IMPACTS OF GLOBAL CHANGES ON A LOWLAND RAINFOREST REGION OF WEST AFRICA

by

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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, South Africa under the supervision of Professor Graham P. W. Jewitt and Dr. Michele L. Warburton Toucher. The research was financially supported by the University of Mines and Technology, Tarkwa, Ghana.

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.

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Signed: Professor Graham P. W. Jewitt

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Signed: Dr. Michele L. Warburton Toucher
Date: January, 2016

DECLARATION 1: PLAGIARISM

I, *Michael Soakodan Aduah*, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation 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 dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

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

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Signed: Michael Soakodan Aduah
Date: January, 2016

DECLARATION 2: PUBLICATIONS

Details of contribution to publications, which form part of this thesis, including publications submitted and published, giving details of the contributions of each author in the research and writing of the publications. The * indicates corresponding author.

Publication 1: Chapter 3 of this thesis

*Aduah, MS, Warburton, ML and Jewitt, G. 2015. **Analysis of land cover changes in the Bonsa catchment, Ankobra Basin, Ghana**. *Applied Ecology and Environmental Research* 13(4)**:**935-955, DOI: 10.15666/aeer/1304_935955.

Field data collection, land cover mapping and analysis and writing of this publication was entirely conducted by MS Aduah with technical advice from ML Warburton and G Jewitt. Additional advice on editing of the text was provided by Mrs. Sharon Rees. Satellite images consisting of Landsat TM/ETM+ and ALOS AVNIR-2 images, were obtained from the GLOVIS database of the United States Geological Surveys and the European Space Agency's Third party mission data (category 1 proposal: C1P14198), respectively.

Publication 2: Chapter 4 of this thesis

*Aduah, MS, Warburton Toucher, ML and Jewitt, GPW.(submitted).**Modelling land use changes in the Bonsa catchment, Ankobra Basin, Ghana**. *Land Use Policy*.

Land use modelling and data analysis, as well as the writing of this publication was entirely executed by MS Aduah with technical advice by ML Warburton Toucher and GPW Jewitt. Advice on editing of the text of the publication was also provided by ML Warburton Toucher. With the exception of those referenced in this publication, all tables and figures were created by MS Aduah.

Publication 3: Chapter 5 of this thesis

*Aduah, MS, Jewitt, GPW and Warburton Toucher, ML.(submitted). **Assessing suitability of the ACRU hydrological model in a rainforest catchment in West Africa.** *Applied Ecology and Environmental Research.*

MS Aduah pre-processed the climate data and conducted the hydrological modelling with technical advice from GPW Jewitt and ML Warburton Toucher. The publication was written entirely by MS Aduah with advice on data interpretation and editing of the text was provided by GPW Jewitt and ML Warburton Toucher. With the exception of those referenced in this publciation, all tables and figures were created by MS Aduah. The climate data was obtained from the Ghana Meteorological Agency and Goldfields Ghana Ltd, Damang Goldmine, while the streamflow records were obtained from the Hydrological Services Department of Ghana. Soil map was obtained from the Soil Research Institute of Ghana.

Publication 4: Chapter 6 of this thesis

*Aduah, MS, Jewitt, GPW and Warburton Toucher, ML. (in preparation). **Assessing impacts of land use changes on the hydrology of a lowland rainforest catchment in West Africa.** *Journal of Hydrology*.

MS Aduah conducted the hydrological modelling and data interpretation with technical advice from GPW Jewitt and ML Warburton Toucher. The publication was written entirely by MS Aduah and editing advice was provided by GPW Jewitt and ML Warburton Toucher. All tables and figures, except those referenced in this publciation, were created by MS Aduah.

Publication 5: Chapter 7 of this thesis

*Aduah, MS, Warburton Toucher, ML and Jewitt, GPW. (in preparation).**Combined impacts of land use and climate changes on the hydrology of a lowland rainforest catchment in West Africa**. *Hydrological Process.*

MS Aduah conducted the hydrological modelling and data interpretation with technical advice from ML Warburton Toucher and GPW Jewitt. GCM climate scenario data selection and downscaling was executed by MS Aduah with advice provided by ML Warburton Toucher. The publication was written entirely by MS Aduah and advice on editing the text was provided by ML Warburton Toucher and GPW Jewitt. All tables and figures, except those referenced in this publciation, were created by MS Aduah.

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ABSTRACT

Impacts of Global changes have the potential to disrupt socio-economic and environmental systems of many countries. However, there is limited understanding of the impacts in West Africa, especially in the rainforest regions, as previous studies have concentrated on the semi-arid and the savannah regions, using limited data for short-term impact analysis. The limited knowledge and understanding of the impacts of Global changes in the rainforest regions of West Africa has the potential to introduce huge uncertainties into catchment development plans. Planning for water supply systems, housing and drainage systems, road networks and agriculture/irrigation systems, which largely drive economic development, require detailed understanding of hydrological dynamics, which is largely unavailable in many West African countries. Understanding of hydrological dynamics under changing landscape and climate conditions is also important in protecting life and property, as well as the environment. The main objective of the study was therefore to assess the long-term impacts of climate change and land cover changes on hydrology, as well as its consequent ecological alterations in a rainforest catchment of West Africa, using multiple downscaled climate scenarios, historical and potential future land use/land cover data. This study adds to the existing studies to improve the understanding of long-term hydrological and consequent ecological alterations of simultaneous land use changes and climate changes in data scarce lowland rainforest catchments, using relatively less data intensive methods and tools. The study was also aimed at improving understanding of the spatial patterns of impacts of current and potential future land use and climate changes in West Africa, using the Bonsa catchment in south west Ghana, as a study site.

Methods used for the study included literature review, land use/land cover mapping, spatially distributed land use modelling, hydrological modelling using ACRU and GIS and statistical analysis. Results of the first paper show that evergreen forest is the largest land cover occupying an area of 68% in 1986, 62% in 1991, 50% in 2002 and 51% in 2011 and during the past 26 years, the largest land cover change in the Bonsa catchment has been the conversion of evergreen and secondary forests to shrubs/farms, mining areas and settlements. During this period, mining areas increased over two-fold, while settlements and shrubs/farms increased more than three and four-fold, respectively. The results suggests that the drivers of the land cover changes in the Bonsa catchment are both local and global and include, international trade, local population growth, agriculture extensification and urbanization. Logistic regression, Markov chain and the Dyna-CLUE models were combined to dynamically simulate historical and potential future land use/land cover patterns, in order to understand the land use change processes, as well as produce information for land use planning and environmental management. The results of the historical simulation revealed that increases in population density, proximity to roads and expansion of mines were the major drivers that significantly increased the probability of settlement expansion and deforestation. Model simulations of future land use under three plausible scenarios showed that settlement expansion and deforestation increased by similar margins for all scenarios, but the increase in secondary forests was higher for the economic growth and reforestation (EGR) scenario, compared to the economic growth (EG) and the business-as-usual (BAU) scenarios. The mining areas more than doubled between 2012 and 2070 for all the scenarios, while shrubs/farms increased in the BAU scenario, but reduced marginally in the EG and the EGR scenarios. The results of the land use modelling study can be used to infill historical data gaps, support effective land use planning and provide a means to evaluate the impacts of different future development pathways.

Furthermore, hydrological modelling was carried out to assess the suitability of the daily time step physical-conceptual ACRU model for the Bonsa catchment of Ghana. Since the catchment lacked adequate data, model calibration was conducted with careful parameterization, using initial values obtained from literature and field observations, as well as climate data for the period 1987 to 1999 and 1991 land use map. The model performance was satisfactory, with monthly NSE index and R^2 of 0.6 and 0.7, respectively. The model simulated the rise and the recession of the hydrograph well, but the accumulated monthly streamflows were underestimated by 5%. Field visits showed that the Bonsa catchment experiences water withdraws for domestic and mining purposes, however, this study did not account for the withdrawals for lack of data, which would have improved the model performance. The main conclusion from the hydrological modelling study is that the ACRU hydrological model is suitable for hydrological modelling in the Bonsa catchment, hence it can be used to assess basic hydrological responses to changing catchment conditions.

Additionally, since impact assessments of actual and potential land use (LU) changes on hydrology is vital in land use planning, which is a prerequisite for effective water resources management, in this study, impacts of actual, as well as potential LU changes on the hydrology of the Bonsa catchment, Ghana, West Africa, were assessed using the ACRU hydrological model. Baseline, current and potential future LU maps for three scenarios; business-as-usual (BAU), economic growth (EG) and economic growth and reforestation (EGR), as well as observed climate between 1990 and 2009, were used for the study. Richter's range of variability analysis, using the indicators of hydrologic alteration software, was used to assess the current, as well as the potential future river ecological impacts of LU changes. The results indicate that peak and dry season streamflows have increased by 21% and 37%, respectively, under the current land use in comparison to the baseline due to a decrease in evergreen and secondary forests by 18% and 39% respectively, and an increase in settlements, mining areas and shrubs/farms by 81%, 310% and 343% respectively, between 1991 and 2011. The potential future LU scenarios suggested that there will be further increases in streamflows, but the historical land use changes between 1991 and 2011 were so substantial that they influenced future hydrological impacts under any of the future land use scenarios. The study also showed that variability of streamflow changes at the catchment scale was lower than at the subcatchment scale and the current land use changes has created the potential for changes in river ecology, relative to the baseline, with further potential alterations expected under the future LU scenarios. For the scenarios of potential future LU changes, the BAU shows the greatest potential alterations in river ecology, as well as increases in streamflows, while the EGR shows the least.

However, since land use and climate affect each other and their joint impacts tend to be non-linear, the study further analysed the separate and the combined impacts of climate and land use changes on hydrology, as well as the consequent potential river ecological impacts on the Bonsa catchment in Ghana, West Africa, using the ACRU hydrological model. The study used five RCP8.5 climate change scenarios (wet, 25th percentile, multi-model median, 75th percentile and a dry GCM scenario), which encompasses the lowest to the highest changes in precipitation from an ensemble of nine CMIP5 AR5 models for near (2020 – 2039) and far (2060 – 2079) future time slices. Change factors were used to downscale the GCM scenarios to the local scale, using observed climate data for the control period of 1990 to 2009. The 1991 land use and three future land use scenarios (BAU, EG, EGR) for two time slices (2030 and 2070), were used for the baseline and the future simulations, respectively.

Richter’s range of variability approach (RVA) was used to assess the potential river ecological impacts. The study has shown that under separate climate change scenarios, overall flows decreased, but under simultaneous climate change and land use changes, streamflows increased. However, under the combined scenarios, the streamflow responses under the different future land use scenarios were not substantially different. Land use is also the dominant controlling factor in streamflow changes in the Bonsa catchment under a dry climate, but under a wet climate change, climate controls changes in streamflows. The spatial variability of the streamflow changes under combined land use and climate changes were higher than the spatial variability of streamflow changes under climate change and the potential river ecological changes in the catchment followed similar trends as the streamflows, where they increased with time. The potential river ecological alterations resulting from combined climate change and land use changes were higher than those resulting from separate climate change impacts.

The results of this study indicate that reforestation alone is not enough if the Bonsa catchment is to be managed effectively. It is suggested that adaptive management strategies including targeting reforestation in shrub land areas, promotion of intensive farming, effective storm water management in settlement and mining areas, as well as installation of additional streamflow and rain gauges and an intensive research and monitoring programme be carried out. In addition to protecting the environment, these measures can also protect the local communities from potential floods, water pollution, as well as its scarcity. The historical and potential future land use data, as well as the range of plausible future streamflows and potential river ecological change indicators derived in this study provides policy makers and managers information that can be used for adaptive catchment management, so as to prepare adequately for climate and land use changes. The information from this study can also be used to plan data collection programmes aimed at improving the understanding of Global Changes in West Africa.

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CHAPTER 1 : INTRODUCTION

Scientists worldwide agree that increase in atmospheric greenhouse gas (GHG) concentrations due to anthropogenic forcing is changing the global climate (Todd *et al.*, 2011; IPCC, 2013). The Assessment Reports of the Inter-Governmental Panel on Climate Change (IPCC) conclude that in the 21st century mean global temperatures, precipitation and evaporation will increase (IPCC, 2007; IPCC, 2013). In Africa and many tropical regions, evidence of climate change are already manifesting (Conway *et al.*, 2009) in the form of erratic rainfall, high temperatures, frequent droughts, severe floods and reduced productivity of crops (Jalloh *et al.*, 2013). In West Africa, mean annual rainfall has reduced by more than 20% and mean annual temperatures have increased by 2°C between 1901 and 1995 (Hulme *et al.*, 2001). According to the IPCC (2007), temperatures will continue to rise in West Africa in the 21stcentury. However, there is no consensus on the trend of rainfall projections for the region. Some Global Climate Models (GCMs) predict increases in the Sahel and decreases in the coastal areas, while others predict the opposite (Ardoin-Bardin *et al.*, 2009). Future climate changes in West Africa are anticipated to continue to significantly impact local and regional hydrological regimes, which will also affect the ecological and socio-economic systems (Kunstmann *et al.*, 2004; Dibike and Coulibaly, 2005).

In addition to the impacts of climate change on the hydrology of the West African region, land cover or land use changes may have significant impacts. Land use controls many biophysical processes on the Earth surface (Dale, 1997). Land use changes through agricultural practices and urbanisation for example, have substantial influence on hydrological processes (Mendoza *et al.*, 2002) by controlling the availability of water through alteration of infiltration, evapotranspiration and runoff (Lambin and Ehrlich, 1997; D'Orgeval and Polcher, 2008). In many West African countries, rapid population growth, urbanization, slush and burn agriculture, open cast mining, bush fires and overgrazing, have severely altered the natural land cover (Lambin and Ehrlich, 1997; Braimoh and Vlek, 2004; Schueler *et al.*, 2011), which have modified the flow regimes of many basins and polluted the water. For example, between 1990 and 2010, approximately 32 million ha of forests have been converted to other land uses in West and Central Africa (FAO, 2010).

Impacts of climate change and land cover changes have many challenges for water resources and environmental management in dealing with problems such as sustained provision of adequate and safe drinking water, magnitudes and frequencies of floods and ecological degradation (Sivapalan *et al.*, 2003; Chin, 2006). Therefore comprehensive procedures are required to plan and to manage the environment in a sustainable manner, which also need reliable information on how Global changes have impacted the past and current environments, as well as information on the potential future impacts. Ideally, these information and understanding, which supports sustainable development, can be derived from long-term observed data, as well as the use of predictive models (Sivapalan *et al.*, 2003). However, to the best of our knowledge, studies that assess both the long-term hydrologic and ecological impacts of separate and combined land use change and climate changes are rare, especially in the rainforest areas of West Africa.

Both the local and the regional scale impacts of climate change and land cover changes on water resource and ecology are still not understood well in West Africa. Although many studies have already been conducted (Giertz and Diekkruger, 2003; Valentin *et al.*, 2004; Giertz *et al.*, 2005; Mahe *et al.*, 2005; Li *et al.*, 2007; Paturel *et al.*, 2007; Leblanc *et al.*, 2008; Ardoin-Bardin *et al.*, 2009; Van de Giesen *et al.*, 2011; Bossa *et al.*, 2012; Ruelland *et al.*, 2012; Cornelissen *et al.*, 2013), they have largely focused on the Sahel/Savannah areas. For the southern rainforest areas, there is generally poor understanding on how Global changes have impacted the catchments water resources and ecology. The potential future impacts are also not understood well in this part of West Africa. Furthermore, only one study (Bossa *et al.*, 2014) considered the spatial variability of Global change impacts and no study has analysed impacts of land use and climate change on ecology. No study has also assessed the spatial and temporal variability of hydrological, as well as the consequent ecological impacts of land use and climate changes jointly for both historical and future periods in West Africa. Only three studies (Bossa *et al.*,2012; Cornelissen *et al.*, 2013; Bossa *et al.*, 2014) conducted in the Savannah part of Benin Republic, applied long-term climate change and consistently downscaled climate scenarios, as well as potential future land use. Majority of Global change impact studies in West Africa have used single GCMs scenarios.

