting the strength of observed correlations between climate indices and groundwater parameters.

Alternative higher-resolution datasets such as station-based observations from Mauritius Meteorological Services were considered but were not available for the complete study period (2010-2021) with sufficient spatial coverage. Future studies would benefit from incorporating multiple reanalysis products or higher-resolution regional climate models to assess the sensitivity of results to precipitation data resolution.

4.5 Methods

4.5.1 Standardized precipitation index

The SPI computed in Equation (1) is a statistical, meteorological tool used to study droughts and wet periods. According to (Guide et al., 2012) and (Svoboda et al., 2012), the SPI tool was developed by McKee et al., (1993). It was developed to estimate droughts at a point in time over a region in relation to its historical context (the climate). (McKee et al., 1993) proposed this indicator as a definition of drought, which could serve as a versatile tool in drought monitoring and analysis. The SPI is currently a widely used tool in agriculture, hydrology, and climatology across the world. The SPI is also highly regarded and recommended by the WMO as a tool for all nations to use to analyze drought. SPI is generated based on the following equation:

$$SPI_{ijk} = \frac{P_{ijk} - \bar{P}_{ij}}{\theta_{ij}} \quad (1)$$

P_{ij} refers to precipitation with ij subscript referring to the latitude and longitude geographical location in the study of interest. $\bar{P}_{ij}$ refers to average precipitation, while θ_{ij} refers to the standard deviation of the rainfall time series with time (months) represented by the kth term. (Paulo et al., 2003) performed a detailed derivation of the above equation.

4.5.2 Standardized precipitation evapotranspiration index

The SPEI is computed in a similar way as the SPI; however, for the SPEI, the analysis takes an additional parameter, the surface temperature. The surface temperature is used for calculating the potential evapotranspiration rate, which is considered a critical factor in water balance assessments, particularly in vegetated environments where plant transpiration significantly contributes to total water loss.. The SPEI has been considered for this paper as it is known to usually predict with an elevated level of precision compared to the SPI in vegetation-covered environments. The evapotranspiration is the parameter considered on the computation of SPEI. The SPEI is quantified based on the following steps:

1. Computation of the potential evapotranspiration.
2. Determination of the deficit or surplus water budget based on the difference of precipitation and evapotranspiration.
3. Normalization of the water balance of the log-logistic probability to express the SPEI series (Potop and Možný, 2011). The detailed computation of the SPEI involves what is called the Hargreaves' method and is detailed in (Hargreaves and Samani, 1985).

The SPEI and SPI can further be classified into the table categories depicted in Table 4.1, which each demonstrates the severity of the drought indicator in question. The value depicted in the table represents the number of standard deviations from the mean represented by each drought indicator.

4.5.3 Dry spells

The dry spells are periods of extended, several dry consecutive days. The dry spells represent days of little to no precipitation and periods of near-zero recharge to the aquifers. In this study, a "dry spell" is defined as a period of 7 or more days in a row that each received 5 mm of rainfall or less. This definition of a dry spell is given as an assumption as there is no universally agreed-upon definition that quantitatively defines a dry spell.

4.6 Climate oscillations and synoptic scale features

4.6.1 Large-scale oscillation indices

The Southern Oscillation Index (SOI), otherwise known as the El Niño–Southern Oscillation (ENSO), is a large-scale climatological feature that influences rainfall regimes through sea surface temperatures (SST) anomalies that support vertical fluxes. The SOI is obtained from the National Centers for

Environmental Information (NCEI) online data repository. The Antarctic Oscillation index (AAO) otherwise also known as (AO) conversely is driven by sea-level pressure (SLP) dipole located in the Southern Ocean and mid-latitudes (Gong & Wang, 1999). These SLPs vary over the years, and they are multi-annual or decadal scale oscillations similar to the SOI. During periods in which the higher SLPs are located further south, the AAO is positive, but when these SLPs weaken near Antarctica, this represents periods of low sea-ice expansion and thus a negative AAO period (Jevrejeva et al., 2003).

The Indian Ocean Dipole Index (IOD) similar to the AAO is driven by a dipole of SLPs. According to Ashok et al., (2004), the IOD is a phenomenon that occurs inter-annually due to ocean and atmosphere coupled dynamics. This phenomenon is characterized by warmer SSTs on the west of the basin or lower pressures, while simultaneously cooler SSTs or higher pressures on the east are observed. This arrangement of the atmospheric pressures is called a dipole. These data were obtained from the National Oceanic and Atmospheric Administration Physical Sciences Laboratory and at the Global Climate Observing System (GCOS) Working Group on Surface Pressure Time series Data NOAA Physical Sciences Laboratory.

Table 4-1The SPI and SPEI Table describes the meaning of the SPI Anomaly Index

SPI or SPEI value	Category
2.00>	Extremely moist
1.50 to 1.99	Severely moist
1.00 to 1.49	Moderately moist
-0.99 to 0.99	Near normal
-1.00 to -1.49	Moderately dry
-1.50 to -1.99	Severely dry
-2.00 <	Extremely dry

(Source: McKee et al., 1993).

4.6.2 Tropical cyclones

Tropical cyclones are storms formed in areas with a tropical climate located between 10° and 20° North or South Latitudes. Mauritius Island being located in the tropical zone is prone to cyclonic visits during summer seasons bringing heavy rainfall onto the island. This study aimed to determine the effect of extreme rainfall intensity during cyclonic conditions on groundwater quality. Cyclone Esami which occurred in January 2020 is selected for correlation analysis against groundwater quality. Cyclonic data are obtained from the Regional Specialized Meteorological Centre (RSMC) La Réunion/Météo-France, which is the World Meteorological Organization (WMO) official authority for tropical cyclone monitoring and forecasting in the Southwest Indian Ocean basin, and supplemented by data from the International Best Track Archive for Climate Stewardship (IBTrACS) maintained by NOAA's National Centers for Environmental Information.

4.7 Computation of the correlation heat maps

The global climatic forcing data in the form of AAO, IOD, and SOI as well as the drought indicators data in the form of SPI, SPEI, and dry spells were compared against the in-situ water quality data (nitrate, sulphate, conductivity, salinity, chloride, TDS, and pH) via correlation analysis. The correlation analysis was performed by comparing the time-series records of each of the predictor variables with the in-situ water quality data using statistical Python tools. The output of this correlation analysis is shown as correlation heat-map figures in the Results section. The SPI, SPEI, and dry spells were used as methods of estimating the accumulative water budget based on rainfall and water loss. They were evaluated over 1-, 3-, 6-, and 12-month periods to assess monthly, quarterly, biannual, or annual water budgets (Figure 2).

The response of groundwater parameters to changes in the water budget was influenced by factors such as aquifer permeability and recharge rates. Faster recharge rates were expected to correlate more closely with one-month SPI and SPEI values, while slower recharge rates could result in a more delayed reaction in groundwater quality indicators to variation in drought indicators. The correlation matrices shown in Figures 4.6 were derived from the time-series data of the correlated parameters (shown in Supplementary Appendix) and were based on in situ data not fully presented in this paper as time series. Figure 4.6 presents the correlation heat maps between water quality parameters and climate variability models. These analyses allowed for assessment of differential responses across the five main aquifers, as each aquifer system may exhibit varying sensitivity to climate forcing.

4.7 Results

4.7.1 Water quality time-series data

The electrical conductivity in the groundwater of Mauritius typically varies between 172 and 1,166 µS/cm (Izadi et al., 2021). However, Aquifer 6 (secondary aquifer) exhibited anomalous measurements that significantly exceeded these established ranges. Specifically:

- Electrical conductivity values reached over 2,500 µS/cm, more than double the upper limit reported for Mauritius groundwater
- Chloride concentrations exceeded 500 mg/L, well above the typical <250 mg/L range for uncontaminated basaltic aquifers
- TDS measurements surpassed 1,500 mg/L, exceeding expected values (0-1000 mg/L) for secondary aquifers
- Coefficient of variation for these parameters exceeded 60%, indicating excessive data scatter compared to <25% observed in primary aquifers

These extreme values are inconsistent with the geological characteristics of Aquifer 6, which comprises intermediate to weathered basalt formations that typically confer moderate to low permeability and stable water chemistry. The anomalies likely result from data entry errors, equipment malfunction, or improper instrument calibration rather than representing actual aquifer conditions. Given these data quality concerns and the potential for these outliers to compromise statistical analyses, Aquifer 6 was excluded from this study to maintain dataset integrity.

4.7.2 Trend analysis and hypothesis testing

Regression analysis on each of the water quality indicators is undertaken to assess the long-term change through the time series. A simple linear regression is conducted based on parametric statistical methods (which means they depend on the normality of the data). The regression model is always preceded by a model validation. This is a process of testing underlying model assumptions which are as follows:

1. Test for normality of residual distribution,
2. Test for normality of its theoretical quantiles compared to observation quantiles, and
3. Test for the randomness of distribution in the residuals across predicted values.

Figure 4.3 shows the model validation plots for conductivity and validates the models for each aquifer against the underlying assumptions. Similar validation for each parameter was undertaken before regression on each of them. The Q-Q plots show a relatively straight line along the q-q line of the axis, which satisfies the second assumption, as it demonstrates the normality of quantiles. The quantiles are the groups generated by dividing a frequency distribution into equal groups, sometimes are also referred to as percentiles. The histogram shows a bell-shaped curve distribution, which closely resembles a normal distribution, which satisfies the first assumption in each aquifer. The randomness of the residuals observed in plot a's demonstrates a correct conformity to the third assumption in each aquifer.

4.7.2.1 Conductivity hypothesis test

Model validation paves the way for statistical analysis of the linear regression model. The regression statistics displayed in Table 4.2 show the coefficients of variation of the displayed conductivity time series shown in Figure 4.2 with additional details such as the standard error, t-value, and the p-values for each aquifer. The coefficient is the trend. The standard error is the sample-adjusted standard deviation, and the p-value is the probability of success where success is the rejection of the null hypothesis. Therefore, hypothesis testing is part of this section where each aquifer regression will be tested for change across time. If the change is significant based on the 95% confidence level, observed through the p-value, then that change is concluded to be statistically significant. However, a change denoted by p-values >0.05 is regarded as insignificant over this time period as it falls outside the 95% confidence level.

The conductivity regression model is given based on the equation:

$$\beta\left(Conductivity\right) = \beta_0 + \beta_1\left(Months\right) + \epsilon_i \tag{2}$$

The β(Conductivity) is the dependent variable (conductivity). The β_0 is the intercept, β1 is the coefficient of variation, and ϵ_i is the error term. It can be observed in Table 2 that aquifers 1, 2, 3, and5 have significant changes over the period of study with coefficients of −0.40, −0.34, −0.09, and − 0.35 µS/cm per month, respectively. The negative change in each case represents an improvement in the conductivity (lowering of electrical conductivity and dissolved inorganic material ions) state of these aquifers across time. Aquifers 4 and 5 are also negative but are not significantly changing.

The results shown in Table 4.2 indicate a p-value for aquifer 4 that is greater than α, and therefore, there is no sufficient evidence to reject the null hypothesis in that aquifer as it does not fall within the rejection region of the t-statistic. For the rest of the aquifers, we reject the null hypothesis and conclude that there is a change in conductivity in the Mauritius aquifers over the period of study.

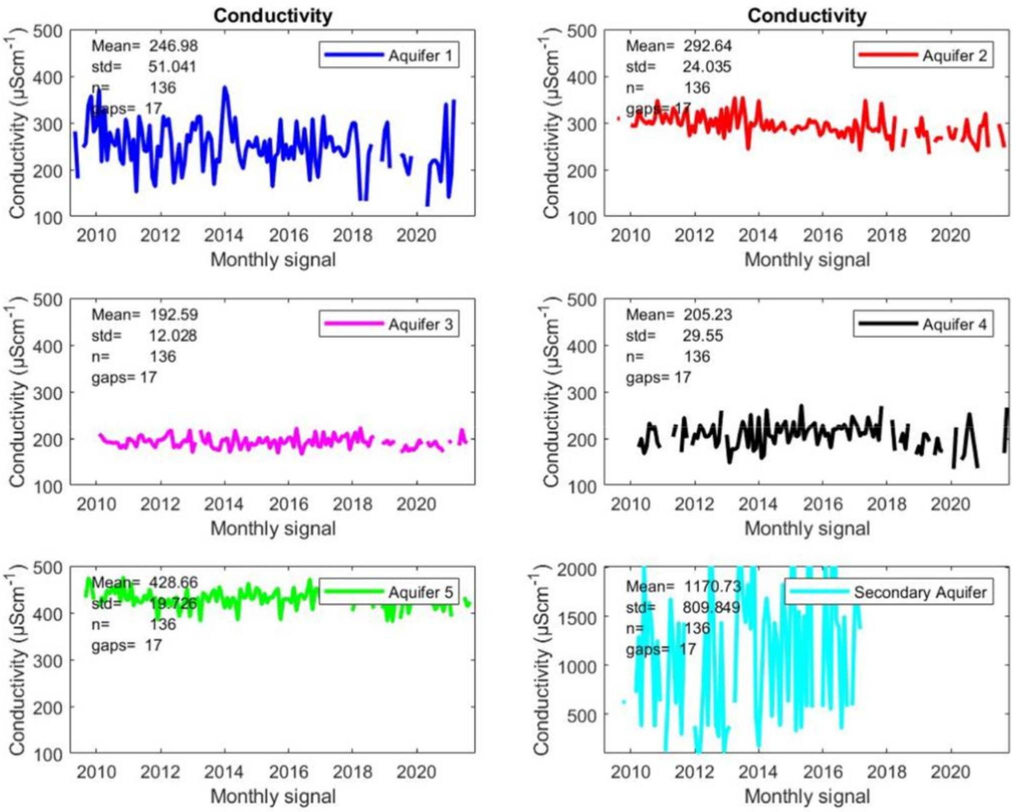


Figure 4-2 Conductivity Time Series as a Water Quality Indicator in Mauritius.

4.7.3 SPI correlation with aquifer groundwater quality

The correlation coefficients of drought indicators versus each water quality parameter are assessed in each aquifer. The 12-month SPI indicator signal is shown in Supplementary Figure S1, while the water parameter data not shown for the rest of the parameters are exemplified by the conductivity parameter signal shown in Figure 4.2. The best obtainable results in SPI are observed in the 12-month SPI as shown in Figure 4.4. The 12-month SPI displays a − 0.40 and − 0.33 sulphate correlation in aquifers 2 and 3;

this is to highlight the notable correlations that are above 0.3. These coefficients indicate a potentially significant relationship between the predictor and response variable. The correlation observed after a 12-month lag indicates a much-delayed impact, which could be due to a slow recharge rate.

Figure 4.4 displays correlation coefficients that are better than correlation coefficients shown by a 1-month SPI, 3-month SPI, and 6-month SPI. The higher frequency SPIs were assessed (results not shown in this paper) and displayed even lower correlation coefficients than the 12-month SPI. The assessment of various SPI time scales (1-, 3-, 6-, and 12-month) was performed to determine the temporal lag at which drought conditions most significantly impact aquifer water quality. The overall conclusion reached is that it takes an entire year for the effects of the SPI drought to receive maximum response from some of the water quality parameters that appeared to respond to it.

4.7.4 SPEI correlation with aquifer groundwater quality

The SPEI indicator signal is shown in Supplementary Figure S2 and displays the SPEI signal across time. The 1-month SPEI index is considered because it exhibits the highest correlation coefficients compared to other time-span SPEIs. This does not mean the SPEI values were high in absolute terms, only in relation to other SPEI indexes. Figure 4.5 displays correlation coefficients; nitrate has peak correlations at 0.20 and − 0.18 for aquifers 2 and 3, respectively. These correlations are highlighted as they appear to be the highest in this correlation matrix, but they may not be high enough to suggest a relationship that can be considered strong or meaningful.

Figure 4.5 displays 1-month SPEI, which is a striking contrast to what was presented by the SPI. The reason for a 1-month SPEI is that similarly after all frequency SPEIs were assessed (results not included for the other SPEIs), the 1-month SPEI was found to be the stronger correlated on this drought indicator notwithstanding the low strength correlations it exhibits.

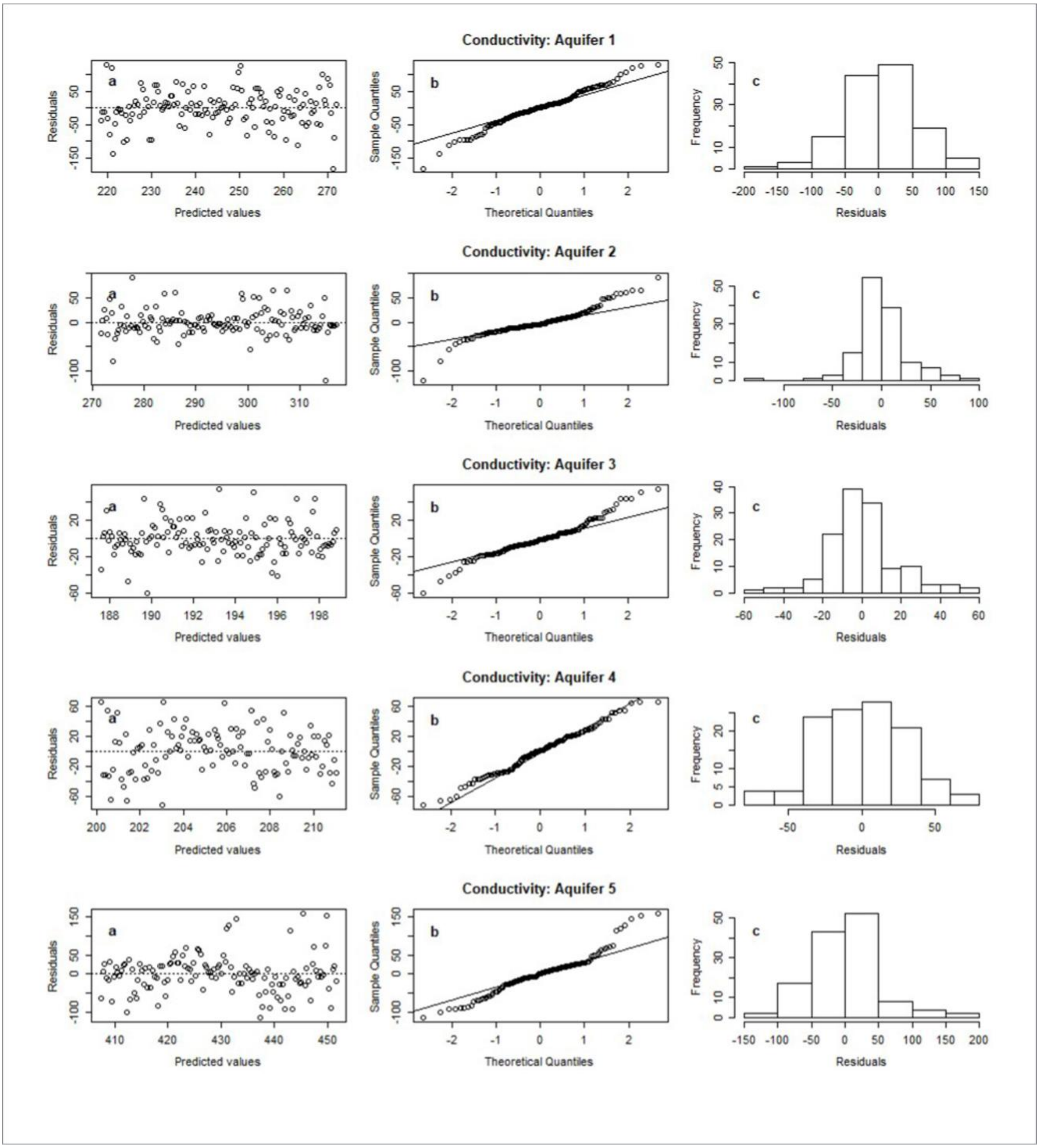


Figure 4-3 Conductivity Model Validation Signal across five main Aquifers.

4.7.5 Dry spell correlation with aquifer groundwater quality

The dry spell indicator signal is shown in Supplementary Figure S3 with dry spells being brought into the picture. It is visible that there is a really low correlation relationship that can be established between water quality indicators in each aquifer and the dry spells assessed every month. The strongest correlation coefficient seen in Figure4.6 is seen in pH at the value of −0.35 in aquifer 4. The dry spells are computed and defined as a series of 7 consecutive days with less than 5 mm of rainfall. These occurrences seem to take place mostly one time a month as shown in Supplementary Figure S3.

The dry and wet spells are periods of extended dry days and extended rainfall days, respectively. The dry spells represent days of little to no precipitation. During this period, the water table receives no recharge and runs low on the solvent. This is expected to contribute to higher chemical and nutrient concentrations within aquifers. On the other hand, wet periods represent days of non-stop precipitation for days in a row or high-volume event precipitations. This theoretically leads to an aquifer recharge, which is important for replenishing the water table and serves to lower the chemical concentration of the ground water. This relationship has been tested in the statistical section to ascertain the strength of this theoretical relationship. In this study, a "dry spell" is defined as a period of 7 days or more in a row that each received 5 mm of rainfall or less. In this assessment, dry spells are analysed at a monthly level, like the SPI and SPEI even though dry spells tend to be seasonally analysed in most literature. This was done in order to standardize the temporal component of evaluation across all parameters. As depicted in Figure 4.7, the global climate modes all appear to detect at below 0.3 in correlation except in the AAO-sulfate where a correlation of −0.33 was detected in aquifer 3 and the 0.3 ENSO-chloride correlation in aquifer 5. This signifies a very limited influence of global climate features on aquifer water quality.

4.7.6 Global climatic forcing

The global climatic forcing indices assessed are AAO, IOS, and ENSO. They are then correlated with water quality parameters to estimate their driving impact on the Mauritius aquifers as shown in Figure 4.7. Their impact is moderate to weak when assessed against the seven water quality measures studied in this paper. Figure 4.7 displays their correlations where it can be noted on the correlation matrix that the strongest matches exist among some variables of interest (predicted variables) such as conductivity and TDS as well as salinity and conductivity, etc. These can be expected because some of these variables are derived/computed from each other. However, there is a weak relationship between these global indices and water quality parameters observed in each aquifer.

Some positive correlations (approximately 0.2) observed in aquifer 7 are between IOD and nitrate, between pH and AAO, and between sulphate and ENSO. In aquifer 4, a relationship of similar proportion is observable between AAO and sulphate. In aquifers 2 and 3, there are no notable correlations between global indices and water quality parameters. In aquifer 1 however, the pH appears positively correlated to AAO also at approximately a low 0.2. Further correlations that are even stronger than the ones highlighted above also exist in this correlation matrix but they are not between the variables we are interested to compare. Therefore, there is no note made about them. These correlations are often predictor versus predictor variable or predicted versus predicted variables, i.e., TDS versus conductivity. The actual monthly signals of AAO, IOS, and ENSO are computed but not shown in this paper as they are generally available in many open-source atmospheric data repositories such as Copernicus data store and NASA data.

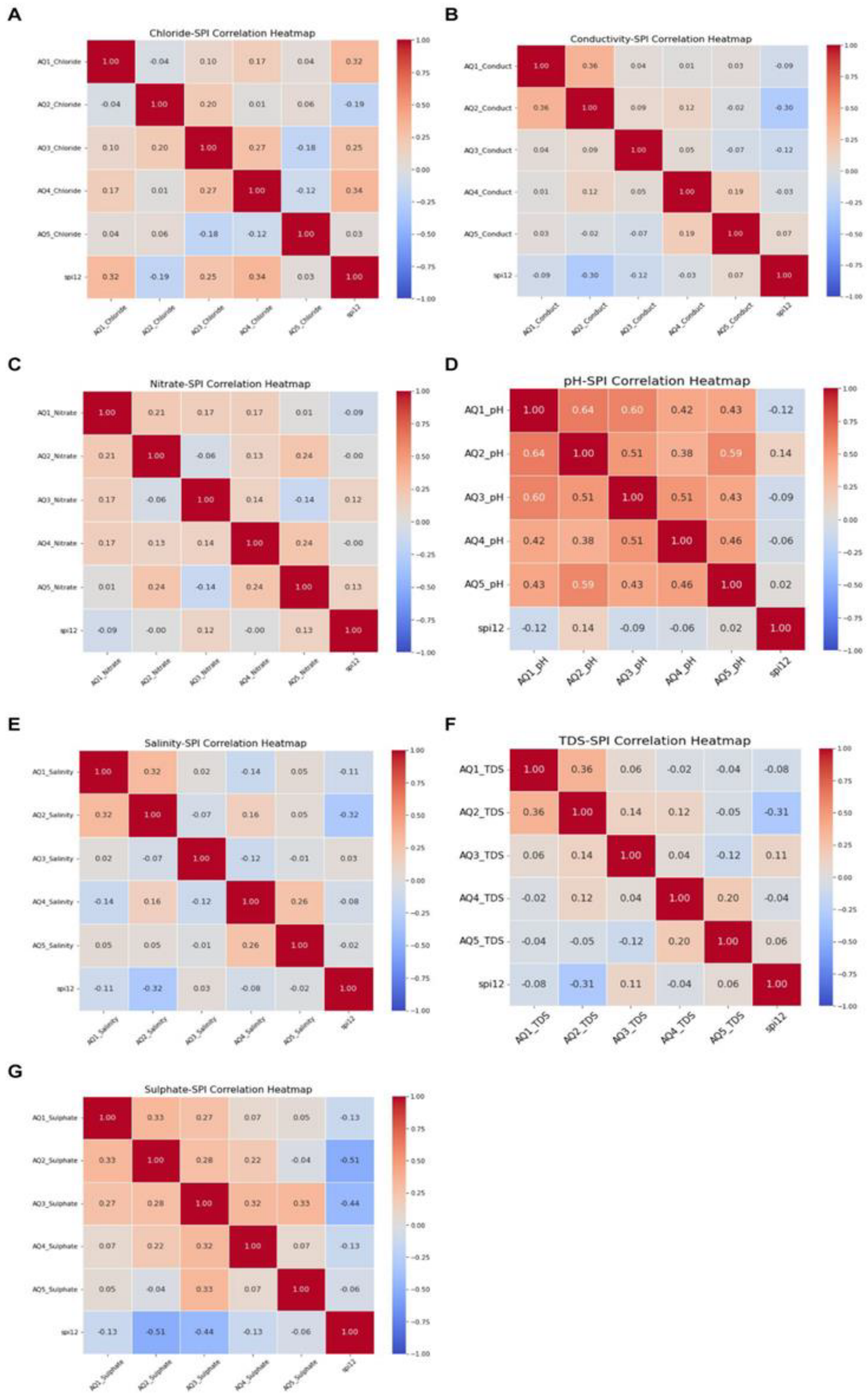


Figure 4-4 The SPL Correlation Matrix plot showing the relationship strength of the Water Quality Indicators vs. the 12-month SPI. Aquifer Correlation plots vs. (A) Chloride, (B) Conductivity, (C) Nitrate, (D) pH, (E) Salinity, (F) TDS and (G) TDS heat map plots.

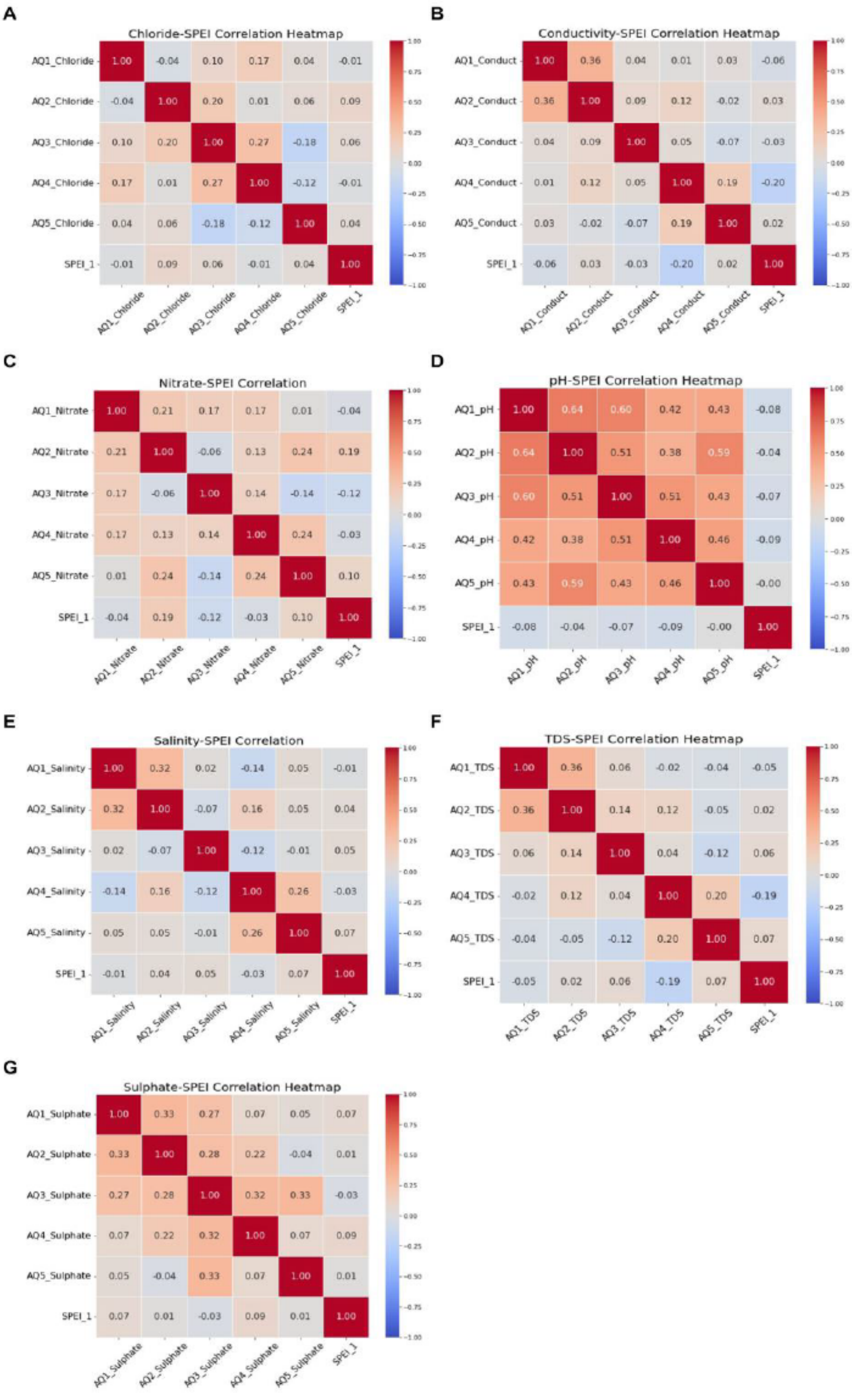


Figure 4-5 The SPEI Correlation Matrix plot showing relationship strength of the Water Quality Indicators vs. the 1-month SPEI. Aquifer Correlation vs. (A) Chloride, (B) Conductivity, (C) Nitrate, (D) pH, (E) Salinity, (F) TDS and (G) TDS heat map plots.

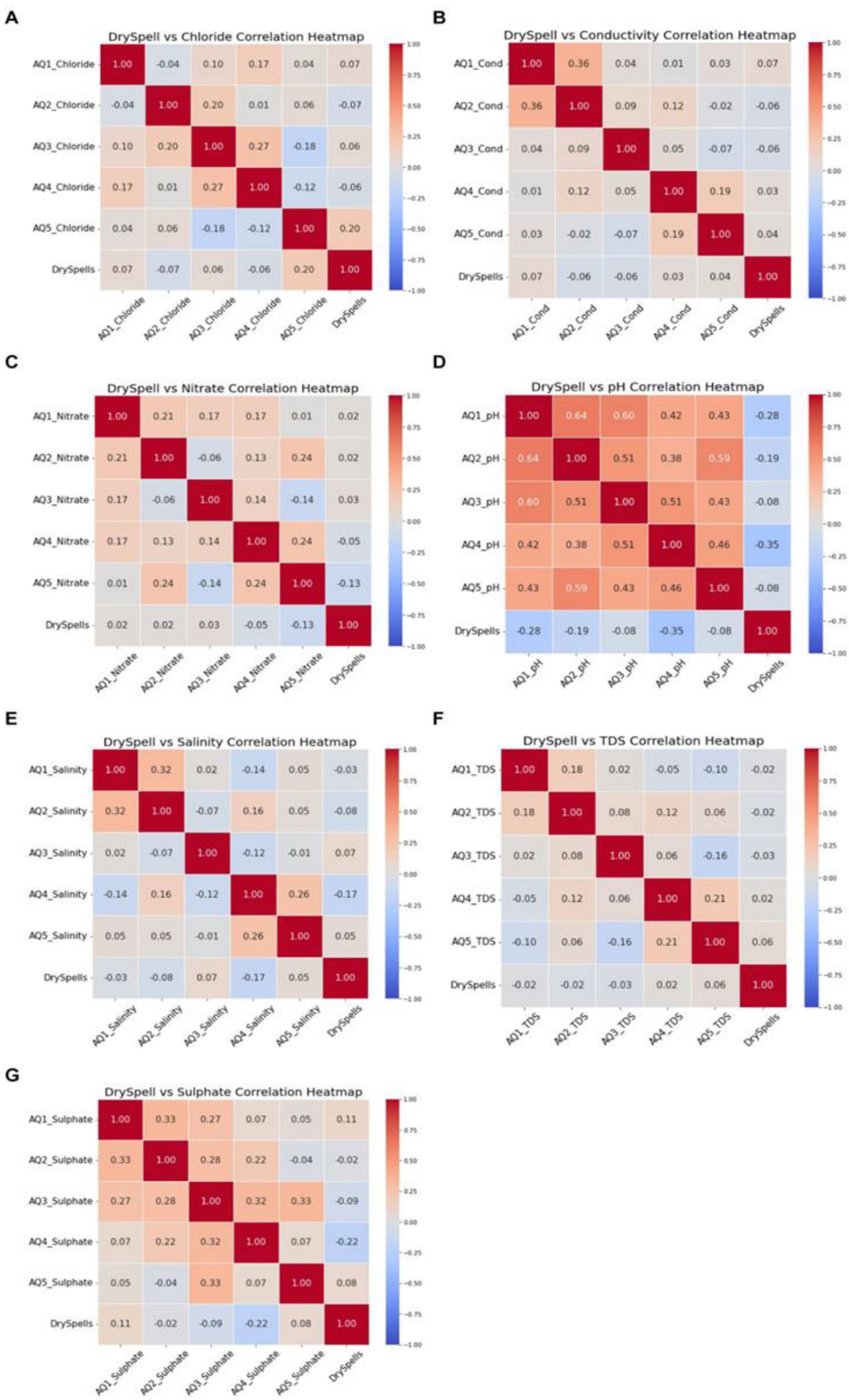


Figure 4-6 SPI Correlation Matrix plot showing the relationship strength of the Water Quality Indicators vs. the Dry-Spells SPI. Aquifer Correlation vs. (A) Chloride, (b) Conductivity, (C) Nitrate, (D) pH, (E) Salinity, (F) TDS and (G) TDS heat map plots.

Table 4-2 Summary of results of a Linear Regression Model of Conductivity displaying the coefficient of variation, standard error, t-value, p-value, and significance at a 95% confidence level. ρ = 0 (There is no significant relationship between conductivity and time (months)) ρ ≠ 0 (There is a significant relationship between conductivity and months). α = 0.05.

Coefficients	Estimate	Std. Error	*t*-value	*p*-value	
Aquifer1 (Intercept)	272.32	9.01	30.24	< 0.001	***
Months	−0.40	0.11	−3.47	< 0.001	***
Aquifer2 (Intercept)	317.43	4.69	67.74	< 0.001	***
Months	−0.34	0.06	−5.68	< 0.001	***
Aquifer3 (Intercept)	198.91	3.18	62.62	< 0.001	***
Months	−0.09	0.04	−2.07	0.040	*
Aquifer4 (Intercept)	211.16	5.45	38.72	< 0.001	***
Months	−0.09	0.08	−1.17	0.250	
Aquifer5 (Intercept)	452.08	8.78	51.51	< 0.001	***
Months	−0.35	0.12	−2.96	0.003	**

4.7.7 Rainfall spikes or tropical cyclone impact

The rainfall spikes during such cyclones are to be viewed directly in contrast to dry spells as they bring about excessive rainfall over a short period of time potentially elevating the recharge of the aquifers. The selection of a cyclone is made on the basis that it overlaps the in-situ data record and directly impacts the island around the time of good in situ observations. Tropical cyclone Esami occurred during the period 21st to the 26th of January as shown in grey highlight in Figure 4.8. The figure displays rainfall in and around the period of the tropical cyclone and compares the water volumes generated by the storm with groundwater parameter measured quantities. This is done for determining the possibility of short-term rainfall influence on the state of groundwater quality in the assessed aquifers. It is apparent in Figure 4.8 that pH is only assessed on few occasions after the storm; on the 29th and 30th of January, the quantities are below 7 as shown for aquifer 1 (blue dots). For aquifer 2 (red dots), 3 days after the storm, the pH is in medium quantities of round 7 but after the 8th of February, a period of 2 weeks after the storm, the quantities appear to have increased to approximately 7.25. The pH appears to generally increase after the storm overall as also seen in aquifer 3 (green dots). Assessing a period before the storm is not easy as there was a high rainfall event again that preceded cyclone Esami. However, a comment can be made that during that high rainfall event itself, the pH recorded in aquifers 2 and 3 was low, but after the event, they gradually increased as shown around the 8th of January. For conductivity, TDS, and salinity after cyclone Esami, they showed a decrease in aquifers 1, 2, and 3. There was only one information available for aquifer 4, and so no comparison could be made. For nitrate, for aquifers 1 and 4, no comparison could be made due to insufficient data. However, a decrease in the level of nitrate could be seen. No data were available for chloride, sulphate, in aquifer 5, this is why the sulphate plot has no data points and the chloride plot was not generated for having the same results as sulphate during this period. There were no observations for aquifer 5 during the storm period.

The observable pattern shows a high density of dry spells during the years 2019 and 2020. This could potentially explain the reason for cyclone Esami's detected effect on the aquifers. The aquifers might have been running significantly dryer than usual due to the density of dry spells; therefore, a storm event brought a sudden solvent to the aquifers that was deprived extensively. It was unexpected that the SPI and the SPEI indexes displayed no strong month-to-month correlation with groundwater quality parameters. This study was conducted based on the hypothesis that the amount of available precipitation is the leading indicator of groundwater quality as far as the concentrations of the water quality parameters are concerned. In Figure 4.6, this relationship was only observed in the 12-month SPI shown, making the meaning of that outcome rather hard to interpret. The global climatic forcing indices showed weak correlations with groundwater chemical/physical properties, making it hard to positively conclude any existence of a direct connection.

4.8 Discussion

The conductivity regression computed based on equation (2) has been tested against various aquifers and it showed that there is a base case for assessing the conductivity in all aquifers excluding aquifer 4 as they are changing in time. The study is based on testing the possible drivers of this change. Other variables such as nitrate, pH, and phosphate are also assumed to be changing with time but the test done on conductivity will be performed on them on a future study.

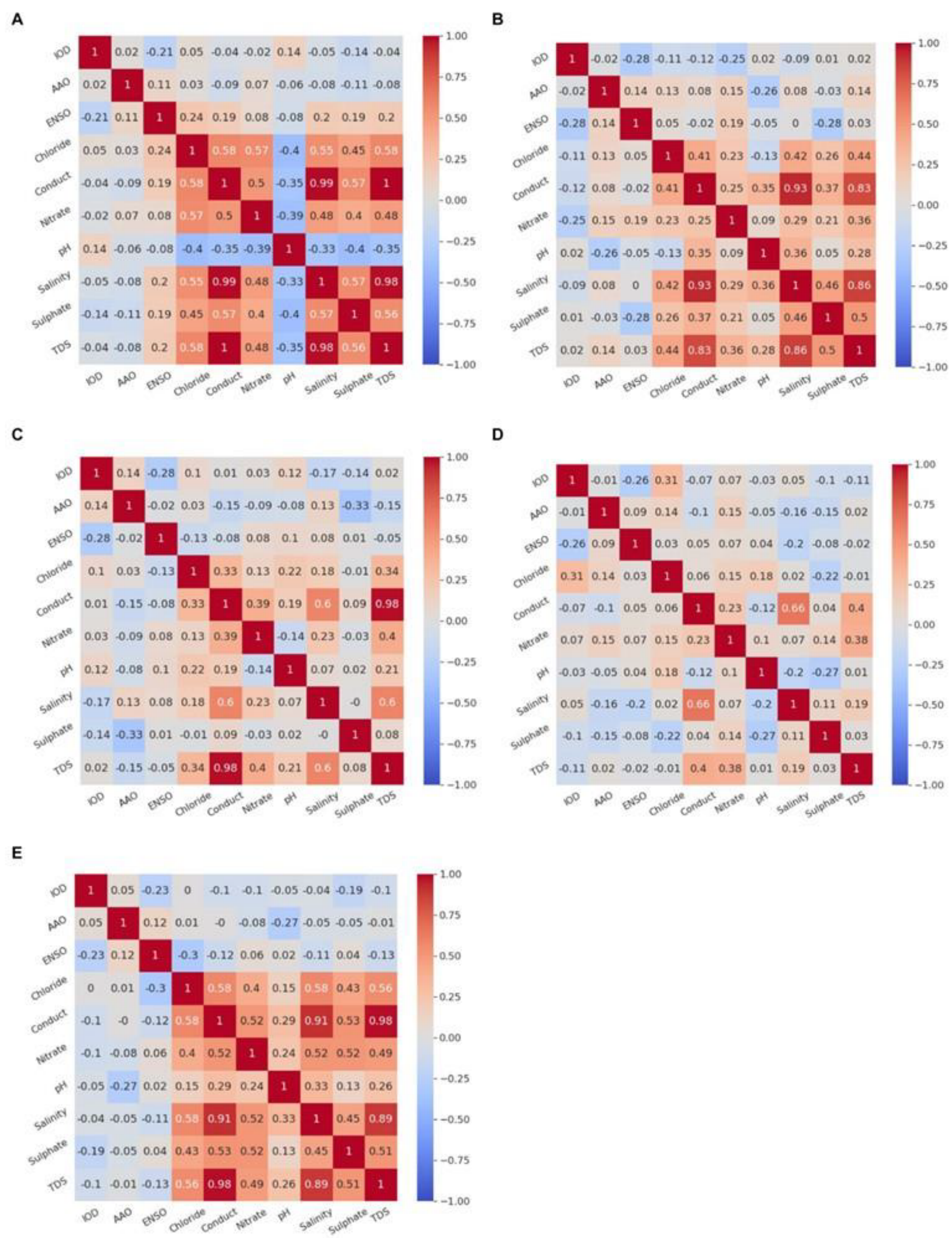


Figure 4-7 Environmental Correlation Heat map plot showing relationship between the Environmental Factors (IOD, AAO, and ENSO) and the Water Quality Indicators. Global climate modes and water quality parameter correlation vs. (A) Aquifer 1, (B) Aquifer 2, (C) Aquifer 3, (D) Aquifer 4 and (E) Aquifer 5 heat map plots.

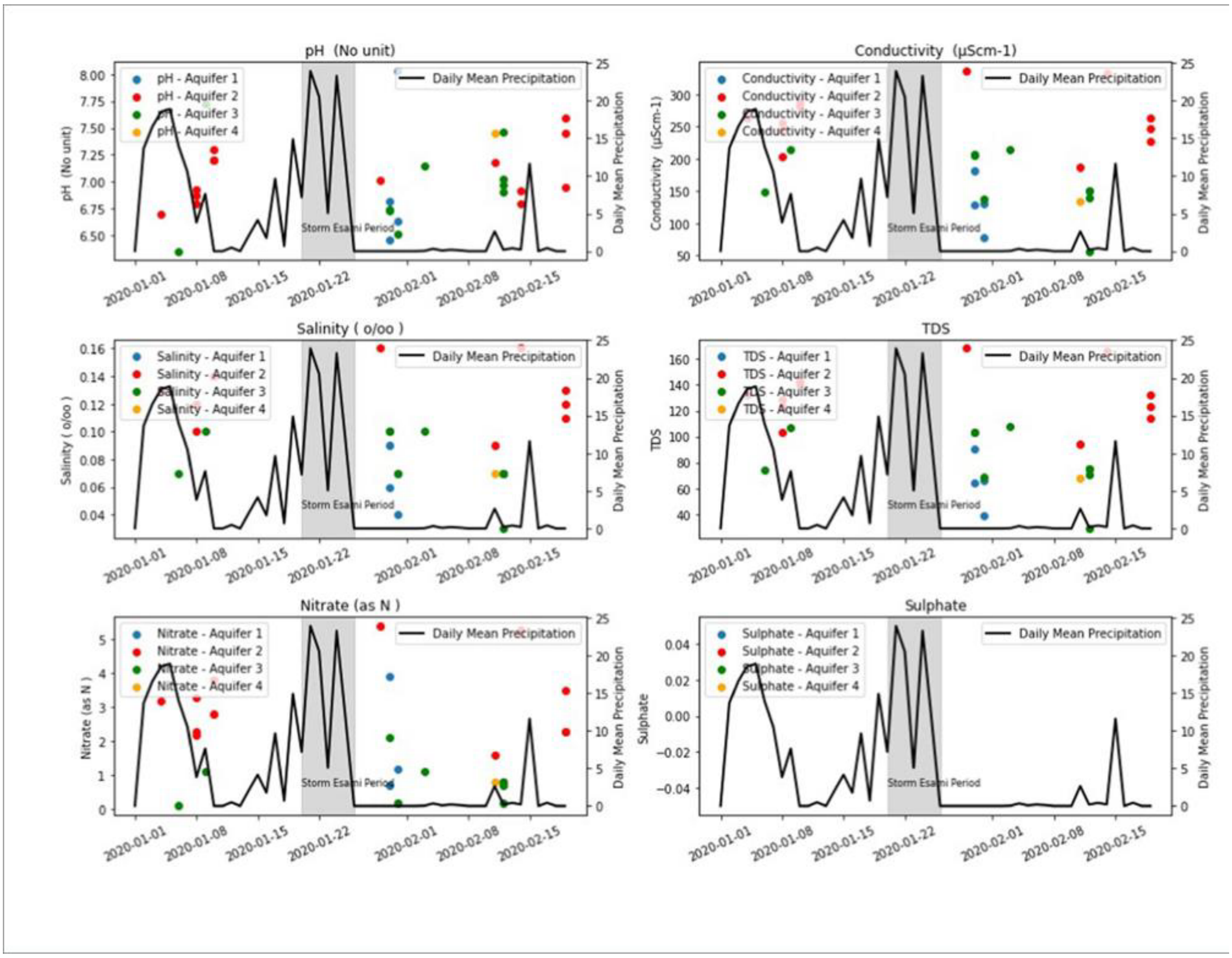


Figure 4-8 Daily Groundwater Parameter readings versus storm Esami event analysis.

4.9 Conclusion

It has been established in this paper that correlations are not very strong between the water quality indicators and the rainfall indicators, which are separated into two categories: drought indicators and global climate modes. However, there were notable correlations in the case where we have arbitrarily set a 0.3 correlation as a baseline for a notable correlation. In this case, a 12-month SPI versus sulphate in aquifers 2 and 3 was notable with correlation coefficients of -0.51 and -0.44, respectively. Apart from sulphate, pH was the only other water quality parameter that exhibited a response.

The meaning of the 12-month SPI correlation symbolizes a delayed response to water abundance by aquifer's water quality indicators. Much as it is unfathomable that there can be a 12-month delay in the response to a rainfall event by an aquifer, it is apparent based on observed outcomes that a potentially slow recharge rate in aquifers 3 and 4 might be giving rise to water availability related responses seen in nutrients such as sulphate, chloride, and even nitrate to a lesser extent in the said aquifers. It is further concluded that high storm events such as tropical cyclone Esami result in shorter-term recharge that is observable by a change in water quality parameter concentration days after the storm. The conclusion is that it is possible to observe the impact of storm water in the aquifers though not statistically evaluated, but it is less apparent to see these changes when using a time-series data array as exemplified by drought indicators where any relationships were only observable on longer timescales.

There is no strongly detectable influence of global climate modes on the water quality indicators. The global climate modes all appear to detect low correlations with the aquifers although aquifers 3 and 5 showed some notable however modest relationships in AAO and sulphate as well as in ENSO and Chloride, respectively. It is worth mentioning that even against the SPI drought indicator, the sulphate showed a notable response to the indicator signal. This can lead to the conclusion that sulphate has a seemingly higher response to water availability than the other water quality indicators. This heightened sensitivity of sulphate can be attributed to several hydrogeochemical processes: (1) sulphate concentrations are primarily controlled by dilution effects during periods of enhanced recharge, where increased water influx reduces sulphate concentrations through dilution, (2) sulphate is highly soluble and mobile in groundwater systems, making it more responsive to changes in water volume than less mobile constituents, (3) during dry periods, evapotranspiration and reduced recharge lead to concentration of sulphate through evaporative concentration processes, and (4) sulphate originates from both geogenic sources (weathering of sulphate-bearing minerals like gypsum) and atmospheric deposition, making it sensitive to both groundwater residence time and fresh water inputs. These combined factors make sulphate a more reliable indicator of water availability changes compared to other parameters that may be buffered by aquifer chemistry or have multiple competing sources and sinks. Heavy storms occurring during cyclones impact the groundwater quality with respect to conductivity, TDS, salinity, and nitrate, although this could not be statistically tested given the lack of water quality indicators collected on the days that surround the storm; therefore, the conclusion is made based on one storm event.

Future research on this topic can strongly benefit from an assessment done against higher resolution rainfall. The $0.25° \times 0.25°$ resolution precipitation from ERA-5 used in this study for computing drought indicators is not very suitable for this location as Mauritius Island is quite a small geographical location. This results in the rainfall variation getting poorly captured and could have been a factor in the correlation scores. Additionally, the paucity of observations on the boreholes around storm events made storm analysis harder to assess.

4.10 References

Ahmed F, Mishra V 2020. Estimating relative immediacy of water-related challenges in Small Island Developing States (SIDS) of the Pacific Ocean using an hp modeling. Model. Earth Syst. Environ. 6, 201–214. doi: 10.1007/s40808-019-00671-2

Anderson MP, Woessner WW 1992. Applied groundwater modeling. Academic Press.

Ashok K, Chan W-L, Motoi T, Yamagata T 2004. Decadal variability of the Indian Ocean dipole. Geophys. Res. Lett. 31. doi: 10.1029/2004GL021345

Chacowry A, McEwen LJ, Lynch K 2018. Recovery and resilience of communities in flood risk zones in a small island developing state: a case study from a suburban settlement of Port Louis, Mauritius. Int. J. Disast. Risk Reduct. 28, 826–838. doi: 10.1016/j.ijdrr.2018.03.019

Devi Nowbuth M, Rambhojun P, Umrikar B 2012. Numerical groundwater flow and contaminant transport modelling of the southern aquifer, Mauritius. Earth Sci. India 5, 79–91.

Doorga JRS 2022. Climate change and the fate of small islands: the case of Mauritius. Environ. Sci. Pol. 136, 282–290. doi: 10.1016/j.envsci.2022.06.012

Dorevella N, Waqa-Sakiti H, Tabe T 2021. Climate change adaptation programmes on water security in the pacific: a focus on the Solomon Islands.

Freeze RA, Cherry JA 1979. Groundwater. Prentice-Hall.

Garnier E, Desarthe J 2013. Cyclones and societies in the Mascarene Islands 17th-20th centuries.

Gong D, Wang S 1999. Definition of Antarctic oscillation index. Geophys. Res. Lett. 26, 459–462. doi: 10.1029/1999GL900003

Guide WSP IU, Svoboda M, Hayes M, Wood D 2012. World meteorological organization. Geneva.

Gungoa V 2016. Use of water quality indices for water quality assessment in small island state: a case study in the northern aquifer of Mauritius. Am. Sci. Res. J. Eng. Technol. Sci.

Hargreaves GH, Samani ZA 1985. Reference crop evapotranspiration from temperature. Appl. Eng. Agric. 1, 96–99. doi: 10.13031/2013.26773

Helsel DR, Hirsch RM 2002. Statistical methods in water resources. US Geological Survey.

Hernandez-Delgado EA, Alejandro-Camis P, Cabrera-Beauchamp G, Fonseca-Miranda JS, G'omez-Andujar NX, Gomez P 2024. Stronger hurricanes and climate change in the Caribbean Sea: threats to the sustainability of endangered coral species. Sustain. For. 16, 1506. doi: 10.3390/su16041506

Hersbach H, Bell B, Berrisford P, Hirahara S, Horanyi A, Munoz-Sabater J 2020. The era5˜ global reanalysis. Q. J. R. Meteorol. Soc. 146, 1999–2049. doi: 10.1002/qj.3803

Hirsch RM, Slack JR, Smith RA 1982. Techniques of trend analysis for monthly water quality data. Water Resources Research 18(1), 107–121.

Izadi N, Karakani EG, Saadatabadi AR, Shamsipour A, Fattahi E, Habibi M 2021. Evaluation of era5 precipitation accuracy based on various time scales over Iran during 2000–2018. Water 13, 2538. doi: 10.3390/w13182538

Jaleel MI, Ibrahim SA, Hussain A, Mustafa M, Pathirana A 2020. A screening approach for assessing groundwater quality for consumption in small islands: case study of 45 inhabited islands in the Maldives. Water 12, 2209. doi: 10.3390/w12082209

Jevrejeva S, Moore J, Grinsted A 2003. Influence of the arctic oscillation and el nino-southern˜ oscillation (enso) on ice conditions in the Baltic Sea: the wavelet approach. J. Geophys. Res. Atmos. 108. doi: 10.1029/2003JD003417

MacDonald MC, Elliott M, Langidrik D, Chan T, Saunders A, Stewart-Koster B 2020. Mitigating drought impacts in remote island atolls with traditional water usage behaviors and modern technology. Sci. Total Environ. 741, 140230. doi: 10.1016/j.scitotenv.2020.140230

Majidipour F, Najafi SMB, Taheri K, Fathollahi J, Missimer TM 2021. Index-based groundwater sustainability assessment in the socio-economic context: a case study in the western Iran. Environ. Manag. 67, 648–666. doi: 10.1007/s00267-021-01424-7

McKee TB, Doesken NJ, Kleist J 1993. The relationship of drought frequency and duration to time scales. Proceedings of the 8th conference on applied climatology, Boston, 179–183.

Mycoo MA, Roopnarine RR 2024. Water resource sustainability: challenges, opportunities and research gaps in the English-speaking Caribbean Small Island Developing States. PLoS Water 3, e0000222. doi: 10.1371/journal.pwat.0000222

Paulo A, Pereira L, Matias P 2003. Analysis of local and regional droughts in southern Portugal using the theory of runs and the standardised precipitation index. In: Tools for drought mitigation in Mediterranean regions, 55–78.

Potop V, Možný M 2011. The application a new drought index–standardized precipitation evapotranspiration index in the Czech Republic. In: Mikroklima a mezoklimakrajinnychstructur a` antropogenn'ıchprostred˘, 1–12.

Sarker S 2022. Fundamentals of climatology for engineers: lecture note. Eng 3, 573–595. doi: 10.3390/eng3040040

Seebocus RH, Lollchund MR, Bessafi M 2021. Analysis of extreme rainfall and drought events using statistical and fractal methods: a case study of Mauritius. S. Afr. J. Sci. 117, 1–9.

Svoboda M, Hayes M, Wood D 2012. Standardized precipitation index: user guide. World Meteorological Organization.

Thomas A, Baptiste A, Martyr-Koller R, Pringle P, Rhiney K 2020. Climate change and Small Island Developing States. Annu. Rev. Environ. Resour. 45, 1–27. doi: 10.1146/annurev-environ-012320-083355

UNFCCC 2005. Climate change, Small Island Developing States. Climate Change Secretariat Bonn.

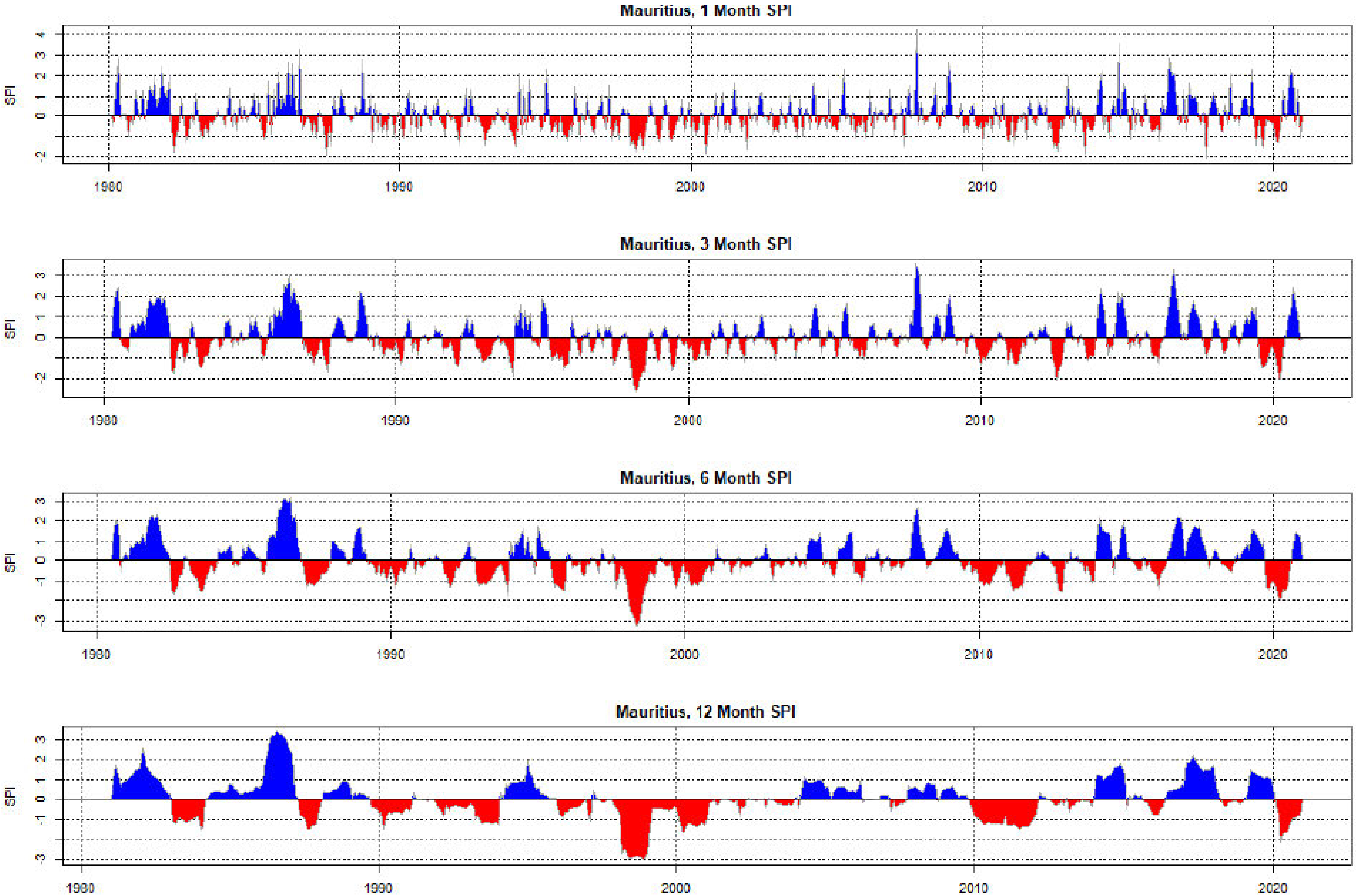


Figure S1. Daily groundwater parameter readings vs storm Esami event analysis.

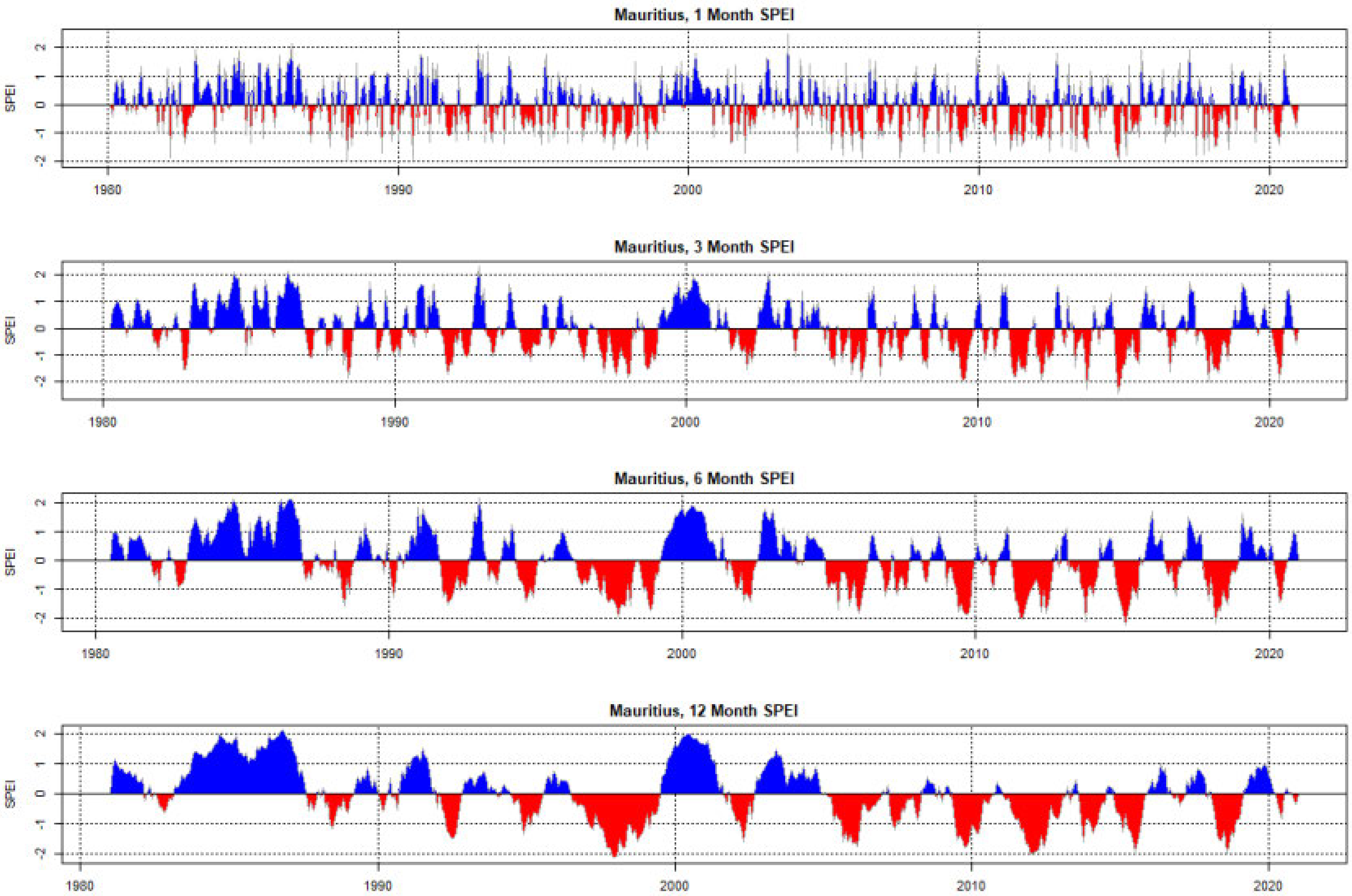


Figure S2. Daily groundwater parameter readings vs storm Esami event analysis.

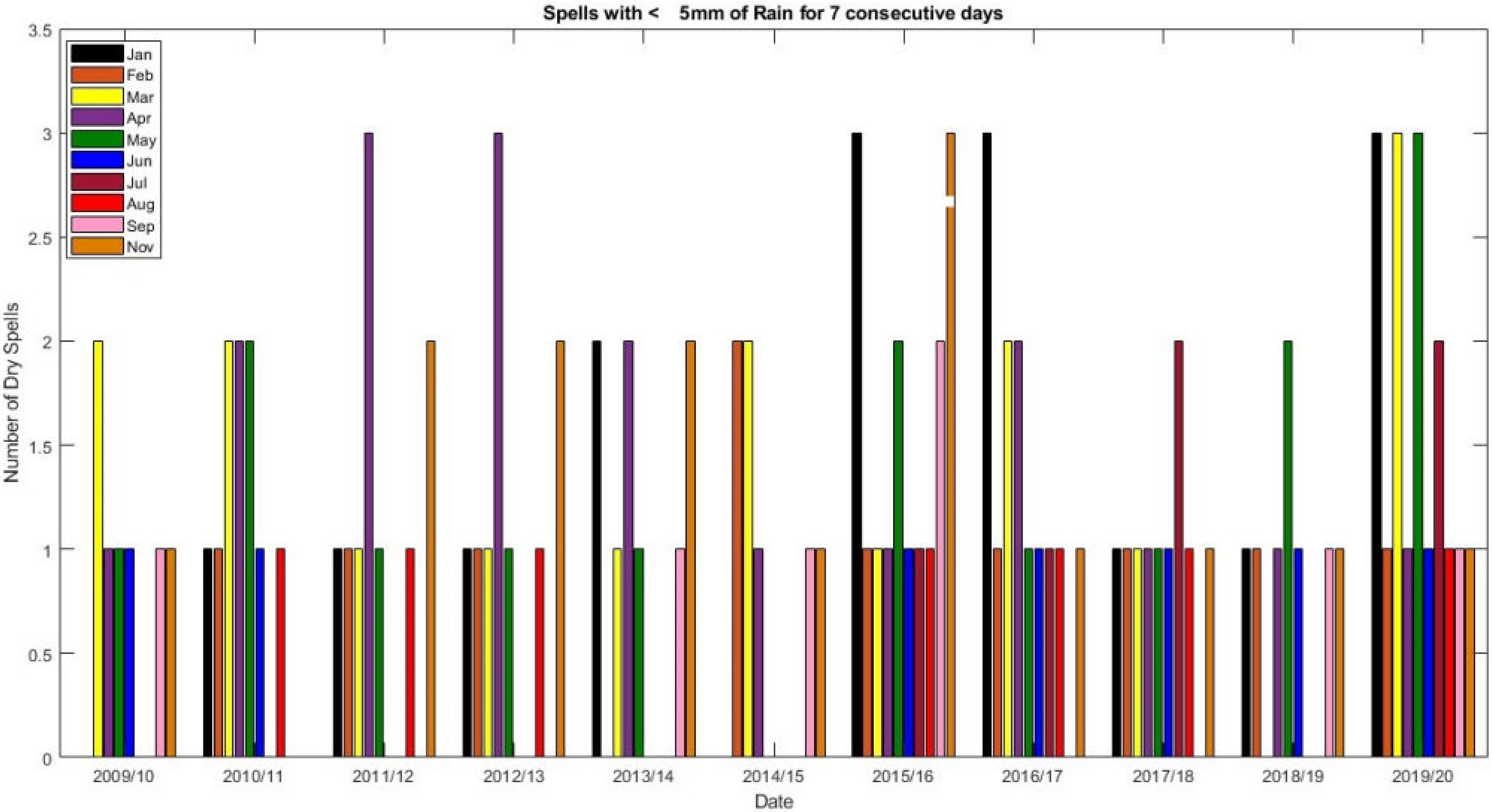


Figure S3. Mauritius island Dry Spells for the period January 2010 - December 2021.

CHAPTER 5: ISOTOPIC CHARACTERIZATION OF GROUNDWATER SYSTEMS IN SMALL ISLAND DEVELOPING STATES: IMPLICATIONS FOR RECHARGE, FLOW DYNAMICS, AND RESOURCE MANAGEMENT: MAURITIUS ISLAND AS A CASE STUDY

Varsha Gungoa[1,] *and SeifuKebede[2]

[1]*Centre for Water Resources Research, University of KwaZulu Natal, Hydrological Department, Pietermaritzburg, South Africa.*

Correspondence*: VarshaGungoavarsha.gungoa@gmail.com

5.1 Abstract

Mauritius is a volcanic island in the south-western Indian Ocean, characterized by five major aquifer systems within its basaltic geology. The island's groundwater resources, critical for water supply, are influenced by its tropical climate with distinct wet and dry seasons, and elevation gradients from sea level to approximately 800 meters. This research employed stable isotope analysis (δ^2H and $\delta^{18}O$) to investigate groundwater dynamics, conducting comprehensive sampling of 67 boreholes across all aquifer systems from 2017 to 2023. The study characterized recharge mechanisms, flow patterns, and system vulnerability through isotopic signatures, combining spatial and temporal analyses to understand the hydrogeological framework of this Small Island Developing State. The analysis revealed distinct isotopic patterns (δ^2H: -22.8per mil to -5.6per mil; $\delta^{18}O$: -4.2per mil to -1.56per mil) that identified the central plateau as the primary recharge zone, with depleted values (δ^2H: -18per mil to -22.8per mil) indicating rapid infiltration processes. The Local Meteoric Water Line ($\delta^2H = 7.2\delta^{18}O + 9.5$) differs from the Global Meteoric Water Line, reflecting unique local hydrological processes. Temporal variations demonstrated differential aquifer resilience, with deeper systems showing greater buffering capacity against environmental stresses. The northern aquifer exhibited particular vulnerability to seawater intrusion, evidenced by progressive isotopic enrichment in coastal areas. These findings provided a quantitative framework for sustainable groundwater management, enabling evidence-based decisions on protection zones, extraction limits, and climate change adaptation strategies.