Owing to the fact that many studies (Klocking and Haberlandt, 2002; Li *et al.*, 2007; Li *et al.*, 2009; Warburton *et al.*, 2012) conclude that the impacts of Global changes on water resources are nonlinear, understanding gained from studies in the Sahel/Savannah are not transferable to the rainforest regions as the climates, vegetation and geologies, which largely influence local scale impacts of climate and land cover changes (Praskievicz and Chang, 2009), differ. The limited knowledge and understanding of the historical, as well as the potential future global change impacts on hydrology of the rainforest catchments in West Africa therefore have the potential to result in poorly informed and ineffectual environmental and natural resources management, which can lead to poor land use and water resources decisions in responding to present or planning for future challenges.

Consequently, there is the need to investigate both the local and catchment scale impacts of Global change i.e the climate and land cover changes for the historical, as well as the potential future time periods to contribute to improving the understanding, planning and managing of water resources and the environment in a sustainable manner. However, in West Africa, data is scarce, partly because of the economic and capacity constraints (Cornelissen *et al.*, 2013), which limit effective research in hydrology. Thus to understand the responses of global changes on hydrology in the rainforest catchments of West Africa, there is the need to address data scarcity and identify reliable techniques for effective impact assessment both at the local and catchment scales. Studies should also be conducted in catchments that are representative of the rainforest region to enable the transfer of knowledge and understanding to similar catchments. This study adds to the limited studies in West Africa and will reduce the knowledge gap on separate and combined impacts of long-term land use changes and climate changes on hydrology across scales, as well as its consequent effects on ecological alterations.

1.1 Rationale for the Research

This study adds to the limited studies to improve the understanding of long-term hydrological and the consequent ecological alterations of simultaneous land use and climate changes in data scarce rainforest catchments, using relatively less data intensive methods and tools. The study is also aimed at improving the understanding of the spatial patterns of impacts of current and potential future land use and climate changes on hydrology in the rainforests of West Africa, as the limited knowledge and understanding of the impacts of Global changes in the rainforest regions of West Africa has the potential to introduce large uncertainties into catchment development plans. Planning for water supply systems, housing and drainage systems, road networks and agriculture/irrigation systems, which largely drive economic development, require detailed understanding of hydrological dynamics, which is largely unavailable in many West African countries including Ghana. Understanding of hydrological dynamics under changing landscape and climate conditions is also important in protecting life and property, as well as the environment.

The reliance on case studies to assess Global change impacts is not only because the impacts are location specific, but also because case studies are vital in advancing theories and techniques to inform real world applications (White *et al.*, 2013). The selection of the Bonsa catchment for this study was predicated on the fact that it has the largest forest reserve (Subri River Forest Reserve: 590 km^2) in Ghana, which has also been recognised as a Globally Significant Biodiversity Area (GSBA) (Buzzard and Parker, 2012). The Bonsa catchment and the surrounding areas have more than six large scale open cast mining operations (Kusimi, 2008), the largest plantations of rubber in Ghana and substantial cocoa and palm plantations. The catchment and the surrounding region is relatively flat and its climate is defined by the north-south movement of the Inter-Tropical Convergence Zone (ITCZ) (Jackson *et al.*, 2009; Manzanas *et al.*, 2014), which brings the West African monsoon, leading to two distinct raining seasons. The catchment is in the southwestern region of Ghana and contributes 22% of the country’s total runoff (Yidana *et al.*, 2007). During the past several decades the land use/land cover have changed drastically, as settlement expansion, agriculture and mining continue to replace the natural forests (Kusimi, 2008). The rainfall has also become erratic (Gyau-Boakye and Tumbulto, 2006; Lacombe *et al.*, 2012), with delays in the onset of the wet season and a reduction in the number of rainy days. The Bonsa catchment is therefore a good site to study impacts of Global changes on hydrology, as well as its consequent ecological alterations, as it is a representative of most rainforest catchments in West Africa, which have similar land use activities, vegetation and climate.

1.2 Research Objectives

The main objective of this research is to assess the long-term impacts of climate change and land cover changes on hydrology and the consequent effects on ecological alterations in a rainforest catchment of West Africa, using multiple downscaled climate scenarios, historical and potential future land use data.

In achieving this objective, the following specific objectives will be pursued, using the Bonsa catchment as the study area:

- Map historical and current land cover and identify potential drivers of land use changes,
- Quantify the relationship between land cover types and their drivers to simulate the spatial distribution of potential future land cover types,
- Identify and downscale suitable GCM scenarios,
- Identify a suitable hydrological model, quantify its efficiency and assess the historical and the potential future hydrological and the consequent ecological responses to climate change and land cover changes, separately and jointly.

To achieve these objectives, the following research questions were addressed:

- Which land use changes have occurred in the Bonsa catchment and what are their potential drivers and hydrological consequences?
- What is the relationship between different land cover types and their drivers and how can potential future land use/land cover in the Bonsa catchment be simulated?
- Can the ACRU hydrological model adequately simulate the hydrological processes of rainforest catchments and what are the separate and combined impacts of historical, as well as the potential future land cover changes and climate changes on hydrology of rainforest catchments?

The research approach followed to address these objectives and research questions is outlined below.

1.3 Research Approach

The study was conducted using the approach illustrated in Figure 1.1. Chapters were written as standalone papers according to guidelines approved by the University of KwaZulu-Natal. The study started with a literature review (Chapter 2), followed by the (1) mapping of historical and current land cover (Chapter 3), as well as identifying the potential drivers and (2) modelling of potential future land cover (Chapter 4). The historical, current and the potential future land cover maps, as well as observed and downscaled GCM climate scenarios were input into the ACRU model to assess (3) efficiency of the model (Chapter 5), (4) impacts of land use changes on hydrology and the consequent river ecological alterations (Chapter 6) and (5) combined impacts of climate change and land use changes on hydrology and the consequent river ecological alterations (Chapter 7). The final part of the study synthesizes the whole study to derive key contributions and to proffer recommendations for catchment management, as well as future research (Chapter 8).

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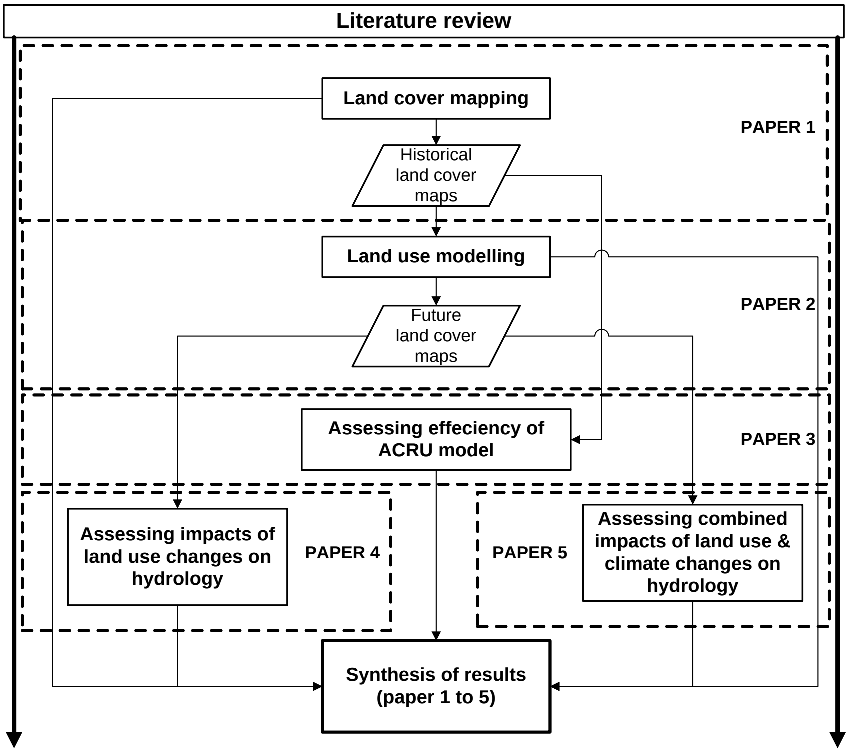


Figure 1.1: Research approach

1.4 References

Ardoin-Bardin, S, Dezetter, A, Servat, E, Paturel, JE, Mahe, G, Niel, H and Dieulin, C. 2009. Using general circulation model outputs to assess impacts of climate change on runoff for large hydrological catchments in West Africa. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 54(1)**:**77-89.

Bormann, H, Breuer, L, Gräff, T, Huisman, JA and Croke, B. 2009. Assessing the impact of land use change on hydrology by ensemble modelling (LUCHEM) IV: Model sensitivity to data aggregation and spatial (re-)distribution. *Advances in Water Resources* 32(2)**:**171-192.

Bossa, AY, Diekkrueger, B and Agbossou, EK. 2014. Scenario-Based Impacts of Land Use and Climate Change on Land and Water Degradation from the Meso to Regional Scale. *Water* 6(10)**:**3152-3181.

Bossa, AY, Diekkrueger, B, Giertz, S, Steup, G, Sintondji, LO, Agbossou, EK and Hiepe, C. 2012. Modeling the effects of crop patterns and management scenarios on N and P loads to surface water and groundwater in a semi-humid catchment (West Africa). *Agricultural Water Management* 115(2012)**:**20-37.

Braimoh, AK and Vlek, PLG. 2004. Land-Cover Change Analyses in the Volta Basin of Ghana. *Earth Interactions* 8(21)**:**1-17.

Breuer, L, Huisman, JA, Willems, P, Bormann, H, Bronstert, A, Croke, BFW, Frede, HG, Gräff, T, Hubrechts, L, Jakeman, AJ, Kite, G, Lanini, J, Leavesley, G, Lettenmaier, DP, Lindström, G, Seibert, J, Sivapalan, M and Viney, NR. 2009. Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM). I: Model intercomparison with current land use. *Advances in Water Resources* 32(2)**:**129-146.

Buzzard, PJ and Parker, AJA. 2012. Surveys from the Subri River Forest Reserve, Ghana. *African Primates* 7(2)**:**175-183

Chin, DA. 2006. *Water Resources Engineering,* Pearson Education Limited,New Jersey, USA.

Chu, H-J, Lin, Y-P, Huang, C-W, Hsu, C-Y and Chen, H-Y. 2010. Modelling the hydrologic effects of dynamic land-use change using a distributed hydrologic model and a spatial land-use allocation model. *Hydrological Processes* 24(18)**:**2538-2554.

Conway, D, Persechino, A, Ardoin-Bardin, S, Hamandawana, H, Dieulin, C and Mahé, G. 2009. Rainfall and Water Resources Variability in Sub-Saharan Africa during the Twentieth Century. *Journal of Hydrometeorology* 10(1)**:**41-59.

Cornelissen, T, Diekkrueger, B and Giertz, S. 2013. A comparison of hydrological models for assessing the impact of land use and climate change on discharge in a tropical catchment. *Journal of Hydrology* 498(2013)**:**221-236.

D'Orgeval, T and Polcher, J. 2008. Impacts of precipitation events and land-use changes on West African river discharges during the years 1951-2000. *Climate Dynamics* 31(2-3)**:**249-262.

Dale, VH. 1997. The relationship between land-use change and climate change. *Ecological Applications* 7(3)**:**753-769.

Dibike, YB and Coulibaly, P. 2005. Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models. *Journal of Hydrology* 307(1-4)**:**145-163.

FAO. 2010. Global Forest Resources Assessment 2010: Main report. Food and Agriculture Organization of the United Nations, Rome, Italy.

Giertz, S and Diekkruger, B. 2003. Analysis of the hydrological processes in a small headwater catchment in Benin (West Africa). *Physics and Chemistry of the Earth* 28(33-36)**:**1333-1341.

Giertz, S, Junge, B and Diekkrüger, B. 2005. Assessing the effects of land use change on soil physical properties and hydrological processes in the sub-humid tropical environment of West Africa. *Physics and Chemistry of the Earth, Parts A/B/C* 30(8–10)**:**485-496.

Gyau-Boakye, P and Tumbulto, JW. 2006. Comparison of rainfall and runoff in the humid south-western and the semiarid northern savannah zone in Ghana. *African Journal of Science and Technology* 7 (1)**:**64–72.

Hulme, M, Doherty, R, Ngara, T, New, M and Lister, D. 2001. African climate change: 1900-2100. *Climate Research* 17(2)**:**145-168.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *In:* Solomon, S, Qin, D, Manning, M, Chen, Z, Marquis, M, Averyt, KB, Tignor, M and Miller, HL (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2013. Summary for Policymakers. *In:* Stocker, TF, Qin, D, Plattner, G-K, Tignor, M, Allen, SK, Boschung, J, Nauels, A, Xia, Y, Bex , V and Midgley, PM (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA.

Jalloh, A, Faye, MD, Roy-Macauley, H, Sérémé, P, Zougmoré, R, Thomas, TS and Nelson, GC. 2013. Overview. *In:* Jalloh, A, Nelson, G. C., Thomas,T. S., Zougmoré,R. And Roy-Macauley, H. (ed.) *West African Agriculture and Climate Change: A Comprehensive Analysis.* International Food Policy Research Institute(IFPRI), Washington, DC, USA.

Klocking, B and Haberlandt, U. 2002. Impact of land use changes on water dynamics-a case study in temperate meso and macroscale river basins. *Physics and Chemistry of the Earth* 27(9-10)**:**619-629.

Kunstmann, H, Schneider, K, Forkel, R and Koche., R. 2004. Impact analysis of climate change on an Alpine catchment using high resolution dynamic downscaling of ECHMAM4 time slices. *Hydrology and Earth System Sciences* 8(6)**:**1030 - 1044.

Kusimi, JM. 2008. Assessing land use and land cover change in the Wassa West District of Ghana using remote sensing. *GeoJournal* 71(2008)**:**249-259.

Lacombe, G, McCartney, M and Forkuor, G. 2012. Drying climate in Ghana over the period 1960-2005: evidence from the resampling-based Mann-Kendall test at local and regional levels. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 57(8)**:**1594-1609.

Lambin, EF and Ehrlich, D. 1997. Land-cover changes in sub-Saharan Africa (1982-1991): Application of a change index based on remotely sensed surface temperature and vegetation indices at a continental scale. *Remote Sensing of Environment* 61(2)**:**181-200.

Leblanc, MJ, Favreau, G, Massuel, S, Tweed, SO, Loireau, M and Cappelaere, B. 2008. Land clearance and hydrological change in the Sahel: SW Niger. *Global and Planetary Change* 61(3-4)**:**135-150.

Lee, A, Cho, S, Kang, DK and Kim, S. 2014. Analysis of the effect of climate change on the Nakdong river stream flow using indicators of hydrological alteration. *Journal of Hydro-environment Research* 8(3)**:**234-247.

Li, KY, Coe, MT, Ramankutty, N and De Jong, R. 2007. Modeling the hydrological impact of land-use change in West Africa. *Journal of Hydrology* 337(3-4)**:**258-268.

Li, Z, Liu, W, Zhang, X and Zheng, F. 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology* 377(2009)**:**35-42.

Mahe, G, Paturel, JE, Servat, E, Conway, D and Dezetter, A. 2005. The impact of land use change on soil water holding capacity and river flow modelling in the Nakambe River, Burkina-Faso. *Journal of Hydrology* 300(1-4)**:**33-43.

Mendoza, M, Bocco, G and Bravo, M. 2002. Spatial prediction in hydrology: status and implications in the estimation of hydrological processes for applied research. *Progress in Physical Geography* 26(3)**:**319-338.

Park, JY, Park, MJ, Joh, HK, Shin, HJ, Kwon, HJ, Srinivasan, R and Kim, SJ. 2011. Assessment of MIROC3.2 HIRES climate and CLUE-S land use change impacts on watershed hydrology using SWAT. *Transactions of the Asabe* 54(5)**:**1713-1724.

Paturel, JE, Barrau, C, Mahe, G, Dezetter, A and Servat, E. 2007. Modelling the impact of climatic variability on water resources in West and Central Africa from a non-calibrated hydrological model. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 52(1)**:**38-48.

Praskievicz, S and Chang, H. 2009. A review of hydrological modelling of basin-scale climate change and urban development impacts. *Progress in Physical Geography* 33(5)**:**650-671.

Ruelland, D, Ardoin-Bardin, S, Collet, L and Roucou, P. 2012. Simulating future trends in hydrological regime of a large Sudano-Sahelian catchment under climate change. *Journal of Hydrology* 424-425(2012)**:**207-216.