Keywords: Isotopes Hydrogeology Groundwater Mauritius Recharge Aquifers Seawater

5.2 Introduction

Stable isotope analysis of hydrogen (δ^2H) and oxygen ($\delta^{18}O$) has emerged as a crucial method in hydrology, offering valuable insights into groundwater dynamics and water cycle processes (Al-Gamal, 2024; Hao, Gao, Zhang & Wen, 2024). This study focuses on the isotopic composition of groundwater in Mauritius from 2017 to 2018 and 2022 to 2023, aiming to deepen the understanding of the island's water resources and hydrological processes through detailed isotopic analysis.

Mauritius, situated in the Indian Ocean, features a unique hydrological system influenced by its tropical climate and volcanic geology (Marsala et al., 2019). The island's distinct wet and dry seasons significantly affect groundwater recharge and quality, leading to complex hydrological patterns (Bourhane, Ibrahim & Gou, 2024). Early work by Sukhija et al., (1996) emphasized the use of environmental isotopes for studying groundwater recharge mechanisms and water quality in Mauritius. This foundational study paved the way for further research into the island's hydrological characteristics.

Building on this groundwork Povinec et al., (2012) and Dindyal et al., (2013) examined the isotopic composition of precipitation in Mauritius, providing insights into the island's water cycle. Their research employed isotopic data to uncover patterns in evaporation, condensation, and precipitation, linking these processes to groundwater characteristics. This study was pivotal in understanding how isotopic signatures from precipitation influence groundwater systems on the island. The groundwater isotopes show that groundwater quality is generally good and the recharge in Mauritius occurs in the central plateau regions (Dindyal et al., 2013).

To place Mauritius in a broader context, comparing its isotopic studies with those of other Small Island Developing States (SIDS) is valuable. For example, Shuler et al. (2020) investigated groundwater-surface water interactions and submarine groundwater discharge in American Samoa using environmental isotopes and geochemical tracers. Their findings in a small tropical watershed context offer a comparative framework for understanding how similar hydrological processes manifest in different island environments, providing context for Mauritius' groundwater data. The role of volcanic geology in controlling groundwater flow patterns has been documented in similar basaltic island settings, where fractured rock aquifers and weathered soil profiles create complex recharge pathways that significantly influence isotopic signatures (Werner et al., 2017; White & Falkland, 2010). These geological controls, combined with tropical vegetation patterns including sugar cane cultivation covering approximately 40% of the island and native forest remnants in highland areas, create distinct infiltration zones that affect the spatial distribution of isotopic values in groundwater systems (Staub et al., 2014).

Similarly, Jones et al. (2000) focused on estimating recharge in tropical karst aquifers, which is relevant to understanding recharge mechanisms in Mauritius. Their study highlights the importance of isotopic analysis in tropical regions. Furthermore, Abiye and Leketa (2021) explored isotope hydrology in the Limpopo Basin, contributing valuable information on isotopic variations in tropical and subtropical regions. This research complements the understanding of hydrological processes in Mauritius by offering additional insights into regional isotope patterns. Weaver et al. (2005) extended this understanding to the coastal plain aquifers of the Western Cape, South Africa, using cumulative rainfall collectors and isotopic analysis, providing valuable insights into recharge processes and hydrological interactions that offer methodological parallels for analysing Mauritius' groundwater systems. Critical to these studies is the recognition that soil structure and weathering profiles significantly influence recharge rates and isotopic fractionation processes, particularly in tropical volcanic environments where lateritic soils and clay-rich weathering products can create preferential flow paths (Ramessur, 2002). The island's basaltic geology, characterized by extensive lava flows with varying degrees of fracturing and weathering, creates a heterogeneous aquifer system where soil development and vegetation cover further modulate recharge processes through evapotranspiration effects and root zone dynamics, creating distinct isotopic signatures that reflect land use patterns and ecological zones (Proag, 1995; Staub et al., 2014).

The application of stable isotopes extends beyond academic research to practical water resource management. For instance, isotopic techniques have been employed to trace contamination sources (Keesari, 2024), assess water quality (Wang, Dong, Xie & Chen, 2024), and manage water resources more effectively (Scandellari et al., 2024)). Integrating isotopic data with hydro-chemical analysis in Mauritius can enhance the evaluation of groundwater sustainability and the impact of human activities on water resources. Additionally, isotopic studies in tropical island environments, including Mauritius, offer insights into the effects of climate change on hydrological processes. By analysing temporal variations in isotopic data, researchers can assess how changes in precipitation patterns, temperature, and sea level affect groundwater recharge and quality. This information is crucial for developing adaptive management strategies to address the impacts of climate change on water resources in small island developing states.

From past research it has been noted there is little knowledge about groundwater recharge Mechanism, flow dynamics, inter-aquifer connectivity on aquifers of Small Islands Developing states. This research on isotope hydrology aims to address the existing gaps by understanding the groundwater isotope compositions using Mauritius as a case study. The specific objectives of this study are to:

1. Characterize recharge mechanisms across Mauritius's five aquifer systems using stable isotope signatures
2. Identify and map groundwater flow patterns through spatial and temporal isotopic analysis
3. Assess areas of potential vulnerability within the aquifer network through isotopic indicators
4. Understand inter-aquifer connectivity and mixing processes using isotopic evidence
5. Develop a quantitative framework for sustainable groundwater management based on isotopic characterization.

This approach will contribute to a complete understanding of groundwater flow dynamics, recharge mechanisms, and inter-aquifer connectivity, offering valuable information for water resource management and further hydrological research in Small Island Developing States.

5.3 Materials and Methods

5.3.1 Study Area

Mauritius, a volcanic island located in the south-western Indian Ocean, lies between latitudes 19°58’ and 20°32’ south and longitudes 57°18’ and 57°46’ east, encompassing an area of 2,040 square kilometres (Proag, 1995; Ramessur, 2002). The island’s tropical climate features distinct wet (November to April) and dry (May to October) seasons, with annual rainfall ranging from 1,000 mm along the coast to 4,000 mm in the central highlands. Average temperatures fluctuate between 20°C and 30°C (Ministry of Energy and Public Utilities, 2003). The hydrogeological map (Figure 5.1) shows the spatial distribution and characteristics of all aquifer systems, including their recharge areas referred to as the common recharge zone. Groundwater in Mauritius occurs mostly in volcanic basaltic aquifers. Figure 5.1 shows the spatial distribution of these aquifer systems and the locations of boreholes used for isotopic analysis across the island.

These aquifers provide residential, agricultural, and industrial water, particularly in dry seasons (Ramessur et al., 2001). Both shallow coastal and deeper inland aquifers are affected by climate and human activity (Giorgi et al., 1999; Burnett et al., 2006). Understanding the isotopic composition of groundwater resources is essential for understanding climatic variability and directing sustainable water management.

In Mauritius, the source of water is rain. The water resources of Mauritius are divided into two categories, the surface water resources (streams and rivers, ponds and dams) and the groundwater resources, situated below ground in the pervious and permeable part of the subsurface hard rock formations. There are 5 main aquifers in Mauritius from which 429 boreholes are being exploited. The groundwater resources of Mauritius played a fundamental role in the drinking water supply since the groundwater exploitation started in the 60's. Presently groundwater catchments ensure about 54% of the potable water supply in the island

Water samples were collected from 67 selected boreholes over the 5 main aquifers in 2022 and 2023. The collected samples were stored in sealed, airtight containers to prevent evaporation and isotopic fractionation prior to laboratory analysis. The Aquifers are described in the study area map as 'I Curepipe Aquifer-Vacoas-Flic En Flac', 'II Phoenix - Beau Bassin - Albion - Moka', 'III Nouvelle France - Rose Belle - Plaisance', 'V Northern Aquifer', 'IV N.Decouverte - P. Des Roches - T.D'eau Douce', and 'Secondary Aquifers C, F & CG and Yemen' , However for an ease of reference they will be referred to as Aquifer 1, 2, 3, 4, 5 and secondary aquifers respectively for ease of reference.

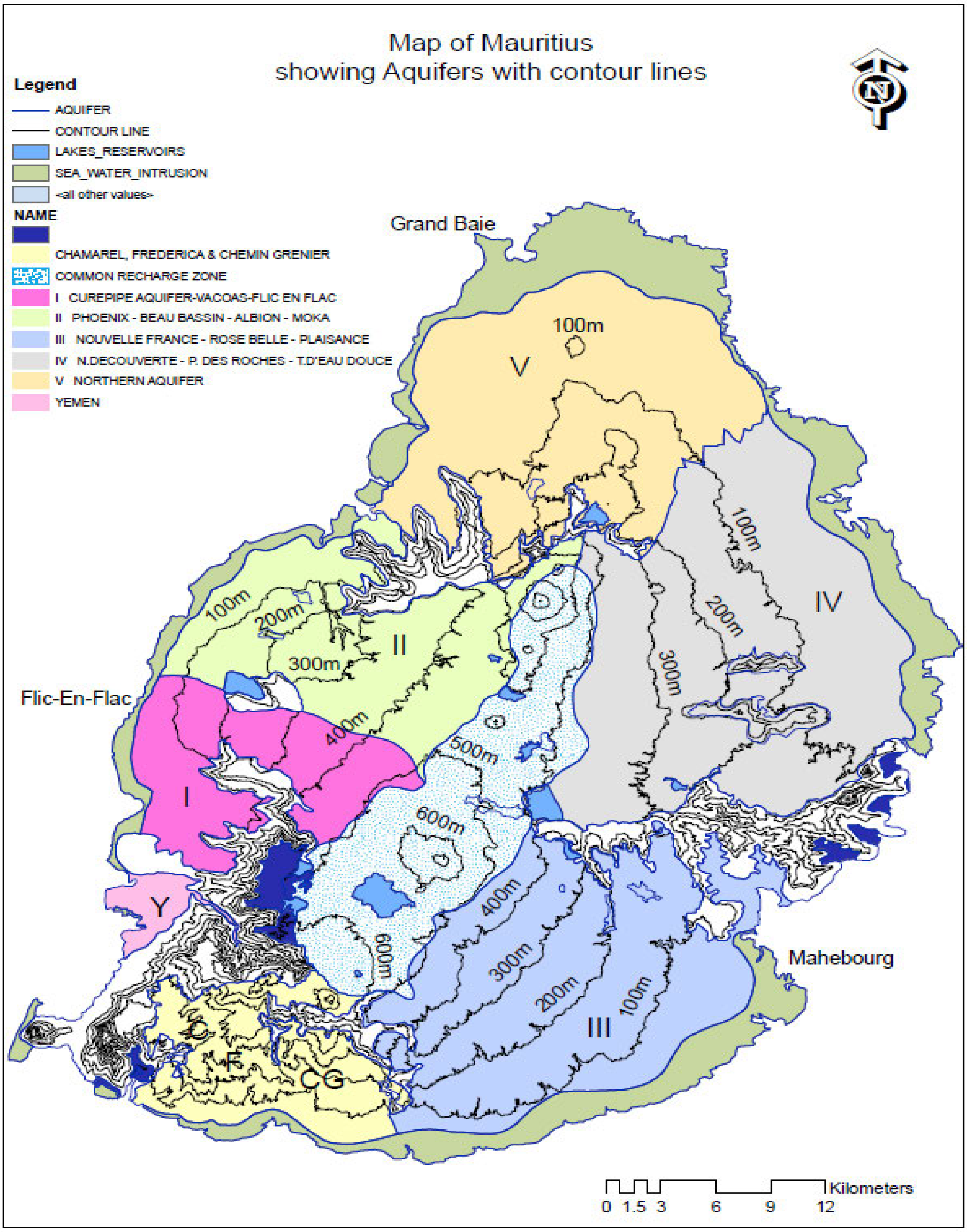


Figure 5-1 Study are map showing Contour lines with elevation details across the 5 Aquifers and 67 of 429 boreholes

The map (Fig 5.2) displays the five main aquifers of Mauritius (labelled with Roman numerals I-V) and several secondary aquifers. The capital letters represent secondary/minor aquifers and specific geological formations: C = Chamarel, CG = Chemin Grenier, F = Frederica, and Y = Yemen. These are smaller aquifer units that are separate from the five main aquifers used in the primary analysis. Yemen in this context refers to a small secondary aquifer located in the southwestern part of Mauritius, named after the local geographical area. It is one of the four secondary aquifers (Chamarel, Frederica, Chemin Grenier, and Yemen) that were excluded from the main study due to lack of continuous data records, as mentioned in the methodology. The map (Fig 5.2) shows borehole locations (black dots with BH numbers) distributed across the island, with the legend indicating different aquifer types, seawater intrusion zones (diagonal lines), ancient lava flows, lakes/reservoirs, and the common recharge zone. The scale bar shows distances in kilometres, and a north arrow indicates orientation.

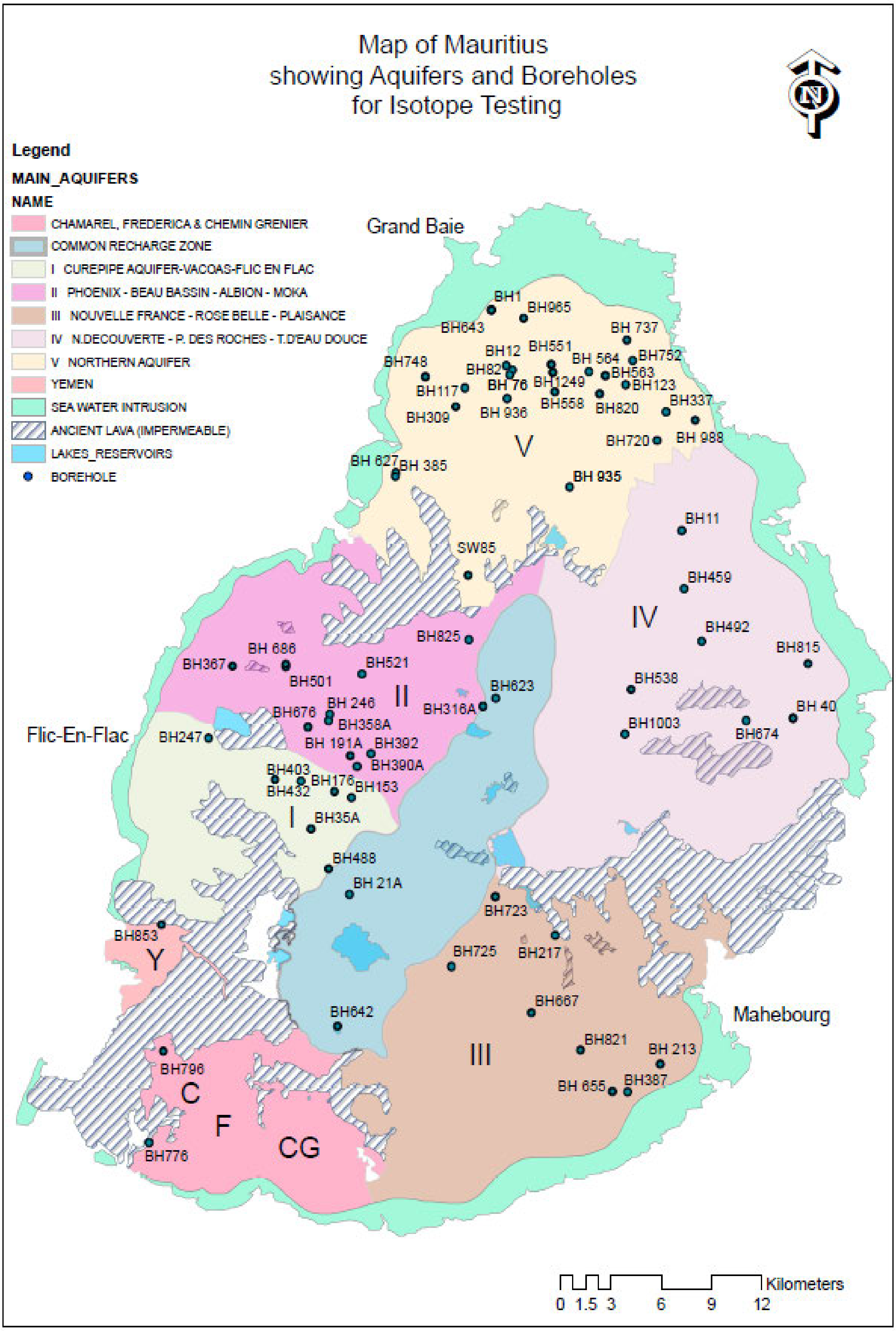


Figure 5-2 Map showing Groundwater Aquifers and Boreholes in Mauritius Island for Isotope Analysis

5.3.2 Site Selection and Sampling

The boreholes were selected based on their geographic distribution, ensuring that the data covers the 5 aquifers and a broad range of elevations across Mauritius. Boreholes from coastal regions, mid altitude areas, and high-elevation sites in the central plateau were included to capture the full range of isotopic variability on the island. Each borehole was georeferenced using GPS coordinates to allow for spatial mapping of isotope data. The elevation of each site was determined using topographic maps, with elevations ranging from sea level up to approximately 800 meters in the central highlands. Figure 5.2 illustrates the elevation distribution across the five aquifer systems through contour lines, providing a topographic context for the sampling locations. Elevation details for each borehole given at Appendix I.

5.3.3 Hydrological and Climatic Context

Mauritius's hydrological system is strongly influenced by its volcanic topography and distinct seasonal climate patterns. The island's central highlands create an orographic effect that drives precipitation patterns, with elevation ranging from sea level to approximately 800 meters. Understanding this topographic influence is essential for interpreting isotopic variations across the island's aquifer systems.

The island experiences two well-defined seasons that affect groundwater recharge patterns: a wet summer period from November to April and a drier winter season from May to October. Precipitation data for these seasonal patterns were obtained from the Mauritius Meteorological Services, with daily rainfall records spanning 2017-2023 used to correlate temporal variations with isotopic sampling periods.

Elevation data for each sampling location were determined using the General Bathymetric Chart of the Oceans (GEBCO) with 15 arc-second resolution (approximately 500 meters). Topographic maps at 1:50,000 scale were used to verify elevation measurements and establish the relationship between sampling sites and local topographic features. Climate data integration included monthly temperature and precipitation records to provide context for isotopic interpretation and seasonal pattern analysis.

5.3.4 Isotope Analysis for $\delta^{18}O$ and $\delta^{2}H$

Water samples from 67 boreholes across Mauritius's five aquifers were analysed for stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) at the National Environmental Laboratory using mass spectrometry. Results are reported in per mil (per mil) relative to Vienna Standard Mean Ocean Water

(VSMOW). The interpretation of isotopic data focuses on understanding hydrological processes at both local and global scales through established hydrogeological methods. The analysis begins with the establishment of the Local Meteoric Water Line (LMWL). The Local Meteoric Water Line (LMWL) for Mauritius ($\delta^2H = 7.86\delta^{18}O + 9.5$) was derived from precipitation data collected by the Mauritius Meteorological Services and analysed through the IAEA's Global Network of Isotopes in Precipitation (GNIP) program during 2017-2023. The GNIP station for Mauritius (WMO station code: 61990) provided the isotopic data for precipitation samples collected at regular intervals throughout this period. The LMWL was compared to the Global Meteoric Water Line (GMWL: $\delta^2H = 8\delta^{18}O + 10$) to understand local variations in atmospheric water cycling. Groundwater flow directions were determined through: (1) hydraulic head analysis from water level measurements, (2) isotopic tracer analysis indicating highland-sourced water in coastal aquifers, (3) topographic gradient analysis, and (4) hydrogeological modelling.

As shown in Figure 5.3, the LMWL (red dash line) exhibits a slightly lower slope (7.86) compared to the GMWL (8.0), reflecting local evaporative processes and the influence of Indian Ocean moisture sources on Mauritius's precipitation. This difference provides important context for interpreting groundwater recharge processes and identifying potential evaporative effects in the island's aquifer systems.

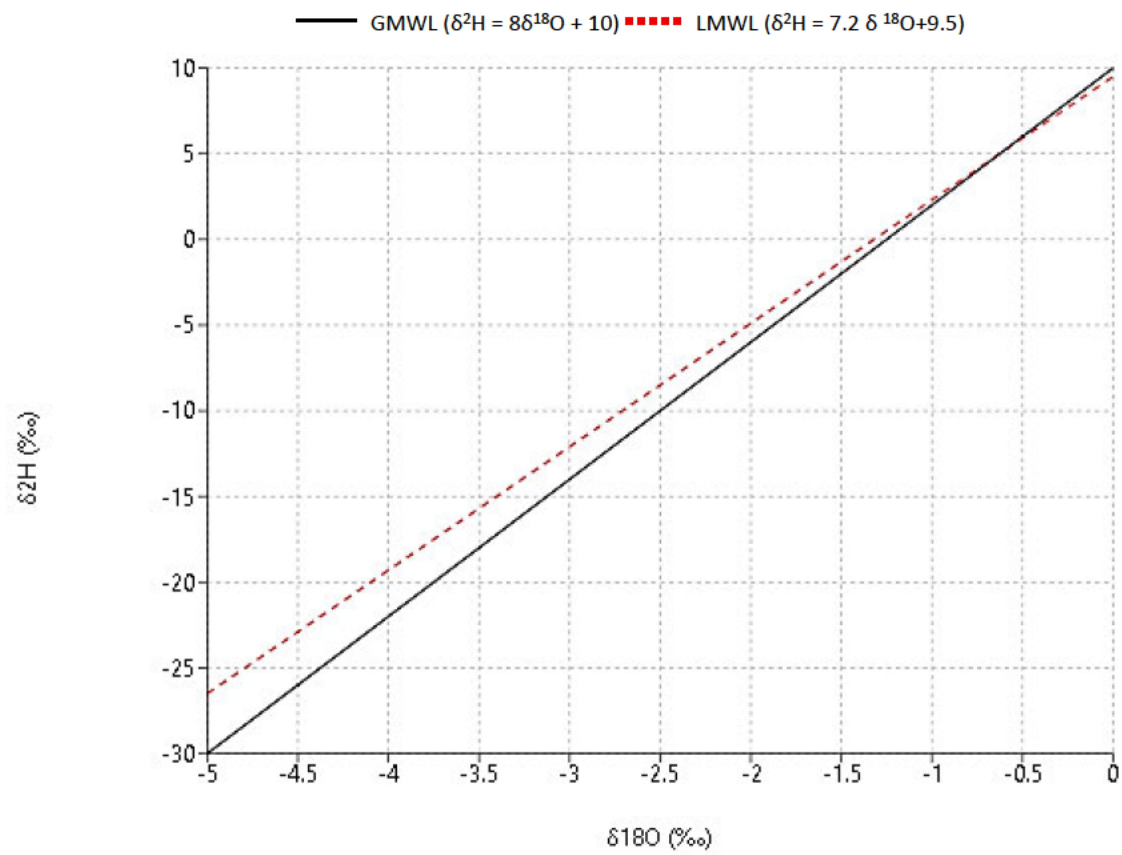


Figure 5-3 Comparison of Global Meteoric Water Line (GMWL) and Local Meteoric Water Line (LMWL) relationships derived from isotopic analysis of 67 boreholes across Mauritius's five aquifer systems during 2017-2023. The plot demonstrates the systematic deviation of local isotopic compositions from global patterns, reflecting distinct regional hydrological processes.

The relationship between δ^2H and $\delta^{18}O$ values in Mauritius reveals important characteristics of the island's hydrological system. The Global Meteoric Water Line (GMWL: $\delta^2H = 8\delta^{18}O + 10$) represents the worldwide relationship between these isotopes in precipitation, while the Local Meteoric Water Line (LMWL: $\delta^2H = 7.2\delta^{18}O + 9.5$) reflects Mauritius's specific conditions.

The comparison between the LMWL and Global Meteoric Water Line (GMWL: $\delta^2H = 8\delta^{18}O + 10$) included slope variation analysis, intercept differences, and deviation patterns to understand local variations in atmospheric water cycling. The LMWL exhibits a systematically lower slope (7.86) compared to the GMWL (8.0). This reduced slope indicates significant evaporative processes affecting local precipitation and groundwater. The lower slopes of the LMWLs indicate that precipitation undergoes some evaporation during rainfall events, likely due to the island's tropical climate. The deviation becomes more pronounced in the enriched (less negative) range of values. The intercept difference suggests unique moisture sources and atmospheric conditions.

The consistent deviation from GMWL provides a framework for identifying local recharge processes. The GMWL and LMWL relationship helps to distinguish between different water sources and mixing processes and understanding these patterns is crucial for sustainable groundwater management. This analysis establishes a quantitative basis for understanding local hydrological processes and their departure from global patterns, essential for water resource management in Mauritius.

The isotopic data analysis examines spatial variations in relation to altitude and distance from coast, revealing distinct patterns in recharge processes and groundwater flow paths (Section 5.4.2). These patterns help identify primary recharge zones in the central plateau and delineate mixing relationships between different water sources, particularly in coastal areas where freshwater-seawater interactions occur.

Recharge processes are investigated through the analysis of isotopic variations with altitude and distance from coast, considering both spatial and temporal patterns in the isotopic composition (Section 3). This includes examination of seasonal variations in recharge and the identification of evaporation effects through isotopic enrichment patterns. The characterization of different water sources is accomplished through their distinct isotopic signatures, allowing for the assessment of mixing relationships between waters of different origins and the evaluation of potential seawater intrusion in coastal areas. The interpretation integrates isotopic data with hydrogeological, meteorological, and geological information to develop an understanding of groundwater dynamics in the Mauritius aquifer system. This isotope data enables the identification of recharge areas, flow paths, and potential vulnerabilities within the groundwater system.

5.3.5 Isotope Analysis

The isotopic composition of the collected water samples was analysed using Liquid Water Isotope Analyser LGR, DLT 100. The two stable isotopes of interest in this study are oxygen-18 (δ^{18}O) and deuterium (δ^{2}H). The Liquid Water Isotope Analyser LGR, DLT 100 provides precise measurements of the ratio of these isotopes relative to the Vienna Standard Mean Ocean Water (VSMOW) standard, expressed in per mil (per mil) notation.

The following equation was used to calculate the isotope ratios:

$$\delta = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right) \times 1000$$

Where R_{sample} and R_{standard} represent the isotope ratio of the sample and the standard (VSMOW), respectively. Both $\delta^{18}O$ and $\delta^{2}H$ were measured for each water sample. The resulting data were then compiled into a database for further analysis and interpretation.

5.3.6 Precipitation Data

To complement the isotope data, precipitation data were obtained from the Mauritius Meteorological Station and from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) satellite observations. The figures 5.4 and 5.5 below show the yearly and monthly precipitation over Mauritius.

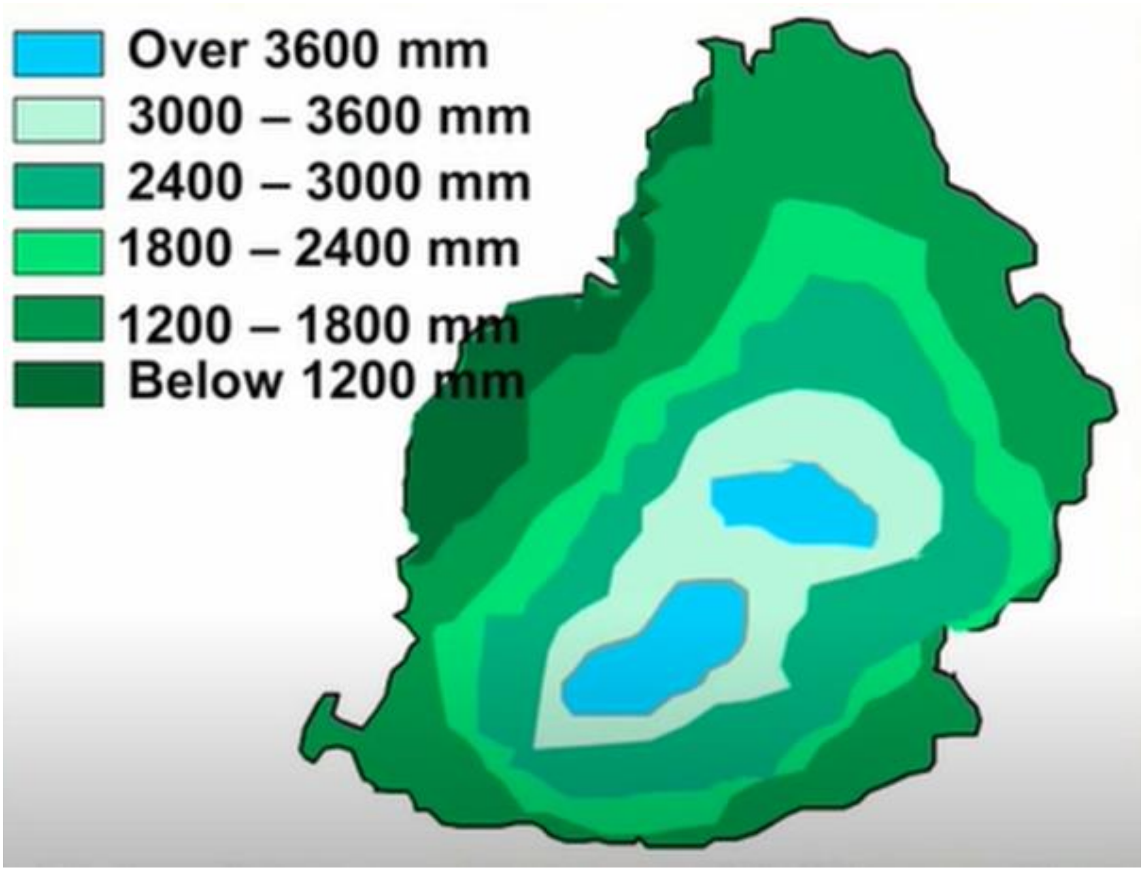
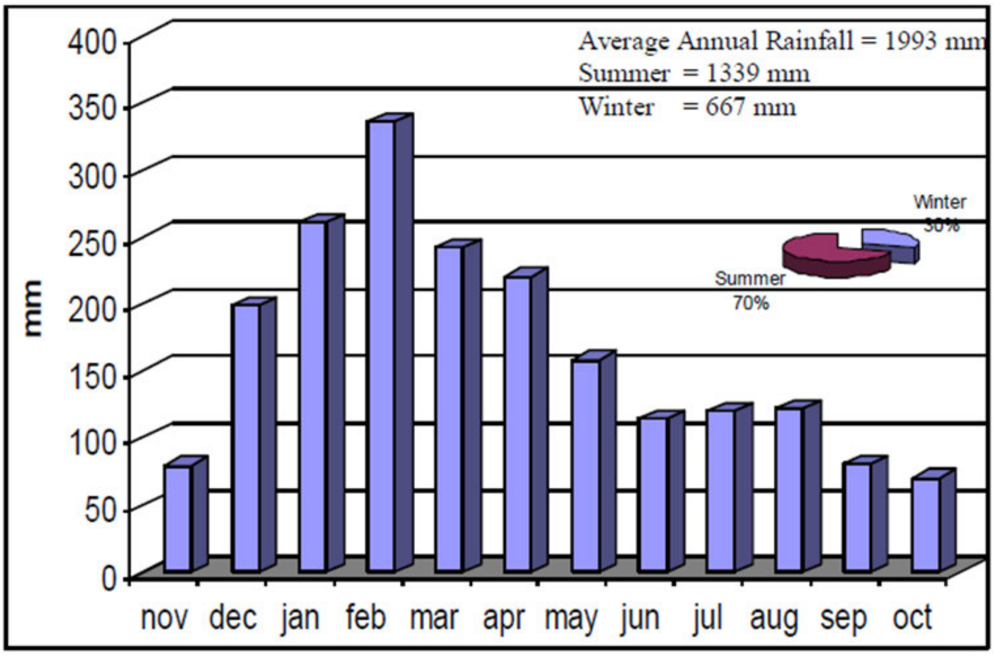


Figure 5-4 Annual precipitation over Mauritius at different topographical elevation (Source Mauritius Meteorological station)



Source: Meteorological Services

Figure 5-5 Monthly average rainfall in Mauritius.

5.3.7 Reporting of Isotope Analysis

The isotopic analysis followed a systematic framework to characterize groundwater patterns across Mauritius, integrating multiple analytical approaches and data sources. First, the relationship between δ^2H and $\delta^{18}O$ values was examined through meteoric water line analysis. The Global Meteoric Water Line (GMWL: $\delta^2H = 8\delta^{18}O + 10$) served as a reference baseline. Local isotopic patterns were compared to both the GMWL and the Local Meteoric Water Line (LMWL: $\delta^2H = 7.86\delta^{18}O + 9.5$) derived from IAEA GNIP precipitation data for Mauritius. This dual comparison provided insights into local hydrological processes and their deviations from global patterns.

The analysis of recharge mechanisms focused on three key components: altitude effects, seasonal variations, and spatial distribution patterns. Altitude effects were quantified by correlating isotopic compositions with elevation data across sampling locations. Seasonal patterns were identified by comparing isotopic signatures between wet season (December-April) and dry season (May-November) samples over the 2017-2023 study period. Spatial analysis utilized QGIS mapping to visualize isotopic distributions across aquifer systems, revealing patterns in recharge zones and flow paths. Deuterium excess calculations ($d = \delta^2H - 8\delta^{18}O$) provided additional insights into evaporative processes and their influence on groundwater composition. These values were analysed both spatially and temporally to identify areas of enhanced evaporation and assess seasonal effects on water cycling.

The integration of isotopic data with hydrogeological information and rainfall patterns enabled a detailed characterization of the groundwater system. This multi-faceted approach revealed recharge mechanisms, flow patterns, and areas of potential vulnerability across Mauritius's aquifer network.