Schueler, V, Kuemmerle, T and Schroeder, H. 2011. Impacts of Surface Gold Mining on Land Use Systems in Western Ghana. *Ambio* 40(5)**:**528-539.

Sivapalan, M, Takeuchi, K, Franks, SW, Gupta, VK, Karambiri, H, Lakshmi, V, Liang, X, McDonnell, JJ, Mendiondo, EM, O'Connell, PE, Oki, T, Pomeroy, JW, Schertzer, D, Uhlenbrook, S and Zehe, E. 2003. IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences. *Hydrological Sciences Journal* 48(6)**:**857-880.

Todd, MC, Taylor, RG, Osborn, TJ, Kingston, DG, Arnell, NW and Gosling, SN. 2011. Uncertainty in climate change impacts on basin-scale freshwater resources - preface to the special issue: the QUEST-GSI methodology and synthesis of results. *Hydrology and Earth System Sciences* 15(3)**:**1035-1046.

Valentin, C, Rajot, JL and Mitja, D. 2004. Responses of soil crusting, runoff and erosion to fallowing in the sub-humid and semi-arid regions of West Africa. *Agriculture, Ecosystems & Environment* 104(2)**:**287-302.

Van de Giesen, N, Stomph, T-J, Ajayi, AE and Bagayoko, F. 2011. Scale effects in Hortonian surface runoff on agricultural slopes in West Africa: Field data and models. *Agriculture, Ecosystems & Environment* 142(1–2)**:**95-101.

Warburton, ML. 2012. Challenges in modelling hydrological responses to impacts and interactions of land use and climate change. Unpublished PhD, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Warburton, ML, Schulze, RE and Jewitt, GPW. 2012. Hydrological impacts of land use change in three diverse South African catchments. *Journal of Hydrology* 414-415(2012)**:**118-135.

White, BE, Gandhi, SJ, Gorod, A, Ireland, V and Sauser, B. On the importance and value of case studies. *Systems Conference (SysCon), 2013 IEEE International*, 114-122.

Yidana, SM, Ophori, D and Banoeng-Yakubo, B. 2007. Irrigation water resource management for sustainable agriculture - The Ankobra basin, Ghana. *Journal of Irrigation and Drainage Engineering-Asce* 133(6)**:**609-615.

CHAPTER 2 : LITERATURE REVIEW

2.1 Dynamics of Global Changes and Hydrology

Global change (in the context of this study) consists of two components, cumulative and systemic changes (Meyer and Turner II, 1994). The cumulative changes, for example land use/land cover changes, are local changes with local scale impacts, but when they are distributed worldwide, can aggregate to have global scale impacts, while the systemic changes (e.g. climate changes) have local causes (e.g. the emission of atmospheric GHG) and both local and global scale impacts, but unlike the cumulative, systemic changes anywhere can result in changes and impacts at local or global scale (Steffen *et al.*, 2004). Currently, Global changes i.e land use/land cover changes and climate changes, are driven by factors (Figure 2.1) such as population changes, wealth/poverty levels, economic structures and technology (Meyer and Turner II, 1994) more than by natural causes, such as volcanoes, wildfires, floods and droughts (Coppin *et al.*, 2004), as well as the natural variability of the Earth system (Steffen *et al.*, 2004). Hydrological and ecological alterations, with consequent impacts on life and property, economies and the degradation of environmental quality, are some of the important changes that have resulted from global changes.

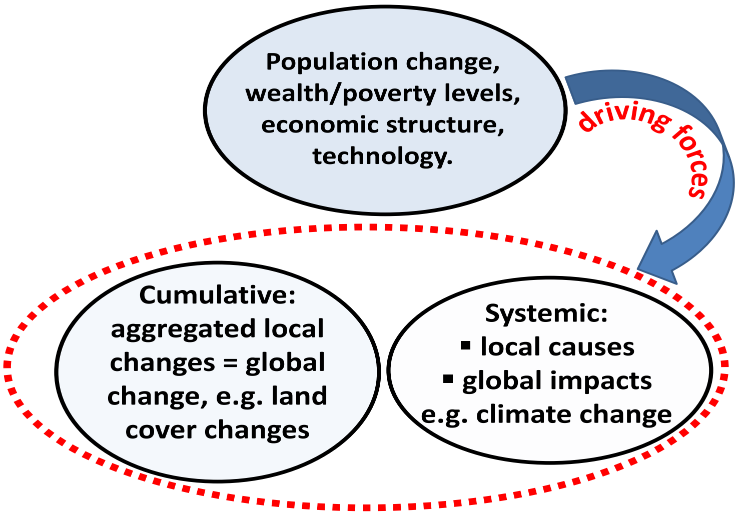


Figure 2.1: Global change components and major drivers, after Meyer and Turner II (1994)

Hence, understanding the interactions between land use, climate changes, the environment and hydrology (Figure 2.2) is essential in sustainable water resources (Warburton *et al.*, 2010; Mango *et al.*, 2011) and environmental management, especially in a region such as West Africa, where the economies are vulnerable to the impacts of Global changes, as the economies depend primarily on natural resources and agriculture (Jalloh *et al.*, 2013). In view of this, the remaining sections of this chapter will review interactions between land use and climate, as well as studies on impacts of Global changes on hydrology in West Africa, to understand the impacts and to identify knowledge gaps. The sections also compare hydrological modelling types to identify the most suitable model for assessing impacts of Global changes in West Africa in the context of data scarcity.

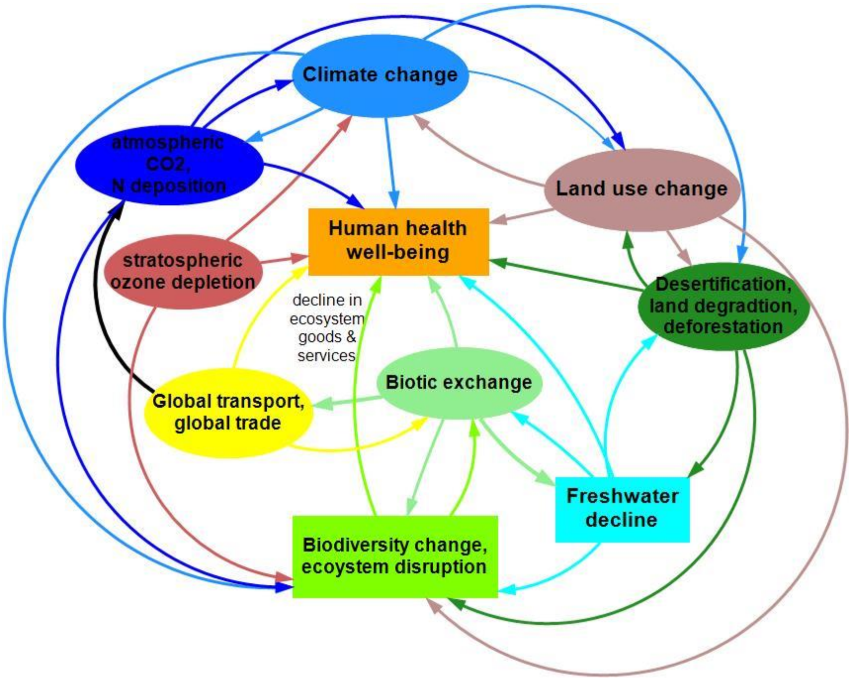


Figure 2.2: **Global changes, driving forces and impacts, adapted from Thuiller (2007)**

2.1.1 Land use, Climate and Hydrology

Land use changes affect the vegetation structure, soil surface properties and alter the energy balance of a basin, thereby changing the balance between rainfall and the components of the hydrological cycle (Costa *et al.*, 2003; D'Orgeval and Polcher, 2008; Warburton *et al.*, 2010), such as infiltration, runoff, actual evapotranspiration and groundwater recharge. Vegetation changes, for example, alter water-use in the ecosystem, as well as infiltration rates; which results from changes in albedo, interception, rooting characteristics, stomatal response, leaf area index (Gerten *et al.*, 2004) and changes in soil surface properties, such as leaf litter (Butterworth *et al.*, 1999) and permeability (Giertz *et al.*, 2005). Reduced infiltration can lead to increased velocity and volumes of runoff (Randolph, 2012), which can cause flooding, soil erosion, sedimentation and pollution of water bodies. With reduced infiltration, groundwater recharge and baseflows will be reduced, which can also lead to drying of streams, during low flows and scarcity of water for communities. Land use changes that also increase evapotranspiration, such as afforestation, reforestation and certain agricultural practices, can lead to reduced runoff (Gerten *et al.*, 2004; Farley *et al.*, 2005; Bren and Hopmans, 2007) and drying of water bodies, as less water is made available for groundwater recharge.

Hydrological responses to land use changes, depend on the scale of the changes, the land use type and the location of the changes within a basin (Mahe *et al.*, 2005; Boulain *et al.*, 2009; Warburton *et al.*, 2012). Warburton *et al.* (2012) noted that land use changes have a stronger influence on streamflows at the subcatchment (10 -100 km^2) than at the catchment (greater 1000 km^2) scale, while different land use types influence partitioning of rainfall into baseflows and stormflows in different ways in three distinct basins in South Africa. Boulain *et al.* (2009) also concluded that variability of infiltration was not only caused by changes in land use, but also by its location in a Sahelian catchment. The impacts of land use changes on hydrology also depend on the climate and size of a basin (Warburton *et al.*, 2012). In view of these geologic, scale and climatic differences, Klocking and Haberlandt (2002) stated that it is unrealistic to make generalised conclusions about impacts of land use changes on hydrology.

Evidence from previous studies, however, suggest that impacts of land use changes on hydrology are easily distinguishable at the local scale (Scott and Lesch, 1997; Seguis *et al.*, 2004; Bren and Hopmans, 2007; Van de Giesen *et al.*, 2011), but at large scales, the impacts are not consistent (Cheng, 1999; Costa *et al.*, 2003; Jewitt *et al.*, 2004; Mahe *et al.*, 2005; Li *et al.*, 2007; D'Orgeval and Polcher, 2008). Hence, it has been suggested that to detect impacts of land use changes on hydrology accurately, spatially distributed hydrological modelling, in addition to field-based studies, using paired or single catchments, should be conducted (Klocking and Haberlandt, 2002; Olsson and Pilesjo, 2002; Zhang and Savenije, 2005; Breuer *et al.*, 2009). For such studies, the impacts are ascertained by comparing the hydrological responses of different land use scenarios under the same climatic conditions (Hu *et al.*, 2005). The land use scenarios depend on objectives of the study and have been developed, using techniques ranging from making assumptions (Li *et al.*, 2007; Legesse *et al.*, 2010) on rate of deforestation or urbanization to the use of spatially distributed land use models (Veldkamp and Verburg, 2004; Verburg and Overmars, 2009; Park *et al.*, 2011). It is argued that distributed hydrological modelling can provide spatially distributed information on water balance components for the past, present and future scenarios, needed for effective water management. Although land use changes and their impacts occur locally, when they are ubiquitous, can aggregate, to affect the functioning of the Earth system at the regional or global scale (Steffen *et al.*, 2004).

Climate change has also become one of the most important subjects in science due to its variable impacts on water resources (Vörösmarty *et al.*, 2000) and the fact that it can amplify effects of land use changes on hydrology (Tong *et al.*, 2012). Climatic changes, such as changes in the means and variability of rainfall and temperature, have the potential to alter seasonal, annual and inter-annual flow regimes of rivers, which can subsequently impact on the ecology and the environment. As rainfall patterns and temperatures change, availability of water is affected, which can change the biodiversity of ecosystems. Therefore, the challenges of climate change in water resources and environmental management cannot be overemphasized, as the ideals of sustainable development cannot be achieved without accounting for it in development planning.

Hydrological impacts of climate changes depend mainly on whether a basin is dominated by rainfall or snow, as well as its latitude and geology (Praskievicz and Chang, 2009). Hence in regions dominated by snow, changes in temperature control the hydrology (Buytaert *et al.*, 2010), while in regions dominated by rainfall, changes in rainfall control the hydrology (Praskievicz and Chang, 2009). Also, basins with deep aquifers are more susceptible to increases in temperatures, compared with those with shallow aquifers (Tague *et al.*, 2008), as the ground water recharge rate is slower. It has also been shown that basins located in the mid- to high latitude regions and Southeast Asia (Steffen *et al.*, 2004), will have increases in runoff as a result of climate change, while those in arid, semi-arid and some tropical regions will experience decreases in runoff (Steffen *et al.*, 2004; Elshamy *et al.*, 2009; Kingston and Taylor, 2010; Tshimanga and Hughes, 2012; Sood *et al.*, 2013). However, there are some uncertainties which affect the magnitudes of hydrological impacts of climate changes. These include differences in impacts within regions (Praskievicz and Chang, 2009), as well as the choice of the climate scenarios (Praskievicz and Chang, 2009; Kingston and Taylor, 2010) and whether downscaled or raw GCM scenarios are applied. The choice of a hydrological model also account for some of the differences in impacts. For example, Cornelissen *et al.* (2013) obtained different magnitudes of hydrological impacts of climate change for each hydrological model applied in a West African basin. Therefore, since impacts of climate change are location specific, to be able to develop effective adaptation measures, there is the need for locally relevant studies, especially in regions with little to no information on how climate changes will affect the hydrology and the environment.

Impacts of climate change on hydrology have been assessed by using scenario modelling, sensitivity analysis or spatial gradient analysis (Praskievicz and Chang, 2009; Peel and Bloeschl, 2011). The scenario approach uses bias corrected and downscaled GCM climate scenarios. It has been suggested that because of the scarcity of data to conduct effective GCM downscaling, the change factor method of downscaling is the best option for data scarce regions (Ruelland *et al.*, 2012). For rainfall the ratio of the mean monthly GCM values for the future and those of the control period are multiplied by daily observed records to derive future climate scenarios, while the differences between mean monthly GCM values for the future and those of the control period are added to daily observed records to obtain future climate scenarios for temperature. The sensitivity analysis relates percentage changes in climate to percentage changes in runoff. The advantage of this approach is that it can be model-based or data driven, unlike the scenario approach, which is entirely model-based. The spatial gradient approach is based on the assumption that under the current climate the hydrological response of a basin may be similar to the responses in another basin under a different climate. Although this approach is data driven, its application is problematic since many other characteristics of a basin may not be similar (Peel and Bloeschl, 2011). Due to the lack of long-term observed data to drive the sensitivity and the spatial gradient approaches, climate change impact studies on hydrology are dominated by the application of the scenario approach (Peel and Bloeschl, 2011). Several studies (Dibike and Coulibaly, 2005; Paturel *et al.*, 2007; Ardoin-Bardin *et al.*, 2009; Elshamy *et al.*, 2009; Tu, 2009; Buytaert *et al.*, 2010; Chang and Jung, 2010; Graham *et al.*, 2011; Mango *et al.*, 2011; Taye *et al.*, 2011; Kienzle *et al.*, 2012; Ruelland *et al.*, 2012; Teng *et al.*, 2012; Tshimanga and Hughes, 2012; Faramarzi *et al.*, 2013) have used the scenario approach to assess climate change impacts on water resources around the world.

Furthermore, climate and land use affect each other (Dale, 1997; D'Orgeval and Polcher, 2008), as climatic changes and human activities can change land uses (Warburton *et al.*, 2012) and land use changes, such as vegetation dynamics, can also affect the regional climate (Xue, 1997; Wang and Eltahir, 2000) and their combined effects on hydrology is nonlinear(Li *et al.*, 2009). Simultaneous climate change and land use changes (Figure 2.2) therefore pose a significant challenge to water resources and environmental management across scales. However, the interactive effects of climate change and land use changes on hydrology are still not understood well in many tropical regions such as West Africa, although severe global changes have already occurred in the region and future changes are predicted to occur at a faster rate (Hulme *et al.*, 2001; L'Hote *et al.*, 2002; Conway *et al.*, 2009; FAO, 2010; Jalloh *et al.*, 2013).

2.1.2 Impacts of Global Changes on Hydrology in West Africa

Previous studies indicate that impacts of Global changes on hydrology are non-linear (Li *et al.*, 2009) and can be substantially different from impacts due to either climate change or land use changes alone (Guo *et al.*, 2008). In West Africa, a few studies have assessed the impacts of global changes in various basins. For example, in a semi-arid Sahelian catchment, Seguis *et al.* (2004) showed that mean annual runoff increased by about 300% between 1950 and 1998, when land use change impacts were evaluated, but the mean annual runoff increased between 30 to 70%, when both land use and climate change impacts were simultaneously evaluated for the same period, indicating a compensation effect of combined impacts. In Bormann (2005), a conceptual hydrological model, UHP, was used to calculate water fluxes, under changing climate and land uses in the upper Oueme catchment in northern Benin, West Africa. The results indicate that as rainfall decreases and temperatures increases, streamflows will reduce, but when only land use changes take place, the streamflow will significantly increase. On the other hand, when both climate change (reduced rainfall and increased temperatures) and land use changes occur, streamflows will increase, at the same levels as the land use change scenario. This meant that land use changes will have a stronger impact on streamflows than the applied climate change scenarios.

Furthermore, Bossa *et al.* (2012) studied effects of cropping patterns and management on nitrogen and potassium loads on surface and groundwater under climate change conditions in the Donga-Pont catchment in northern Benin, West Africa. The study applied SWAT hydrological model and downscaled climate scenarios (AIB and B1 for 2010-2014 and 2025-2029) from the regional climate model, REMO. The downscaling was performed, using weather generator and statistical matching to observed climate records. Results show that conversion of 40% of the savannah area to crop land will increase runoff and water pollution, while an increase in temperature and decreasing rainfall alone will result in reduced runoff, as well as water pollution. It was further shown that combined changes (i.e. conversion of more savannah land to croplands and climate changes), will increase runoff. Bossa *et al.* (2012) also concluded that land use changes will have stronger impact on hydrology than climate changes. Additionally, Cornelissen *et al.* (2013) analysed effects of combined impacts of climate change and land use changes in the Térou catchment, Benin, West Africa, using several hydrological models, downscaled climate data from REMO, a regional climate model and dynamic land use scenarios for 2000-2024. It was observed that increases in cropland resulted in increased runoff for all models, while climate change scenarios resulted in different impacts for all the models.

Concerning the impacts of Global changes across spatial scales, only one study has been conducted in West Africa by Bossa *et al.* (2014). Contrary to the results of similar global change impact study in South Africa by Warburton (2012),Bossa *et al.* (2014) concluded that although land use change impacts on hydrology were higher than separate impacts of climate change, the impacts of simultaneous land use and climate changes on hydrology were higher at the catchment scale than at the subcatchment scale in Benin, West Africa. This was because of the high conversion rates of natural vegetation to croplands at the catchment than the subcatchment scale. The study applied land use scenarios generated from spatial land use modelling and two downscaled climate scenarios. The study by Bossa *et al.* (2014) indicates the importance of analysing the spatial scale-effects of global change impacts on hydrology for effective water resources and environmental management, as it enables identification of subcatchments with higher or lower runoff, to target possible restoration measures.

Several studies have also been conducted to evaluate the separate impacts of climate change (Paturel *et al.*, 2007; Ardoin-Bardin *et al.*, 2009; Ruelland *et al.*, 2012; Sood *et al.*, 2013), as well as land use change impacts on hydrology (Giertz and Diekkruger, 2003; Valentin *et al.*, 2004; Giertz *et al.*, 2005; Mahe *et al.*, 2005; Li *et al.*, 2007; Leblanc *et al.*, 2008; Van de Giesen *et al.*, 2011)in West Africa. For example, Ruelland *et al.* (2012) assessed impacts of climate change on hydrology for the Bani catchment in Mali, by applying downscaled GCM data and the HydroStrahler, a conceptual hydrological model. The downscaling was performed with a bias-correction and a delta method, as well as a spatial and temporal downscaling technique. The results indicated that under a changed climate, catchment runoff could decrease to the same levels witnessed during the drought of the 1970 and 80s. Ardoin-Bardin *et al.* (2009) also used a conceptual hydrological model, GR2M and downscaled climate change scenarios to assess climate change impacts for the Senegal, the Gambia, the Sassandra and the Chari catchments in West Africa. The study employed climate data generated from a simple disaggregation of GCM climate data, based on climate records from the database of the Climate Research Unit (CRU) of the University of East Anglia, UK. The results show that under climate change, runoff will decrease for the Senegal and the Gambia catchments, but it will increase for the Chari, as well as the Sassandra catchments, suggesting that the impacts will be higher in the Sahelian catchment, compared to the Guinean. Sood *et al.* (2013) assessed impacts of climate change in the Volta basin in West Africa, using consistent climate change scenarios, as well as a physically-based semi-distributed model, SWAT, and concluded that generally, there will be a decrease of river flows of up to 40% within the Volta basin, as rainfalls decreases and temperatures increases.

For the separate impacts of land use changes in West Africa, studies by Mahe *et al.* (2005) and Li *et al.* (2007) are key examples. The study by Mahe *et al.* (2005), used two conceptual models, GR2M and WBM, while that by Li *et al.* (2007), used the integrated biosphere simulator (IBIS) and an aquatic transport model. Mahe *et al.* (2005) observed that runoff increased substantially due to extensive land use changes in Nakambe, a large Sahelian basin in Burkina Faso. During the period under investigation, natural vegetation decreased from 43 to 13%, while cultivated areas increased from 53 to 76% and bare soil areas increased from 4 to 11%. Contrary, Li *et al.* (2007) concluded that although tropical forest area was less than 5% of the total area of the Niger and Lake Chad basins in West Africa, its removal could increase streamflows between 35-65%, while a 100% overgrazing could increase streamflows up to 91%. Li *et al.* (2007) therefore observed threshold effects between the rate of changing land use and hydrological impacts, in addition to the general trend of land use change impacts, which was confirmed through field observations by Leblanc *et al.* (2008). The study by Mahe *et al.* (2005) conducted a historical analysis, based on historical land use, while Li *et al.* (2007) used assumed land use change scenarios for potential natural vegetation.

The results of separate impacts of climate changes and land use changes varied, depending on location of study site, the choice of hydrological models and the data used. The data used were mostly single GCM scenarios and unrealistic downscaling methods for the climate change impact studies and extreme land use scenarios (complete afforestation/deforestation) for the land use change impact studies. The studies were also conducted mainly in the Sahel and Savannah areas of the region.

The results of Global change impact studies in West Africa indicate that generally the hydrological cycle has been modified during the past four decades and it may undergo further and severe changes in the coming decades, which may affect discharge of rivers and water availability, agriculture and economic development. Although the combined impact evaluation have reduced the uncertainties and improved understanding, by accounting for both land use and climate changes, the studies conducted in West Africa still have some shortcomings. While some of the studies applied regional climate models and statistical downscaling (Bossa *et al.*, 2012; Cornelissen *et al.*, 2013; Sood *et al.*, 2013; Bossa *et al.*, 2014), studies such as Bormann (2005) and Paturel *et al.* (2007), among others cited in Sood *et al.* (2013), relied on simple and limited downscaling techniques to generate the climate scenarios. All the studies, except Sood *et al.* (2013) and Bossa *et al.* (2014), did not account for long-term climate changes, while Seguis *et al.* (2004) did not account for future climate changes at all. Future land use has also not been accounted for in Seguis *et al.* (2004) and only Cornelissen *et al.* (2013) and Bossa *et al.* (2014) incorporated dynamic changes in land use for both present and future scenarios, based on realistic land use estimates. Surprisingly, all the studies have either been conducted at the regional scale or in the Savannah and semi-arid Sahelian ecological zones. Moreover, apart from Bossa *et al.* (2012) and Bossa *et al.* (2014), who used two climate change scenarios, the rest of the studies relied on single climate scenarios, which is unrealistic since GCMs generate different realisations of climates for each scenario (IPCC, 2007). None of the studies have also analysed the potential ecological alterations due to impacts of global changes on hydrology in the region.

Information on the impacts of combined climate change and land use changes, generated from comprehensive impact assessments that consider both short-term, long-term and spatial variability of land use changes, as well as climate changes is non-existent for West Africa, especially the humid rainforest catchments in the south, where majority of the population live. The previous studies have also mainly analysed mean values of streamflows, which does not account for extreme conditions. In addition, none of the studies reviewed analysed the consequent ecological alterations due to impacts of simultaneous land use and climate changes on hydrology. Studies that account for short-term and long-term future global change impacts on hydrology and ecology, using reliable hydrological models, ensemble GCMs, as well as different scenarios and different downscaling techniques, are needed in order to develop effective climate change adaptation strategies and to manage land use and water recourses effectively in West Africa. There is also the need for studies that consider the full range of streamflows, not just the means, so as to improve understanding of the extreme hydrological conditions, as well.

2.1.3 Models for Assessing Global Change Impacts on Hydrology

Hydrological impacts of land use change and climate change have been quantified using catchment experiments (data driven methods) and hydrological modelling (Brown *et al.*, 2005; Lane *et al.*, 2005; Breuer *et al.*, 2009; Warburton *et al.*, 2010; Gosling *et al.*, 2011; Park *et al.*, 2011; Peel and Bloeschl, 2011; Li and Ishidaira, 2012). Hydrological modelling simulates the physical reality of the hydrological system (Schulze, 2005; Zhang and Savenije, 2005) whether catchment characteristics are changing or not (Breuer *et al.*, 2009; Peel and Bloeschl, 2011). Hydrological modelling under changing catchment conditions can be categorized into three forms (Peel and Bloeschl, 2011). These are application of a model (i) at the same location under changed catchment conditions, (ii) at different locations and (iii) at different location and periods. Several authors (Klocking and Haberlandt, 2002; Olsson and Pilesjo, 2002; Zhang and Savenije, 2005; Breuer *et al.*, 2009) have suggested that physically-based fully distributed models are the most suitable tools to investigate these changes for both historical and future scenarios, since physically-based fully distributed models describe the temporal and spatial variability of water balance components, based on physical and measurable catchment characteristics (Neitsch *et al.*, 2011). Application of distributed models is further supported by the fact that often only part of a catchment changes and models that can capture these partial changes can reproduce the correct response (Breuer *et al.*, 2009) for the whole or part of a catchment (Krajewski *et al.*, 1991; Krysanova *et al.*, 1999).

Physically-based fully distributed models, however have a disadvantage of being data intensive and their application scale is larger than the scale of field data measurement (Zhang and Savenije, 2005; Pechlivanidis *et al.*, 2011) necessitating upscaling and the adoption of a priori parameters (Breuer *et al.*, 2009). Estimating a priori model parameters is a challenge in hydrological modelling due to the problem of equifinality (Beven, 1993). Equifinality arises when different sets of model parameters produce similar model performance (Beven, 1993; Peel and Bloeschl, 2011). Physically-based fully distributed models are also computationally intensive and require huge computing resources. Due to these shortcomings amongst others, physically-based semi-distributed models have become alternative to fully distributed models (Breuer *et al.*, 2009) especially in data poor catchments (Legesse *et al.*, 2003; Jewitt *et al.*, 2004; Bekoe, 2005; Chang and Jung, 2010; Mango *et al.*, 2011; Faramarzi *et al.*, 2013). Semi-distributed models discretize a catchment using spatially non-explicit hydrological response units (HRUs) as the smallest spatial unit, making them less data-intensive. HRUs represent some of the variability of a catchment with respect to land uses, soil and topographic characteristics (Eckhardt *et al.*, 2003; Breuer *et al.*, 2009).

The hydrological processes are lumped in each HRU to generate runoff, which is then routed through the river network (Eckhardt *et al.*, 2003; Breuer *et al.*, 2009). The HRUs are of a coarser spatial resolution, compared to the concept of grid cells in fully spatially distributed models. Several processed-based semi-distributed models (e.g. HYLUC, SLURP, SWAT, ACRU, PRMS and HSPF) have been applied widely to investigate spatial patterns of hydrological impacts of climate change and land use changes either separately or jointly for decades (Legesse *et al.*, 2003; Dibike and Coulibaly, 2005; Sharma *et al.*, 2007; Breuer *et al.*, 2009; Warburton *et al.*, 2010; Mango *et al.*, 2011; Park *et al.*, 2011; Huang *et al.*, 2012; Kienzle *et al.*, 2012; Tong *et al.*, 2012). Lumped modelling approaches, since they describe hydrological processes, using average catchment variables and parameters (Krysanova *et al.*, 1999; Olsson and Pilesjo, 2002; Gosling *et al.*, 2011; Pechlivanidis *et al.*, 2011), do not account for the spatial variability of hydrological processes and inputs (Gosling *et al.*, 2011; Pechlivanidis *et al.*, 2011) and therefore not suitable for prediction of the spatial patterns of land use and climate change impacts on hydrology. The models only predict hydrological responses at the catchment outlets (Rosbjerg and Madsen, 2005); a quantity which can also be generated by distributed models. However, since distributed models consider the spatial variability within the catchment, the predicted hydrological response is superior (Krysanova *et al.*, 1999; Carpenter and Georgakakos, 2006; Gosling *et al.*, 2011). The application of semi-distributed models therefore supports the analysis of hydrological impacts of environmental changes at all locations within a basin; providing a means to understand the impacts at smaller scales (Warburton *et al.*, 2012), on conditon that data is available at the scale of interest.

In view of the above disadvantages of fully distributed models for application in data poor regions, such as West Africa and the limitations of lumped models, the rest of the review on hydrological models is restricted to the ACRU model. The model has been selected because it has been applied widely in a variety of catchments to assess impacts of global changes on hydrology.

2.1.3.1 The ACRU Model

The ACRU Model (Schulze, 1995; Schulze, 2005; Warburton *et al.*, 2010) is a daily time step physical-conceptual agro-hydrological model developed by the former School of Bioresources Engineering and Environmental Hydrology of the University of KwaZulu-Natal, South Africa to simulate catchment hydrological responses to land management. It is a multi-purpose model (Figure 2.3) that can be used for catchment water resources assessment, design floods, irrigation water planning, crop yield estimation, assessment of land use change and climate change impact (Schulze, 1995). The ACRU model is not a parameter optimising model, but uses variables derived from catchment physical properties and rely on daily inputs such as, rainfall, temperature and reference potential evaporation (PET) (Schulze, 1995; Schulze, 2005; Warburton *et al.*, 2010). However, when daily values of temperature and reference PET are not available, Fourier analysis is used to transform the monthly values into daily values.

The main engine of the ACRU model is multi-layer soil water budgeting, based on total evaporation (Figure 2.3). Therefore, the ACRU model is sensitive to climate and land cover/land use changes and is able to simulate their impacts on water flows. The land use component in the ACRU model is modelled using canopy interception losses, total evaporation and soil water extraction by plant roots (Schulze, 1995; Warburton *et al.*, 2010). In addition, the ACRU model can also respond to watering from irrigation and water extraction and can assess impacts of different agricultural land management practices on streamflows. The ACRU is a multi-level model, with options for calculating water balance depending on the available data and required model outputs. Hence, the model can operate as a point model or as lumped small catchments model (Schulze, 1995). In large catchments with complex soils and land uses, the model can be used as a distributed cell-type model, where each cell is a sub-catchment. Therefore, the ACRU model can generate outputs uniquely for each sub-catchment, depending on the type and level of details of the inputs (Schulze, 1995). The ACRU model is also user-friendly (Schulze, 1995), since it has simple menus for preparing inputs and accessing outputs.

The ACRU model uses a modified soil conservation (SCS-SA) curve number which relates antecedent soil moisture to runoff (Kienzle *et al.*, 2012) and has been used successfully to simulate streamflows under land use changes (Schulze, 2000; Jewitt *et al.*, 2004; Schmidt *et al.*, 2009; Warburton *et al.*, 2012) and climate changes (Forbes *et al.*, 2011; Graham *et al.*, 2011; Kienzle *et al.*, 2012) in several catchments with different land use and climates. The advantage of using the ACRU model in West Africa is that its modelling approach is flexible as it allows user inputs based on, for example information obtained by reading of the landscape of a catchment, as suggested by the outcome of the International Association of Hydrological Science's (IAHS) predictions in ungauged basins (PUB) initiative (McGlynn *et al.*, 2013). Furthermore, the application of the model in data scarce catchments can be useful in generating the needed information for effective water management, since the model is not a parameter optimizing model, but rather uses physically meaningful variables (Schulze, 1995) which can be derived directly from catchment data. Hence relevant information can be generated for water management in data scarce catchments although they do not have enough data.