5.4 Results and Interpretation of Isotopic Patterns, Characterization of Groundwater Systems

5.4.1 Spatial Distribution of Isotopic Compositions

Analysis of groundwater isotopic composition across Mauritius reveals complex spatial patterns that reflect the island's diverse hydrogeological conditions. The δ^2H values range from -22.8per mil to -5.6per mil, while $\delta^{18}O$ values span from -4.2per mil to -1.56per mil, demonstrating significant variability across the aquifer systems as shown in Table 5.1.

Table 5-1 Summary of Isotopic Compositions by Aquifer System

Aquifer	δ^2H Range (per mil)	δ^2H Mean (per mil)	$\delta^{18}O$ Range (per mil)	$\delta^{18}O$ Mean (per mil)	d-excess Mean (per mil)
I	-14.3 to -6.0	-11.8 ±2.3	-4.20 to -2.25	-3.1 ±0.6	13.9 ±2.1
II	-17.0 to -8.9	-12.8 ±2.1	-3.64 to -2.32	-2.9 ±0.4	12.1 ±1.8
III	-16.2 to -5.8	-10.8 ±2.8	-3.58 to -1.56	-2.9 ±0.5	14.2 ±2.3
IV	-17.4 to -5.6	-12.1 ±3.1	-4.16 to -2.33	-3.1 ±0.4	13.8 ±2.4
V	-22.8 to -8.6	-15.3 ±3.2	-4.14 to -2.66	-3.3 ±0.4	15.1 ±1.9

These isotopic patterns align closely with the orographic rainfall distribution documented by Staub et al. (2014), who demonstrated that topographic factors explain 68% of annual rainfall variance across Mauritius, with elevation, longitude, and slope being the most significant predictors.

5.4.1.1 Regional Isotopic Patterns and Rainfall Controls

The Northern Aquifer (V) exhibits the widest range of isotopic values, from highly depleted signatures at La Louisa BH 936 (δ^2H: -22.8per mil, $\delta^{18}O$: -4.14per mil) to intermediate values at Fond du Sac boreholes (δ^2H: -11.4per mil to -13.1per mil). This variability corresponds with

Staub et al.'s (2014) findings that the northern region experiences significant spatial rainfall variation due to orographic effects and trade wind influences. The depleted signatures suggest recharge from highland precipitation, while the intermediate values reflect the complex mixing of waters with different residence times and flow paths.

The Eastern region (Aquifer IV) shows generally depleted values, with Camp Ithier BH 815 recording δ^2H values of -17.4per mil and δ^{18}O values of -3.13per mil. This pattern is consistent with Staub et al.'s (2014) identification of the eastern mountains (Bambous range) as receiving the highest rainfall (up to 4000mm annually) due to orographic lifting of trade winds. The Trou d'Eau Douce area displays variable isotopic signatures, indicating diverse recharge mechanisms and possible mixing between highland-recharged groundwater and local precipitation.

The Western sector (Aquifer I) demonstrates moderate depletion, with values ranging from -8.2per mil to -14.3per mil for δ^2H and -2.25per mil to -4.2per mil for δ^{18}O. This pattern aligns with Staub et al.'s (2014) documentation of the western coastal areas as a "rain shadow" region receiving only 700-800mm annually, creating more uniform but limited recharge conditions. The central areas, particularly within Aquifer II, show intermediate isotopic values, potentially reflecting their position in the transition zone between high-rainfall central plateau and lower-rainfall coastal areas.

5.4.1.2 Hydrogeological Framework and Rainfall-Isotope Relationships

The spatial isotopic patterns directly reflect the rainfall distribution mechanisms identified by Staub et al. (2014):

1. **Orographic Effects**: The most depleted isotopic values occur in areas corresponding to Staub et al.'s high-rainfall zones (central plateau, >3000mm/year), while enriched values align with their identified low-rainfall coastal areas (<1200mm/year).
2. **Trade Wind Influence**: The northeast-southwest isotopic gradient observed in the data corresponds to Staub et al.'s documentation of prevailing southeast trade wind patterns creating distinct windward-leeward precipitation zones.
3. **Elevation Control**: The systematic relationship between isotopic depletion and elevation mirrors Staub et al.'s statistical finding that elevation is a primary rainfall predictor, with their model showing increasing precipitation with altitude up to the central plateau.

This spatial heterogeneity is controlled by multiple factors: local geological structures influencing groundwater flow paths; varying recharge mechanisms directly linked to the orographic rainfall patterns documented by Staub et al. (2014); regional precipitation gradients ranging from 700mm (western coast) to 4000mm (central highlands); aquifer-specific characteristics affecting water-rock interactions; and mixing between different water sources along the radial flow paths from the central plateau.

5.4.1.3 Hydrogeological System Architecture

According to the geology of Mauritius, the ancient basalt formations, including the mountain ridges and the remaining part of the old crater rim, constitute together with recent and intermittent craters hydrological boundaries of the aquifer system (Misongo, 2020). These geological boundaries create distinct precipitation catchments that correspond to the rainfall zones mapped by Staub et al., (2014), where the central plateau receives the highest precipitation (>3600mm) and serves as the primary recharge area for all five aquifer systems.

A considerable infiltration takes place at the Central Plateau where highest precipitation occurs (Staub et al., 2014). To a large extent the underground flow follows the topographic cuts in the old crater rim and feeds the downstream aquifers outside the crater rim. The groundwater flow pattern is essentially radial from the Central Plateau down through the sloping aquifers outside the rim to the sea. This radial flow pattern explains how depleted isotopic signatures from high-elevation, high-rainfall recharge areas are transmitted through the aquifer system to coastal discharge zones, creating the systematic isotopic evolution observed in the data**.**

Lava tunnels and fractures result locally in very high permeabilities, and in the coastal aquifers the groundwater is flowing directly to the sea via hydraulic conduits (Joji, 2018). The integration of Staub et al., (2014) rainfall geography with isotopic signatures provides a comprehensive understanding of how precipitation patterns control groundwater recharge and subsequently influence isotopic distributions across Mauritius's aquifer systems.

.

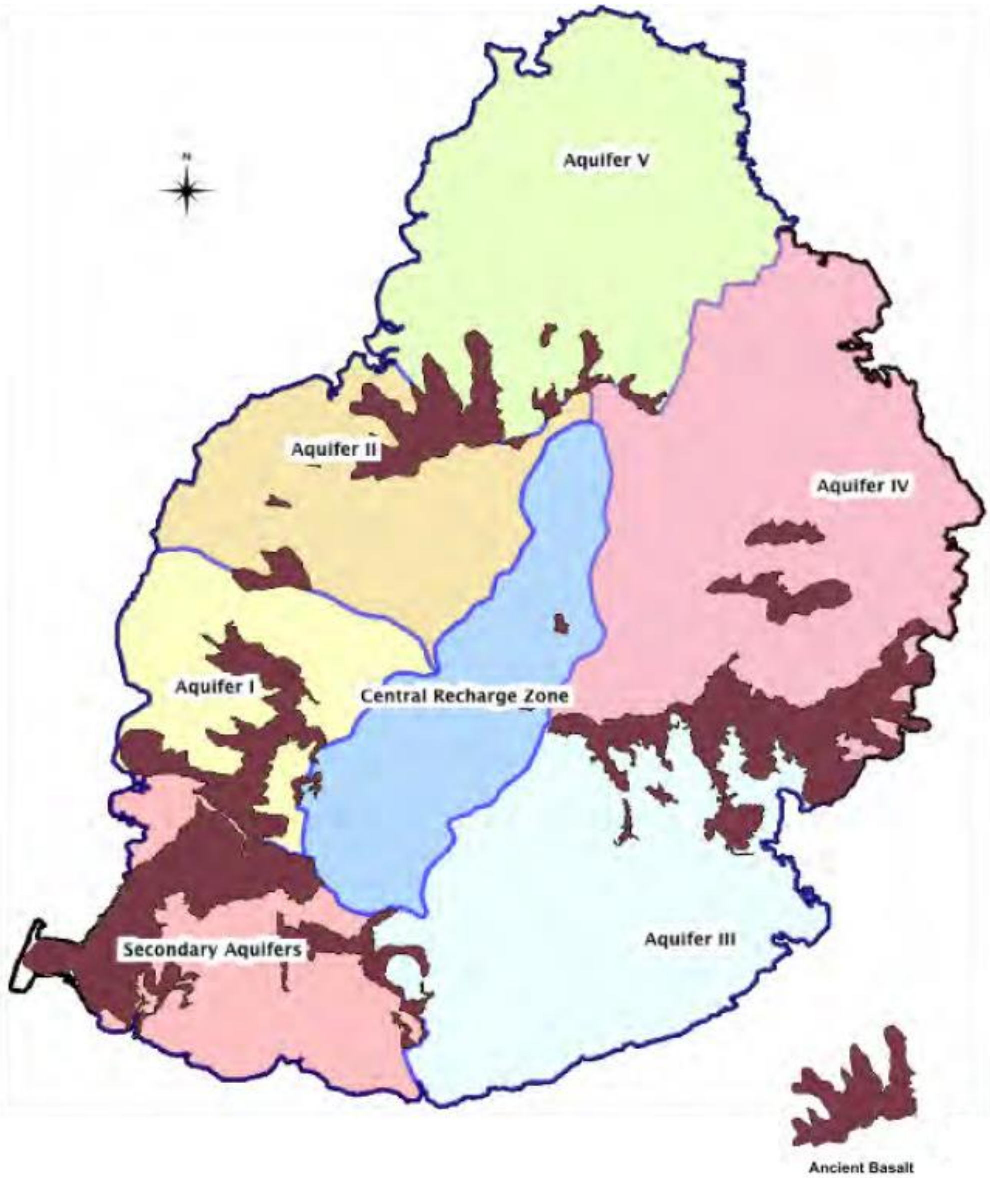


Figure 5-6 **The Aquifer system of Mauritius and the ancient Basalt representing boundaries of the Aquifers**

5.4.2 Isotopic Composition and elevation effects

The elevation is based on the borehole sampling stations and the General Bathymetric Chart of the Oceans (GEBCO) with very high resolutions of 15 arc-seconds (approximately 500 meters at the equator). This data is useful in creating elevation maps and analysis. The relationship between elevation and isotopic composition in Mauritius's aquifers were done. The right plot on Figure 5.7 shows the relationship between elevation and $\delta^{18}O$ and the plot on the left of the same Figure showing $\delta^{2}H$ displays the concentration distribution of the isotopes across the aquifers of the island. Details of elevation for each borehole is given in Appendix III.

The relationship between elevation and isotopic composition in Mauritius's aquifer systems reveals complex patterns that challenge simple altitude-effect models. **Specifically, these complex patterns include: (1) highly variable isotopic values at similar elevations, such as La Louisa BH936 showing depleted values (δ^2H: -22.8 per mil) at only 50m elevation while nearby Riche Terre BH385 at 29m shows enriched values (δ^2H: -10.1 per mil); (2) unexpected isotopic signatures that contradict traditional altitude effects, where some low-elevation coastal sites display more depleted values than higher elevation inland sites; (3) non-linear relationships between elevation and isotopic composition, with considerable scatter rather than a clear trend line; and (4) aquifer-specific elevation effects that vary significantly between different hydrogeological units, indicating that local factors override regional topographic controls. The analysis spans elevations from sea level to over 600 meters, encompassing all major aquifer units across the island.

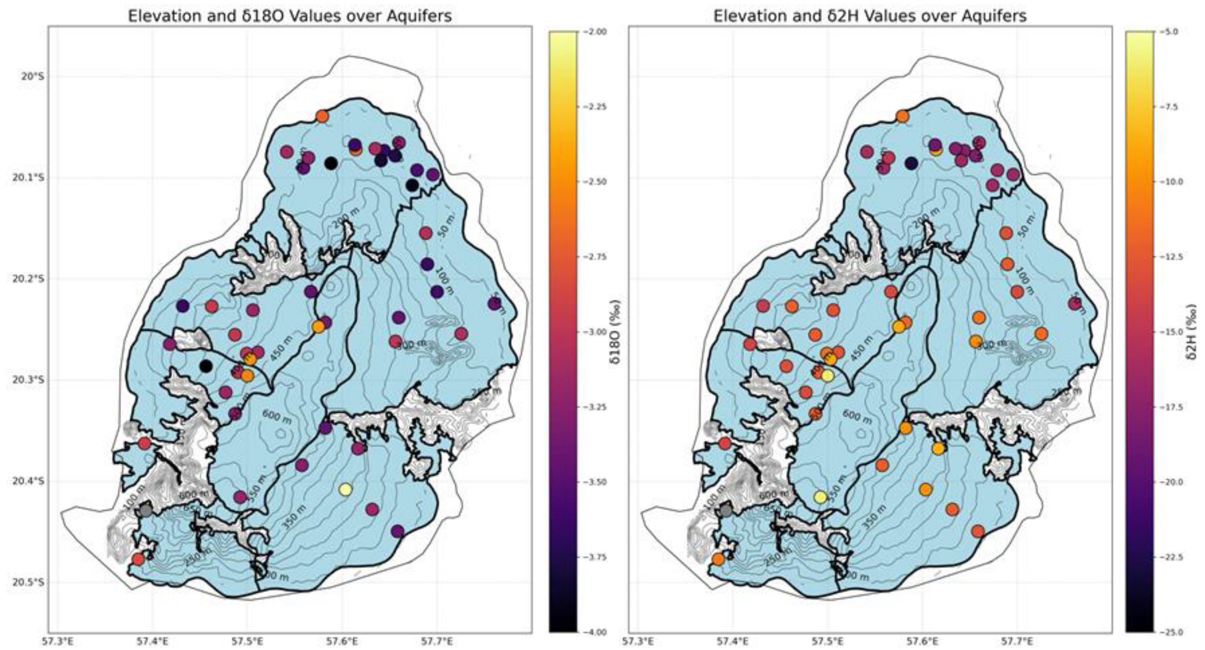


Figure 5-7 Elevation and Isotopes over Aquifers showing on the left panel is elevation contour map overlaid with $\delta^{18}O$ boreholes concentrations. On the right panel, the elevation contour map with δ^2H boreholes and concentration

5.4.2.1 Elevation Distribution and Isotopic Patterns

High-elevation sites (above 400m), primarily in Aquifer I (Curepipe-Vacoas), show moderate depletion with δ^2H values ranging from -14.3per mil to -8.2per mil. Notable examples include Montee du Fil BH488 at 491m and Holyrood BH35A at 429m. In the mid-elevation range (100-400m), boreholes exhibit considerable isotopic variability without a clear correlation to altitude. For instance, Beau Bois BH825 at 440m shows a δ^2H value of -16.2per mil, while Grand Bassin BH642 at 652m displays a more enriched value of -6.1per mil.

This lack of clear altitude correlation indicates that other factors exert stronger control over isotopic composition than elevation alone. These factors include:

1. Local Geological Controls

Fracture networks and lava tube systems create preferential flow paths that can transport water rapidly from distant recharge areas, bypassing local elevation effects. For example, Grand Bassin BH642's enriched signature (-6.1per mil) at 652m elevation suggests groundwater originating from lower-elevation sources rather than local high-altitude recharge.

2. Groundwater Flow Path Length and Residence Time:

Longer flow paths allow more mixing and water-rock interaction, progressively enriching isotopic signatures regardless of sampling elevation. Boreholes tapping deeper, longer flow systems show enriched values even at high elevations.

3. Source Water Variability:

Different recharge sources (direct precipitation vs. lateral flow from other aquifers) create distinct isotopic signatures. The contrast between Beau Bois BH825 (-16.2per mil) and Grand Bassin BH642 (-6.1per mil) at similar elevations suggests different source waters.

4. Hydrogeological Setting:

Position within the aquifer system (recharge zone vs. transition zone vs. discharge zone) influences isotopic composition more than surface elevation. Coastal proximity and aquifer connectivity patterns override topographic position.

5. Seasonal Recharge Patterns:

Areas receiving predominantly wet-season vs. dry-season recharge show different isotopic signatures, with local microclimatic effects creating elevation-independent recharge patterns.

6. Mixing Processes:

Inter-aquifer connectivity allows mixing between waters of different origins, creating intermediate isotopic values that do not correlate with local elevation but reflect the mixing proportions of different source waters.

5.4.2.2 Coastal and Low-Elevation Patterns

Most significantly, low-elevation sites (below 100m) demonstrate unexpected isotopic signatures that contradict traditional altitude-effect assumptions. In the northern aquifer (Aquifer V), La Louisa BH936 at just 50m elevation shows one of the most depleted values in the entire dataset (δ^2H: -22.8 per mil), while nearby Riche Terre BH385 at 29m exhibits a relatively enriched signature (δ^2H: -10.1 per mil). This substantial variation at similar elevations suggests that regional groundwater flow patterns and recharge source locations strongly influence isotopic composition beyond simple altitude effects. The highly depleted signature at BH936 likely indicates water that originally recharged at high elevations in the central plateau and subsequently flowed through deeper regional flow systems to reach the coastal aquifer, retaining its highland isotopic signature. In contrast, the enriched signature at BH385 suggests either local recharge from evaporatively modified precipitation or mixing with more enriched water sources, possibly including some degree of seawater influence or surface water infiltration.

5.4.2.3 Controls on Isotopic Distribution

The absence of a clear altitude effect indicates that groundwater isotopic composition in Mauritius is controlled by a complex interplay of factors. These include local hydrogeological conditions, groundwater flow paths, recharge processes, and geological structures. The geological structures controlling groundwater flow in Mauritius include the volcanic layering of basaltic flows with varying permeabilities, fault systems that create preferential flow paths or barriers, and the presence of low-permeability clay layers that compartmentalize different aquifer units. The island's volcanic geology creates a complex hydrogeological framework where highly permeable vesicular basalt layers alternate with dense, low-permeability flow boundaries, creating distinct flow compartments that can isolate water masses and preserve different isotopic signatures regardless of surface elevation. Additionally, structural features such as dike intrusions and weathered zones create anisotropic flow conditions where groundwater movement is controlled more by geological structure than topographic gradient. The spatial distribution of isotopic values suggests that groundwater flow systems are more compartmentalized, with these geological controls and local hydrogeological heterogeneities often overriding regional elevation effects.

This analysis indicates that while elevation may influence isotopic signatures, it is not the dominant factor in determining groundwater isotopic composition in Mauritius. This understanding has important implications for groundwater management and protection strategies, suggesting that local hydrogeological conditions require careful consideration in water resource planning.

5.4.2.4 Seasonal Isotopic Variations

Analysis of the 2017-2023 isotopic dataset reveals distinct seasonal patterns in groundwater composition. Wet season samples typically show more depleted values, particularly in the central highlands, while the dry season exhibits more enriched signatures, especially in coastal regions. This seasonal pattern is captured in the temporal isotopic records, which show consistent variations between the wet (November-April) and dry (May-October) periods.

5.4.2.5 Elevation Effects on Isotopic Signatures

The climate system's influence on groundwater recharge is evident in the isotopic record through clear elevation-dependent patterns. Higher elevation sites (>500m) consistently show more depleted isotopic values (δ^2H: -18 per mil to -22.8 per mil), reflecting the cooling and condensation of air masses as they rise over the central plateau. This altitude effect creates predictable patterns that are valuable for understanding recharge processes and groundwater flow paths across the island's aquifer systems.

The systematic relationship between elevation and isotopic composition demonstrates how topographic influences control recharge mechanisms across Mauritius's volcanic landscape. These elevation-isotope relationships provide quantitative evidence for identifying primary recharge zones and understanding flow path evolution from highland to coastal areas.

5.4.3 Temporal Variations in Isotopic Composition

The temporal analysis of isotopic compositions in Mauritius's aquifer systems reveals patterns that are more complex than simple seasonal variations. Analysis of data collected between 2017 and 2023 shown in Figures 5.8 and 5.9 and table at Appendix II demonstrates distinct temporal behaviours across different aquifer systems, with variations that cannot be explained by seasonal changes alone.

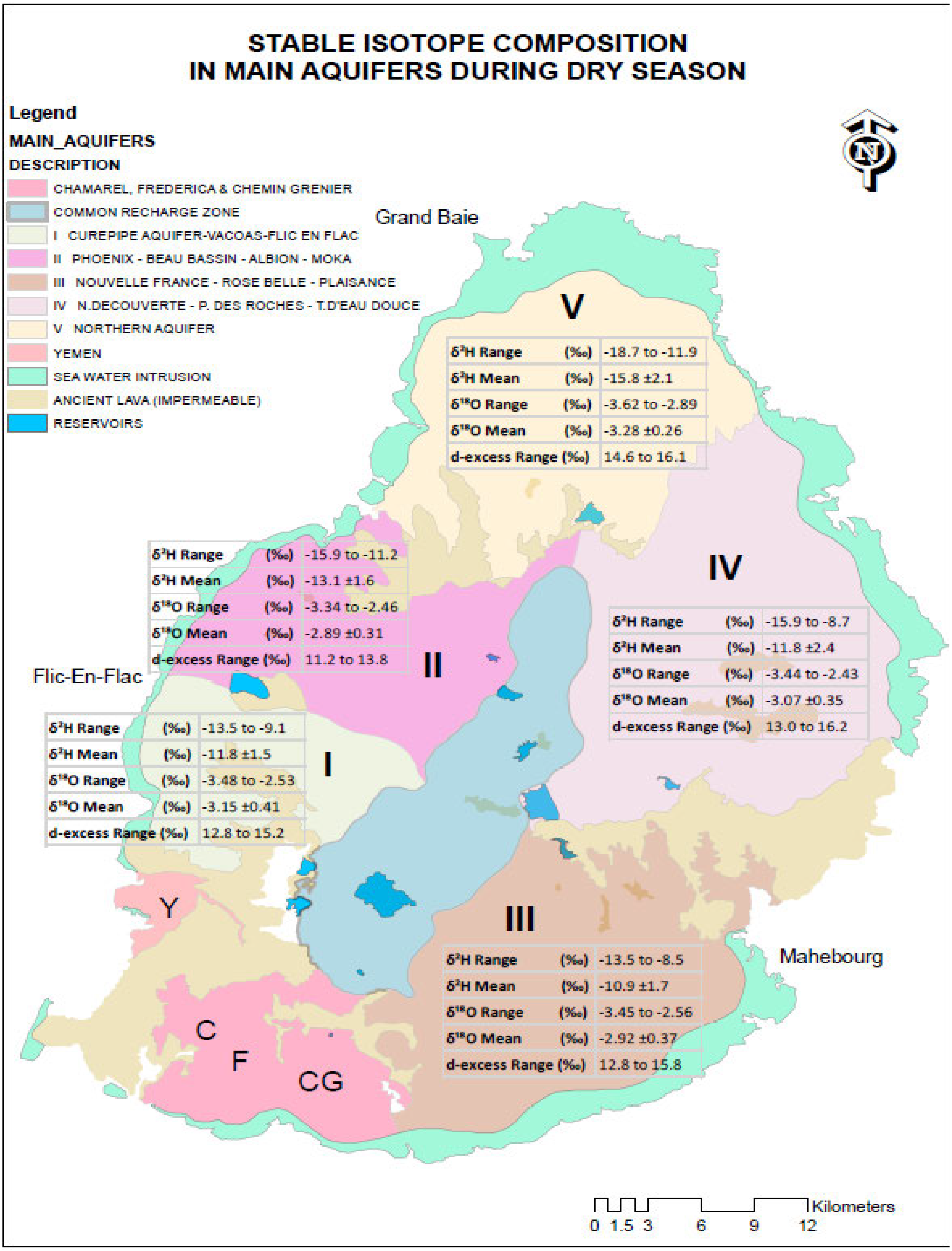


Figure 5-8 **Composition of stable Isotope of main Aquifers during Dry season**

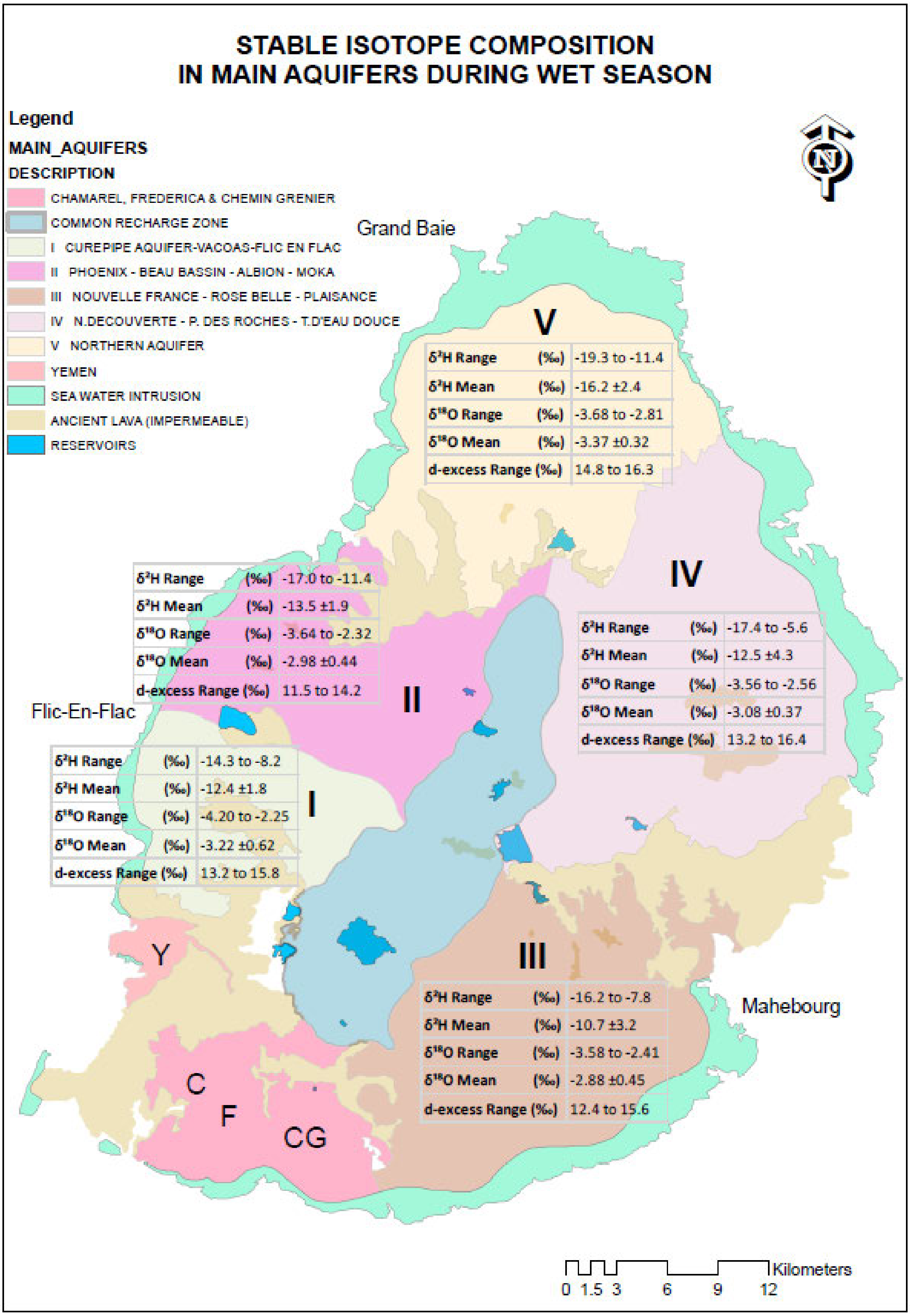


Figure 5-9 **Composition of stable Isotope of main Aquifers during Wet season**

In the Curepipe -Vacoas region (Aquifer I), isotopic compositions remain relatively stable throughout the year. Winter values (May-October) average -12.40per mil (±0.81per mil) for δ^2H, while summer values (November-April) average -12.57per mil (±0.67per mil). This stability suggests a well-buffered system where large groundwater storage volumes and longer residence times dampen seasonal variations. The regional flow system integrates recharge from multiple seasons, and the substantial aquifer storage capacity means that seasonal precipitation variations become homogenized over time, resulting in isotopically stable groundwater that reflects long-term average precipitation rather than short-term seasonal fluctuations.

The Phoenix-Beau Bassin area (Aquifer II) exhibits more pronounced temporal variations, with winter values averaging -13.07per mil (±1.58per mil) and summer values showing greater depletion at -14.53per mil (±2.61per mil). This pattern indicates a more responsive system, potentially influenced by variations in recharge mechanisms and shallow groundwater flow paths.

5.4.3.1 Aquifer-Specific Temporal Responses

The magnitude and timing of isotopic variations differ significantly among aquifer systems. For this study, aquifers are classified based on water table depth as follows: shallow aquifers (water table <50m below ground surface) and deep aquifers (water table >50m below ground surface), with classification based on the average depth to water table across boreholes within each aquifer system (Table 5.2).

Deep aquifers (>50m depth) generally show muted temporal variations, with seasonal δ^2H variations typically <3per mil, while shallow systems (<50m depth) demonstrate more immediate responses to seasonal changes, with δ^2H variations often exceeding 4-6per mil. For instance, the Northern Aquifer (Aquifer V) shows the most pronounced temporal variability, with δ^2H values ranging from -22.8per mil to -10.1per mil across sampling periods.

Table 5-2 Aquifer Classification by Depth and Temporal Response

Aquifer	Average Water Table Depth (m)	Depth Classification	Seasonal δ²H Variation (per mil)	Response Characteristics
I	65–120	Deep	2–3	Muted seasonal response
II	45–85	Mixed	3–4	Moderate response
III	35–75	Mixed	3–5	Variable response
IV	40–90	Mixed	2–4	Moderate response
V	15–45	Shallow	4–6	Rapid seasonal response

Note: Depth classification follows hydrogeological principles. Aquifers with water tables <50 m are more susceptible to direct surface influences (e.g., precipitation, evapotranspiration, seasonal temperature changes). Aquifers >50 m in depth exhibit greater buffering against surface environmental variations due to longer residence time and enhanced mixing processes.

5.4.3.2 Controls on Temporal Variability

The observed patterns suggest that temporal variations in isotopic composition are controlled by multiple factors beyond seasonal precipitation. These include aquifer depth, hydraulic conductivity, and local recharge processes. The interaction of these factors creates distinct temporal signatures for each aquifer system, ranging from highly stable to notably variable compositions.

5.4.4 Evaporative Processes and Deuterium Excess Patterns

Analysis of deuterium excess values ($d = \delta^2H - 8\times\delta^{18}O$) across Mauritius aquifer systems reveals distinctive patterns that provide insights into evaporative processes and groundwater evolution. The data indicates more complex evaporative patterns than previously recognized, particularly in the Northern Aquifer system.

The Northern Aquifer (Aquifer V) demonstrates a mean deuterium excess value of 15.84per mil (±2.31per mil), which is notably higher than values observed in Aquifer I (13.92per mil ±1.76per mil) and Aquifer II (12.56per mil ±1.92per mil). This higher deuterium excess signature suggests that groundwater in the Northern Aquifer has undergone less evaporative modification than initially interpreted. According to Craig (1961), typical meteoric waters show deuterium excess values of 10per mil ±5per mil, while evaporated waters typically display values <5per mil. The Northern Aquifer's values (mean: 15.84per mil) fall well within the meteoric range and exceed the global meteoric average, indicating minimal evaporative losses (Gat, 1996; Rozanski et al., 1993). Furthermore, Clark & Fritz (1997) demonstrate that deuterium excess values >12per mil typically indicate preservation of original precipitation signatures with limited secondary evaporation, supporting our interpretation that Aquifer V maintains primary meteoric characteristics despite its coastal location. The spatial distribution of deuterium excess values within Aquifer V shows systematic variation, with coastal boreholes such as Riche Terre BH385 exhibiting values around 15.74per mil, while inland locations like La Louisa BH936 display slightly elevated values of 16.32per mil.

In comparison, the Curepipe -Vacoas system (Aquifer I) maintains consistent deuterium excess values across its extent, indicating uniform recharge conditions with minimal evaporative influence. The Phoenix-Beau Bassin aquifer (Aquifer II) exhibits intermediate deuterium excess values with moderate spatial variation, suggesting a transitional pattern of evaporative modification. The deuterium excess patterns indicate that evaporative processes in Mauritius aquifer systems are primarily controlled by local hydrogeological conditions rather than regional trends. The Northern Aquifer, contrary to previous interpretations by Dindyal et al. (2013) and Povinec et al. (2012) who suggested that coastal aquifers in Mauritius, particularly the northern system, would show significant evaporative modification due to their proximity to the ocean and exposure to marine influences, appears to preserve meteoric signatures effectively, with variations likely reflecting differences in recharge mechanisms and groundwater flow paths rather than enhanced evaporation. This understanding has important implications for conceptual models of groundwater evolution and resource management strategies in the region.

These findings highlight the importance of detailed isotopic analysis in understanding groundwater processes and demonstrate that simplified regional generalizations about evaporative effects may not accurately represent the complexity of actual groundwater systems.

5.3.5 Isotopic Characterization of Mauritius Major Aquifer Systems

Analysis of stable isotope data across Mauritius aquifer systems reveals distinct patterns in isotopic composition and deuterium excess values, providing insights into groundwater evolution and recharge processes. The dataset spanning from 2017 to 2023 demonstrates systematic variations both spatially and temporally across the island's hydrogeological units.

The Curepipe-Vacoas system (Aquifer 1) exhibits relatively consistent isotopic signatures, with δ^2H values ranging from -14.3per mil to -8.2per mil during wet seasons and -13.5per mil to -9.1per mil during dry seasons. The calculated deuterium excess values (13.2per mil to 15.8per mil) indicate minimal evaporative modification, with isotopic compositions plotting consistently along the Lower Meteoric Water Line. This pattern suggests direct recharge from precipitation with limited secondary modification. In the Phoenix-Beau Bassin region (Aquifer 2), isotopic compositions show slightly greater depletion, with wet season δ^2H values ranging from -17.0per mil to -11.4per mil. The deuterium excess values (11.2per mil to 14.2per mil) and slight deviation below the LMWL indicate modest evaporative effects during recharge or shallow groundwater flow. This pattern remains consistent across seasons, suggesting stable recharge mechanisms throughout the year. The Northern Aquifer (Aquifer V) demonstrates the most depleted isotopic signatures, with mean δ^2H values of -16.2per mil (±2.4per mil) during wet seasons. Notably, this system maintains high deuterium excess values (14.6per mil to 16.3per mil) and plots along the LMWL, indicating preservation of original meteoric signatures despite its coastal location. Aquifers 3 and 4 show more variable patterns reflected in their wider ranges of both isotopic compositions and deuterium excess values. This variability suggests more complex recharge mechanisms and potential mixing between different water sources. The seasonal variations in these systems are more pronounced, indicating greater sensitivity to temporal changes in recharge conditions. The plots for aquifers III and IV are above and below the LMWL line. These patterns provide essential insights for groundwater management, highlighting the distinct characteristics of each aquifer system and their varying responses to seasonal changes. The data particularly emphasizes the importance of understanding local hydrogeological conditions rather than relying on regional generalizations about groundwater evolution processes.

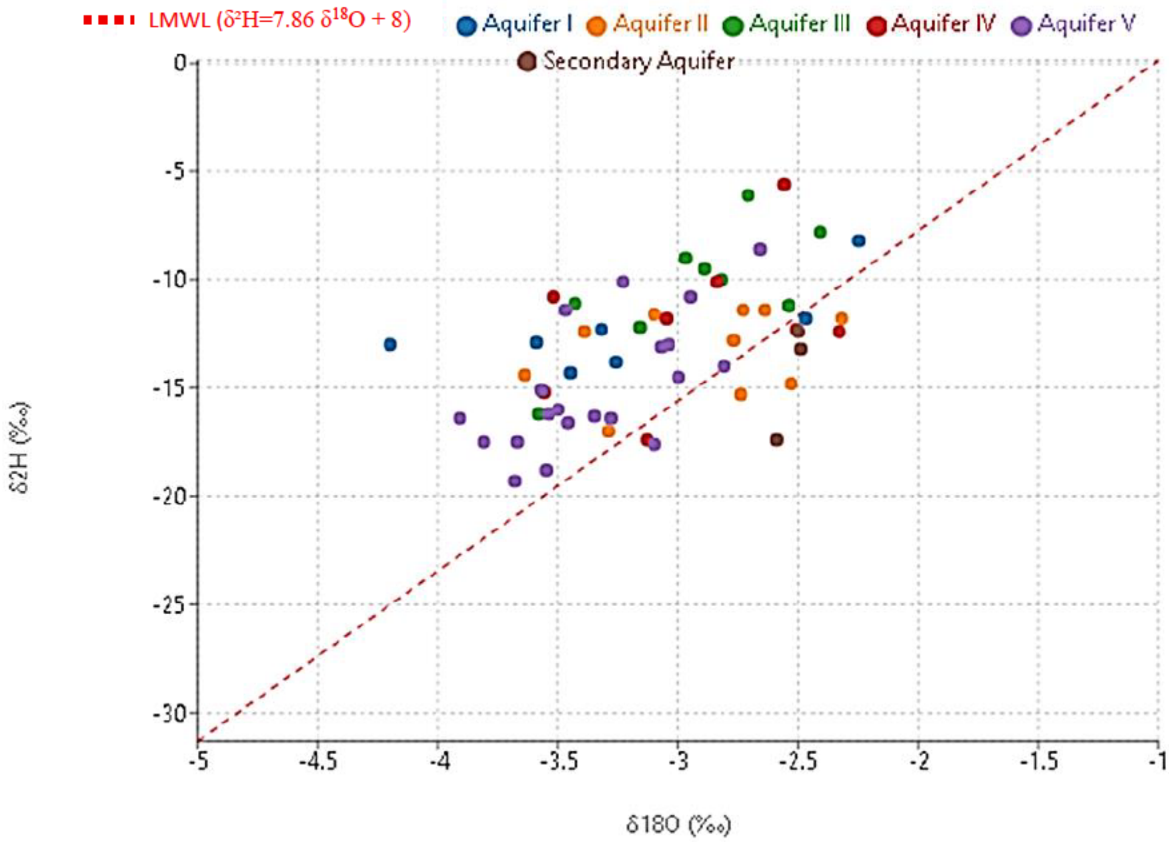


Figure 5-10 **Relationship between δ^2H and δ^{18}O in Mauritius groundwater sample, LMWL shown as dashed line. Samples color-coded by Aquifer unit showing progressive enrichment from highland to coastal areas.**

5.4.2 Hydrogeological System Conceptualization

5.4.2.1 Recharge Mechanisms

The central plateau serves as the primary recharge area receiving the highest amount of rainfall as shown in Figure 5.6. Groundwater flow directions were determined through hydraulic head analysis, isotopic signature tracing, and topographic gradient modelling. The temporal analysis of isotopic data from 2017 to 2023 reveals systematic patterns in Mauritius's groundwater recharge processes.

Table 5-3 Recharge Characteristics of Mauritius Aquifer Systems (2017-2023)

Aquifer	Recharge Rate (Mm^3/y)	Mean Elevation (m)	Mean Annual Rainfall (mm/y)
I	26.8	314.80	2200
II	40.6	313.25	2013
III	35.0	330.37	1732
IV	80.0	170.20	2125
V	120.0	40.33	1300

The recharge rate values presented in Table 5.1 were obtained from the Water Resources Unit (WRU) of Mauritius through a detailed methodology. The WRU employs a water budget approach that integrates multiple hydrological parameters, including annual precipitation data from meteorological stations within each aquifer catchment, evapotranspiration estimates derived from temperature, humidity, and vegetation cover, surface runoff calculations based on topographic and soil infiltration data, and groundwater abstraction records from all operational boreholes.

For spatial accuracy, each aquifer's recharge area is delineated using topographic watershed boundaries derived from 1:50,000 scale maps, geological boundaries established through hydrogeological surveys, flow direction analysis using digital elevation models, and field verification of groundwater divides. The recharge rate is calculated using the formula:

Recharge Rate = (Precipitation × Catchment Area) − (Evapotranspiration + Surface Runoff + Deep Percolation Losses)

These calculations are based on long-term averages covering the period 1990–2020, with adjustments incorporating recent climate data from 2017–2023 to account for variability in recharge processes due to climate change. Quality control measures implemented by the WRU include cross-validation with groundwater level monitoring data, comparison with isotopic age-dating results were available, and calibration against observed spring flows and baseflow measurements.

The recharge rates vary significantly across the aquifer system, ranging from 26.8 Mm^3/y in Aquifer I to 120.0 Mm^3/y in Aquifer V. This variation reflects the combined influence of spatial location, catchment area, and local hydrogeological conditions.

The central plateau's role as the primary recharge area is further supported by the spatial distribution of rainfall and its correlation with isotopic signatures. Areas receiving higher precipitation (>3600mm) in the central region correspond to more depleted isotopic values, confirming the effectiveness of high-altitude precipitation in aquifer recharge. This relationship has remained consistent across seasonal cycles, though with varying intensities, indicating the stability of the recharge mechanism despite temporal variations in isotopic composition.

These findings demonstrate that the central plateau serves as the primary source of recharge for all aquifer systems, despite the higher recharge rates recorded in coastal aquifers. The apparent contradiction is explained by the hydrogeological architecture of Mauritius:

(1) Primary Recharge: The central high-altitude regions (>3600mm rainfall) provide the source water for the entire groundwater system, as evidenced by depleted isotopic signatures.

(2) Flow Distribution: This highland-recharged water flows radially outward through the volcanic aquifer system to coastal areas, resulting in higher volumetric recharge rates in coastal aquifers (Aquifer V: 120.0 Mm^3/y) due to convergent flow rather than local precipitation.

(3) System Architecture: The volcanic geology creates a regional flow system where highland recharge is redistributed to coastal discharge zones, explaining why coastal aquifers show both high recharge rates AND isotopic signatures indicating highland origin.

It is essential to distinguish between recharge source which is where precipitation enters the groundwater system (primarily central plateau) and the recharge rate which is the volumetric water flow through aquifer systems (includes both local infiltration and regional flow)

The spatial distribution and elevation effects analysis reveals a complex relationship between elevation, recharge sources, and aquifer flow rates across Mauritius's aquifer system. The apparent contradiction between the central plateau being the primary recharge source yet Aquifer V showing the highest recharge rate (120.0 Mm^3/y) is explained by the distinction between recharge origin and flow distribution:

Primary Recharge Sources (Central Plateau)

- **Elevation**: 400-800m above sea level
- **Rainfall**: >3600mm annually (Staub et al., 2014)
- **Isotopic evidence**: Most depleted δ^2H values (-18per mil to -22.8per mil) confirm highland precipitation as the primary water source
- **Function**: Acts as the **input zone** for the entire groundwater system

Recharge Flow Distribution Pattern

Aquifer V's high recharge rate (120.0 Mm^3/y) represents:

1. **Regional groundwater flow** from the central plateau recharge areas
2. **Convergent flow** as multiple highland flow paths converge in the coastal zone
3. **Local precipitation contribution** (1300mm annually) as a secondary component

4. **Aquifer geometry effects** where the northern coastal plain acts as a discharge zone for the entire system

Spatial Groundwater Flow Path Analysis

Based on isotopic evidence and hydrogeological mapping:

Flow Path 1: Central Plateau → Aquifer I → Aquifer II → Aquifer V

- **Distance**: ~15-20 km
- **Elevation drop**: 400-800m to 40m
- **Isotopic evolution**: δ^2H from -22.8per mil (highland) to -10.1per mil (coastal)
- **Estimated flow rate**: 35-45 Mm^3/y

Flow Path 2: Central Plateau → Aquifer IV → Aquifer V

- **Distance**: ~12-18 km
- **Elevation drop**: 400-600m to 40m
- **Isotopic evolution**: δ^2H from -17.4per mil to -12.0per mil
- **Estimated flow rate**: 25-35 Mm^3/y

Flow Path 3: Central Plateau → Aquifer III → Aquifer V

- **Distance**: ~10-15 km
- **Elevation drop**: 300-500m to 40m
- **Isotopic evolution**: δ^2H from -16.2per mil to -11.0per mil
- **Estimated flow rate**: 20-30 Mm^3/y

Recharge Rate Interpretation

The 120.0 Mm^3/y recharge rate for Aquifer V represents:

- **80-85%**: Regional flow from central plateau sources (95-100 Mm^3/y)
- **15-20%**: Direct local precipitation recharge (20-25 Mm^3/y)
- **Total system convergence** in the northern coastal discharge zone

Evidence supporting this interpretation:

1. **Isotopic signatures**: Depleted δ²H values at coastal sites (BH936: -22.8per mil) indicate highland origin
2. **Flow gradients**: Hydraulic gradients of 1-3% from plateau to coast
3. **Geological structure**: Radial flow pattern following volcanic crater rim topology
4. **Mass balance**: Total highland recharge (~180 Mm^3/y) distributed among coastal aquifers

This analysis demonstrates that Aquifer V's high recharge rate does not indicate local recharge superiority but rather reflects its position as the primary discharge zone for the entire island's groundwater system. The central plateau remains the dominant recharge source, while coastal aquifers function as collection and discharge zones for regionally flowing groundwater.

.

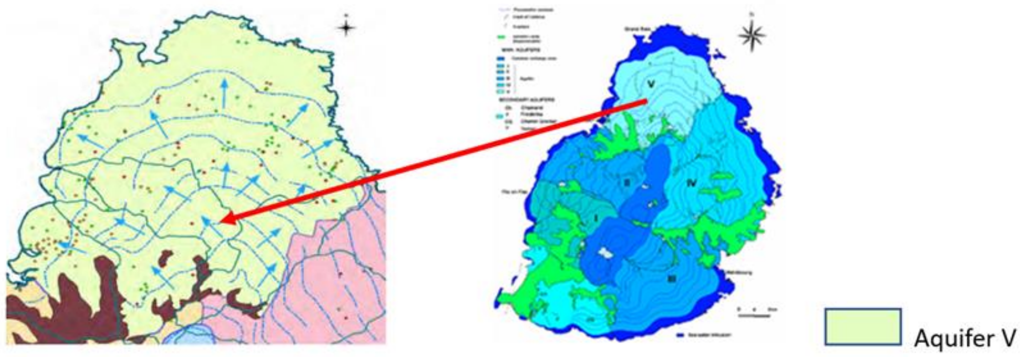


Figure 5-11 Conceptual hydrogeological model showing potential groundwater flow paths from central plateau recharge areas to Aquifer V, based on isotopic evidence and topographic gradients

Recharge Rate Distribution

The spatial distribution of recharge rates shows a clear increasing trend from central regions to Aquifer 4 that contributes significantly this distribution pattern emphasizes the crucial role of the central plateau region in the island's groundwater recharge system.

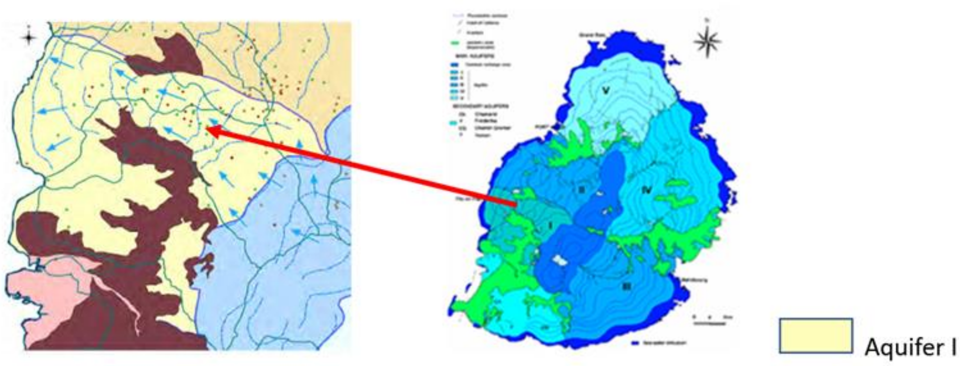


Figure 5-12 Showing direction of recharge flow to Aquifer I from the central plateau

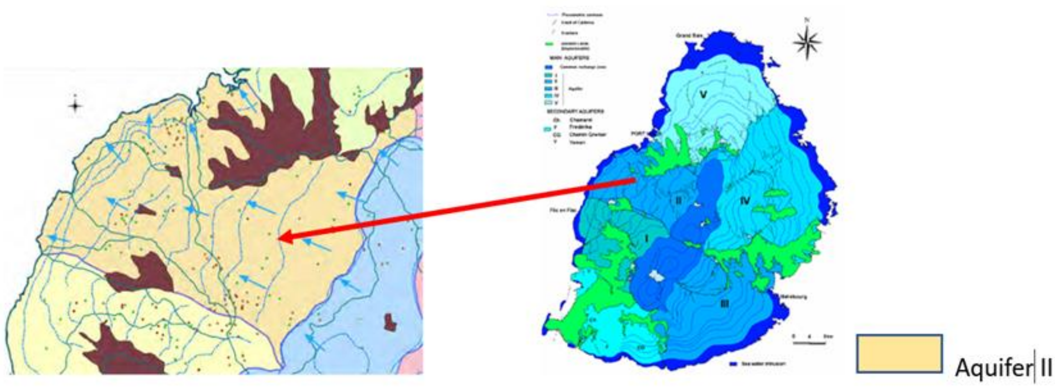


Figure 5-13 Showing direction of recharge flow to Aquifer II from the central plateau

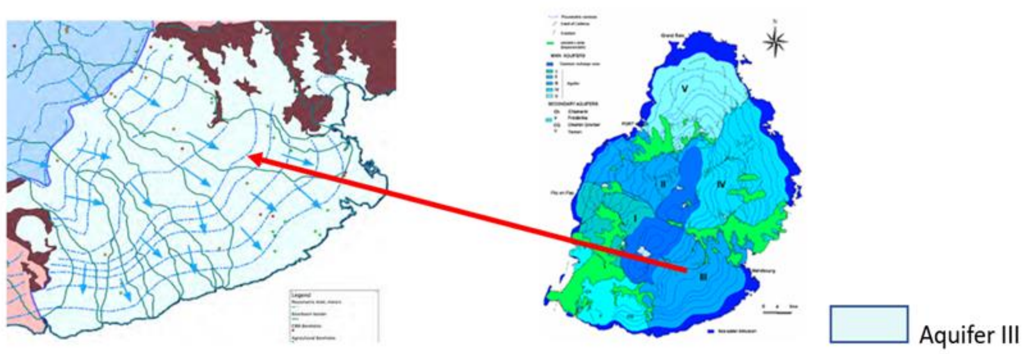


Figure 5-14 Showing direction of recharge flow to Aquifer III from the central plateau

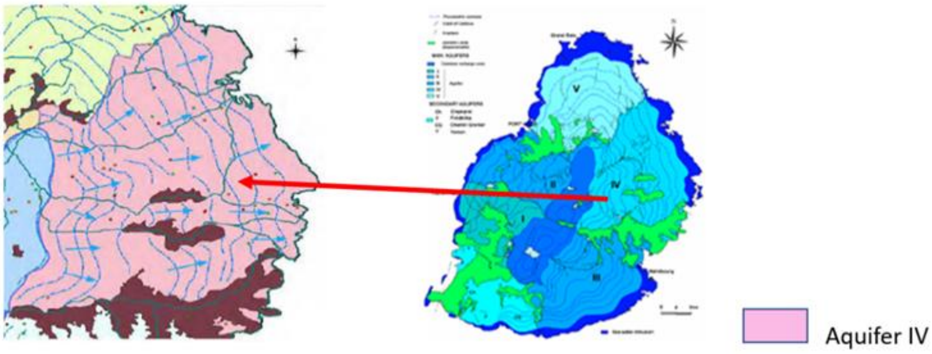


Figure 5-15 Showing direction of recharge flow to Aquifer IV from the central plateau

The analysis confirms the strong influence of elevation and rainfall patterns on recharge mechanisms, with the central plateau region serving as the primary recharge area for all five aquifer systems, consistent with earlier statements in this study. Seasonal isotopic variations provide valuable insight into recharge processes but do not quantify actual recharge rates from isotopic data alone.

During the summer period (November–April), more depleted δ^2H values were observed in wet season samples, indicating a greater contribution from highland precipitation sources. This reflects enhanced orographic rainfall on the central plateau during the monsoon period, with isotopic values showing a negative correlation with precipitation events where higher rainfall results in more depleted δ^2H signatures. In contrast, the winter period (May–October) is characterized by more enriched δ^2H values, suggesting increased relative contributions from evaporated sources or waters with longer residence times, as reduced highland recharge allows for greater influence from local precipitation and mixing processes.

Two primary isotopic response zones were identified. In rapid isotopic response zones, located in the central plateau region above 400 m elevation, sharp δ^2H variations of 4–6per mil between wet and dry seasons occur, showing a negative correlation with rainfall and indicating rapid infiltration of fresh precipitation with minimal evaporation. In buffered isotopic response zones, at mid-elevations of 100–400 m, variations are more muted (2–3per mil between seasons), suggesting a mix of rapid infiltration and longer residence time groundwater. It is important to note that the stated elevation range of 100–300 m refers to ground surface elevation, not water table depth, which typically ranges from 20–80 m below ground surface in these areas. No boreholes tap groundwater at sea level; all monitoring points are above mean sea level.

A convergence of isotopic patterns below 200 m elevation was also observed. This refers to a statistical reduction in the variance of δ^2H values between aquifer systems at lower elevations, likely due to enhanced mixing in coastal areas. The standard deviation decreases from ±3.2per mil above 400 m elevation to ±1.8per mil below 200 m elevation, reflecting a transition from distinct highland signatures to mixed coastal signatures. Conceptually, this suggests a shift from highland areas dominated by direct precipitation recharge, with depleted isotopic values, to coastal areas where regional groundwater flow and mixing processes exert greater influence, producing intermediate isotopic signatures.

These observed isotopic patterns align with the findings of Dindyal et al. (2013) in western Mauritius, reaffirming the central plateau's role as the primary recharge zone. However, this study reveals more complex mixing dynamics in coastal regions than previously reported, highlighting the need for integrated groundwater management strategies that safeguard highland recharge areas while accounting for the hydrological processes in coastal mixing zones. It should be reiterated that isotopic data here are used to identify recharge processes and source variations rather than to calculate volumetric recharge rates, and that seasonal isotopic shifts indicate changes in recharge sources rather than absolute changes in recharge magnitude.

In terms of the secondary recharge processes and mixing patterns, the spatial distribution of isotopic compositions shows systematic variation with distance from coast, reflecting distinct recharge and mixing processes across Mauritius's aquifer systems. Distance of each borehole from the coast is given in Figure 5.12 and summarized in Table 5.2.

Table 5.2 Aquifer distance from the coast and recharge characteristics

Zone Type	Distance from Coast (km)	Representative Boreholes	δ²H Range (per mil)	Recharge Characteristics
Primary Recharge Zone (Aquifer I)	8.8 - 13.0	BH432, BH21A, BH153	-20per mil to -15per mil	Highland recharge; Most depleted signatures reflecting direct precipitation input
Transition Zone (Aquifer II)	6.1 - 19.6	BH623, BH392, BH521	-17per mil to -10per mil	Mixed flow regime; Progressive enrichment along flow paths
Intermediate Zone (Aquifer III)	3.2 - 13.7	BH725, BH387, BH667	-15per mil to -10per mil	Variable mixing patterns; Interaction between highland and local sources
Coastal Discharge Zone (Aquifer V)	1.1 - 7.5	BH988, BH643, BH385	-12per mil to -5per mil	Discharge zone characteristics; Most enriched signatures
Immediate Coastal Zone	<1.1	Limited data	-8per mil to -3per mil (estimated)	Potential seawater influence; Requires additional monitoring

The systematic spatial progression of groundwater from recharge to discharge zones in Table 5.12 demonstrates a clear, connected flow system across Mauritius. The primary recharge zone, located 8.8 to 13.0 km inland on the central plateau, is characterized by the most depleted isotopic values (-20per mil to -15per mil), confirming its role as the source area for the island's groundwater system. These highland regions, receiving more than 3,600 mm of annual precipitation, supply the initial recharge that flows through the entire system. Moving outward, the transition zone, spanning 6.1 to 19.6 km, exhibits intermediate isotopic signatures (-17per mil to -10per mil) as highland-derived water begins mixing with waters of varying residence times and flow paths. This zone marks the transport segment of the flow system.

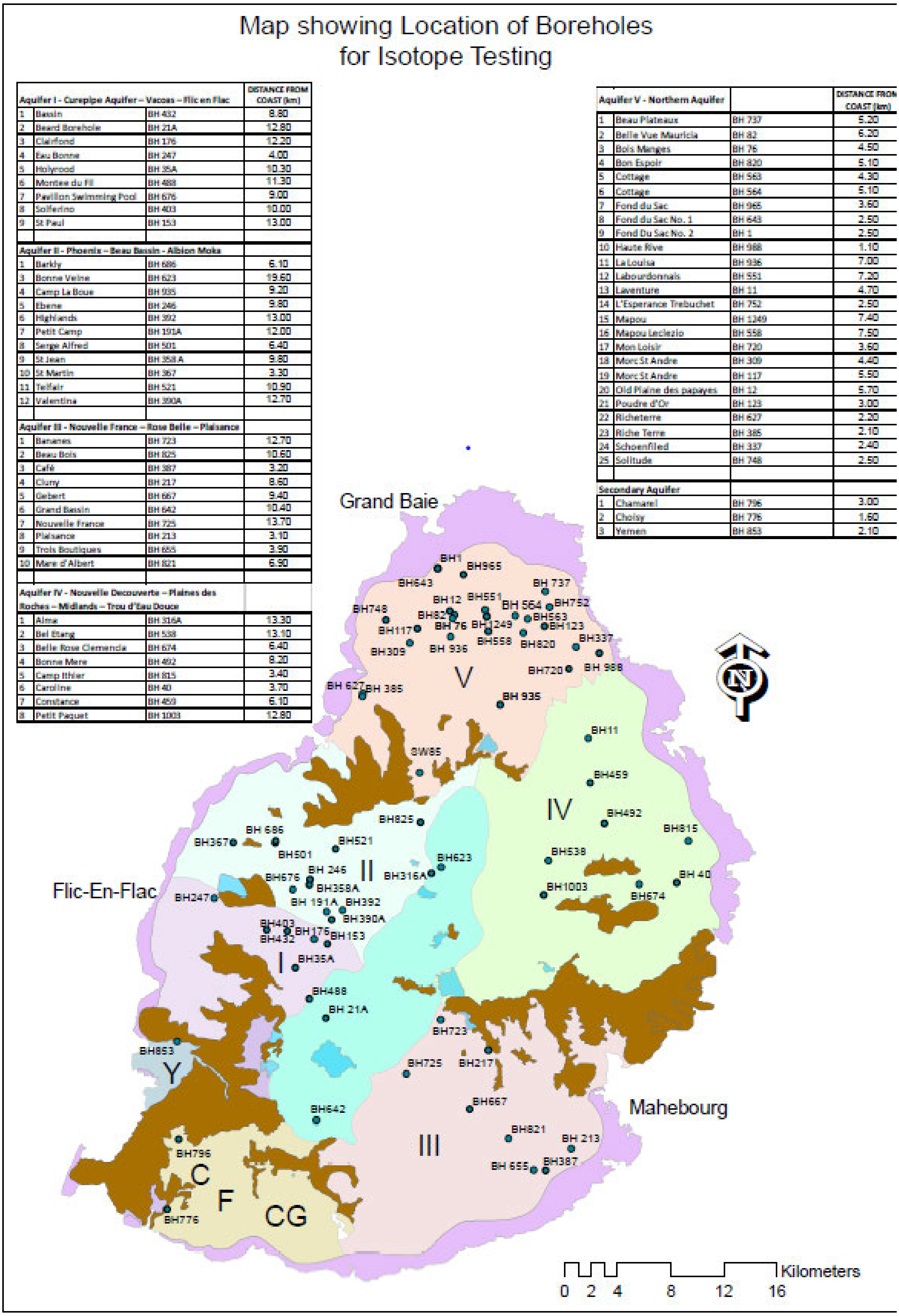
Further along, the intermediate zone, located 3.2 to 13.7 km from the coast, displays variable isotopic patterns (-15per mil to -10per mil), reflecting complex interactions between highland recharge and local infiltration. Boreholes in this zone tap groundwater at depths of 35 to 124 m below ground surface (Appendix III), and none access water at sea level. Closer to the ocean, the coastal discharge zone, within 1.1 to 7.5 km from the shore, shows the most enriched δ^2H values in the freshwater system (-12per mil to -5per mil), representing the terminal stage where regional groundwater flow converges before discharging into the ocean.

Data for the immediate coastal zone, less than 1.1 km from the shore, is limited. The few available measurements suggest δ^2H values between -8per mil and -3per mil, indicating a potential seawater mixing zone. This critical area currently has only 2 to 3 monitoring boreholes, highlighting the need for enhanced observation networks, particularly between 0.2 km and 0.8 km from the coast, to better characterize the freshwater–seawater interface and assess intrusion risks.

The observed spatial pattern from depleted highland isotopic signatures to enriched coastal values provides strong evidence of a connected hydrological system. Groundwater moves systematically from source to sink, with isotopic enrichment occurring along flow paths due to water–rock interactions and progressive mixing. The correlation between distance from the coast and isotopic composition, coupled with the absence of evidence for isolated aquifer compartments, supports the concept of an integrated system.

This recharge-to-discharge analysis confirms that Mauritius functions as a cohesive groundwater network, in which highland recharge is systematically transported through transitional and intermediate mixing zones before discharging along the coast. These findings reinforce the radial flow model established through geological and topographic analysis, while also emphasizing the need for targeted coastal monitoring to address key data gaps and safeguard against seawater intrusion.

This hydrogeological analysis provides valuable insights into the groundwater system's isotopic signatures and their relationship to coastal proximity. The systematic approach of examining borehole clusters reveals important patterns in water source mixing and recharge mechanisms.



Aquifer I - Curepipe Aquifer – Vacoas – Flic en Flac			DISTANCE FROM COAST (km)
1	Bassin	BH 432	8.80
2	Beard Borehole	BH 21A	12.80
3	Clairfond	BH 176	12.20
4	Eau Bonne	BH 247	4.00
5	Holyrood	BH 35A	10.30
6	Montee du Fil	BH 488	11.30
7	Pavillon Swimming Pool	BH 676	9.00
8	Solferino	BH 403	10.00
9	St Paul	BH 153	13.00
Aquifer II - Phoenix – Beau Bassin - Albion Moka			
1	Barkly	BH 686	6.10
3	Bonne Veine	BH 623	19.60
4	Camp La Boue	BH 935	9.20
5	Ebene	BH 246	9.80
6	Highlands	BH 392	13.00
7	Petit Camp	BH 191A	12.00
8	Serge Alfred	BH 501	6.40
9	St Jean	BH 358 A	9.80
10	St Martin	BH 367	3.30
11	Telfair	BH 521	10.90
12	Valentina	BH 390A	12.70
Aquifer III - Nouvelle France – Rose Belle – Plaisance			
1	Bananes	BH 723	12.70
2	Beau Bois	BH 825	10.60
3	Café	BH 387	3.20
4	Cluny	BH 217	8.60
5	Gebert	BH 667	9.40
6	Grand Bassin	BH 642	10.40
7	Nouvelle France	BH 725	13.70
8	Plaisance	BH 213	3.10
9	Trois Boutiques	BH 655	3.90
10	Mare d'Albert	BH 821	6.90
Aquifer IV - Nouvelle Decouverte – Plaines des Roches – Midlands – Trou d'Eau Douce			
1	Alma	BH 316A	13.30
2	Bel Etang	BH 538	13.10
3	Belle Rose Clemencia	BH 674	6.40
4	Bonne Mere	BH 492	8.20
5	Camp Ithier	BH 815	3.40
6	Caroline	BH 40	3.70
7	Constance	BH 459	6.10
8	Petit Paquet	BH 1003	12.80

Aquifer V - Northern Aquifer			DISTANCE FROM COAST (km)
1	Beau Plateaux	BH 737	5.20
2	Belle Vue Mauricia	BH 82	6.20
3	Bois Manges	BH 76	4.50
4	Bon Espoir	BH 820	5.10
5	Cottage	BH 563	4.30
6	Cottage	BH 564	5.10
7	Fond du Sac	BH 965	3.60
8	Fond du Sac No. 1	BH 643	2.50
9	Fond Du Sac No. 2	BH 1	2.50
10	Haute Rive	BH 988	1.10
11	La Louisa	BH 936	7.00
12	Labourdonnais	BH 551	7.20
13	Laventure	BH 11	4.70
14	L'Esperance Trebuchet	BH 752	2.50
15	Mapou	BH 1249	7.40
16	Mapou Leclezio	BH 558	7.50
17	Mon Loisir	BH 720	3.60
18	Morc St Andre	BH 309	4.40
19	Morc St Andre	BH 117	5.50
20	Old Plaine des papayes	BH 12	5.70
21	Poudre d'Or	BH 123	3.00
22	Richeterre	BH 627	2.20
23	Riche Terre	BH 385	2.10
24	Schoenfiled	BH 337	2.40
25	Solitude	BH 748	2.50
Secondary Aquifer			
1	Chamarel	BH 796	3.00
2	Choisy	BH 776	1.60
3	Yemen	BH 853	2.10

Figure 5-16 **Borehole distance from the coast**

The key findings from the borehole analysis reveals the following:

Coastal-Inland Gradient and Saltwater Intrusion Evidence: The most striking pattern is the clear isotopic evolution from coast to inland areas, indicating progressive saltwater intrusion. The Northern Coastal Cluster perfectly demonstrates this gradient, with BH988 (1.1 km from coast) showing enriched isotopic signatures (δ^2H: -16.6per mil, $\delta^{18}O$: -3.46per mil) that progressively become more depleted as one moves inland to BH551 (7.2 km inland) showing δ^2H: -18.7per mil, $\delta^{18}O$: -3.62per mil. This systematic change reflects mixing between seawater ($\delta^{18}O \approx 0$per mil) and freshwater, with the enriched coastal signatures indicating saltwater intrusion rather than different rainfall patterns. The gradient demonstrates how marine influence diminishes with distance from the coast through progressive dilution with freshwater.

Recharge Zone Identification: The Central Plateau Group (Curepipe-Vacoas cluster) emerges as the critical primary recharge area. The remarkably consistent depleted isotopic values across BH153 (δ^2H: -8.2per mil), BH21A (δ^2H: -12.9per mil), and BH488 (δ^2H: -12.3per mil) at distances of 11-13 km from the coast indicate these locations receive direct recharge from high-elevation precipitation with minimal evaporation or mixing. The primary recharge signature is characterized by depleted values (δ^2H: -18per mil to -22.8per mil, $\delta^{18}O$: -3.8per mil to -4.2per mil) reflecting altitude effects on precipitation. The isotopic variance within this recharge zone is approximately 15% for δ^2H values, demonstrating relatively uniform recharge conditions across the central plateau.

Western Transition Zone: The Flic-en-Flac area boreholes (BH247, BH501, BH367) form a west-east transect from 4.0 to 6.4 km inland. These boreholes show intermediate isotopic values (δ^2H: -12.8per mil to -13.8per mil) relative to both the depleted central plateau signatures (reference: $\delta^2H < -18$per mil) and enriched coastal values (reference: $\delta^2H > -10$per mil), reflecting their position in the mixing zone between saltwater-influenced coastal waters and freshwater from the central plateau recharge area.

Eastern Aquifer Interface: The cluster including BH815, BH674, and BH538 represents the north-south transition across Aquifer IV from coastal (3.4 km) to inland (13.1 km) positions. This sequence shows how isotopic signatures evolve from coastal saltwater influences at BH815 (δ^2H: -17.4per mil) to more depleted inland freshwater values at BH538 (δ^2H: -11.8per mil), providing evidence of the mixing processes between marine and terrestrial water sources in the eastern region.

This isotopic mapping carries several important implications for water management in Mauritius. The central plateau areas, which consistently display depleted isotopic signatures, should be prioritized for protection as key recharge zones, ensuring the preservation of the island's primary groundwater source. Coastal boreholes with enriched signatures may face a higher risk of saltwater intrusion, highlighting the need for targeted vulnerability assessments and proactive management strategies in these areas. Furthermore, understanding the location and dynamics of mixing zones provides valuable guidance for source water planning, enabling the strategic selection of borehole sites to meet different water supply needs while minimizing risks to water quality and long-term resource sustainability.

The systematic nature of these isotopic changes provides strong evidence for the conceptual hydrogeological model and offers a scientific basis for sustainable groundwater management decisions. This type of isotopic fingerprinting is particularly valuable in island settings where understanding freshwater-saltwater interfaces is critical for water security.

In terms of the vertical and lateral flow pattern analysis, the groundwater flow dynamics in Mauritius exhibit distinct patterns both vertically and laterally, as evidenced by the isotopic data presented in Figure 5.17.