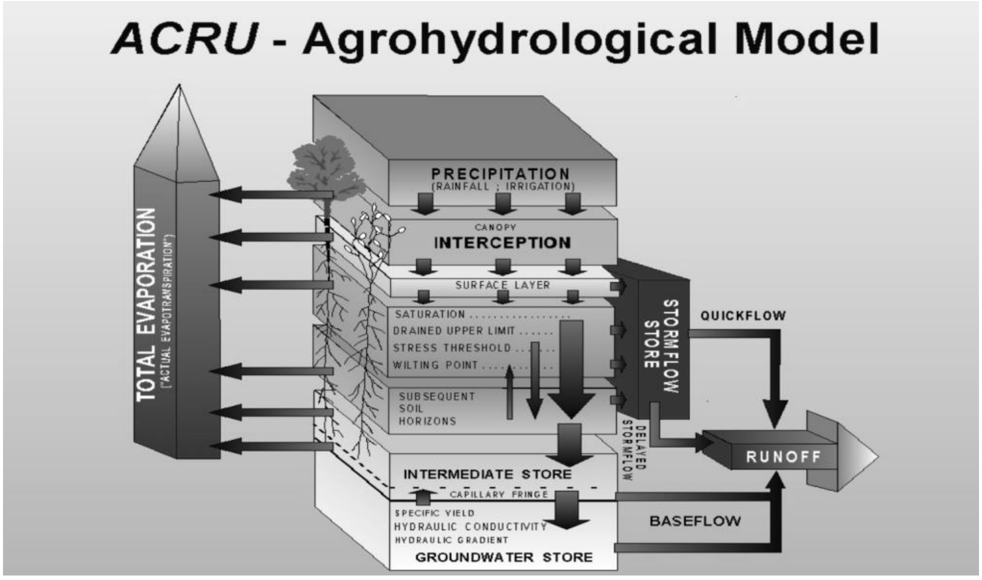


Figure 2.3: Representation of hydrological processes in the ACRU model (Schulze, 1995)

2.2 Discussion

2.2.1 Global Change Impact Studies in West Africa

The review illustrates that the influence of land use changes on hydrological responses is non-linear and depends on many factors. Studies in West Africa have shown that land use changes have significant impacts on local hydrology regardless of the magnitude and type of land use change. It has also been shown that previous studies have mainly relied on extreme and unrealistic land use scenarios, such as complete deforestation or reforestation and the studies have not also considered the spatial variability of land use change impacts. Only few studies (Bossa *et al.*, 2012; Cornelissen *et al.*, 2013; Bossa *et al.*, 2014) carried out in the same study area in Benin, have used realistic land use scenarios, where simulated land use change was influenced by socio-economic and biophysical driving forces.

Moreover, although the use of the scenario approach to climate change impact analysis generates valuable information for sustainable water resources management, studies in West Africa have generated varied results depending on the scale of analysis, the season and the hydrological model applied. The results of the reviewed studies show that the hydrological cycle in West Africa will undergo severe changes, if the applied climate change scenarios come true. Nevertheless, the uncertainties with climate change scenarios and to some extent the downscaling methods, were the most important factors affecting the simulation accuracies, which is also confirmed in studies elsewhere in the world (Dibike and Coulibaly, 2005; Buytaert *et al.*, 2010; Kingston and Taylor, 2010; Tshimanga and Hughes, 2012). IPCC (2007) reports indicate that different GCMs project different climates, especially rainfall for West Africa. Hence, the over-reliance on single climate scenarios, as well as single GCMs, for climate impact analysis in West Africa, has also resulted in large uncertainties in predicted hydrological impacts. It has been suggested that downscaled ensemble climate scenarios, are required in order to reduce climate impact simulation uncertainties at the regional/local scales (Buytaert *et al.*, 2010; Quintana Segui *et al.*, 2010; Taye *et al.*, 2011). In West Africa, the opportunity to assess the range of uncertainties of predicted impacts of climate change on hydrology will be improved with ensemble simulations, which will pave the way for probabilistic planning of water resources (Fowler *et al.*, 2007).

In addition, case studies elsewhere in the world (Li *et al.*, 2009; Park *et al.*, 2011; Tong *et al.*, 2012), illustrate that it is not enough to conduct separate assessment of land use change and climate change impacts on hydrology to provide information for effective land use planning and water resources management. It is essential to quantify the combined impacts across scales, using appropriate methods and tools. This is because land use and climate affect each other (Dale, 1997; IPCC, 2007; D'Orgeval and Polcher, 2008) and their separate and simultaneous impacts are non-linear. Unfortunately, in West Africa, where climate change and land use change are affecting all aspects of life (Jalloh *et al.*, 2013), studies focusing on the combined impacts of climate change and land use changes on hydrology are rare (Seguis *et al.*, 2004; Bormann, 2005; Paturel *et al.*, 2007; Bossa *et al.*, 2012; Cornelissen *et al.*, 2013;

Bossa *et al.*, 2014) and none of them assessed the potential alteration in ecology due to impacts of global changes on hydrology.

Finally, almost all the climate change impacts studies (Paturel *et al.*, 2007; Ardoin-Bardin *et al.*, 2009; Bossa *et al.*, 2012; Ruelland *et al.*, 2012; Cornelissen *et al.*, 2013; Sood *et al.*, 2013) in West Africa analysed short-term impacts, based on single GCMs, regional scales and focused on the Savannah/semi-arid regions. Studies on either separate or joint impacts of global changes in West Africa have also used mainly conceptual hydrological models, which lack the ability to describe the spatial variability of hydrological processes across scales. Previous studies in West Africa have also neglected the full range of streamflow responses to land use changes and climate changes, by focusing more on mean streamflows, which does not consider extreme hydrological conditions. To our knowledge, there is no comprehensive and quantitative information on the impacts of global change on hydrology and ecology in the tropical rainforest regions of West Africa, where majority of the population live and where land use changes may exacerbate impacts of climate change on water resources, due to rapid population changes. The most likely reason for this state of affairs is that of data scarcity and limited capacity in West Africa, which makes the region vulnerable to the consequences of climate changes and land use changes. Adaptation strategies in the region can therefore benefit from improved understanding of the regions hydrology by resolving key issues in data scarcity (e.g. improve meteorological network and use of remote sensing for mapping land use and realistically simulating future land use) and building institutional capacities to make reliable predictions on global change impacts, across scales.

2.2.2 Hydrological Model Selection

Fully-distributed models are the best for assessing spatial patterns of land use and climate change impacts on streamflows, but are data intensive. The use of semi-distributed models such as the ACRU is important for data scarce catchments since the models although require less data, compared to fully distributed models, they are able to represent some of the spatial patterns in streamflows, required for effective water resources management at the local scale. The ACRU model for example is useful for data scarce regions because it is relatively less data intensive and its flexible approach to simulation allows users to input information based on reading of the landscape. The model is also sensitive to changes in land use and climate and has been applied successfully in a variety of catchments with diverse land use and climates. The ACRU model can therefore be useful for streamflow simulation in the rainforest catchments of West Africa, as these catchments are undergoing significant land use changes.

2.3 Conclusions

In West Africa, most climate change studies have been conducted at the regional scale or focused mainly in the Savannah/semi-arid regions. Most of the studies analysed short-term impacts, using single GCM climate scenarios. Studies that analysed separate impacts of land use change on hydrology rarely considered realistic land use change scenarios. Also, only three studies in West Africa have analysed combined impacts of land use and climate changes, using realistic land use and downscaled climate scenarios and only one of them considered the scale effects of the impacts. In addition, in West Africa no study has analysed the potential ecological alterations due land use changes and climate changes impacts on hydrology, either for the current or future scenarios. The studies also failed to analyse the full range of streamflow variability, which is necessary for effective water management, as well as riparian and aquatic environmental conservation.

This reinforces the need to build on previous research in West Africa by quantifying the combined impacts of climate change and land use change on hydrology across multiple scales for the full range of streamflow variability, by considering realistic land use change scenarios, as well as using long-term multiple downscaled GCM climate scenarios. Literature shows that land use mapping and modelling (Verburg *et al.*, 1999; Chu *et al.*, 2010; Park *et al.*, 2011; Vermeiren *et al.*, 2012; Arsanjani *et al.*, 2013) can be used to generate realistic land use data for both historical and future scenarios and GCM downscaling (Kunstmann *et al.*, 2004; Dibike and Coulibaly, 2005; Hewitson and Crane, 2006; Fowler *et al.*, 2007; Sharma *et al.*, 2007; Buytaert *et al.*, 2010; Taye *et al.*, 2011)can be used to generate high resolution climate change scenarios. The review has also shown that the ACRU model can be useful in streamflow simulations in data scarce catchments since it needs only a minimal calibration as it is run using directly observable catchment variables. The model is also less data intensive, compared to other semi-distributed models (e.g SWAT), yet it is capable of generating useful simulations in catchments with different land uses and climates. The use of ACRU model also permits to incorporate landscape reading into the modelling, where for example forested areas can be assigned higher root storages, compared to grasslands. The use of realistic constraints based on landscape reading is consistent with current thinking in hydrology (Savenije, 2009; Wagener *et al.*, 2013) and has the potential to improve modelling in ungauged basins.

2.4 References

Ardoin-Bardin, S, Dezetter, A, Servat, E, Paturel, JE, Mahe, G, Niel, H and Dieulin, C. 2009. Using general circulation model outputs to assess impacts of climate change on runoff for large hydrological catchments in West Africa. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 54(1)**:**77-89.

Arsanjani, JJ, Helbich, M, Kainz, W and Boloorani, AD. 2013. Integration of logistic regression, Markov chain and cellular automata models to simulate urban expansion. *International Journal of Applied Earth Observation and Geoinformation* 21265-275.

Bekoe, EO. 2005. Application of a hydrological model in a data-poor tropical West African catchment: a case study of the Densu Basin of Ghana. Unpublished PhD Thesis, Institute of Water and Environment, Cranfield University at Silsoe, UK.

Beven, K. 1993. Prophecy, reality and uncertainty in distributed hydrological modeling. *Advances in Water Resources* 16(1)**:**41-51.

Bormann, H. 2005. Regional hydrological modelling in Benin (West Africa): Uncertainty issues versus scenarios of expected future environmental change. *Physics and Chemistry of the Earth, Parts A/B/C* 30(8–10)**:**472-484.

Bossa, AY, Diekkrueger, B and Agbossou, EK. 2014. Scenario-Based Impacts of Land Use and Climate Change on Land and Water Degradation from the Meso to Regional Scale. *Water* 6(10)**:**3152-3181.

Bossa, AY, Diekkrueger, B, Giertz, S, Steup, G, Sintondji, LO, Agbossou, EK and Hiepe, C. 2012. Modeling the effects of crop patterns and management scenarios on N and P loads to surface water and groundwater in a semi-humid catchment (West Africa). *Agricultural Water Management* 115(2012)**:**20-37.

Boulain, N, Cappelaere, B, Séguis, L, Favreau, G and Gignoux, J. 2009. Water balance and vegetation change in the Sahel: A case study at the watershed scale with an eco-hydrological model. *Journal of Arid Environments* 73(12)**:**1125-1135.

Bren, L and Hopmans, P. 2007. Paired catchments observations on the water yield of mature eucalypt and immature radiata pine plantations in Victoria, Australia. *Journal of Hydrology* 336(3–4)**:**416-429.

Breuer, L, Huisman, JA, Willems, P, Bormann, H, Bronstert, A, Croke, BFW, Frede, HG, Gräff, T, Hubrechts, L, Jakeman, AJ, Kite, G, Lanini, J, Leavesley, G, Lettenmaier, DP, Lindström, G, Seibert, J, Sivapalan, M and Viney, NR. 2009. Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM). I: Model intercomparison with current land use. *Advances in Water Resources* 32(2)**:**129-146.

Brown, AE, Zhang, L, McMahon, TA, Western, AW and Vertessy, RA. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* 310(1-4)**:**28-61.

Butterworth, JA, Schulze, RE, Simmonds, LP, Moriarty, P and Mugabe, F. 1999. Hydrological processes and water resources management in a dryland environment IV: Long-term groundwater level fluctuations due to variation in rainfall. *Hydrology and Earth System Sciences* 3(3)**:**353-361.

Buytaert, W, Vuille, M, Dewulf, A, Urrutia, R, Karmalkar, A and Celleri, R. 2010. Uncertainties in climate change projections and regional downscaling in the tropical Andes: implications for water resources management. *Hydrology and Earth System Sciences* 14(7)**:**1247-1258.

Carpenter, TM and Georgakakos, KP. 2006. Intercomparison of lumped versus distributed hydrologic model ensemble simulations on operational forecast scales. *Journal of Hydrology* 329(1–2)**:**174-185.

Chang, H and Jung, I-W. 2010. Spatial and temporal changes in runoff caused by climate change in a complex large river basin in Oregon. *Journal of Hydrology* 388(3–4)**:**186-207.

Cheng, G. 1999. Forest Change: Hydrological Effects in the Upper Yangtze River Valley. *Ambio* 28(5)**:**457-459.

Chu, H-J, Lin, Y-P, Huang, C-W, Hsu, C-Y and Chen, H-Y. 2010. Modelling the hydrologic effects of dynamic land-use change using a distributed hydrologic model and a spatial land-use allocation model. *Hydrological Processes* 24(18)**:**2538-2554.

Conway, D, Persechino, A, Ardoin-Bardin, S, Hamandawana, H, Dieulin, C and Mahé, G. 2009. Rainfall and Water Resources Variability in Sub-Saharan Africa during the Twentieth Century. *Journal of Hydrometeorology* 10(1)**:**41-59.

Coppin, P, Jonckheere, I, Nackaerts, K, Muys, B and Lambin, E. 2004. Digital change detection methods in ecosystem monitoring: a review. *International Journal of Remote Sensing* 25(9)**:**1565-1596.

Cornelissen, T, Diekkrueger, B and Giertz, S. 2013. A comparison of hydrological models for assessing the impact of land use and climate change on discharge in a tropical catchment. *Journal of Hydrology* 498(2013)**:**221-236.

Costa, MH, Botta, A and Cardille, JA. 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. *Journal of Hydrology* 283(1–4)**:**206-217.

Dale, VH. 1997. The relationship between land-use change and climate change. *Ecological Applications* 7(3)**:**753-769.

Dibike, YB and Coulibaly, P. 2005. Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models. *Journal of Hydrology* 307(1-4)**:**145-163.

D'Orgeval, T and Polcher, J. 2008. Impacts of precipitation events and land-use changes on West African river discharges during the years 1951-2000. *Climate Dynamics* 31(2-3)**:**249-262.

Eckhardt, K, Breuer, L and Frede, HG. 2003. Parameter uncertainty and the significance of simulated land use change effects. *Journal of Hydrology* 273(1-4)**:**164-176.

Elshamy, ME, Seierstad, IA and Sorteberg, A. 2009. Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios. *Hydrology and Earth System Sciences* 13(5)**:**551-565.

FAO. 2010. Global Forest Resources Assessment 2010: Main report. Food and Agriculture Organization of the United Nations, Rome, Italy.

Forbes, KA, Kienzle, SW, Coburn, CA, Byrne, JM and Rasmussen, J. 2011. Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada. *Climatic Change* 105(3-4)**:**555-576.

Faramarzi, M, Abbaspour, KC, Vaghefi, SA, Farzaneh, MR, Zehnder, AJB, Srinivasan, R and Yang, H. 2013. Modeling impacts of climate change on freshwater availability in Africa. *Journal of Hydrology* 480(2013)**:**85-101.

Farley, KA, Jobbágy, EG and Jackson, RB. 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology* 11(10)**:**1565-1576.

Fowler, HJ, Blenkinsop, S and Tebaldi, C. 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. *International Journal of Climatology* 27(12)**:**1547-1578.