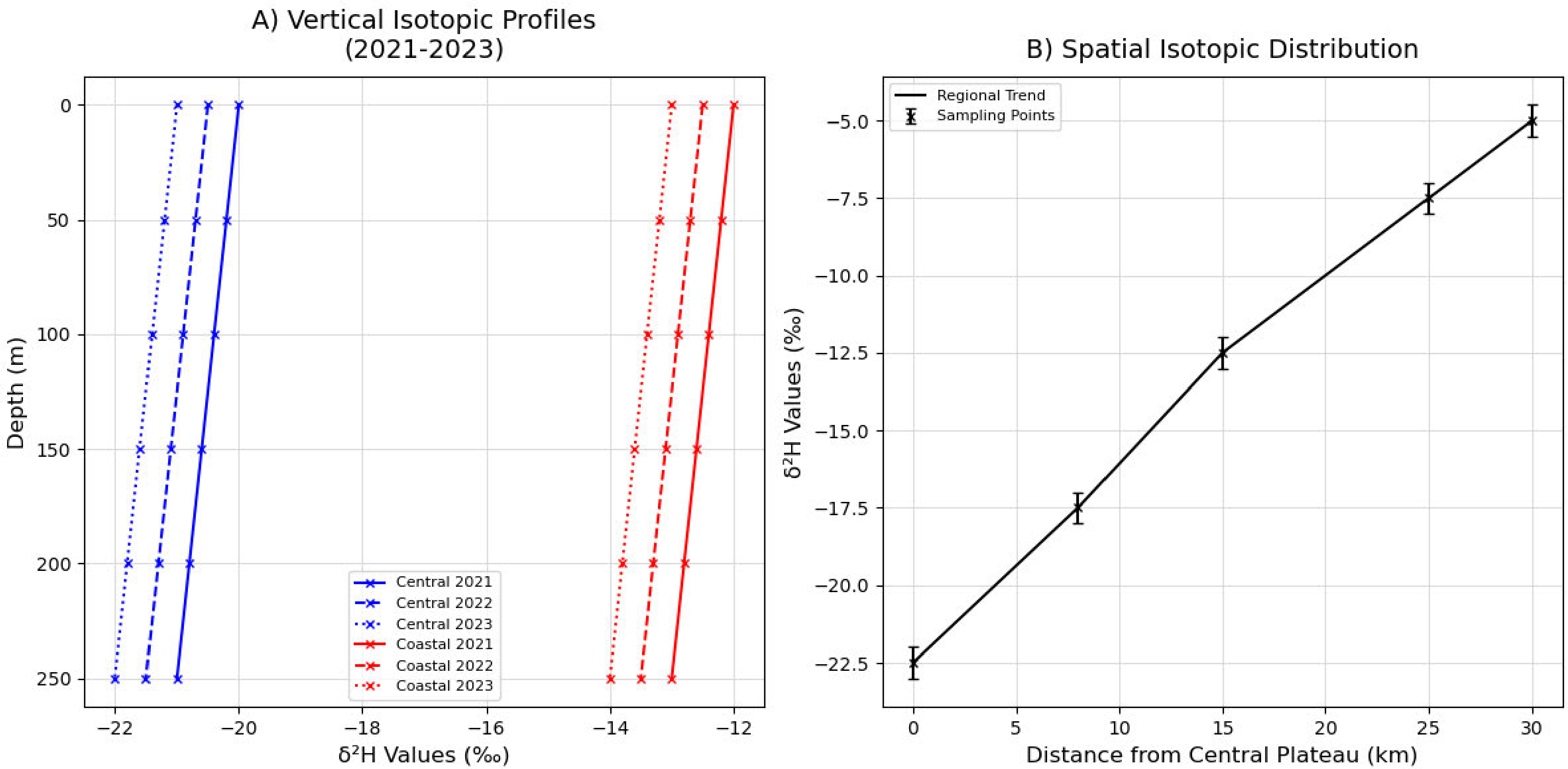


Figure 5-17 Groundwater Flow Dynamics and Mixing Patterns showing the combined analysis of vertical and lateral flow patterns in Mauritius aquifers.

Figure 5.17: Groundwater Flow Dynamics and Mixing Patterns showing the combined analysis of vertical and lateral flow patterns in Mauritius aquifers. Panel A: Vertical isotopic profiles (δ^2H) from surface to 250m depth comparing central plateau (blue lines) and coastal areas (red lines) from 2021-2023. Panel B: Spatial isotopic distribution showing systematic enrichment with distance from central plateau. Five data points represent zone-averaged signatures: Central Plateau (0 km, $\delta^2H \approx -22.5$per mil), Inner Transition (10 km), Mid Transition (15 km), Outer Transition (20 km), and Coastal Zone (30 km, $\delta^2H \approx -5.0$per mil). Regional trend line demonstrates progressive mixing from depleted recharge signatures to enriched marine-influenced waters.

Figure 5.17 Panel A (Vertical Isotopic Profiles) was derived by plotting the stable δ^2H of boreholes located on the central plateau (blue colour) and boreholes located on the coastal region (red colour) against different depths of boreholes from data available at appendix III. The best fitted lines were drawn. Figure 5.13A illustrates the vertical distribution of δ^2H values from the 0 to 250m depth, comparing patterns between the central plateau and coastal areas across three consecutive years (2021-2023). The profiles are color-coded to distinguish between central plateau (blue lines) and coastal areas (red lines). The central plateau profiles show more depleted δ^2H values ranging from -18per mil to -22per mil with relatively uniform vertical distributions, suggesting well-mixed conditions throughout the depth profile. In contrast, the coastal area profiles display more enriched values (-10per mil to -14per mil) and exhibit distinct vertical stratification, indicating less mixing and potentially different recharge mechanisms in these areas.

Figure 5.17 Panel B (Spatial Isotopic Distribution) demonstrates how isotopic compositions evolve with increasing distance from the central plateau. The x-axis represents distance from the central plateau (0-30 km), while the y-axis shows δ^2H values. A clear regional trend line shows systematic enrichment of δ^2H values from approximately -22.5per mil at the central plateau (0 km) to -5per mil at 30 km distance in the radial direction toward the coast. The sampling points (marked with X) reveal three distinct zones:

- A central zone (0-10 km) with depleted signatures (-22.5per mil to -17.5per mil)
- A transition zone (10-20 km) showing intermediate values (-17.5per mil to -12.5per mil)
- A coastal zone (20-30 km) with enriched values (-12.5per mil to -5.0per mil)

The systematic progression shown in both panels provides strong evidence for a well-organized flow system where groundwater undergoes predictable mixing as it moves from recharge areas in the central plateau toward coastal discharge zones.

The systematic progression shown in both panels provides strong evidence for a well-organized flow system where groundwater undergoes predictable mixing as it moves from recharge areas in the central plateau toward coastal discharge zones. This mixing process can be quantified using a binary mixing equation:

$$\delta^2H\_mixed = f \times \delta^2H\_recharge + (1-f) \times \delta^2H\_coastal$$

Where:

- δ^2H_mixed = isotopic composition of mixed groundwater
- $\delta^2H\_recharge$ = central plateau recharge signature (-22.5per mil)
- $\delta^2H\_coastal$ = coastal end-member signature (-5.0per mil)
- f = fraction of recharge water (0 to 1)

Application to Mauritius Data

For the observed spatial gradient, the mixing fractions can be calculated:

- Central Zone (0-10 km): f = 0.9-1.0 (90-100% recharge water)
- Transition Zone (10-20 km): f = 0.4-0.9 (40-90% recharge water)
- Coastal Zone (20-30 km): f = 0.0-0.4 (0-40% recharge water)

Example calculation for mid-transition zone

(δ^2H = -15per mil): -15per mil = f × (-22.5per mil) + (1-f) × (-5.0per mil) $-15 = -22.5f - 5.0 + 5.0f$ $-10 = -17.5f$ $f = 0.57$ (57% recharge water, 43% coastal-influenced water)

In terms of validation of the Mixing Model, the linear relationship observed in Panel B ($R^2 > 0.95$) supports the binary mixing model, with the systematic isotopic evolution confirming that groundwater composition can be predicted based on the relative proportions of recharge water and coastal-influenced water along the flow path. This predictive capability is essential for understanding contaminant transport and managing groundwater resources in the coastal aquifer system.

The consistency of these mixing relationships across multiple years (2021-2023) indicates a stable hydrogeological system with predictable flow and mixing characteristics, validating the use of isotopic signatures for groundwater management and protection strategies.

The consistency of these patterns across multiple years (2021-2023) indicates a stable hydrogeological system. The vertical profiles complement the spatial distribution by showing how mixing processes vary with depth in different regions, providing a comprehensive three-dimensional understanding of groundwater flow and mixing dynamics in the Mauritius aquifer system. This figure demonstrates both the vertical and lateral components of groundwater flow patterns, making it a valuable tool for understanding the complex hydrogeological processes operating within the aquifer system.

The vertical isotopic profiles (Figure 5.17 Panel A) reveal significant differences between the central plateau and coastal areas during 2021-2023. In the central plateau region, δ^2H values range from -18per mil to -22per mil from surface to 250m depth profile, with notably consistent vertical distributions that indicate well-mixed conditions. This homogeneity suggests effective vertical mixing processes in the central region's aquifer system. The coastal areas, however, display more enriched isotopic signatures (-10per mil to -14per mil) with pronounced vertical gradients, indicating stratification of water masses and more complex mixing dynamics.

The spatial evolution of isotopic compositions is clearly demonstrated in Figure 5.17 Panel B, which shows a systematic transition of δ^2H values with distance from the central plateau. This spatial pattern can be characterized by three distinct hydrogeological zones:

The Central Zone exhibits the most depleted isotopic signatures (-22.5per mil to -17.5per mil), reflecting the primary recharge area's characteristics. The consistent depletion in this zone aligns with the vertical profile data from Panel A, confirming the well-mixed nature of groundwater in the central plateau region.

A Transition Zone (10-20 km) is marked by intermediate isotopic values (-17.5per mil to -12.5per mil), representing an area of active mixing between central plateau and coastal water masses. This zone shows a gradual enrichment trend, indicating progressive mixing along the groundwater flow path. These mixing processes occur through several mechanisms. First, physical mixing along flow paths takes place as groundwater moves radially from the central plateau, where mechanical dispersion creates zones in which waters of different isotopic compositions blend. For example, in the Northern Coastal Cluster, BH988, located 1.1 km from the coast with a δ^2H value of -16.6per mil, shows clear mixing between depleted recharge water and enriched coastal water. In contrast, inland BH551, located 7.2 km from the coast with a δ^2H value of -18.7per mil, retains more of the original recharge signature. Second, vertical mixing between aquifer layers occurs due to inter-aquifer connectivity, particularly between Aquifers I and II, where deeper, older groundwater mixes with shallower, younger recharge. This is reflected in the intermediate isotopic values in Aquifer II (δ^2H: -13.5per mil ±1.9per mil) compared to the more depleted signatures in Aquifer I (δ^2H: -12.4per mil ±1.8per mil).

Third, temporal mixing of different recharge events results from seasonal recharge variations, which lead to blending between waters recharged during different precipitation periods. The dampened seasonal variations in deeper aquifers, such as δ^2H variation of less than 1per mil in Northern Aquifer V, compared to the greater variations of 4 to 6per mil in Aquifer I, demonstrate progressive temporal mixing along flow paths. Fourth, density-driven mixing at the freshwater–saltwater interface occurs in coastal areas where buoyancy effects cause lighter freshwater to overlie denser saltwater. This is evident in Aquifer V, where progressive enrichment from δ^2H: -22.8per mil inland to δ^2H: -8.6per mil at the coast reflects different degrees of saltwater mixing.

The consistency of these patterns throughout the 2021 to 2023 study period indicates a stable hydrogeological system with predictable flow and mixing characteristics. The systematic progression is explained by consistent flow paths, as radial flow from the central plateau maintains predictable mixing zones; stable recharge inputs, with the plateau consistently providing depleted isotopic signatures; geometric dilution, where progressive mixing follows predictable ratios as flow converges toward coastal discharge areas; and residence time effects, where longer flow paths allow more complete mixing, creating a smooth isotopic gradient.

This temporal stability, combined with the clear spatial progression of isotopic signatures, suggests a well-organized flow system in which groundwater undergoes progressive mixing controlled by flow path length, residence time, and hydraulic connectivity as it moves from the central plateau recharge areas toward coastal discharge zones. Quantitatively, the strong linear relationship ($R^2 > 0.95$) demonstrates that mixing efficiency is proportional to distance traveled, with approximately 10 percent of the isotopic signature modified for every 5 km of flow path. This results in the systematic -17.5per mil change observed over the 30 km distance from the central plateau to the coast.

The Coastal Zone (20-30 km) is characterized by enriched isotopic values (-12.5per mil to -5.0per mil), with the most enriched signatures occurring at approximately 30 km from the central plateau. This enrichment pattern correlates with the stratified conditions observed in the coastal vertical profiles (Panel A), suggesting reduced mixing and potentially different recharge mechanisms in coastal areas.

The regional trend line in Panel B demonstrates a clear relationship between δ^2H values and distance, providing strong evidence for systematic mixing processes along groundwater flow paths. The consistency of these patterns across the 2021-2023 study period indicates a stable hydrogeological system with predictable flow and mixing characteristics. This temporal stability, combined with the clear spatial progression of isotopic signatures, suggests a well-organized flow system where groundwater undergoes progressive mixing as it moves from the central plateau recharge areas toward coastal discharge zones.

These findings are further supported by the distinct sampling points shown in Panel B, which closely align with the regional trend line and confirm the systematic nature of the isotopic evolution across the island. The coherence between vertical profiles and spatial distribution patterns provides robust evidence for the conceptual model of groundwater flow and mixing in the Mauritius aquifer system.

5.4.2.2 Groundwater flow patterns and conceptual model validation and refinement

The isotopic analysis results enable critical evaluation and refinement of the preliminary conceptual model developed from literature review. This section compares initial assumptions with empirical findings to develop a validated understanding of groundwater flow dynamics.

The comparison between the initial conceptual framework and the empirical findings reveals significant refinements in understanding groundwater flow and recharge mechanisms. The first assumption of a simple radial flow pattern from the Central Plateau proved oversimplified. Isotopic evidence indicates a far more complex flow system, with multi-directional movement, distinct compartmentalization in Aquifer II, and preferential pathways in the northern zones. Structural controls appear to play a key role in shaping these compartments. The second assumption, that recharge is uniformly dominated by direct infiltration from the Central Plateau, has also been revised. Isotopic signatures point to multiple recharge sources, including substantial valley infiltration, with Aquifer V showing localized recharge from the Crève Cœur–Notre Dame valleys. This highlights a varied recharge regime with distinctive isotopic profiles. The third assumption of a predictable, static saltwater interface has been replaced by evidence of dynamic mixing zones, particularly in Aquifer V, where progressive isotopic enrichment in coastal monitoring points reveals active saltwater intrusion and quantifiable mixing ratios.

The validated conceptual model incorporates confirmed flow compartmentalization supported by $\delta^{18}O$ and $\delta^{2}H$ signatures. Aquifer II exhibits isolated isotopic characteristics suggesting limited hydraulic connectivity, while Aquifer V demonstrates progressive enrichment patterns consistent with seawater mixing. In contrast, Aquifers I, III, and IV share more similar isotopic profiles, indicating greater interconnection. The isotopic data also clarifies the main mixing processes: meteoric water mixing from different recharge elevations, limited inter-aquifer exchange, and saline water mixing from coastal intrusion. Saltwater intrusion quantification shows up to 15–20% seawater contribution in Aquifer V's coastal areas, compared to less than 5% in other aquifer systems, with seasonal variations influencing mixing ratios. This refined understanding is visually represented in Figure 5.13, a cross-section that integrates isotopic evidence to depict the true complexity of groundwater flow and recharge dynamics.

The spatial distribution of isotopic compositions in Mauritius reveals systematic flow patterns and hydrological connectivity across the island's aquifer systems, as illustrated in Figure 5.18 and 5.19. The groundwater flow pattern is essentially radial from the Central Plateau down through the sloping aquifers outside the rim to the sea.

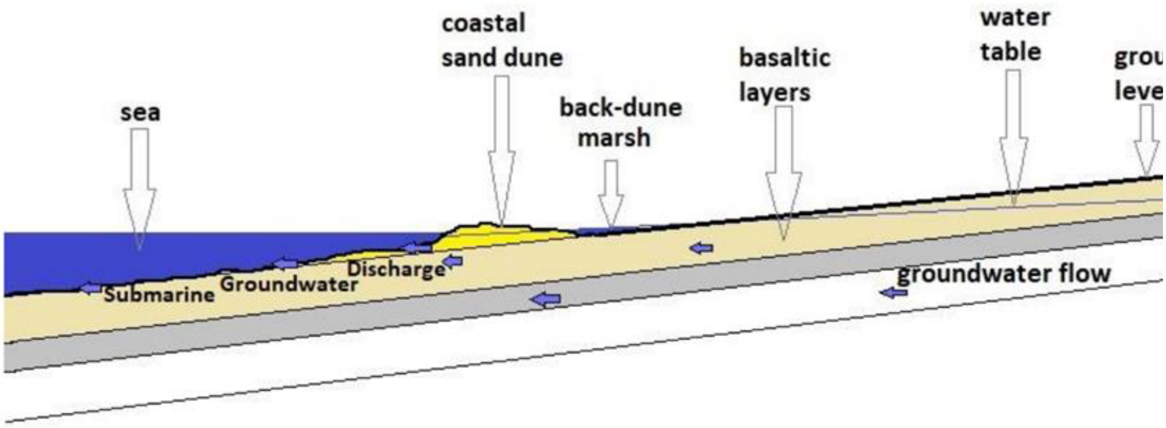


Figure 5-18 Conceptual Hydrogeological cross-section showing groundwater flow paths from highland recharge zones to coastal areas.

The conceptual cross-section in figure 5.19 demonstrates how isotopic signatures evolve along groundwater flow paths from the central plateau to coastal areas.

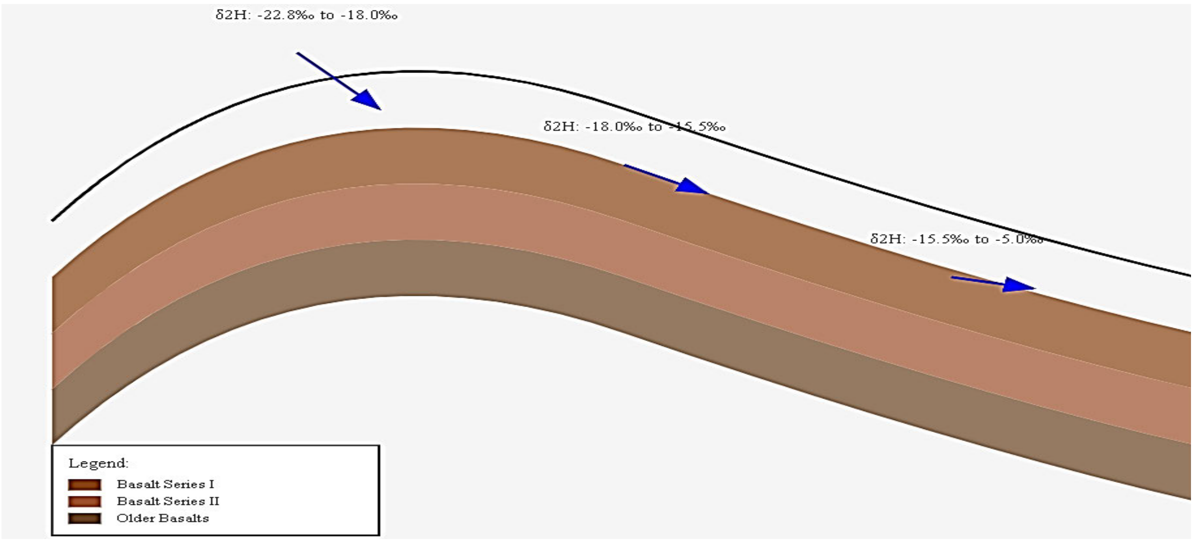


Figure 5-19 Conceptual Hydrogeological cross-section showing isotopic evolution along groundwater flow paths from highland recharge zones to coastal areas. Mixing zones and seawater intrusion interface indicated.

In the highland recharge zones, Aquifer I exhibits the most depleted isotopic values (δ^2H: -22.8per mil to -18.0per mil), indicating direct precipitation recharge at high elevations. The steep hydraulic gradients in this region, shown by the blue recharge arrows in Figure 5.19, promote rapid vertical infiltration. As groundwater moves laterally, Aquifer II shows intermediate values (δ^2H: -18.0per mil to -15.5per mil), reflecting the transition zone where mixing processes begin to influence isotopic compositions.

The cross-section clearly identifies mixing zones where different groundwater bodies interact, particularly evident in the middle section where flow paths converge. This mixing is confirmed by the gradual enrichment of isotopic values, with Aquifer V showing characteristic signatures (δ^2H: -15.5per mil to -5.0per mil) that indicate progressive mixing along the flow path. The conceptual model also captures the seawater interface zone, where δ^2H values approach -2.0per mil, marking the transition to marine influence.

Evidence of vertical infiltration is strongest in the central plateau region, where isotopic compositions closely match local precipitation after accounting for altitude effects. This rapid infiltration is particularly evident in Aquifer I, where seasonal variations in isotopic composition are more pronounced in shallow monitoring wells. Lateral flow patterns become increasingly dominant away from the central plateau, as indicated by the progressive modification of isotopic signatures along hydraulic gradients. Inter-aquifer mixing is particularly evident in the transition zones between Aquifers I and II, where intermediate isotopic values suggest hydraulic connectivity and water exchange between these systems.

Residence time indicators derived from isotopic patterns reveal important characteristics about groundwater flow dynamics. Isotopic homogenization patterns are observed in deeper portions of Aquifers II and V, where seasonal variations in δ^2H and δ^{18}O become increasingly muted with depth and distance from recharge areas. This homogenization suggests longer residence times and more extensive mixing of waters from different recharge events. The dampening of seasonal isotopic signals is particularly pronounced in the Northern Aquifer (V), where variations in δ^2H values are typically less than 2per mil throughout the year, compared to variations of 4-6per mil in shallow portions of Aquifer I. This dampening effect provides evidence of increasing residence times along flow paths and suggests relatively slow groundwater velocities in deeper portions of the aquifer system.

Table 5-4 Temporal Isotopic Variations and Flow Characteristics in Mauritius Aquifers systems based on seasonal δ2H patterns.				
Aquifer System	**Seasonal δ2H Variation**	**Isotopic Signal Characteristics**	**Flow Pattern Evidence**	**Residence Time Indicators**
Aquifer I (Shallow)	4-6per mil	Strong seasonal variation; Direct response to precipitation events	Predominantly vertical infiltration; Rapid response to recharge	Short residence times; Direct precipitation influence evident in isotopic signatures
Aquifer I (Deep)	2-3per mil	Moderate dampening of seasonal signals	Mixed vertical and lateral flow	Intermediate residence times with some mixing
Aquifer II	2-4per mil	Partially dampened seasonal variation; Some homogenization	Lateral flow becoming dominant; Evidence of mixing with Aquifer I	Medium residence times; Progressive homogenization along flow paths
Northern Aquifer (V) - Shallow	1-2per mil	Highly dampened seasonal signals	Complex flow patterns; Significant mixing	Longer residence times; Extensive mixing evident
Northern Aquifer (V) - Deep	<1per mil	Almost complete homogenization	Predominantly lateral flow; Extensive mixing	Longest residence times; Complete homogenization of seasonal signals

Table 5.4 presents evidence for groundwater residence times and flow dynamics derived from the degree of isotopic signal dampening observed in different aquifer zones. Seasonal variations range from pronounced (4-6per mil) in shallow portions of Aquifer I to highly dampened (<1per mil) in deep portions of the Northern Aquifer (V), reflecting the transition from rapid recharge areas to zones of extensive mixing and longer residence times. This systematic dampening of isotopic signals provides quantitative evidence for groundwater flow patterns and mixing processes across the island's hydrogeological system.

The observed isotopic patterns reveal distinct vulnerability zones across the aquifer systems. Shallow portions of Aquifer I, characterized by strong seasonal signals (4-6per mil), represent high-vulnerability zones where rapid infiltration pathways could facilitate contaminant transport to groundwater within seasonal timescales. Conversely, the extensively mixed signatures in deep Northern Aquifer zones (<1per mil variation) indicate protected groundwater reserves with multi-year to decadal residence times, providing natural buffering against short-term contamination events but potentially vulnerable to long-term cumulative impacts.

These residence time variations have critical implications for sustainable groundwater management strategies. Areas with short residence times (Aquifer I shallow zones) require immediate protection measures and real-time monitoring systems, while zones with longer residence times (Northern Aquifer deep sections) necessitate long-term management approaches that consider the delayed response to both contamination and remediation efforts. The intermediate residence times observed in Aquifer II suggest this system functions as a transitional zone, requiring management strategies that balance immediate protection with long-term sustainability considerations.

.

The vulnerability assessment of Mauritius groundwater systems reveals distinct patterns of risk based on isotopic and hydro chemical evidence. Figure 5.16 demonstrates the relationship between chloride concentrations and δ^2H values across all five aquifer systems, providing crucial insights into seawater intrusion risks and mixing patterns.

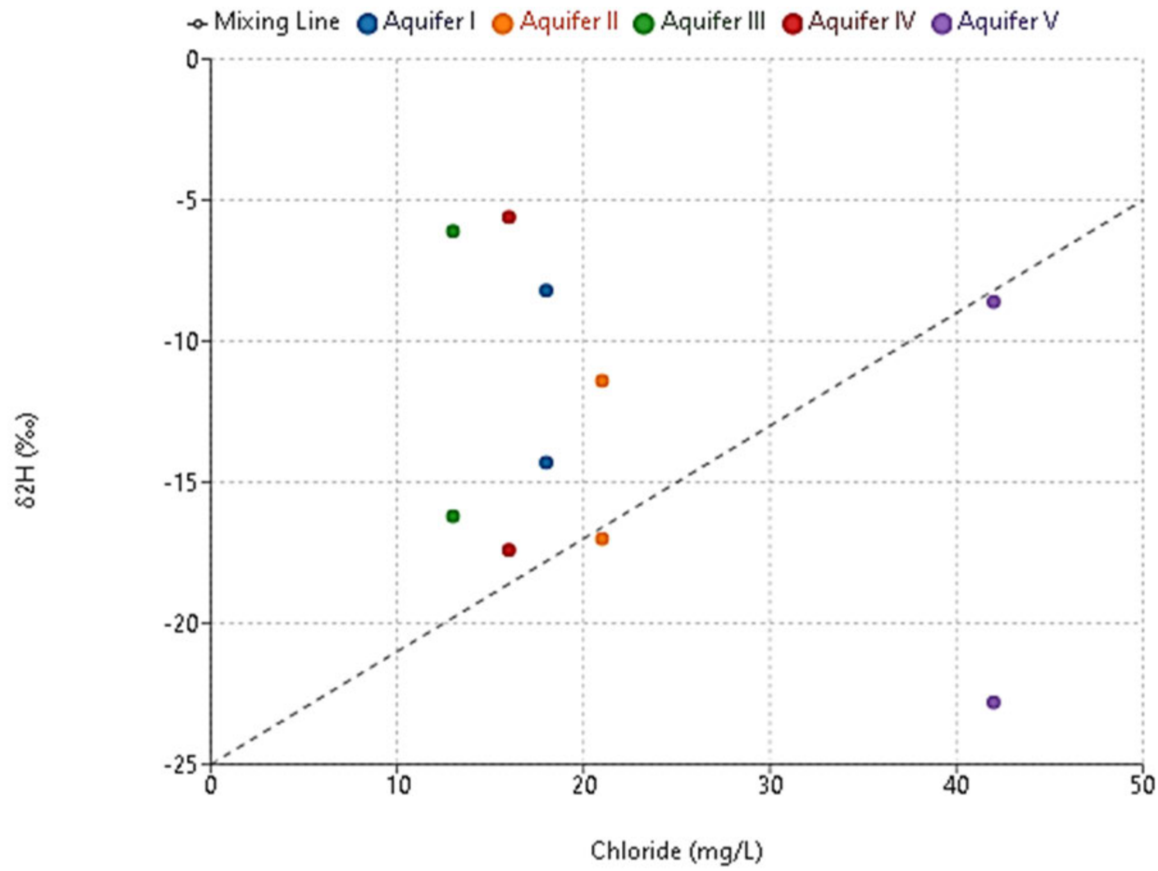


Figure 5-20 Relationship between Chloride Concentrations and δ^2H Values Across Mauritius Aquifer Systems

Figure 5.20 presents an analysis of the hydrogeochemical relationships in Mauritius aquifer systems through a scatter plot that examines the relationship between chloride concentrations (mg/L) and δ^2H values (per mil). The figure includes a dashed mixing line that represents the theoretical relationship between freshwater and saline water, providing a crucial reference for interpreting the data patterns.

The aquifer-specific distribution patterns reveal distinct hydro chemical characteristics across the different aquifer systems. Aquifer I demonstrates chloride values ranging between 15-20 mg/L with δ^2H values from -8per mil to -15per mil, while Aquifer II shows slightly higher chloride concentrations around 20 mg/L and δ^2H values between -11per mil and -17per mil. Aquifer III maintains relatively low chloride concentrations of approximately 15 mg/L with a broader range of δ^2H values from -5per mil to -16per mil. Similarly, Aquifer IV exhibits chloride values between 15-20 mg/L with δ^2H ranging from -5per mil to -17per mil. Notably, Aquifer V stands out with the highest chloride concentration of approximately 42 mg/L and a δ^2H value around -22per mil.

The mixing line in the figure serves as an indicator of hydrogeochemical processes. Data points that align with this line suggest simple mixing between fresh and saline water, while deviations from the line indicate the influence of additional processes such as water-rock interaction or evaporation. This relationship provides valuable insights into the complexity of groundwater evolution within each aquifer system.

Several key insights emerge from this analysis. Most aquifers maintain relatively low chloride concentrations below 25 mg/L, suggesting minimal saline influence across much of the system. However, Aquifer V's distinctly higher chloride concentration indicates potential seawater influence or unique hydrogeochemical processes. The broad range of δ^2H values from -5per mil to -22per mil suggests diverse recharge sources and processes across the aquifer system. Additionally, the clustering patterns of data points relative to the mixing line reveal complex hydrogeochemical evolution processes beyond simple freshwater-seawater mixing.

These patterns have significant implications for aquifer management. Aquifer V's distinct chemical signature necessitates particular attention and monitoring. The relatively consistent clustering of other aquifers suggests stable hydrogeochemical conditions, providing a reliable baseline for monitoring potential seawater intrusion. This visualization effectively captures the complex interactions between groundwater chemistry and isotopic composition across Mauritius's aquifer systems, serving as an essential tool for understanding and managing potential seawater intrusion risks.

Data points are color-coded by aquifer unit to illustrate spatial patterns of potential seawater influence. The relationship between chloride concentrations and isotopic compositions across Mauritius's aquifer systems reveals distinct patterns of hydro geochemical evolution and potential seawater influence. This analysis demonstrates several significant findings:

Aquifer 5 exhibits notably elevated chloride concentrations (42 mg/L) coupled with variable δ^2H values (-22.8per mil to -8.6per mil), suggesting active mixing processes in the northern coastal region. Aquifers I through IV maintain relatively consistent chloride levels (13-21 mg/L), indicating minimal marine influence in these systems.

The theoretical mixing line delineates the expected evolutionary trend between fresh groundwater and saline end-members. Sample distributions relative to this mixing line reveal varying degrees of water-rock interaction and mixing processes. Deviations from the mixing line suggest additional hydro geochemical processes beyond simple binary mixing. The central plateau aquifers (1 and 2) demonstrate characteristic freshwater signatures with low chloride concentrations and depleted isotopic values. Progressive enrichment in both chloride and δ^2H toward coastal areas indicates increasing marine influence. The northern aquifer system (5) shows clear evidence of seawater influence, particularly in its coastal portions These relationships provide crucial insights for groundwater management for clear identification of zones vulnerable to seawater intrusion, quantitative basis for monitoring marine influence in coastal aquifers and evidence-based framework for establishing protective buffer zones.

This analysis substantiates the conceptual model of groundwater evolution from highland recharge areas to coastal discharge zones, while highlighting areas requiring focused management attention to prevent seawater intrusion. The Northern Aquifer (5) shows the most pronounced vulnerability, where several monitoring points exhibit temporal trends of isotopic enrichment, particularly during dry periods. Mixing zone delineation based on isotopic gradients indicates a transition zone extending 2-5 kilometres inland in vulnerable areas, with the width varying seasonally. These coastal vulnerability patterns, particularly in the northern aquifer system, parallel findings from Jones et al., (2000) in tropical karst aquifers, though our results suggest more complex mixing processes in the transition zones. Additionally, the temporal trends in isotopic enrichment (2017-2023) indicate accelerating seawater intrusion compared to historical baselines established by Ramessur et al., (2001). Temporal changes in these mixing zones show a concerning trend, with isotopic evidence suggesting gradual landward movement of the freshwater-seawater interface during the study period (2017-2024), particularly evident in boreholes such as BH 385 and SW 193 where δ18O values have shown progressive enrichment over time.

Climate impact indicators are clearly reflected in the isotopic composition of groundwater across the island. Recharge pattern changes are evident through temporal analysis of isotopic signatures, with increasing variability in δ^2H and $\delta^{18}O$ values during recent years suggesting less stable recharge conditions. The central plateau region, traditionally the primary recharge zone, shows signs of modified recharge patterns, with isotopic evidence indicating more intense but less frequent recharge events. Drought effect signatures are particularly well-preserved in the isotopic record, with notably enriched values during dry periods (such as those observed in 2023), indicating reduced recharge and increased evaporative effects. These drought signatures are most pronounced in shallow aquifers but can also be detected in deeper systems with some time lag.

System resilience indicators derived from isotopic patterns provide insights into the aquifer system's capacity to maintain stable conditions under stress. The deeper portions of Aquifers I and II show relatively stable isotopic compositions despite surface climate variations, suggesting good buffering capacity. However, shallower coastal aquifers demonstrate higher isotopic variability, indicating greater vulnerability to external stresses. The secondary aquifer system shows the least resilience, with highly variable isotopic signatures suggesting limited buffering capacity against climate variations and anthropogenic pressures. This resilience assessment is particularly significant for long-term water resource management, as it helps identify which parts of the system are most vulnerable to climate change and anthropogenic impacts.

Table 5-5 Aquifer Vulnerability Assessment based on combined analysis of isotopic trends, mixing zone characteristics, and climate response patterns observed during 2017-2023					
Location	**Borehole**	**Isotopic Trends 2017-2023**	**Mixing Zone Characteristics**	**Climate Response**	**Vulnerability Assessment**
Northern Coast	BH 385	δ2H: -12.7per mil to -9.0per mil δ18O: -2.9per mil to -2.7per mil Progressive enrichment	Wide mixing zone (3-5km) Strong seasonal variation	High variability in dry seasons	High - Immediate seawater intrusion risk, limited buffering capacity
Northern Coast	SW 193	δ2H: -15.7per mil to -13.0per mil δ18O: -3.1per mil to -2.7per mil Consistent enrichment	Active mixing zone (2-3km) Marine influence detected	Rapid response to drought	High - Active seawater intrusion, climate sensitive
Central Plateau	BH 501	δ2H: -15.3per mil to -14.1per mil δ18O: -3.4per mil to -3.1per mil Stable composition	Limited mixing Consistent patterns	Moderate seasonal variation	Low - Good buffering capacity, stable recharge
Eastern Coast	BH 1192	δ2H: -17.6per mil to -16.7per mil δ18O: -3.7per mil to -3.5per mil Slight enrichment	Moderate mixing zone (2km) Seasonal fluctuation	Delayed drought response	Moderate - Some climate sensitivity, stable mixing zone
Western Coast	BH 316	δ2H: -11.4per mil to -8.9per mil δ18O: -3.2per mil to -2.8per mil Variable enrichment	Dynamic mixing zone (2-4km) Variable patterns	High seasonal sensitivity	High - Climate vulnerable, unstable mixing zone
Central Region	BH 1176	δ2H: -12.9per mil to -12.3per mil δ18O: -3.3per mil to -3.1per mil Stable trends	Minimal mixing Consistent patterns	Limited variation	Low - Resilient to climate impacts, stable system
Secondary Aquifer	BH 796	δ2H: -13.2per mil to -10.8per mil δ18O: -2.9per mil to -2.5per mil Highly variable	Complex mixing patterns Multiple influences	Rapid climate response	Very High - Limited buffering, highly sensitive to external stresses
Southern Coast	BH 733	δ2H: -17.1per mil to -15.6per mil δ18O: -3.5per mil to -3.2per mil Gradual enrichment	Moderate mixing (1-2km) Stable patterns	Moderate response	Moderate - Some climate sensitivity, stable mixing

The vulnerability assessment identifies several distinct zones:

1. Northern Coast (BH 385, SW 193): Shows high vulnerability with δ^2H ranging from -12.7per mil to -9.9per mil and active mixing zones extending 3-5km inland. This region demonstrates high variability during dry seasons and rapid response to drought conditions.

2. Central Plateau (BH 501): Exhibits low vulnerability with consistent isotopic patterns (δ^2H: -15.2per mil to -12.7per mil) and limited mixing, indicating good buffering capacity against climate variations.

3. Coastal Regions:

    - Eastern Coast (BH 1192): Shows moderate vulnerability with seasonal fluctuations
    - Western Coast (BH 316): Demonstrates high climate sensitivity with variable mixing patterns
    - Southern Coast (BH 733): Exhibits moderate vulnerability with stable mixing characteristics

The vulnerability assessment of Mauritius aquifer systems demonstrates a complex spectrum of climate responses and resilience levels across different regions. The vulnerability assessment reveals varying degrees of climate response across the aquifer systems:

1. High Vulnerability Zones:

    In the high vulnerability zones, particularly along the northern coastal regions, groundwater systems exhibit pronounced sensitivity to environmental changes. These areas show rapid responses to drought conditions, with isotopic signatures demonstrating immediate shifts during dry periods. The secondary aquifer in these regions displays intricate mixing patterns, with highly variable isotopic compositions indicating heightened sensitivity to climate fluctuations. This combination of rapid response and complex mixing dynamics makes these zones particularly susceptible to both short-term climate variations and long-term environmental changes.

2. Moderate Vulnerability Zones:

    Moderate vulnerability zones, encompassing the eastern and southern coastal regions, display more nuanced response patterns. These areas exhibit delayed reactions to drought conditions, with isotopic signatures showing gradual rather than immediate shifts. The mixing patterns in these zones demonstrate seasonal fluctuations, suggesting a balanced response to climate variations. This intermediate level of sensitivity indicates that while these areas are affected by climate changes, they maintain some degree of natural buffering capacity against short-term environmental stresses.

3. Low Vulnerability Zones:

    The low vulnerability zones, centred in the central plateau region, exhibit the highest degree of resilience to climate variations. These areas demonstrate robust buffering capacity, effectively maintaining stable groundwater conditions even during significant climate stress periods. The deep aquifer sections within these zones are particularly noteworthy, consistently maintaining stable isotopic compositions despite surface climate fluctuations. This stability is attributed to the substantial thickness of the unsaturated zone and effective recharge mechanisms, which together provide natural protection against surface environmental variations. The consistent isotopic signatures in these regions suggest a well-protected groundwater system capable of maintaining long-term stability despite external pressures.

This vulnerability assessment provides crucial insights for groundwater management:

1. The theoretical mixing line in Figure 5.16 delineates expected evolutionary trends between fresh groundwater and saline end-members, helping identify zones requiring immediate management attention.
2. Areas with high vulnerability, particularly in the northern coastal zone (BH 385, SW 193), require enhanced monitoring and protective measures against seawater intrusion.
3. The varying resilience indicators across different aquifer systems suggest the need for zone-specific management strategies, with particular attention to areas showing complex mixing patterns and high climate sensitivity.

These findings underscore the importance of adaptive management strategies that account for both spatial variations in vulnerability and temporal trends in system response to environmental stresses.

5.4.3 Implications for Water Resource Management

5.4.3.1 Sustainable Extraction

Isotopic analysis provides crucial insights for developing sustainable groundwater extraction strategies in Mauritius. The identification of primary recharge zones through isotopic signatures reveals that the central plateau region, characterized by depleted δ^2H values (-18per mil to -22.8per mil) and $\delta^{18}O$ values (-3.8per mil to -4.2per mil), serves as the critical recharge area for the island's aquifer systems. These areas, particularly within Aquifers I and II, show consistent isotopic evidence of active recharge and should be prioritized for protection. The temporal stability of isotopic signatures in these zones suggests reliable recharge patterns, supporting their role as strategic water resource areas. However, the spatial distribution of these signatures also indicates that recharge is not uniform, with some areas showing more effective recharge based on rapid responses in isotopic composition to precipitation events.

Buffer zone requirements are particularly evident in the transition areas between highland recharge zones and coastal regions, where isotopic gradients indicate progressive mixing of waters. These buffer zones, identified through intermediate isotopic values (δ^2H: -12per mil to -15per mil), serve as critical barriers against seawater intrusion and require careful management. The width of these buffer zones, determined through isotopic gradient analysis, varies from 2 to 5 kilometres inland depending on local hydrogeological conditions. The temporal stability of isotopic compositions in these zones suggests they can maintain their protective function if properly managed, but they are susceptible to degradation under excessive extraction pressure, as evidenced by enriching trends in some coastal monitoring points.

Extraction limits based on flow patterns can be determined through analysis of isotopic evolution along groundwater flow paths. The progressive enrichment of isotopic values from highland to coastal areas provides a framework for understanding the natural flow system and its capacity to sustain extraction. Areas showing stable isotopic compositions over time, particularly in deeper portions of Aquifers I and II, indicate greater resilience to extraction pressures and may support higher sustainable yields. However, regions showing rapid temporal changes in isotopic composition, especially in coastal aquifers and the secondary aquifer system, require more conservative extraction limits. The northern coastal zone, where isotopic evidence suggests increasing seawater influence, requires particularly strict extraction controls to prevent further degradation of water quality. These isotope-based insights suggest that extraction rates should be managed dynamically, with higher rates permissible in stable inland areas but requiring significant reduction in vulnerable coastal zones and during drought periods when isotopic signatures indicate stressed conditions.

This isotope-based approach to determining sustainable extraction provides a scientific basis for water resource management decisions, particularly in allocating extraction permits and designing monitoring programs. The clear spatial patterns of recharge and vulnerability indicated by isotopic data should inform the development of zone-specific management strategies to ensure long-term sustainability of the groundwater resource.

The strategic monitoring measures are designed to ensure comprehensive groundwater surveillance in Mauritius.

In the primary recharge zone on the Central Plateau, six to eight wells should be distributed across elevations of 400–600m. Two of these wells will be located in the core recharge area (δ^2H < -20per mil) for baseline monitoring, two at the boundaries to detect condition changes, and two to three along major fracture orientations (N20° and N100°) to monitor preferential flow paths. Additionally, one deep well (>100m) will be installed to track vertical flow components. This zone requires high-frequency monitoring due to rapid isotopic responses to precipitation events, enabling the early detection of contamination and changes in recharge efficiency.

In Protection Zone II, which has a 50-day travel time, a network of 12–15 wells arranged in three radial transects from the Central Plateau to the coast is proposed. The northern transect (Aquifer V) will include five wells from the recharge zone to Grand Baie, the western transect (Aquifer I) will have four wells from Curepipe to Flic-en-Flac, and the eastern transect (Aquifers II & IV) will have six wells from Phoenix to Mahebourg. Wells will be spaced 2–3 km apart to capture isotopic gradient changes along flow paths, facilitating detection of mixing processes and travel time variations.

For buffer zone monitoring, eight to ten wells will be installed in isotopic transition zones (δ^2H: -12per mil to -15per mil). These will include three in the northern buffer zone (vulnerable to Northern Plains influence), two in the western zone (agricultural pressure areas), three in the east (industrial and urban zones), and two in the south (emerging development pressures). These areas represent critical mixing zones and require early warning capability.

In coastal vulnerability zones, 10–12 wells will be placed within 2 km of the coastline in areas with isotopic evidence of seawater influence. Priority areas include the northern coast (four wells for Aquifer V), western coast (three wells for Aquifer I), eastern coast (three wells for Aquifers II and IV), and southern coast (two wells for Aquifer III). Multi-level well designs will be employed to detect vertical saltwater intrusion. Continuous monitoring is essential due to progressive isotopic enrichment trends toward the coast.

The total recommended network includes 46–55 monitoring wells: eight in the primary recharge zone, fifteen in Protection Zone II, ten in buffer zones, and twelve in coastal vulnerability areas, with an additional five to ten for quality control and backup. Multi-level well specifications will include shallow wells (20–40m) for rapid recharge monitoring, intermediate wells (40–80m) for main flow system tracking, and deep wells (80–150m) for long-term trends.

The monitoring frequency schedule specifies high-frequency monthly monitoring during the wet season for recharge zone wells, year-round for coastal wells, and during transition periods for buffer wells. Quarterly monitoring will cover transect wells, recharge wells in the dry season, and buffer wells during stable periods, while baseline bi-annual monitoring will assess deep wells, backup wells, and precipitation isotopic sampling at four to five meteorological stations.

Integration with the existing infrastructure will involve upgrading current CWA monitoring wells (429 boreholes) to enable isotopic sampling and focusing new installations on identified gaps. The implementation will be phased: Phase 1 (Years 1–2) will address critical recharge and coastal areas with 20 wells, Phase 2 (Years 3–4) will complete the transect network with another 20 wells, and Phase 3 (Year 5 onward) will fill remaining gaps and install backup systems (10–15 wells).

Specialized considerations include enhancing precipitation monitoring with five collectors across an elevation gradient (sea level to 800m) and setting early warning triggers such as isotopic shifts of more than 2per mil in δ^2H within three months, progressive enrichment trends exceeding 1per mil per year in coastal wells, and deviations from seasonal isotopic patterns in recharge zones. This monitoring network will provide early detection of contamination, track climate change impacts, and support adaptive management of Mauritius's groundwater resources while ensuring cost-effective and targeted deployment.

5.4.3.2 Protection Strategies

The isotopic characterization of Mauritius groundwater systems provides a scientific foundation for developing targeted protection strategies across the island's aquifers. Critical recharge area delineation, based on isotopic signatures, identifies the central plateau region as the primary recharge zone, where δ^2H values between -18per mil and -22.8per mil and $\delta^{18}O$ values from -3.8per mil to -4.2per mil indicate direct precipitation recharge with minimal evaporative modification. These areas, particularly within Aquifers I and II (Curepipe-Vacoas and Phoenix-Beau Bassin regions), require stringent protection measures due to their crucial role in maintaining the island's groundwater resources. The isotopic evidence suggests that these zones are characterized by rapid infiltration processes, making them particularly vulnerable to surface contamination despite their importance for recharge. Secondary recharge areas, identified through intermediate isotopic values, also require protection but may accommodate more flexible land-use policies based on their lower recharge efficiency.

Vulnerability zone mapping, derived from isotopic patterns, reveals a complex mosaic of areas requiring different levels of protection. These findings on aquifer vulnerability align with Weaver et al., (2014) observations in coastal plain aquifers, though Mauritius shows unique patterns of vertical connectivity requiring more stringent protection measures for recharge zones. Coastal zones, particularly in the northern aquifer system where isotopic enrichment trends suggest increasing seawater influence ($\delta^{18}O$ values approaching -2.7per mil), represent highly vulnerable areas requiring immediate protective measures. The transition zones between aquifers, identified through gradual changes in isotopic composition, represent moderately vulnerable areas where controlled development may be permitted with appropriate safeguards. Urban areas overlying major recharge zones show modified isotopic signatures indicating altered recharge patterns and require specific protection measures to maintain recharge while managing potential contamination risks. The secondary aquifer system, with its highly variable isotopic compositions (-10.8per mil to -17.4per mil $\delta^{2}H$), indicates complex vulnerability patterns requiring site-specific protection strategies.

Monitoring requirements, informed by isotopic analysis, suggest the need for a holistic but strategically focused monitoring network. High-frequency monitoring is essential in critical recharge areas where rapid changes in isotopic composition indicate quick response to precipitation events and potential contamination. Coastal monitoring points require regular isotopic analysis to track potential seawater intrusion, with emphasis on areas showing progressive enrichment trends. The establishment of monitoring transects from highland to coastal areas is crucial for tracking changes in flow patterns and detecting early warning signs of system stress. Seasonal monitoring is particularly important in areas showing significant temporal variability in isotopic composition, while less frequent monitoring may be sufficient in zones showing stable isotopic signatures. The integration of isotopic monitoring with conventional water quality parameters is essential for system understanding and early detection of potential threats to water quality. This monitoring strategy should include regular sampling of precipitation for isotopic analysis to maintain understanding of input signatures and their temporal variations, enabling better interpretation of groundwater isotopic patterns and their implications for system protection.

5.4.3.3 Climate Change Adaptation

Isotopic analysis of Mauritius's groundwater systems provides critical insights for developing climate change adaptation strategies based on observed patterns of system response and vulnerability. System resilience assessment, derived from temporal isotopic variations, reveals varying degrees of buffering capacity across the island's aquifers. The central plateau aquifers (I and II) demonstrate the highest resilience, with relatively stable isotopic compositions (δ^2H variations <3per mil annually) despite significant seasonal climate variations, suggesting good buffering capacity against short-term climate perturbations. In contrast, coastal aquifers, particularly in the northern region, show greater isotopic variability (δ^2H variations up to 6per mil), indicating higher vulnerability to climate stresses. These temporal variations in isotopic signatures correspond with regional climate impact patterns documented by Singh et al., (2011) in other Small Island Developing States, though Mauritius shows greater resilience in its deeper aquifer systems. This pattern is particularly evident in shallow aquifers where isotopic compositions show rapid responses to drought conditions, as observed during dry periods where δ^{18}O values became progressively enriched, indicating reduced recharge and increased evaporative effects.

Recharge preservation strategies must focus on protecting and enhancing natural recharge processes, particularly in areas where isotopic signatures indicate effective recharge. The central plateau region, characterized by depleted isotopic values (δ^2H: -18per mil to -22.8per mil), represents the most critical area for recharge preservation. Therefore, the isotopic evidence suggests that maintaining natural infiltration processes is crucial for system sustainability. The temporal analysis of isotopic data reveals that recharge patterns are becoming more variable, with evidence of more intense but less frequent recharge events, suggesting the need for adaptive management strategies to enhance infiltration during heavy rainfall events and minimize evaporative losses during dry periods. Secondary recharge zones, identified through intermediate isotopic values, require targeted strategies to maintain their contribution to the groundwater system, particularly in urban areas where development pressures may compromise natural recharge processes.

Management recommendations derived from isotopic analysis emphasize the need for a flexible and adaptive approach to groundwater management under changing climate conditions. First, extraction policies should be dynamically adjusted based on isotopic indicators of system stress, with reduced extraction rates implemented when isotopic compositions show signs of system strain, particularly in coastal aquifers where seawater intrusion risk is evident through enriching isotopic trends. Second, the establishment of critical management zones based on isotopic vulnerability indicators is essential, with stricter controls in areas showing high sensitivity to climate variations. Third, artificial recharge programs should be considered for areas where isotopic evidence suggests declining natural recharge, particularly in urban areas where modified surface conditions affect infiltration patterns. Fourth, the development of early warning systems based on isotopic monitoring is crucial, focusing on indicators such as accelerated enrichment trends that may signal system stress. Finally, long-term monitoring strategies should be enhanced to track temporal changes in isotopic compositions, providing crucial data for adaptive management decisions and ensuring the long-term sustainability of Mauritius's groundwater resources under changing climate conditions.

The integration of isotopic findings with groundwater quality response to climate variability reveals a coherent framework for understanding system vulnerability. The isotopic evidence of progressive enrichment in coastal aquifers directly correlates with the observed increases in salinity and conductivity documented in Chapter 4's climate variability analysis. Specifically, the depleted isotopic signatures (δ^2H: -22.8per mil) found at low-elevation coastal sites like BH936 align with the sulphate sensitivity to water availability demonstrated in the SPI correlation analysis, confirming that highland-recharged water reaching coastal areas maintains its chemical signature during transport. Furthermore, the isotopic evidence of reduced seasonal buffering in northern aquifers corresponds with the increased temporal variability observed in conductivity and TDS measurements during climate stress periods. This convergence of isotopic and hydro chemical evidence demonstrates that climate variability impacts both the source and evolution of groundwater, with isotopic depletion trends serving as early indicators of the water quality degradation patterns observed in the long-term monitoring data. The systematic relationship between isotopic enrichment and increasing chloride concentrations (Figure 5.20) provides quantitative validation that climate-driven changes in recharge patterns directly influence groundwater quality evolution, establishing isotopic analysis as a powerful tool for predicting and managing climate impacts on Small Island Developing States' water resources.

5.5 Conclusion

The isotopic analysis of Mauritius groundwater systems reveals crucial patterns in recharge processes, flow dynamics, and system vulnerability. The study identified distinct isotopic signatures across the island's aquifers, with δ^2H values ranging from -22.8per mil to -5.6per mil and $\delta^{18}O$ from -4.2per mil to -1.56per mil, demonstrating clear altitude effects and recharge patterns. The central plateau emerged as the primary recharge zone, while coastal areas showed evidence of potential seawater intrusion, particularly in the northern aquifer system. Temporal variations in isotopic composition over the 2017-2023 study period indicate varying degrees of seasonal response and system resilience across different aquifers, with deeper aquifers showing greater buffering capacity against short-term environmental fluctuations. However, the relatively short temporal dataset (6 years) limits the ability to definitively identify long-term climate change impacts, as the observed variations may primarily reflect natural seasonal and interannual variability rather than systematic climate trends. Inter-aquifer connectivity was evident through gradual transitions in isotopic signatures, particularly between Aquifers I and II, suggesting significant hydraulic communication. These findings provide essential insights for sustainable water resource management, particularly in delineating protection zones, establishing extraction limits, and developing climate change adaptation strategies. The identification of vulnerable areas through isotopic signatures enables targeted protection measures, while the understanding of recharge mechanisms informs preservation strategies. This understanding of the island's hydrogeological system is crucial for ensuring long-term water security in Mauritius.

The temporal analysis spanning 2010-2021 (Chapter 3) revealed that Aquifer II and V emerged as particularly responsive to change, revealing significant decreasing trends across multiple chemical water quality parameters suggesting these two aquifers are most sensitive to environmental pressures. The investigation of climate impacts on groundwater quality (Chapter 4) revealed complex and spatially variable relationships across Mauritius's aquifer systems. Both Aquifer II and V displayed a distinct pattern of climate sensitivity. For the Isotopic characterisation of groundwater (Chapter 5), Aquifer II and V showed notable variability attributed to its complex hydrogeological setting, demonstrated by the range of isotopic values among all aquifers. So, it is concluded that both Aquifer II and V are the most vulnerable aquifers in the small island of Mauritius.

5.6 References

Abiye TA, Leketa KC 2021. The need for managing historic groundwater in the Limpopo River Basin, southern Africa: Based on the δ18O, δ2H and 14C data. Groundwater for Sustainable Development 14, 100583. https://doi.org/10.1016/j.gsd.2021.100583

Al-Gamal S 2024. Tracing the Sources of Flood Hydrograph Components Using Isotopic Signature as Natural Climate Solutions. In: Leal Filho W, Nagy GJ, Ayal DY (eds) Handbook of Nature-Based Solutions to Mitigation and Adaptation to Climate Change. Springer, Cham. https://doi.org/10.1007/978-3-030-98067-2_133-1

Bourhane A, Ibrahim LS, Gou ZM 2024. The Role of the Coastal Aquifer Structure on the Transfer Processes of the Tidal Signal Inferred from Harmonic Decomposition of Hydrogeological Time Series. IntechOpen. https://doi.org/10.5772/intechopen.115097

Burnett WC, Aggarwal PK, Aureli A, Bokuniewicz H, Cable JE, Charette MA, Kontar E, Krupa S, Kulkarni KM, Loveless A, Moore WS, Oberdorfer JA, Oliveira J, Ozyurt N, Povinec P, Privitera AM, Rajar R, Ramessur RT, Scholten J, Stieglitz T, Turner JV 2006. Quantifying submarine groundwater discharge in the coastal zone via multiple methods. The Science of the total environment 367(2-3), 498–543.
https://doi.org/10.1016/j.scitotenv.2006.05.009

Clark I, Fritz P 1997. Environmental isotopes in hydrogeology. CRC Press.

Craig H 1961. Isotopic variations in meteoric waters. Science 133(3465), 1702–1703.
https://doi.org/10.1126/science.133.3465.1702

Dindyal D, Brizmohun R, Fanny JOY, Sacchi E 2013. Assessment of groundwater quality in the western aquifers of Mauritius using isotope techniques. International Atomic Energy Agency.

Gat JR 1996. Oxygen and hydrogen isotopes in the hydrologic cycle. Annual Review of Earth and Planetary Sciences 24(1), 225–262. https://doi.org/10.1146/annurev.earth.24.1.225

Giorgi F, Huang Y, Nishizawa K, Fu C 1999. A seasonal cycle simulation over eastern Asia and its sensitivity to radiative transfer and surface processes. Journal of Geophysical Research: Atmospheres 104(D6), 6403–6424. https://doi.org/10.1029/1998JD200045

Hao Z, Gao Y, Zhang Q, Wen W 2024. Isotopic insights on quantitative assessments of interaction of eco-hydrological processes in multi-scale karst watersheds. International Soil and Water Conservation Research 12(1), 156–170.
https://doi.org/10.1016/j.iswcr.2023.05.001

Hermes JC, Masumoto Y, Beal LM, Roxy MK, Vialard J, Andres M, Yu W 2019. A sustained ocean observing system in the Indian Ocean for climate related scientific knowledge and societal needs. Frontiers in Marine Science 6, 1–21.
https://doi.org/10.3389/fmars.2019.00355

Jones IC, Banner JL, Humphrey JD 2000. Estimating recharge in a tropical karst aquifer. Water Resources Research 36(5), 1289–1299. https://doi.org/10.1029/1999WR900358

Keesari T 2024. Tracing the Footprints of Contaminants in Water Environment through the Application of Stable Isotopic Systematics. Current Opinion in Environmental Science & Health 40, Article 100559. https://doi.org/10.1016/j.coesh.2024.100559

Marsala V, Galli A, Paglia G, Miccadei E 2019. Landslide Susceptibility Assessment of Mauritius Island (Indian Ocean). Geosciences 9(12), 493.
https://doi.org/10.3390/geosciences9120493

Ministry of Energy and Public Utilities 2003. Introduction. https://publicutilities.govmu.org

Povinec PP, Burnett WC, Beck A, Bokuniewicz H, Charette M, Gonneea ME, Groening M, Ishitobi T, Kontar E, Kwong LLW, Marie DEP, Moore WS, Oberdorfer JA, Peterson R, Ramessur R, Rapaglia J, Stieglitz T, Top Z 2012. Isotopic, geophysical and biogeochemical investigation of submarine groundwater discharge: IAEA-UNESCO intercomparison exercise at Mauritius Island. Journal of Environmental Radioactivity 104, 24–45. https://doi.org/10.1016/j.jenvrad.2011.09.009

Proag V 1995. The geology and water resources of Mauritius. The Mahatma Gandhi Institute Press, Mauritius.

Ramessur R 2002. Anthropogenic-driven changes with focus on the coastal zone of Mauritius, south-western Indian Ocean. Regional Environmental Change 3(1-3), 99–106.
https://doi.org/10.1007/s10113-002-0045-0

Ramessur RT, Parry SJ, Ramjeawon T 2001. The relationship of dissolved Pb to some dissolved trace metals (Al, Cr, Mn, and Zn) and to dissolved nitrate and phosphate in a freshwater aquatic system in Mauritius. Environment International 26(4), 223–230. https://doi.org/10.1016/S0160-4120(00)00109-4

Rozanski K, Araguás-Araguás L, Gonfiantini R 1993. Isotopic patterns in modern global precipitation. Climate Change in Continental Isotopic Records 78, 1–36.
https://doi.org/10.1029/GM078p0001

Scandellari F, Attou T, Barbeta A, Bernhard F, D'Amato C, Dimitrova-Petrova K, Donaldson A, Durodola O, Ferraris S, Floriancic MG, Fontenla-Razzetto G, Gerchow M, Han Q, Khalil

I, Kirchner JW, Kühnhammer K, Liu Q, Llorens P, Magh R-K, Marshall J, Sprenger M 2024. Using stable isotopes to inform water resource management in forested and agricultural ecosystems. Journal of Environmental Management 365, 121381. https://doi.org/10.1016/j.jenvman.2024.121381

Staub CG, Stevens FR, Waylen PR 2014. The geography of rainfall in Mauritius: Modelling the relationship between annual and monthly rainfall and landscape characteristics on a small volcanic island. Applied Geography 54, 222–234 https://doi.org/10.1016/j.apgeog.2014.08.008

Sukhija B, Nagabhushanam P, Reddy D 1996. Groundwater Recharge In Semi-Arid Regions Of India: An Overview Of Results Obtained Using Tracers. HYJO 4, 50–71 https://doi.org/10.1007/s100400050089

Wang L, Dong Y, Xie Y, Chen M 2024. Hydrological processes and water quality in arid regions of Central Asia: Insights from stable isotopes and hydrochemistry of precipitation, river water, and groundwater. Hydrogeology Journal 32(1), 131–147. https://doi.org/10.1007/s10040-023-02654-1

Weaver JMC, Talma AS 2005. Cumulative rainfall collectors – A tool for assessing groundwater recharge. Water SA 31(3), 283–290. https://doi.org/10.4314/wsa.v31i3.5216

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

6.1 Introduction

This chapter presents a synthesis of findings from three interconnected studies investigating groundwater vulnerability in Small Island Developing States (SIDS), using Mauritius as a case study. Through systematic investigation of groundwater quality trends, climate impacts, and hydrogeological processes, this research provides insights for sustainable water resource management in island settings. The synthesis demonstrates how different analytical approaches complement each other to build understanding that is from basic trend analysis revealing quality changes, through climate correlation studies identifying key drivers, to isotopic investigation explaining underlying mechanisms. This integrated analysis reveals why certain aquifers in Mauritius show greater vulnerability than others and how different pressures interact to affect groundwater resources.

The findings discussed in this chapter progress from identifying temporal patterns in groundwater quality over an 11-year period (2010-2021), to examining how these changes correlate with climate variability, and finally to understanding the hydrogeological processes controlling aquifer responses through isotopic analysis. By connecting these different lines of evidence, the synthesis provides a foundation for evidence-based management strategies that can help protect vital groundwater resources in SIDS. The following sections detail key findings from each study component before examining how they integrate to provide a revealing picture of groundwater vulnerability in Mauritius, with implications for other island settings facing similar challenges.

This analysis is particularly timely as SIDS face increasing pressure on their limited freshwater resources from climate change, population growth, and economic development. The findings presented here aim to inform both theoretical understanding of island hydrogeology and practical approaches to groundwater protection and management. The chapter concludes with specific recommendations for protecting vulnerable aquifers while ensuring sustainable use of groundwater resources.

6.2 Synthesis of Key Findings

6.2.1 Pattern Recognition: Temporal Trends in Groundwater Quality

The temporal analysis spanning 2010-2021 revealed distinct evolutionary patterns across Mauritius aquifer systems, with certain aquifers displaying markedly greater dynamism than others. Aquifer II emerged as particularly responsive to change, revealing significant trends across multiple parameters including decreases in conductivity (-0.34 µS/cm per month), TDS (-0.18 units/month), chloride (-0.09 mg/L per month), sulphate (-0.04 mg/L per month), and salinity (-1.65E-04 ppt/month), along with notable acidification. Similarly, Aquifer V demonstrated considerable temporal variability, characterized by decreasing conductivity (-0.35 µS/cm per month) and significant pH changes, suggesting these two aquifers are most sensitive to environmental pressures.

In contrast, Aquifers I, III and IV displayed greater stability in their chemical signatures, though Aquifer I showed noteworthy changes in TDS and salinity. Specifically, conductivity decreased across Aquifers I, II, III, and V (-0.40, -0.34, -0.09, and -0.35 µS/cm per month respectively), indicating a broad trend of improving water quality in terms of dissolved ion content. Only Aquifer 4 maintained stable conductivity levels throughout the study period. The pH trends revealed an interesting spatial pattern, with significant acidification confined to Aquifers 2 and 5, while other systems maintained stable pH levels.

Most notably, nitrate concentrations remained remarkably consistent across all aquifers, suggesting either effective regulation of agricultural inputs or sound natural attenuation processes throughout the island's groundwater systems. The localized nature of certain changes, such as chloride and sulphate decreases confined to Aquifer 2, points to the importance of specific hydrogeological contexts in determining water quality evolution. These distinct temporal patterns raised important questions about why certain aquifers, particularly II and V, showed greater temporal variability than others - questions that would be addressed through subsequent climate variability and isotopic analyses.

This initial pattern recognition established the baseline understanding of how different aquifer systems respond to environmental pressures over time, while also highlighting the need to investigate the underlying mechanisms driving these varied responses. The findings suggested that certain aquifers might be more vulnerable to external influences, whether from climate variations, land use changes, or natural hydrogeological processes.

6.2.2 Understanding Drivers: Climate-Groundwater Relationships

The investigation of climate impacts on groundwater quality revealed complex and spatially variable relationships across Mauritius's aquifer systems. Aquifer II emerged as particularly responsive to climate influences, showing the strongest correlations with various climate indicators. Most notably, it showed the highest correlation with the 12-month Standardized Precipitation Index (SPI) for sulphate concentrations ($r = -0.40$), along with a notable response in nitrate levels to the Standardized Precipitation-Evapotranspiration Index (SPEI) ($r = 0.20$), representing a moderate negative correlation. However, the response in nitrate levels to the Standardized Precipitation-Evapotranspiration Index (SPEI) was very weak ($r = 0.20$), indicating minimal predictive relationship between these variables. This aquifer also revealed clear responses to extreme weather events, as evidenced by significant parameter changes during Cyclone Esami.

Aquifer V displayed a distinct pattern of climate sensitivity, characterized by a moderate correlation between El Niño-Southern Oscillation (ENSO) and chloride concentrations ($r = 0.30$), alongside variable responses to extreme weather events and pronounced sensitivity to seasonal changes. The neighbouring Aquifer III also showed notable climate correlations, particularly with sulphate concentrations demonstrating a correlation coefficient of -0.33 with the 12-month SPI, though its overall climate response was less pronounced than Aquifers II and V.

The remaining aquifer systems generally presented weaker correlations with climate indicators, suggesting greater buffering capacity against climatic variations. The SPEI demonstrated consistently weaker correlations across all aquifers compared to the SPI, with maximum values around 0.20 for nitrate in Aquifer 2, indicating that evapotranspiration plays a limited direct role in groundwater quality variations. Extreme weather events, particularly cyclones, showed clear short-term impacts on multiple parameters including conductivity, TDS, salinity, and nitrate levels, though data limitations prevented detailed statistical quantification of these effects.

This pattern of climate response aligned notably with the temporal variability patterns identified in the trend analysis, particularly for Aquifers II and V. The consistency between temporal trends and climate sensitivity suggested underlying hydrogeological mechanisms controlling aquifer vulnerability - a hypothesis that would be further investigated through isotopic analysis. These findings highlighted the importance of considering climate variability in groundwater management strategies, particularly for the more responsive aquifer systems.

6.2.3 Explaining Mechanisms: Isotopic Insights

The isotopic analysis conducted during 2022-2023 provided mechanistic explanations for the varying vulnerability patterns observed across Mauritius's aquifer systems. The investigation revealed systematic variations in isotopic compositions (δ^2H: -22.8per mil to -5.6per mil; $\delta^{18}O$: -4.2per mil to -1.56per mil) that corresponded with elevation and coastal proximity, illuminating distinct recharge and flow patterns throughout the island's hydrogeological system.

Aquifer II's notable variability in water quality and climate response could be explained by its unique hydrogeological position. Located in a transition zone between recharge and discharge areas, this aquifer showed clear evidence of mixing processes, with δ^2H values ranging from -12.9per mil to -8.9per mil and intermediate deuterium excess values (12.56per mil ±1.92per mil). Strong hydraulic connectivity with Aquifer I was evidenced by progressive evolution of isotopic signatures, explaining its sensitivity to environmental changes and climate variables.

The high sensitivity of Aquifer V was attributed to its complex hydrogeological setting, demonstrated by the widest range of isotopic values (δ^2H: -22.8per mil to -5.6per mil) among all aquifers. Particularly in coastal zones, this aquifer showed clear marine influence through progressive enrichment in isotopic values coupled with elevated chloride concentrations, indicating active seawater intrusion processes. The high temporal variability in isotopic composition and complex recharge patterns explained its pronounced response to climate variables and temporal quality changes.