Gerten, D, Schaphoff, S, Haberlandt, U, Lucht, W and Sitch, S. 2004. Terrestrial vegetation and water balance - hydrological evaluation of a dynamic global vegetation model. *Journal of Hydrology* 286(1-4)**:**249-270.

Giertz, S and Diekkruger, B. 2003. Analysis of the hydrological processes in a small headwater catchment in Benin (West Africa). *Physics and Chemistry of the Earth* 28(33-36)**:**1333-1341.

Giertz, S, Junge, B and Diekkrüger, B. 2005. Assessing the effects of land use change on soil physical properties and hydrological processes in the sub-humid tropical environment of West Africa. *Physics and Chemistry of the Earth, Parts A/B/C* 30(8–10)**:**485-496.

Gosling, SN, Taylor, RG, Arnell, NW and Todd, MC. 2011. A comparative analysis of projected impacts of climate change on river runoff from global and catchment-scale hydrological models. *Hydrology and Earth System Sciences* 15(1)**:**279-294.

Graham, LP, Andersson, L, Horan, M, Kunz, R, Lumsden, T, Schulze, R, Warburton, M, Wilk, J and Yang, W. 2011. Using multiple climate projections for assessing hydrological response to climate change in the Thukela River Basin, South Africa. *Physics and Chemistry of the Earth* 36(14-15)**:**727-735.

Guo, H, Hu, Q and Jiang, T. 2008. Annual and seasonal streamflow responses to climate and land-cover changes in the Poyang Lake basin, China. *Journal of Hydrology* 355(1-4)**:**106-122.

Hewitson, BC and Crane, RG. 2006. Consensus between GCM climate change projections with empirical downscaling: Precipitation downscaling over South Africa. *International Journal of Climatology* 26(10)**:**1315-1337.

Hu, Q, Willson, GD, Chen, X and Akyuz, A. 2005. Effects of climate and landcover change on stream discharge in the Ozark Highlands, USA. *Environmental Modeling & Assessment* 10(1)**:**9-19.

Huang, G, Kadir, T and Chung, F. 2012. Hydrological response to climate warming: The Upper Feather River Watershed. *Journal of Hydrology* 426–427(0)**:**138-150.

Hulme, M, Doherty, R, Ngara, T, New, M and Lister, D. 2001. African climate change: 1900-2100. *Climate Research* 17(2)**:**145-168.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *In:* Solomon, S, Qin, D, Manning, M, Chen, Z, Marquis, M, Averyt, KB, Tignor, M and Miller, HL (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jalloh, A, Faye, MD, Roy-Macauley, H, Sérémé, P, Zougmoré, R, Thomas, TS and Nelson, GC. 2013. Overview. *In:* Jalloh, A, Nelson, G. C., Thomas,T. S., Zougmoré,R. And Roy-Macauley, H. (ed.) *West African Agriculture and Climate Change: A Comprehensive Analysis.* International Food Policy Research Institute(IFPRI), Washington, DC, USA.

Jewitt, GPW, Garratt, JA, Calder, IR and Fuller, L. 2004. Water resources planning and modelling tools for the assessment of land use change in the Luvuvhu Catchment, South Africa. *Physics and Chemistry of the Earth* 29(2004)**:**1233–1241.

Kienzle, SW, Nemeth, MW, Byrne, JM and MacDonald, RJ. 2012. Simulating the hydrological impacts of climate change in the upper North Saskatchewan River basin, Alberta, Canada. *Journal of Hydrology* 412–413(2012)**:**76-89.

Kingston, DG and Taylor, RG. 2010. Sources of uncertainty in climate change impacts on river discharge and groundwater in a headwater catchment of the Upper Nile Basin, Uganda. *Hydrology and Earth System Sciences* 14(2010)**:**1297–1308.

Klocking, B and Haberlandt, U. 2002. Impact of land use changes on water dynamics-a case study in temperate meso and macroscale river basins. *Physics and Chemistry of the Earth* 27(9-10)**:**619-629.

Krajewski, WF, Lakshmi, V, Georgakakos, KP and Jain, SC. 1991. A monte-carlo study of rainfall sampling effect on a distributed catchment model. *Water Resources Research* 27(1)**:**119-128.

Krysanova, V, Bronstert, A and Muller-Wohlfeil, DI. 1999. Modelling river discharge for large drainage basins: from lumped to distributed approach. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 44(2)**:**313-331.

Kunstmann, H, Schneider, K, Forkel, R and Koche., R. 2004. Impact analysis of climate change on an Alpine catchment using high resolution dynamic downscaling of ECHMAM4 time slices. *Hydrology and Earth System Sciences* 8(6)**:**1030 - 1044.

L'Hote, Y, Mahe, G, Some, B and Triboulet, JP. 2002. Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 47(4)**:**563-572.

Lane, PNJ, Best, AE, Hickel, K and Zhang, L. 2005. The response of flow duration curves to afforestation. *Journal of Hydrology* 310(1-4)**:**253-265.

Leblanc, MJ, Favreau, G, Massuel, S, Tweed, SO, Loireau, M and Cappelaere, B. 2008. Land clearance and hydrological change in the Sahel: SW Niger. *Global and Planetary Change* 61(3-4)**:**135-150.

Legesse, D, Abiye, TA, Vallet-Coulomb, C and Abate, H. 2010. Stream flow sensitivity to climate and land cover changes: Meki River, Ethiopia. *Hydrology and Earth System Science* 14(2010)**:** 2277-2287.

Legesse, D, Vallet-Coulomb, C and Gasse, F. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *Journal of Hydrology* 275(1-2)**:**67-85.

Li, KY, Coe, MT, Ramankutty, N and De Jong, R. 2007. Modeling the hydrological impact of land-use change in West Africa. *Journal of Hydrology* 337(3-4)**:**258-268.

Li, Q and Ishidaira, H. 2012. Development of a biosphere hydrological model considering vegetation dynamics and its evaluation at basin scale under climate change *Journal of Hydrology* 412–413(2012)**:**3-13.

Li, Z, Liu, W, Zhang, X and Zheng, F. 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology* 377(2009)**:**35-42.

Mahe, G, Paturel, JE, Servat, E, Conway, D and Dezetter, A. 2005. The impact of land use change on soil water holding capacity and river flow modelling in the Nakambe River, Burkina-Faso. *Journal of Hydrology* 300(1-4)**:**33-43.

Mango, LM, Melesse, AM, McClain, ME, Gann, D and Setegn, SG. 2011. Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: results of a modeling study to support better resource management. *Hydrology and Earth System Science* 15(2011)**:**2245-2258.

Meyer, WB and Turner II, BL. 1994. *Changes in Land Use and Land Cover: A Global Perspective,* Cambridge University Press,Cambridge, United Kingdom.

McGlynn, BL, Blöschl, G, Borga, M, Bormann, H, Hurkmans, R, Komma, J, Nandagiri, L, Uijlenhoet, R and Wagener, T. 2013. A data acquisition framework for runoff predictions in ungauged basins. *In:* Blöschl, G, Sivapalan, M, Wagener, T, Viglione, A and Savenije, HHG (eds.) *Runoff Predictions in Ungauged basins: Synthesis across processes, places and scales.* Cambridge University Press, Cambridge, UK.

Neitsch, SL, Arnold, JG, Kiniry, JR and Williams, JR. 2011. Soil and Water Assessment Tool. Theoretical Documentation: Version 2009 Texas Water Resources Institute, College Station, TX.

Olsson, L and Pilesjo, P. 2002. Approaches to spatially distributed hydrological modelling in a GIS environment. *In:* Skidmore, A (ed.) *Environmental Modelling with GIS and Remote Sensing.* Taylor and Francis, London, United Kingdom.

Park, JY, Park, MJ, Joh, HK, Shin, HJ, Kwon, HJ, Srinivasan, R and Kim, SJ. 2011. Assessment of MIROC3.2 HIRES climate and CLUE-S land use change impacts on watershed hydrology using SWAT. *Transactions of the Asabe* 54(5)**:**1713-1724.

Paturel, JE, Barrau, C, Mahe, G, Dezetter, A and Servat, E. 2007. Modelling the impact of climatic variability on water resources in West and Central Africa from a non-calibrated hydrological model. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 52(1)**:**38-48.

Pechlivanidis, IG, Jackson, BM, Mcintyre, NR and Wheater, HS. 2011. Catchment scale hydrological modelling: a review of model types, calibration approaches and uncertainty analysis methods in the context of recent developments in technology and Applications. *Global NEST Journal* 13(3)**:**193-214.

Peel, MC and Bloeschl, G. 2011. Hydrological modelling in a changing world. *Progress in Physical Geography* 35(2)**:**249-261.

Praskievicz, S and Chang, H. 2009. A review of hydrological modelling of basin-scale climate change and urban development impacts. *Progress in Physical Geography* 33(5)**:**650-671.

Quintana Segui, P, Ribes, A, Martin, E, Habets, F and Boe, J. 2010. Comparison of three downscaling methods in simulating the impact of climate change on the hydrology of Mediterranean basins. *Journal of Hydrology* 383(1-2)**:**111-124.

Randolph, J. 2012. *Environmental Land Use Planning and Management,* Island Press,Washington, USA.

Rosbjerg, D and Madsen, H. 2005. Concepts of hydrologic modeling. *Encyclopedia of hydrological sciences.* John Wiley and Sons, Chichester, England.

Ruelland, D, Ardoin-Bardin, S, Collet, L and Roucou, P. 2012. Simulating future trends in hydrological regime of a large Sudano-Sahelian catchment under climate change. *Journal of Hydrology* 424-425(2012)**:**207-216.

Savenije, HHG. 2009. HESS Opinions "The art of hydrology"*. Hydrol. Earth Syst. Sci. 13(2):157-161.

Schmidt, J, Kienze, SW and Srinivasan, MS. 2009. Estimating increased evapotranspiration losses caused by irrigated agriculture as part of the water balance of the Orari catchment, Canterbury, New Zealand. *Journal of Hydrology (Wellington North)* 48(2)**:**73-94.

Schulze, RE. 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System,* Water Research Commission,Pretoria, South Africa.

Schulze, RE. 2000. Modelling hydrological responses to land use and climate change: A southern African perspective. *Ambio* 29(1)**:**12-22.

Schulze, RE. 2005. Selection of a Suitable Agrohydrological Model for Climate Change Impact Studies over Southern Africa. *In:* Schulze, RE (ed.) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation.* Water Research Commission, Pretoria, RSA.

Scott, DF and Lesch, W. 1997. Streamflow responses to afforestation with Eucalyptus grandis and Pinus patula and to felling in the Mokobulaan experimental catchments, South Africa. *Journal of Hydrology* 199(3-4)**:**360-377.

Seguis, L, Cappelaere, B, Milesi, G, Peugeot, C, Massuel, S and Favreau, G. 2004. Simulated impacts of climate change and land-clearing on runoff from a small Sahelian catchment. *Hydrological Processes* 18(17)**:**3401-3413.

Sharma, D, Das Gupta, A and Babel, MS. 2007. Spatial disaggregation of bias-corrected GCM precipitation for improved hydrologic simulation: Ping River Basin, Thailand. *Hydrology and Earth System Sciences* 11(4)**:**1373-1390.

Sood, A, Muthuwatta, L and McCartney, M. 2013. A SWAT evaluation of the effect of climate change on the hydrology of the Volta River basin. *Water International* 38(3)**:**297-311.

Steffen, W, Sanderson, A, Tyson, PD, Jäger, J, Matson, PA, Moore III, B, Oldfield, F, Richardson, K, Schellnhuber, HJ, Turner, BL and Wasson, RJ. 2004. *Global Change and the Earth System: A Planet Under Pressure,* Springer-Verlag Berlin Heidelberg New York, Germany.

Tague, C, Grant, G, Farrell, M, Choate, J and Jefferson, A. 2008. Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades. *Climatic Change* 86(1-2)**:**189-210.

Taye, MT, Ntegeka, V, Ogiramoi, NP and Willems, P. 2011. Assessment of climate change impact on hydrological extremes in two source regions of the Nile River Basin. *Hydrology and Earth System Sciences* 15(1)**:**209-222.

Teng, J, Chiew, FHS, Timbal, B, Wang, Y, Vaze, J and Wang, B. 2012. Assessment of an analogue downscaling method for modelling climate change impacts on runoff. *Journal of Hydrology* 472111-125.

Thuiller, W. 2007. Biodiversity: Climate change and the ecologist. *Nature* 448(7153)**:**550-552.

Tong, STY, Sun, Y, Ranatunga, T, He, J and Yang, YJ. 2012. Predicting plausible impacts of sets of climate and land use change scenarios on water resources. *Applied Geography* 32 (2012)**:**477 - 489.

Tshimanga, RM and Hughes, DA. 2012. Climate change and impacts on the hydrology of the Congo Basin: The case of the northern sub-basins of the Oubangui and Sangha Rivers. *Physics and Chemistry of the Earth* 50-52(2012)**:**72-83.

Tu, J. 2009. Combined impact of climate and land use changes on streamflow and water quality in eastern Massachusetts, USA. *Journal of Hydrology* 379(3-4)**:**268-283.

Valentin, C, Rajot, JL and Mitja, D. 2004. Responses of soil crusting, runoff and erosion to fallowing in the sub-humid and semi-arid regions of West Africa. *Agriculture, Ecosystems & Environment* 104(2)**:**287-302.

Van de Giesen, N, Stomph, T-J, Ajayi, AE and Bagayoko, F. 2011. Scale effects in Hortonian surface runoff on agricultural slopes in West Africa: Field data and models. *Agriculture, Ecosystems & Environment* 142(1–2)**:**95-101.

Veldkamp, A and Verburg, PH. 2004. Modelling land use change and environmental impact. *Journal of Environmental Management* 72(1–2)**:**1-3.

Verburg, PH, de Koning, GHJ, Kok, K, Veldkamp, A and Bouma, J. 1999. A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. *Ecological Modelling* 116(1)**:**45-61.

Verburg, PH and Overmars, KP. 2009. Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. *Landscape Ecology* 24(9)**:**1167-1181.

Vermeiren, K, Van Rompaey, A, Loopmans, M, Serwajja, E and Mukwaya, P. 2012. Urban growth of Kampala, Uganda: Pattern analysis and scenario development. *Landscape and Urban Planning* 106(2)**:**199-206.

Vörösmarty, CJ, Green, P, Salisbury, J and Lammers, RB. 2000. Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science* 289(5477)**:**284-288.

Wagener, T, Blöschl, G, Goodrich, DC, Gupta, HV, Sivapalan, M, Tachikawa, T, Troch, PA and Weiler, M. 2013. A synthesis framework for runoff prediction in ungauged basins. *In:* Blöschl, G, Sivapalan, M, Wagener, T, Viglione, A and Savenije, HHG (eds.) *Runoff prediction in ungauged basins. Synthesis across processes, places and scales.* Cambridge University Press, Cambridge, UK.

Wang, G and Eltahir, EAB. 2000. Role of vegetation dynamics in enhancing the low-frequency variability of the Sahel rainfall. *Water Resources Research* 36(4)**:**1013-1021.

Warburton, ML. 2012. Challenges in modelling hydrological responses to impacts and interactions of land use and climate change. Unpublished PhD, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Warburton, ML, Schulze, RE and Jewitt, GPW. 2010. Confirmation of ACRU model results for applications in land use and climate change studies. *Hydrology and Earth System Sciences* 14(2010)**:**2399-2414.

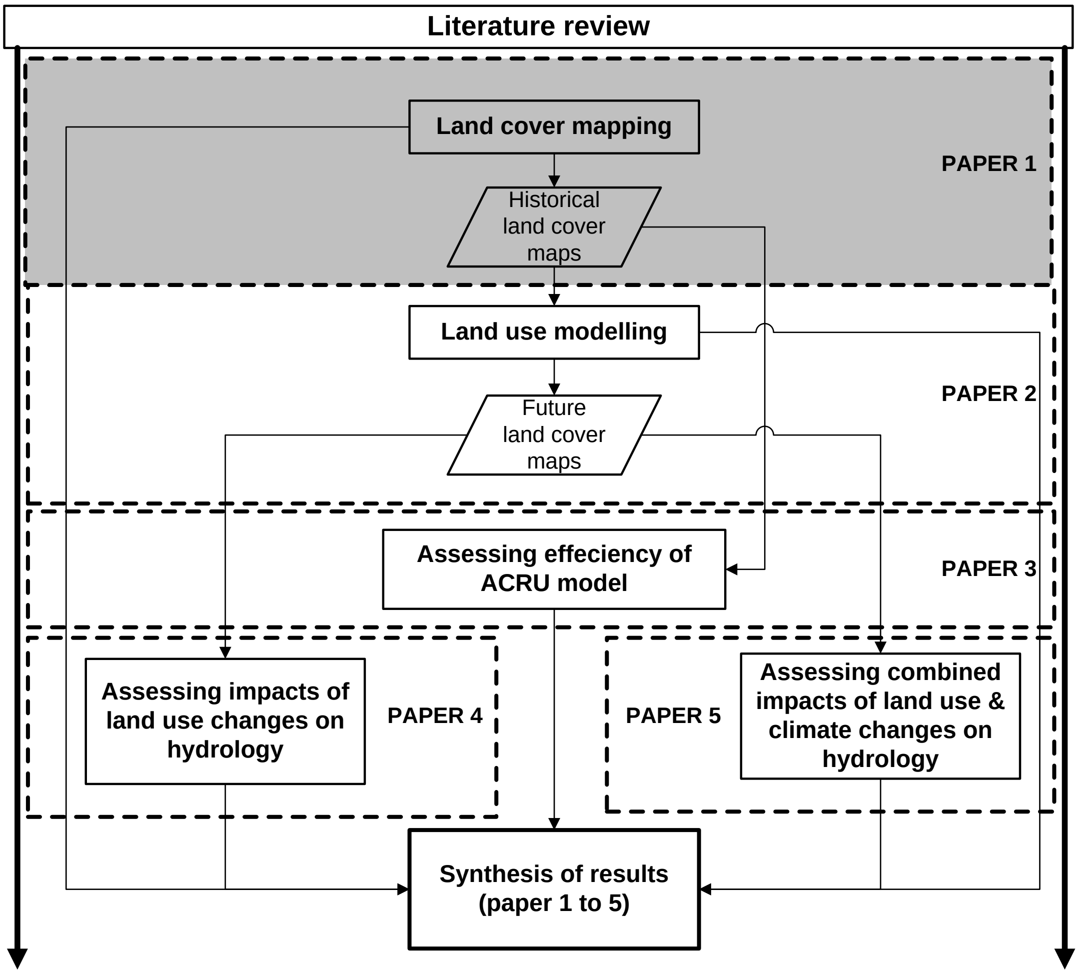
Warburton, ML, Schulze, RE and Jewitt, GPW. 2012. Hydrological impacts of land use change in three diverse South African catchments. *Journal of Hydrology* 414-415(2012)**:**118-135.

Xue, Y. 1997. Biosphere feedback on regional climate in tropical North Africa. *Quarterly Journal of the Royal Meteorological Society* 123(542)**:**1483-1515.

Zhang, GP and Savenije, HHG. 2005. Rainfall-runoff modelling in a catchment with a complex groundwater flow system: application of the Representative Elementary Watershed (REW) approach. *Hydrol. Earth Syst. Sci.* 9(3)**:**243-261.

Preface to Chapter 3

In order to understand how land use/land cover changes have affected the water resources and the environment of a data scarce region, which is a prerequisite for effective land use planning and environmental management, it is important to inventory (first step of research approach: shown in shaded part of figure below) both the current and historical land use/land cover, through land cover mapping and identification of the potential drivers of the changes (objectives of Chapter 3). Such an inventory is effectively conducted, based on catchment boundary, instead of political or administrative boundaries, which do not account for natural flow paths. The land use data can be applied to conduct hydrological modelling, as well as assess potential ecological alterations in the environment.



CHAPTER 3 : ANALYSIS OF LAND COVER CHANGES IN THE BONSA CATCHMENT, ANKOBRA BASIN, GHANA[1]

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3.1 Abstract

Multi-temporal land cover changes in the Bonsa catchment of the Ankobra Basin in Ghana were determined using four satellite images from 1986, 1991, 2002 and 2011. The results indicate that evergreen forest is the largest class occupying an area of 68% in 1986, 62% in 1991, 50% in 2002 and 51% in 2011 and during the past 26 years, the largest land cover change has been the conversion of evergreen and secondary forests to shrubs/farms, mining areas and settlements. During this period, mining areas increased over two-fold, while settlements and shrubs/farms increased more than three and four-fold, respectively. This resulted in increasing annual deforestation rate of 0.33% between 1986 and 1991, 0.70% between 1991 and 2002 and 2% between 2002 and 2011. The results suggests that the drivers of the land cover changes in the Bonsa catchment, are both local and global and include, international trade, local population growth, agriculture extensification and urbanization. The identified land cover changes have the potential to impact negatively on the hydrological regimes of the Bonsa River and the local communities by leading to flooding, soil erosion and the siltation and pollution of the river during peak seasons[2] and the scarcity of water during dry seasons. Therefore, the maps and statistics generated can be applied to assess the impacts of the land use changes on the local hydrology and provide a better basis for future land use

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[1] Aduah, MS, Warburton, ML and Jewitt, G. 2015. Analysis of land cover changes in the Bonsa catchment, Ankobra Basin, Ghana. *Applied Ecology and Environmental Research* 13(4)**:**935-955, DOI: 10.15666/aeer/1304_935955.

[2] Peak season can also be referred to as wet season

planning. Through these findings the importance of multi-temporal analysis of satellite imagery for planning in data poor regions is highlighted.

Key Words: Bonsa catchment, Ghana, hydrological regimes, land cover change, multi-temporal analysis.

3.2 Introduction

Land cover/land use changes occur by the alteration of the natural landscape through both anthropogenic activities and natural processes (Coppin *et al.*, 2004; Hu *et al.*, 2005). Natural causes include volcanoes, storm surges, floods, droughts, earthquakes and wildfires, while anthropogenic land cover/land use changes are influenced mainly by socio-economic drivers such as population growth, rural-urban migration, immigration, urbanization, government policy and economic development (Lambin *et al.*, 2003; Cohen, 2004; D'Orgeval and Polcher, 2008).These changes in land use, in turn impact the hydrological responses of a catchment by altering the partitioning of precipitation into different components of the hydrological cycle, such as interception, infiltration, runoff, evapotranspiration and groundwater recharge rate (Costa *et al.*, 2003; D'Orgeval and Polcher, 2008), as well as influencing water quality (Rogers, 1994; Randolph, 2012). To predict and manage the impacts of land cover/land use changes on hydrology, it is imperative to understand the land cover/land use change processes, the rates and possible causes of the changes. Satellite sensors, with their wide spatial and synoptic coverage over large areas, can provide spatially continuous and consistent data, which can be analysed to derive land cover maps and change statistics (Foody, 2002), required for effective land use planning and water resources management in a catchment. Such land cover maps and change statistics can be derived through the process of change detection and land cover mapping (Song *et al.*, 2001).

Land cover/land use change detection is the process of categorizing differences in the state of the land cover by mapping it at different times over a period (Lambin and Ehrlich, 1997). The analysis of satellite images to detect land cover/land use changes is, based on the assumption that the recorded electromagnetic radiation, which is the basis of categorizing land covers, is altered as the land cover/land use of the same geographic area changes (Lambin and

Ehrlich, 1997; Abuelgasim *et al.,* 1999). Change detection techniques can be categorized as algebraic, transformation, classification and visual analysis techniques (Coppin *et al*., 2004). Algebraic based methods include image differencing, image regression, image ratioing, normalised difference vegetation index (NDVI) differencing and change vector analysis (CVA) (Braimoh and Vlek, 2004; Coppin *et al*., 2004), while those in the transformation category include multi-date Principal Component Analysis (PCA), Kauth-Thomas (KT) and Chi-square transformations (Coppin *et al*., 2004). The classification methods consist of post-classification comparison, multi-date classification, spectral–temporal combined analysis and unsupervised change detection (Coppin *et al.,* 2004; Braimoh and Vlek, 2005). Algebraic and transformation methods are suitable for detecting continuous changes, while classification methods are effective for categorical changes (Abuelgasim *et al*., 1999), but depend on the accurate geometric registration and classification of individual images (Coppin *et al.*, 2004). Continuous changes refer to changes in the concentration or amount of an attribute (e.g. biomass and the leaf area index of a forest), while categorical changes are the conversion of one land cover type to another (e.g. evergreen forest to a mining area). Visual analysis techniques (Lu *et al*., 2004) are primarily based on the visual interpretation of aerial photographs and high resolution images.

Image classification techniques, using either unsupervised or supervised classification (Campbell, 2002; Foody, 2002; Richards and Jia, 2006) can be used to implement the post-classification comparison methods. However, supervised classification systems have found a wider usage, because it is possible to create specific thematic classes (Campbell, 2002) with respect to the objectives of a study. Supervised classification systems can be grouped as either parametric or non-parametric methods. The parametric methods include maximum likelihood classification (MLC) (Campbell, 2002; Richards and Jia, 2006),fuzzy-set classifiers (Suresh Babu and Viswanath, 2009; Stavrakoudis *et al.*, 2011), sub-pixel classifiers (Verhoeye and De Wulf, 2002; Frazier and Wang, 2011), spectral mixture analysis (Nichol *et al.*, 2010; Youngentob *et al.*, 2011) and object-oriented classifiers (Geneletti and Gorte, 2003; Platt and Rapoza, 2008). The non-parametric methods include artificial neural networks (ANN) (Atkinson and Tatnall, 1997; Abuelgasim *et al.*, 1999; Laurin *et al.*, 2013), decision tree and support vector machines (Huang *et al.*, 2002). In terms of image classification accuracies, literature shows that the ANN and the MLC algorithms perform better than the other methods (Atkinson and Tatnall, 1997; Abuelgasim *et al.*, 1999; Laurin *et al.*, 2013). Nevertheless, the application of the statistically-based MLC algorithm is more common, as it is widely accessible in much remote sensing software and it is considered easier to implement, compared to ANN (Richards and Jia, 2006; Lu and Weng, 2007).

When applying methods of land cover change detection, the advantages vary, depending on the techniques employed and the nature of the change under investigation. According to Coppin *et al.* (2004) among others, complementary use of more than one technique has the potential to generate the best results. Nonetheless, available literature indicates that post-classification comparison techniques are preferred by many researchers (Braimoh and Vlek, 2004; Aduah and Aabeyir, 2012; Kumi-Boateng *et al.*, 2012; Wasige *et al.*, 2013). It is advantageous to use post-classification comparison methods because individual images are classified separately, which minimizes the requirement to conduct absolute radiometric corrections and the techniques also produce change matrices (Coppin *et al.*, 2004), which are needed to identify change trajectories. The methods are also simple and accessible in a variety of software and can be used to detect categorical land cover changes.

Previous studies (Kusimi, 2008; Schueler *et al.*, 2011; Kumi-Boateng *et al.*, 2012) within the Ankobra River basin of the Western region of Ghana indicates that there is extensive deforestation, as a result of increasing urbanisation, mining and farming. Even though these studies analysed land cover changes for the Wassa West District within the Ankobra River basin (Kusimi, 2008; Schueler *et al.*, 2011; Kumi-Boateng *et al.*, 2012), none covered the entire Bonsa subcatchment nor applied the results of the studies to project potential future land use changes, as well as assessing the impacts of the land use changes on catchment hydrology. As a first stage in projecting potential future land use changes and assessing their impacts on Bonsa catchment hydrology, a more recent and multi-temporal land cover information for the entire catchment is needed. In this study, the post-classification comparison and the MLC methods were selected to map and to detect the multi-temporal land cover changes in the Bonsa subcatchment of the Ankobra River basin in Ghana, West Africa, over a period of 26 years (i.e. 1986 to 2011). The study seeks to determine the rates of change in the land cover types, the transitions between different land cover types and to elicit an understanding of the possible drivers[3] of the land cover changes and their impacts on the environment.

3.3 Methodology

3.3.1 Description of Study Area

The Bonsa catchment, a subcatchment of the Ankobra River basin in Ghana, West Africa (Figure 3.1), is located between longitudes 1° 41´ and 2° 13´ West and latitudes 5° 4´and 5° 43´ North and it straddles the intersection of four administrative districts, namely: Twifo Heman Lower Denkyira to the north, Tarkwa Nsuaem and the Prestea-Huni Valley to the west and Mpohor Wassa East to the east. The catchment has a generally low relief, with the elevations ranging between 30 and 340 m above mean sea level and it drains an area of 1482km^2.The rainfall regime is bimodal, with the peak season between February and July and the minor season between August and November. The rainfall ranges between 1578 mm and 1982 mm per annum and the annual average minimum and maximum temperatures are 22ºC and 32ºC, respectively. Predominant land cover consists of thick evergreen and secondary forests, with scattered shrubs and farms. The basin's geology is characterized by Birimian and Tarkwaian rock systems (Akabzaa *et al.*, 2009), while the soil is composed mostly of Ferric Acrisols, according the Food and Agricultural Organisations' (FAO) soil classification system and forest oxysols (Dwomo and Dedzoe, 2010), according to the Ghana soil classification system. Major economic activities in the catchment include open-pit gold mining, rubber cultivation and small-scale cocoa and food crop production.

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[3] The land use change drivers were identified based on literature, local knowledge of study area and field visits

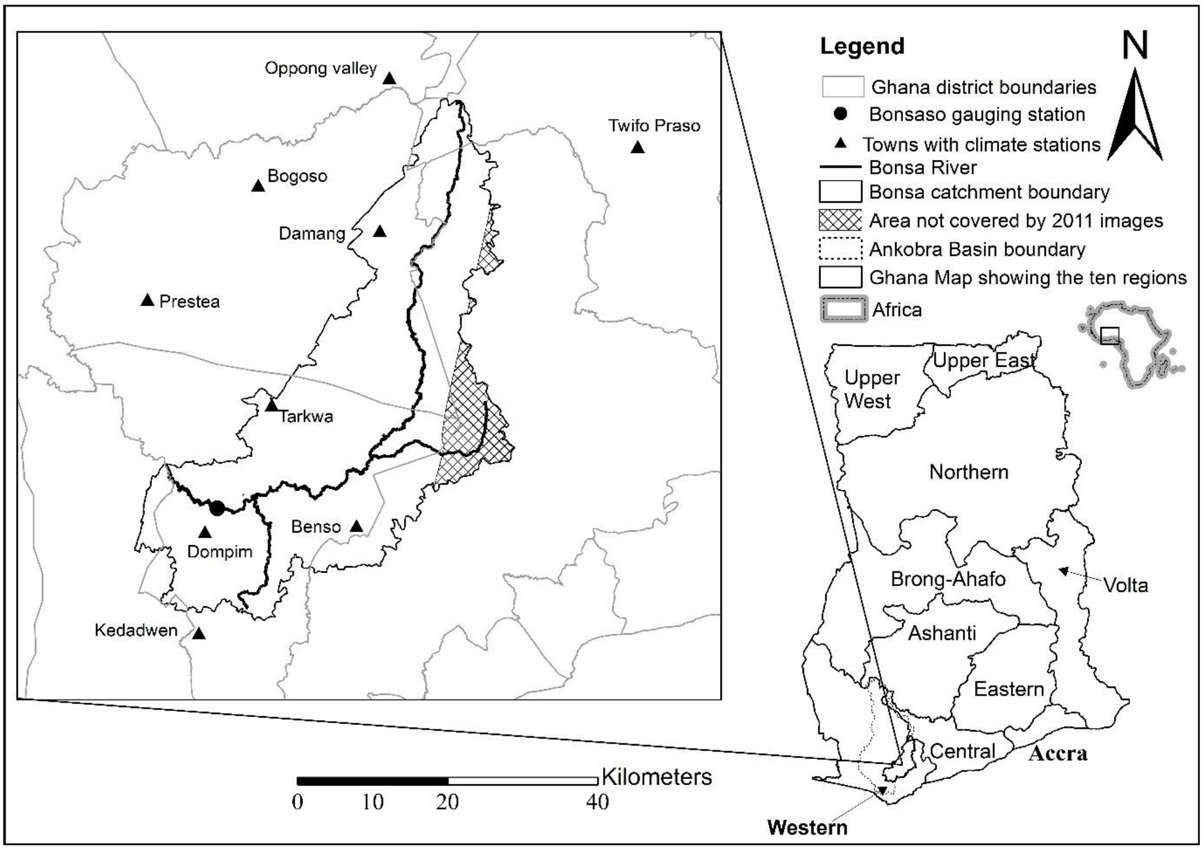

Figure 3.1: Map of Bonsa catchment, a subcatchment of the Ankobra River basin in Ghana, West Africa

3.3.2 Data Acquisition

Data used for the study included two digital topographic maps obtained from the Survey of Ghana (SOG). One of the maps is part of the SOG's 1:50,000[4] series topographic maps produced in 1974 for the whole country, while the other is a 1:5000 topographic and detail map (produced in 2003) covering only the urban area of Tarkwa. Four satellite images covering the period 1986 to 2011 were also acquired from the United States Geological Survey (USGS) and the European Space Agency (ESA) (Table 3.1). In selecting the satellite images, near-anniversary image acquisition dates were selected to minimize seasonal vegetation differences. Fieldwork was conducted between July and August 2013 to collect ground truth data for image classification. The field data collection was based on an

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[4] Number format has been changed compared to published paper

unsupervised classified map of the 2011 satellite images. In order to obtain information on the land cover for the historical images, the local knowledge of the first author and that of some inhabitants of the sites visited, was applied, as well as the SOG topographic map for 2003.