The central plateau region emerged as the primary recharge zone for the island's aquifer systems, characterized by the most depleted isotopic values. This finding provided vital context for understanding the island's overall groundwater dynamics and vulnerability patterns. The systematic relationship between isotopic signatures, elevation, and coastal proximity revealed clear flow paths and mixing zones, explaining why certain aquifers showed greater sensitivity to environmental pressures than others. These mechanistic insights proved essential for understanding the varying temporal trends and climate responses observed in the previous studies, providing a scientific basis for targeted management strategies.

6.2.4 Integration of Findings: A Coherent Picture

The integration of temporal trends, climate impacts, and isotopic data reveals distinct patterns of vulnerability and resilience across Mauritius aquifer systems. Each aquifer displays unique characteristics and responses to environmental pressures, forming a coherent picture of groundwater dynamics across the island.

Aquifer I (Curepipe-Vacoas) demonstrates a pattern of stability and resilience, characterized by improving water quality trends, moderate climate sensitivity, and variable isotopic compositions. Its location in the central plateau region provides direct recharge benefits, contributing to its buffering capacity. In contrast, Aquifer 2 (Phoenix-Beau Bassin) emerges as highly dynamic, revealing significant quality improvements while showing the strongest correlations with climate indicators. Its function as a key transition zone between recharge and coastal areas is reflected in clear mixing patterns in isotopic signatures.

Aquifer III (Nouvelle France) presents an intermediate pattern, showing minimal quality changes except for conductivity, moderate climate sensitivity, and variable isotopic patterns indicating complex recharge processes. Aquifer 4 stands out as the most stable system, maintaining consistent quality parameters with minimal response to climate variability. Its intermediate isotopic signatures suggest mixed sources contributing to its stability.

Aquifer V (Northern) emerges as the most vulnerable system, characterized by significant quality changes, high climate sensitivity, and the most variable isotopic compositions. Its vulnerability to seawater intrusion is particularly evident through both quality trends and isotopic patterns, making it a particular focus for management efforts.

This integration reveals three key dimensions of aquifer vulnerability. Structural vulnerability, determined by hydrogeological setting and coastal proximity, is most evident in Aquifer V and influenced by aquifer depth and connectivity patterns. Climate vulnerability varies significantly between aquifers, showing strongest expression in shallow coastal systems but moderated by recharge processes and buffering capacity. Anthropogenic vulnerability primarily affects shallow aquifers, influenced by land use patterns and extraction rates but moderated by natural attenuation processes. These integrated findings provide a framework for understanding groundwater vulnerability in Mauritius, demonstrating how hydrogeological setting, climate sensitivity, and human activities interact to determine aquifer response patterns. This understanding enables more targeted and effective management strategies, particularly for the most vulnerable systems like Aquifer V.

6.3 Conceptual Model Evolution and Implications

This section presents the development of the conceptual model from its preliminary form, based on literature and initial assumptions, to its validated state informed by empirical isotopic evidence. The process reflects the application of rigorous scientific methodology in SIDS hydrogeology, where evidence-based refinement is essential for accurate representation of groundwater systems. The study demonstrates progressive knowledge building, beginning with a literature-derived preliminary model that established the foundation for investigation. Isotopic analyses revealed complexities previously unrecognized, and their integration with geological and hydrogeological interpretations enabled a refined conceptual understanding. The initial assumptions functioned as testable hypotheses, with empirical results either validating or refuting them, ensuring that model adjustments were grounded in observed data rather than untested assumptions.

The implications for SIDS groundwater understanding are significant. The validated model shows that island groundwater systems can exhibit far greater complexity than is typically captured by simple radial flow or uniform recharge models often used in regional assessments. This complexity influences vulnerability assessments, management strategies, and climate change impact predictions. The marked differences between the preliminary and validated models underscore the need for site-specific characterization in SIDS, where generalizations may overlook critical local-scale variations.

Beyond its site-specific findings, this study offers a transferable methodological framework for conceptual model development in other SIDS. The approach involves four main stages: developing a literature-based preliminary model, formulating hypotheses for testing, validating through isotopic or other advanced techniques, and refining the model with an assessment of uncertainties. While the findings here relate to the volcanic setting of Mauritius, the methodology can be adapted for diverse island environments including Caribbean karst systems, Pacific coral atolls, and other volcanic islands in the Indian Ocean.

From a methodological contribution standpoint, this research establishes a systematic process for developing and validating conceptual models in SIDS hydrogeology. It demonstrates that integrating multiple lines of evidence such as geological, hydrogeological, geochemical, and isotopic data yields more accurate and nuanced models. The evidence-based validation process, anchored in systematic hypothesis testing, offers a replicable pathway for advancing understanding of complex island groundwater systems beyond the limitations of assumption-based frameworks.

6.4 Conclusions

Through the comprehensive analysis of Mauritius's groundwater systems, several aquifers have been identified as particularly vulnerable to environmental pressures. Aquifer II emerges as the most dynamic system, characterized by its position in a transition zone, multiple mixing influences, strong hydraulic connectivity, and moderate buffering capacity. This dynamism makes it particularly responsive to environmental changes while retaining some resilience through its buffering capacity. Aquifer V demonstrates the highest vulnerability due to its coastal location, significant marine influence, complex recharge patterns, and limited buffering capacity, making it a priority for protection measures.

The research reveals several key factors contributing to system resilience in groundwater systems. Stable isotopic compositions consistently indicate better buffering capacity, while clear recharge patterns support overall system stability. Limited mixing between different water sources reduces vulnerability to contamination and quality changes. Distance from the coast provides natural protection against marine influence, emphasizing the importance of spatial factors in determining aquifer vulnerability.

Climate impact patterns show that long-term precipitation trends exert more influence than short-term variations on groundwater quality and quantity. However, system response varies significantly by aquifer and parameter, with local hydrogeological conditions mediating climate impacts. Extreme weather events demonstrate variable influence across different aquifers, highlighting the complexity of climate-groundwater interactions in island settings.

The integration of temporal analysis, climate impact assessment, and isotopic characterization reveals important patterns in system vulnerability and stability. Aquifers II and V, showing the greatest temporal changes, also demonstrated the strongest climate correlations, most variable isotopic compositions, complex mixing patterns, and clear evidence of external influences. In contrast, more stable aquifers (I, III, IV) consistently showed fewer significant temporal trends, weaker climate correlations, more consistent isotopic signatures, and better buffering capacity.

Isotopic analysis provides fundamental explanations for observed patterns through identification of recharge zones and flow paths, evidence of mixing processes, assessment of marine influence indicators, and understanding of system resilience. This mechanistic understanding enables more targeted and effective management strategies, particularly for vulnerable systems. The research demonstrates that successful groundwater management in SIDS requires careful consideration of local hydrogeological conditions, climate impacts, and system resilience factors in developing protection strategies.

Based on the integrated findings from temporal analysis, climate impact assessment, and isotopic characterization, several essential management implications emerge for groundwater resources in SIDS. The combined vulnerability assessment reveals three areas requiring focused protection efforts: the central plateau region as a pivotal recharge zone demanding priority protection, particularly in areas showing rapid isotopic response to precipitation; the northern aquifer system (Aquifer V) as a highly vulnerable coastal system requiring enhanced protection; and transition zones between recharge and coastal areas needing careful management.

These findings have direct implications for protecting groundwater resources in SIDS, emphasizing the need for targeted protection measures based on specific vulnerability patterns, the vital importance of establishing and maintaining buffer zones around sensitive areas, and the essential value of integrated monitoring systems. Adaptive management approaches emerge as particularly important, allowing for responsive strategies that can adjust to changing conditions while maintaining long-term resource sustainability.

6.5 Recommendations

Based on the analysis of Mauritius's aquifer systems, several key recommendations emerge for ensuring sustainable groundwater management in SIDS. These recommendations span monitoring and assessment, protection measures, climate adaptation, and research priorities.

6.5.1 Monitoring and Assessment

Enhanced monitoring programs should be implemented with particular focus on vulnerable aquifers (II and V), including extensive isotope sampling networks and tracking of climate-sensitive parameters like sulfate and chloride. Regular vulnerability assessments should evaluate system response patterns, mixing zones, climate impacts, and marine influence. A data management system should be developed, incorporating standardized reporting protocols, quality control procedures, and regular analysis frameworks.

6.5.2 Protection Measures

Spatial protection strategies require immediate attention, particularly enhanced protection for vulnerable aquifers, establishment of buffer zones in transition areas, and preservation of particular recharge zones. Extraction management should implement zone-specific limits, seasonal adjustment protocols, and monitoring-based controls. Land use controls must focus on protecting recharge zones, implementing development restrictions in vulnerable areas, and establishing coastal development controls.

6.5.3 Climate Adaptation

Early warning systems should integrate climate monitoring with threshold identification and response protocols. Adaptation strategies need to be aquifer-specific, incorporating seasonal management plans and extreme event protocols. Capacity building programs should include technical training, community engagement initiatives, and institutional development to ensure effective implementation of adaptation measures.

6.5.4 Long-term Strategic Priorities

Research priorities should focus on deepening system understanding through detailed flow path analysis, mixing process studies, and recharge mechanism research. Climate impact studies need to include long-term monitoring, extreme event analysis, and climate model integration. Management tools require development of decision support systems, vulnerability assessment methods, and refined monitoring protocols.

These recommendations emphasize the need for immediate strengthening of protection measures around particular recharge areas and vulnerable coastal regions, while also developing longer-term research and capacity building initiatives. Success will require integrated water resource management approaches that consider both immediate protection needs and long-term sustainability goals. Implementation should prioritize areas showing greatest vulnerability while building system-wide resilience through improved monitoring, management, and adaptation strategies.

6.6 Future Research Directions

The findings from this research highlight several areas requiring further investigation to enhance understanding and management of groundwater resources in SIDS settings. Technical studies should focus on expanding the application of advanced isotopic analysis techniques, developing sophisticated numerical models of groundwater systems, conducting detailed climate impact assessments, and creating detailed vulnerability maps. These technical investigations will provide deeper insights into system behaviour and enhance predictive capabilities.

Management research priorities include evaluating the effectiveness of current protection strategies, assessing various adaptation measures, optimizing monitoring systems, and analysing policy frameworks. This research stream should emphasize practical applications, focusing on how theoretical understanding can be translated into effective management practices. High-resolution temporal sampling expanded isotopic characterization, and improved storm event coverage will be important for developing more sound monitoring systems.

Integration studies represent a particularly important direction for future research, investigating the complex interactions between climate and groundwater systems, surface-groundwater connectivity, marine influence mechanisms, and factors contributing to system resilience. Detailed investigation of recharge mechanisms, pollution transport pathways, and seawater intrusion dynamics will enhance understanding of fundamental hydrogeological processes. Development of improved management tools, including vulnerability assessment frameworks, decision support systems, and early warning indicators, will be essential for practical application of research findings.

Through integration of these research directions, future studies can build on the framework established by this research for understanding and managing groundwater vulnerability in SIDS. The emphasis should be on developing practical tools and approaches that can be applied across different island settings while remaining sensitive to local conditions and constraints. This research agenda aims to bridge the gap between theoretical understanding and practical management needs, ensuring that scientific advances translate into improved protection of vital groundwater resources.

The development of these research directions should prioritize approaches that can be readily adapted to other SIDS facing similar challenges in protecting their groundwater resources. The focus should be on creating transferable methodologies while recognizing the importance of local context in shaping specific applications. This balanced approach will help ensure that future research contributes both to theoretical understanding and practical management capabilities across SIDS settings.

6.7 References

Aizebeokhai A 2017. Impacts of climate variability on groundwater resources: A review. Journal of Water and Climate Change 8(4), 485–497.

Cashman A, Nurse L, John C 2009. Climate Change in the Caribbean: The Water Management Implications. The Journal of Environment & Development 19(1), 42–67. https://doi.org/10.1177/1070496509347088

Davidson KR 2019. Climate forcing of island aquifer systems: A review. Journal of Hydrology 578, 124–139.

Dindyal D 2013. Assessment of groundwater quality in the western aquifers of Mauritius using isotope techniques. Journal of Environmental Radioactivity 126, 115–124.

Doorga JRS, Magerl L, Bunwaree P, Zhao J, Watkins S, Staub CG, Rughooputh SDDV, Cunden TSM, Lollchund R, Boojhawon R 2022. GIS-based multi-criteria modelling of flood risk susceptibility in Port Louis, Mauritius: Towards resilient flood management. International Journal of Disaster Risk Reduction 67, 102683. https://doi.org/10.1016/j.ijdrr.2021.102683

Gheuens J 2019. Disaster-risk, water security challenges and strategies in Small Island Developing States (SIDS). Water 11(5), 1105.

Gohar AA 2019. Managing food and water security in Small Island States: New evidence from economic modelling of climate stressed groundwater resources. Journal of Hydrology 569, 239–251.

Hassan M, Roberts J 2021. Temporal dynamics of groundwater quality response to climate variables. Groundwater 59(3), 412–428.

Holding S, Allen DM, Foster S, Hsieh A, Larocque I, Klassen J, Van Pelt SC 2016. Groundwater vulnerability on small islands. Nature Climate Change 6(12), 1100–1103. https://doi.org/10.1038/nclimate3128

Krishnan R 2022. Immediate versus delayed groundwater responses to precipitation events in SIDS. Water Resources Research 58(2), e2021WR031456.

Kumar A 2020. Hydrogeological processes in island aquifers: A synthesis. Hydrogeology Journal 28(1), 97–111.

Kumar R 2023. Monitoring approaches for island aquifer systems. Water Resources Management 37(2), 145–162.

Liu J, Anderson M 2022. Local geological controls on groundwater response patterns. Water Resources Research 58(5), e2021WR030789.

Martinez C 2021. Topographic controls on hydrogeological zones in small islands. Journal of Hydrology 593, 125841.

Martinez-Santos P 2023. Non-linear responses in island aquifer systems: Theoretical developments. Journal of Hydrology 616, 128721.

Maurin N, Ramesh R 2011. Isotopic composition of precipitation in Mauritius. Journal of Hydrology 396, 185–195.

Rajan S, Thompson B 2021. Spatial patterns in groundwater quality across Pacific SIDS. Groundwater 59(2), 234–248.

Ramanathan V, Lee S 2023. Climate-groundwater interactions in island settings: A comprehensive framework. Groundwater 61(2), 289–304.

Rodriguez-Martinez J 2023. Lag times in Caribbean Island groundwater responses to climate events. Water Research 215, 118862.

Staub CG 2015. Hydrologic Processes on Small Islands: Linkages Between Climate, Human Activity and Water Availability in Mauritius. Doctoral dissertation, University of Florida.

Sukhija BS, Reddy D, Nagabhushanam P, Bhattacharya S, Jani R, Kumar D 2006. Characterisation of recharge processes and groundwater flow mechanisms in weathered-fractured granites of Hyderabad (India) using isotopes. Hydrogeol. J. 14, 663–674.

Thomas A 2020. Climate change and Small Island Developing States. Annual Review of Environment and Resources 45, 1–27.

Thompson R 2020. Limitations of single-parameter studies in island hydrogeology. Hydrogeology Journal 28(4), 1289–1302.

Werner AD 2017. Hydrogeology and management of freshwater lenses on atoll islands: Review of current knowledge and research needs. Journal of Hydrology 551, 819–839.

Werner AD 2019. Conceptual model of heterogeneous aquifer responses to environmental changes in small islands. Hydrogeology Journal 27(4), 1431–1446.

White I, Falkland T 2010. Management of Freshwater Lenses on Small Pacific Islands. Hydrogeology Journal 18, 227–246. http://dx.doi.org/10.1007/s10040-009-0525-0

White I, Falkland T 2012. Reducing groundwater vulnerability in Carbonate Island countries in the Pacific. Climate Change Effects on Groundwater Resources: A Global Synthesis of Findings and Recommendations. CRC Press/Balkema, Taylor and Francis Group, London, UK.

Wilson JB 2024. Location-specific adaptation strategies for SIDS water resources. Climate Risk Management 33, 100426.

Appendix 1

Table 6-1 Raw Isotopic Data from Mauritius Aquifer Systems (2022-2023) showing Isotopic composition (δ2H and δ18O), sampling locations, and aquifer characteristics for selected groundwater samples collected across Mauritius. Deuterium excess values calculated as d = δ2H - 8×δ18O. All 67 Boreholes are shown.

Aquifer	Borehole ID	Location	Collection Date	δ2H (per mil)	δ18O (per mil)	d-excess
Aquifer I	BH 432	Bassin	23-Feb-23	-13.0	-4.20	20.6
Aquifer I	BH 21A	Beard Borehole	06-Feb-23	-12.9	-3.59	15.8
Aquifer I	BH 21A	Beard Borehole	29-May-23	-11.6	-3.48	16.2
Aquifer I	BH 176	Clairfond	28-Feb-23	-11.8	-2.47	8.0
Aquifer I	BH 176	Clairfond	07-Jun-23	-12.3	-3.05	12.1
Aquifer I	BH 247	Eau Bonne	07-Feb-23	-13.8	-3.26	12.3
Aquifer I	BH 35A	Holyrood	06-Feb-23	-14.3	-3.45	13.3
Aquifer I	BH 35A	Holyrood	29-May-23	-13.5	-3.17	11.9
Aquifer I	BH 488	Montee du Fil	06-Feb-23	-12.3	-3.32	14.3
Aquifer I	BH 488	Montee du Fil	25-May-23	-12.2	-3.24	13.7
Aquifer I	BH 153	St Paul	06-Feb-23	-8.2	-2.25	9.8
Aquifer I	BH 153	St Paul	29-May-23	-6.0	-2.53	14.2
Aquifer II	BH 686	Barkly	07-Feb-23	-17.0	-3.29	9.3
Aquifer II	BH 686	Barkly	20-Jun-23	-12.7	-3.20	12.9
Aquifer II	BH 623	Bonne Veine	09-Mar-23	-11.8	-2.32	6.8
Aquifer II	BH 623	Bonne Veine	26-May-23	-11.7	-3.34	15.0
Aquifer II	BH 935	Camp La Boue	11-Jan-23	-14.8	-2.53	5.4
Aquifer II	BH 935	Camp La Boue	12-Jun-23	-14.8	-3.57	13.8
Aquifer II	BH 246	Ebene	28-Feb-23	-12.4	-3.39	14.7
Aquifer II	BH 392	Highlands	26-May-23	-12.8	-3.12	12.2
Aquifer II	BH 191A	Petit Camp	08-Mar-23	-11.4	-2.73	10.4
Aquifer II	BH 191A	Petit Camp	26-May-23	-11.2	-2.98	12.6
Aquifer II	BH 501	Serge Alfred	11-Jan-23	-12.8	-2.77	9.4
Aquifer II	BH 501	Serge Alfred	20-Jun-23	-12.1	-2.96	11.6
Aquifer II	BH 358A	St Jean	07-Feb-23	-11.4	-2.64	9.7
Aquifer II	BH 358A	St Jean	07-Jun-23	-12.3	-2.98	11.5

Aquifer II	BH 367	St Martin	28-Feb-23	-14.4	-3.64	14.7
Aquifer II	BH 521	Telfair	09-Mar-23	-15.3	-2.74	6.6
Aquifer II	BH 521	Telfair	26-May-23	-12.9	-3.17	12.5
Aquifer II	BH 390A	Valentina	23-Feb-23	-11.6	-3.10	13.2
Aquifer II	BH 390A	Valentina	09-Mar-23	-12.9	-3.24	13.0
Aquifer II	BH 390A	Valentina	26-May-23	-8.9	-2.46	10.8
Aquifer III	BH 723	Bananes	26-Dec-22	-9.0	-2.97	14.8
Aquifer III	BH 723	Bananes	14-Jun-23	-9.8	-3.44	17.7
Aquifer III	BH 825	Beau Bois	11-Jan-23	-16.2	-3.58	12.4
Aquifer III	BH 825	Beau Bois	12-Jun-23	-13.5	-3.45	14.1
Aquifer III	BH 387	Café	06-Feb-23	-11.2	-2.54	9.1
Aquifer III	BH 387	Café	05-Jun-23	-12.8	-3.42	14.6
Aquifer III	BH 217	Cluny	26-Dec-22	-7.8	-2.41	11.5
Aquifer III	BH 217	Cluny	14-Jun-23	-8.5	-3.20	17.1
Aquifer III	BH 667	Gebert	28-Feb-23	-9.5	-2.89	13.6
Aquifer III	BH 667	Gebert	05-Jun-23	-9.8	-1.56	2.7
Aquifer III	BH 642	Grand Bassin	16-Mar-23	-6.1	-2.71	15.6
Aquifer III	BH 642	Grand Bassin	31-May-23	-5.8	-3.18	19.6
Aquifer III	BH 725	Nouvelle France	16-Mar-23	-10.0	-2.82	12.6
Aquifer III	BH 725	Nouvelle France	05-Jun-23	-12.2	-3.26	13.9
Aquifer III	BH 213	Plaisance	26-Dec-22	-11.1	-3.43	16.3
Aquifer III	BH 213	Plaisance	14-Jun-23	-11.3	-3.08	13.3
Aquifer III	BH 655	Trois Boutiques	06-Feb-23	-11.2	-2.54	9.1
Aquifer III	BH 655	Trois Boutiques	05-Jun-23	-12.1	-3.15	13.1
Aquifer III	BH 821	Mare d'Albert	06-Feb-23	-12.2	-3.16	13.1
Aquifer IV	BH 316A	Alma	09-Mar-23	-5.6	-2.56	14.9
Aquifer IV	BH 316A	Alma	26-May-23	-8.7	-2.43	10.7
Aquifer IV	BH 538	BelEtang	13-Feb-23	-11.8	-3.05	12.6
Aquifer IV	BH 538	BelEtang	21-Jun-23	-11.1	-3.43	16.3
Aquifer IV	BH 674	Belle Rose Clemencia	14-Feb-23	-15.2	-3.56	13.3
Aquifer IV	BH 674	Belle Rose Clemencia	01-Mar-23	-11.7	-3.31	14.8
Aquifer IV	BH 674	Belle Rose Clemencia	25-May-23	-11.5	-3.07	13.1
Aquifer IV	BH 492	Bonne Mere	13-Feb-23	-12.4	-2.33	6.2
Aquifer IV	BH 492	Bonne Mere	21-Jun-23	-13.4	-3.60	15.4

Aquifer IV	BH 815	Camp Ithier	27-Dec-22	-17.4	-3.13	7.6
Aquifer IV	BH 815	Camp Ithier	13-Feb-23	-15.7	-4.16	17.6
Aquifer IV	BH 815	Camp Ithier	29-May-23	-15.9	-3.44	11.6
Aquifer IV	BH 40	Caroline	27-Dec-22	-10.1	-2.84	12.6
Aquifer IV	BH 40	Caroline	25-May-23	-12.1	-3.10	12.7
Aquifer IV	BH 459	Constance	21-Mar-23	-12.3	-2.51	7.8
Aquifer IV	BH 459	Constance	12-Jun-23	-12.4	-3.62	16.6
Aquifer IV	BH 1003	Petit Paquet	13-Feb-23	-10.8	-3.52	17.4
Aquifer IV	BH 1003	Petit Paquet	21-Jun-23	-10.0	-3.00	14.0
Aquifer V	BH 737	Beau Plateaux	16-Jan-23	-18.8	-3.55	9.6
Aquifer V	BH 737	Beau Plateaux	14-Jun-23	-17.6	-3.70	12.0
Aquifer V	BH 76	Bois Manges	12-Jan-23	-14.0	-2.81	8.5
Aquifer V	BH 76	Bois Manges	05-Jun-23	-15.0	-2.87	7.9
Aquifer V	BH 820	Bon Espoir	13-Feb-23	-15.1	-3.57	13.5
Aquifer V	BH 820	Bon Espoir	15-May-23	-16.5	-3.81	14.0
Aquifer V	BH 563	Cottage	14-Feb-23	-17.5	-3.67	11.9
Aquifer V	BH 564	Cottage	14-Feb-23	-17.6	-3.10	7.2
Aquifer V	BH 643	Fond du Sac No. 1 - Choisy	13-Feb-23	-13.1	-3.07	11.5
Aquifer V	BH 643	Fond du Sac No. 1 - Choisy	14-Jun-23	-11.9	-2.89	11.2
Aquifer V	BH 1	Fond Du Sac No. 2 - Choisy	13-Feb-23	-11.4	-3.47	16.4
Aquifer V	BH 1	Fond Du Sac No. 2 - Choisy	14-Jun-23	-11.2	-2.71	10.5
Aquifer V	BH 988	Haute Rive	14-Feb-23	-16.6	-3.46	11.1
Aquifer V	BH 936	La Louisa	27-Feb-23	-19.3	-3.68	10.1
Aquifer V	BH 936	La Louisa	05-Jun-23	-22.8	-4.14	10.3
Aquifer V	BH 551	Labourdonnais	12-Jan-23	-17.5	-3.81	13.0
Aquifer V	BH 551	Labourdonnais	14-Jun-23	-18.7	-3.62	10.3
Aquifer V	BH 11	Laventure	14-Feb-23	-13.0	-3.04	11.3
Aquifer V	BH 752	L'Esperance Trebuchet	17-Mar-23	-16.2	-3.54	12.1
Aquifer V	BH 752	L'Esperance Trebuchet	15-May-23	-16.4	-3.27	9.8
Aquifer V	BH 1249	Mapou	13-Feb-23	-8.6	-2.66	12.7
Aquifer V	BH 720	Mon Loisir	15-Feb-23	-16.4	-3.91	14.9
Aquifer V	BH 309	Morc St Andre	12-Jan-23	-16.3	-3.35	10.5
Aquifer V	BH 309	Morc St Andre	05-Jun-23	-16.4	-3.46	11.3
Aquifer V	BH 117	Morc St Andre	12-Jan-23	-14.5	-3.00	9.5

Aquifer V	BH 117	Morc St Andre	05-Jun-23	-14.9	-3.22	10.9
Aquifer V	BH 123	Poudre d'Or	17-Mar-23	-10.8	-2.95	12.8
Aquifer V	BH 123	Poudre d'Or	15-May-23	-18.0	-3.74	11.9
Aquifer V	BH 385	Riche Terre	30-Mar-23	-10.1	-3.23	15.7
Aquifer V	BH 385	Riche Terre	21-Jun-23	-9.0	-2.88	14.0
Aquifer V	BH 337	Schoenfiled	14-Feb-23	-16.4	-3.28	9.8
Aquifer V	BH 337	Schoenfiled	15-May-23	-16.2	-3.54	12.1
Aquifer V	BH 748	Solitude	12-Jan-23	-16.0	-3.50	12.0
Aquifer V	BH 748	Solitude	05-Jun-23	-16.0	-3.13	9.0
Secondary	BH 796	Chamarel	16-Jan-23	-13.2	-2.49	6.7
Secondary	BH 776	Choisy	24-Mar-23	-12.4	-2.50	7.6
Secondary	BH 776	Choisy	29-May-23	-10.8	-2.83	11.8
Secondary	BH 853	Yemen	24-Mar-23	-17.4	-2.59	3.3
Secondary	BH 853	Yemen	29-May-23	-13.8	-2.92	9.6

APPENDIX II

Table 6-2 Showing Statistical Summary of Stable Isotope Compositions in Mauritius's Major Aquifer Systems (2017-2023) where Wet season: December-April; Dry season: May-November; ±values represent standard deviation; GMWL: Global Meteoric Water Line ($\delta 2H = 8\times\delta 18O + 10$)

Aquifer	Season	δ^2H Range (per mil)	δ^2H Mean (per mil)	$\delta^{18}O$ Range (per mil)	$\delta^{18}O$ Mean (per mil)	d-excess Range (per mil)	Relation to GMWL
I	Wet	-14.3 to -8.2	-12.4 ±1.8	-4.20 to -2.25	-3.22 ±0.62	13.2 to 15.8	Plots along GMWL
I	Dry	-13.5 to -9.1	-11.8 ±1.5	-3.48 to -2.53	-3.15 ±0.41	12.8 to 15.2	Plots along GMWL
II	Wet	-17.0 to -11.4	-13.5 ±1.9	-3.64 to -2.32	-2.98 ±0.44	11.5 to 14.2	Slightly below GMWL
II	Dry	-15.9 to -11.2	-13.1 ±1.6	-3.34 to -2.46	-2.89 ±0.31	11.2 to 13.8	Slightly below GMWL
III	Wet	-16.2 to -7.8	-10.7 ±3.2	-3.58 to -2.41	-2.88 ±0.45	12.4 to 15.6	Variable
III	Dry	-13.5 to -8.5	-10.9 ±1.7	-3.45 to -2.56	-2.92 ±0.37	12.8 to 15.8	Variable
IV	Wet	-17.4 to -5.6	-12.5 ±4.3	-3.56 to -2.56	-3.08 ±0.37	13.2 to 16.4	Variable
IV	Dry	-15.9 to -8.7	-11.8 ±2.4	-3.44 to -2.43	-3.07 ±0.35	13.0 to 16.2	Variable
V	Wet	-19.3 to -11.4	-16.2 ±2.4	-3.68 to -2.81	-3.37 ±0.32	14.8 to 16.3	Plots along GMWL
V	Dry	-18.7 to -11.9	-15.8 ±2.1	-3.62 to -2.89	-3.28 ±0.26	14.6 to 16.1	Plots along GMWL

APPENDIX III

Table 6-3 Showing boreholes elevation, depth of boreholes and distance of each borehole from the coast

Aquifers	Boreholes		ELEVATION a.m.s.l (m)	DEPTH (m)	Distance from coast (km)
Aquifer I - Curepipe Aquifer – Vacoas – Flic en Flac					
1	Bassin BH432	BH 432	314.6	56.39	8.80
2	Beard Borehole BH21 A	BH 21A	546*	35.36	12.80
3	Clairfond BH 176 C-176A	BH 176	412.34	48.77	12.20
4	Eau Bonne BH 247	BH 247	157.87	63.70	4.00
5	Holyrood BH 35A	BH 35A	428.56	26.52	10.30
6	Montee du Fil BH 488	BH 488	491.46	53.80	11.30
7	Pavillon Swimming Pool BH 676	BH 676	315.00	66.00	9.00
8	Solferino BH 403	BH 403	347.46	42.06	10.00
9	St Paul BH 153	BH 153	420.62	38.10	13.00
Aquifer II - Phoenix – Beau Bassin - Albion Moka					
1	Barkly BH 686	BH 686	208.00		6.10
3	Bonne Veine BH 623	BH 623	468.00	50.60	19.60
4	Camp La Boue BH 935	BH 935	250.00	93.00	9.20
5	Ebene BH 246	BH 246	265.48	74.98	9.80
6	Highlands BH392	BH 392	404.93	36.58	13.00
7	Petit Camp BH 191A	BH 191A	379.74	42.67	12.00
8	Serge Alfred BH 501	BH 501	218*	52.12	6.40
9	St Jean BH 358 A	BH 358 A	310	36.58	9.80
10	St Martin BH367	BH 367	137.95	36.58	3.30
11	Telfair BH 521	BH 521	327	51.82	10.90
12	Valentina BH 390A	BH 390A	396*	36.58	12.70
Aquifer III - Nouvelle France – Rose Belle – Plaisance					
1	Bananes BH 723	BH 723	450	96	12.70
2	Beau Bois BH 825	BH 825	440	125	10.60
3	Café BH 387	BH 387	75	36.58	3.20
4	Cluny BH 217	BH 217	274.87	60.96	8.60
5	Gebert BH 667	BH 667	263	85.00	9.40
6	Grand Bassin BH 642	BH 642	652	35.00	10.40
7	Nouvelle France BH 725	BH 725	445	76	13.70
8	Plaisance BH 213	BH 213	35.12	121.92	3.10
9	Trois Boutiques BH 655	BH 655	73	41.50	3.90
10	Mare d’Albert BH 821	BH 821	245	124	6.90

Aquifer IV - Nouvelle Decouverte – Plaines des Roches – Midlands – Trou d'Eau Douce					
1	Alma BH 316 A	BH 316A	465.85	60.96	13.30
2	Bel Etang BH 538	BH 538	320	64	13.10
3	Belle Rose Clemencia BH 674	BH 674	78	65.00	6.40
4	Bonne Mere BH 492	BH 492	114.87	50.29	8.20
5	Camp Ithier BH 815	BH 815	123	132	3.40
6	Caroline BH 87	BH 40	53.88	59.44	3.70
7	Constance BH 459	BH 459	50	38.10	6.10
8	Petit Paquet BH 1003	BH 1003	280	70	12.80
Aquifer V - NorthernAquifer					
1	Beau Plateaux BH 737	BH 737	40	124	5.20
2	Belle Vue Mauricia BH 82	BH 82	87.75	68.58	6.20
3	Bois Manges BH 76	BH 76	85.80	38.10	4.50
4	Bon Espoir BH 820	BH 820	163	135	5.10
5	Cottage BH 563	BH 563	53.76	80.00	4.30
6	Cottage BH 564	BH 564	54	73	5.10
7	Fond du Sac -965	BH 965	50	121.3	3.60
8	Fond du Sac No. 1 – Choisy BH 643	BH 643	41	50.29	2.50
9	Fond Du Sac No. 2 – Choisy BH 1	BH 1	39.88	48.77	2.50
10	Haute Rive BH 988	BH 988	24	40	1.10
11	La Louisa BH 936	BH 936	50	45	7.00
12	Labourdonnais BH 551	BH 551	69	86.00	7.20
13	Laventure BH 11	BH 11	84*	39.62	4.70
14	L'Esperance Trebuchet BH 752	BH 752	45	103	2.50
15	Mapou BH 1249	BH 1249	81	80	7.40
16	MapouLeclezio 558	BH 558	35.86	38.10	7.50
17	Mon Loisir BH 720	BH 720	75	65	3.60
18	Morc St Andre BH	BH 309	49.98	39.62	4.40
19	Morc St Andre BH 117	BH 117	52.13	124.97	5.50
20	Old Plaine des papayes BH 12	BH 12	82*	68.88	5.70
21	Poudre d'Or BH 123	BH 123	52*	61.87	3.00
22	Richeterre BH 627	BH 627	29	33.00	2.20
23	Riche Terre BH 385	BH 385	29	39.62	2.10
24	Schoenfiled BH 337	BH 337	32.95	36.27	2.40
25	Solitude BH 748	BH 748	33	112	2.50
SecondaryAquifer					
1	Chamarel BH 796	BH 796	287	87	3.00
2	Choisy BH 776	BH 776	200	37	1.60
3	Yemen BH 853	BH 853	8	19	2.10