Table 3.1: Satellite images used for the study

Sensor	No. bands	Path/row orbit/frame	No. scenes	Spatial resolution (m)	Acquisition date	Source
Landsat TM/ETM+	7, 8	194/056	3	30, 60	12/1986, 01/1991, 01/2002	USGS
ALOS AVNIR-2	4	26495/3490, 26495/3500	2	10	01/2011	ESA category 1 proposal (Third party mission data)

3.3.3 Image Pre-processing

Errors in mapping land cover/land use changes can be reduced by performing image pre-processing before classification and change detection methods are applied. There are two main types of image pre-processing: geometric and radiometric corrections (Campbell, 2002; Narumalani *et al.*, 2002; Richards and Jia, 2006). The geometric distortions resulting from sensor and platform errors, as well as the rotation of the Earth in relation to the sensor, are corrected by image registration. Geometric correction converts the satellite image geometry to real world coordinate and projection systems (Narumalani *et al.*, 2002; Lu and Weng, 2007), to enable the comparison of two or more images, the extraction of information for use in a Geographic Information System (GIS) and to overlay images with maps from different sources. Radiometric correction, on the other hand, corrects for the effects of the atmosphere on satellite images (Campbell, 2002). The objective of radiometric correction in change detection is to ensure that available images are compared on the basis of similar radiometric properties (Coppin *et al.*, 2004). Image pre-processing in this study consisted of only geometric correction. All the images had been geo-referenced to the UTM WGS84 Zone 30 North projection by the data suppliers, but they did not match with the geo-referenced topographic map of the study area. Hence each of the images was geometrically corrected, using the study area topographic map as a reference.

The high resolution Advanced Visible and Near Infrared Radiometer Type 2 images of the Advanced Land Observation Satellite system (ALOS AVNIR-2) were first geometrically corrected after which the rest of the images were co-registered to them. Haze removal was not executed, because available algorithms distorted the images and reduced their quality. However, haze was not considered problematic since the change detection technique adopted was post-classification comparison, which relies on classified individual images. As the Bonsa catchment was the area of interest for the study, images were clipped, based on the catchment boundary (Figure 3.1).

3.3.4 Image Classification and Accuracy Assessment

Image classification was conducted by generating spectral signatures, using training samples created for each satellite image. The training samples were created by randomly selecting 70% of the sample class data for each satellite image. Six thematic classes were selected to represent the land cover of the Bonsa catchment, using the USGS's land cover classification scheme for Landsat data (Jensen, 2000). The classes used are secondary forests, water, evergreen forests, settlements, shrubs/farms and mining areas (Table 3.2). After creating the spectral signatures, the separability of the thematic classes was checked using the Jefferies-Matusita's matrices (Richards and Jia, 2006), and finally, the MLC algorithm was used to classify all the images using the generated spectral signatures. Since the ALOS AVNIR-2 images covered only 92% of the Bonsa Catchment, a strip of a 2009 SLC-off Landsat image was used to map the remaining (Figure 3.1) and it was merged with the land cover data from ALOS AVNIR-2 images to produce land cover data for 2011. It was observed from a field visit that the study area not covered by the 2011 images was part of a protected forest reserve (evergreen forest area as at January 2014). Hence in the absence of a current satellite image for the area, it was reasonable to map its land cover using the 2009 image, which depicts the area as evergreen forest.

To evaluate the performance of the classification algorithm, accuracies of the land cover/land use maps were assessed by using 30% of the sample class data generated for each satellite image. The accuracy assessment was conducted by creating confusion matrices between the land cover maps and the test data and calculating the overall accuracy, user accuracy, producer accuracy and the Kappa statistic (Congalton, 1991). The Kappa statistic was based on the formula provided by Congalton (1991), as shown in Equation (3.1).

$$K=\frac{N\sum_{i=1}^{r} x_{ii}-\sum_{i=1}^{r}(x_{i+}*x_{+i})}{\mathrm{N}^2-\sum_{i=1}^{r}(x_{i+}*x_{+i})} \qquad (3.1)$$

Where K is the Kappa statistic, N is the total number of observations in the matrix, r is the number of rows, x is the number of observations in row i and column i, x_{+i} and x_{i+} are the marginal totals of row i and column i, respectively.

Table 3.2: Land cover classification nomenclature

Land cover	**Description**	**Photo**
Water	water courses, ponds/flooded mine pits and rivers	
Shrubs/farms	short tree species and non-tree vegetation such as herbs, grasses and farms (cocoa, palm, plantain, cassava, maize), recently cleared forests	
Evergreen forest	tall trees including indigenous species and mature rubber located mostly in forest reserves and plantation farms	
Secondary forest	degraded/re-growth forest and tree crops (cocoa, palm) and rubber with open canopy	
Settlement	urban areas, villages, paved/unpaved roads, car/lorry parks, bare lands, playing fields	
Mining areas	areas where open cast/surface mining has taken place and mining infrastructure (roads, factories, workshops, houses)	

3.3.5 Change Detection

Land cover/land use change was detected using the post-classification comparison method. The land cover maps for 1986, 1991, 2002 and 2011, generated after image classification were reclassified and combined to form multiple bi-temporal land cover change maps for the periods 1986-1991, 1991-2002 and 2002-2011, using GIS spatial analysis. The areas and proportions of change from one thematic class to another (change matrix) between the periods and the annual rates of the changes, were computed to explain the magnitudes and directions of the land cover transitions within the three periods. Finally, the overall deforestation rates were determined, by merging evergreen and secondary forest classes in each period and calculating the proportion of changes per year, between the three periods, using the Food and Agriculture Organisation’s (FAO) definition of forests (FAO, 2010).The change detection in this study is based on the assumption that land cover classes between 1986 and 2011 remained the same.

3.4 Results

The land cover/land use maps generated from image classification for 1986, 1991, 2002 and 2011 are presented in Figure 3.2, while the land cover proportions are shown in Table 3.3. The classification accuracies of the maps ranged between an overall accuracy of 90%, 80%, 88% and 78%, while the Kappa statistic was 87%, 76%, 86% and 73% for the 1986, 1991, 2002 and the 2011 images, respectively. The Kappa statistics achieved in the land cover mapping are acceptable, according to the ranking by Landis and Koch (1977) and they are comparable to results of previous studies in the same study region (Kusimi, 2008; Schueler *et al.*, 2011; Kumi-Boateng *et al.*, 2012) and similar fragmented landscapes in West Africa (Braimoh and Vlek, 2005; Laurin *et al.*, 2013). In Appendix, the confusion matrices, showing how the accuracies were calculated, are presented.

Figure 3.2 and Table 3.3show that the Bonsa catchment is covered by five broad land cover classes: evergreen forest, secondary forest, shrubs/farms, mining areas and settlements. The percentage of the water class, which is mainly water contained in tailings dams, is less than 0.2% of the study area. Overall, the areal coverage of evergreen forest and secondary forest have reduced between 1986 and 2011, while mining areas and settlements have increased substantially. Evergreen forest, the dominant land cover, occupied 68% of the catchment area in 1986, reduced to 62% in 1991, decreased substantially again between 1991 and 2002 (50%), after which it remained relatively constant (51% for 2011). The results for the secondary forest class, however, were not consistent. The area under secondary forest increased from 27% in 1986 to 31% in 1991, 35% in 2002 and decreased again to 19% in 2011(Table 3.3). For the shrubs/farms class, the area increased consistently between 1986 and 2011. In 1986 the area under shrubs/farms was 5% and it increased to 6% in 1991, doubled in 2002 and more than quadrupled in 2011(Table 3.3). For the non-vegetative classes, the areal coverage increased substantially between 1986 and 2011. Settlement areas increased from 0.32% (4.8 km^2) in 1986 to 0.84% (12.4 km^2) in 1991 and remained almost the same for 2002, but increased again in 2011 by 1.5% (22.4 km^2), while mining areas increased from 0.49% (7.2 km^2) in 1986 to 1.63% (24.2 km^2) in 2011(Table 3.3).

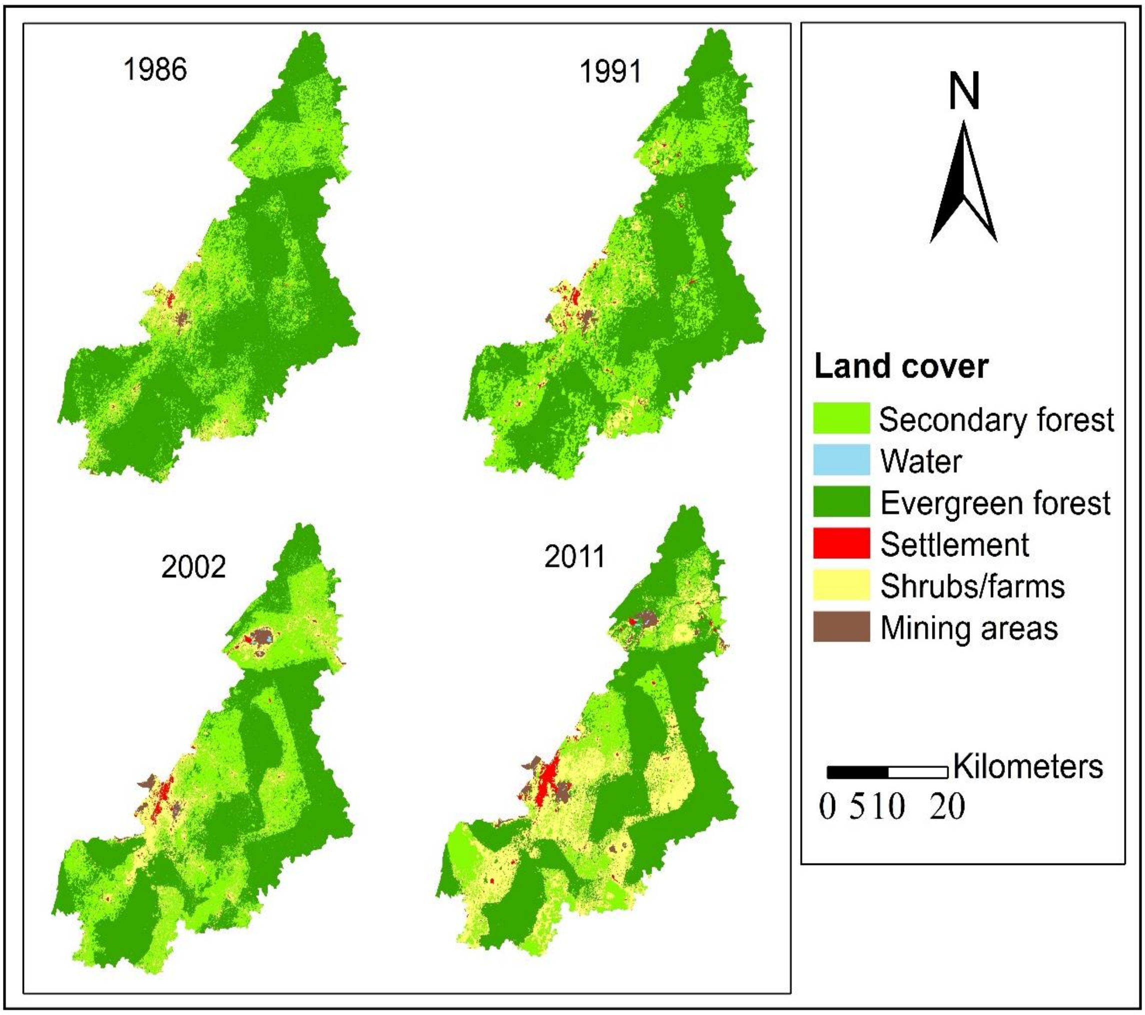

Figure 3.2: Land cover maps of 1986, 1991, 2002 and 2011

Table 3.3: Proportion of land cover between 1986 and 2011

	1986		1991		2002		2011	
Land cover	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%
Secondary forest	393.8	26.6	457.3	30.8	523.7	35.3	280.3	18.9
Water	0.9	0.1	0.2	0.0	1.9	0.1	1.4	0.1
Evergreen forest	1003.2	67.7	916.5	61.8	744.0	50.2	754.6	50.9
Settlement	4.8	0.3	12.4	0.8	12.6	0.8	22.4	1.5
Shrubs/farms	72.4	4.9	90.0	6.1	180.1	12.1	399.4	26.9
Mining areas	7.2	0.5	5.9	0.4	20.1	1.4	24.2	1.6
Total	1482.3	100.0	1482.3	100.0	1482.3	100.0	1482.3	100.0

The change matrices and the annualized rates of changes for 1986, 1991, 2002 and 2011 land cover/land use are presented in Table 3.4 and Figure 3.3, respectively. The change matrix illustrates the change in proportions of land cover from the initial year to the final year. The diagonal elements in the change matrix indicate areas of no change, while the off-diagonals show changes from one class to the other. Therefore, the sum of the diagonal elements represents the total area of land cover that did not change. The annualized rate of change shows the percentage of change in land cover area in a period divided by the number of years between the initial and the final year. Table 3.4illustrates that between 1986 and 1991, 75% (1110 km^2) of the land cover did not change, compared to 67% (998 km^2) between 1991 and 2002 and 63% (933 km^2) between 2002 and 2011.

Table 3.4: Land cover/land use change matrices (%)

(a) 1986-1991

		From 1986					
	Land cover	Secondary forest	Water	Evergreen forest	Settlement	Shrubs/ farms	Mining areas
To 1991	Secondary forest	16.9	0.0	11.7	0.0	2.1	0.1
	Water	0.0	0.0	0.0	0.0	0.0	0.0
	Evergreen forest	6.1	0.0	55.4	0.0	0.3	0.0
	Settlement	0.3	0.0	0.1	0.2	0.2	0.0
	Shrubs/farms	3.2	0.0	0.5	0.1	2.2	0.1
	Mining areas	0.1	0.0	0.0	0.0	0.1	0.2

(b) 1991-2002

		From 1991					
	Land cover	Secondary forest	Water	Evergreen forest	Settlement	Shrubs/ farms	Mining areas
To 2002	Secondary forest	19.1	0.0	13.5	0.2	2.5	0.0
	Water	0.1	0.0	0.0	0.0	0.0	0.0
	Evergreen forest	4.9	0.0	45.1	0.0	0.2	0.0
	Settlement	0.2	0.0	0.0	0.3	0.4	0.0
	Shrubs/farms	6.1	0.0	2.9	0.3	2.6	0.2
	Mining areas	0.5	0.0	0.2	0.1	0.4	0.2

(c) 2002-2011

		From 2002					
	Land cover	Secondary forest	Water	Evergreen forest	Settlement	Shrubs/ farms	Mining areas
To 2011	Secondary forest	12.9	0.0	3.5	0.0	2.4	0.1
	Water	0.0	0.0	0.0	0.0	0.0	0.1
	Evergreen forest	6.5	0.0	42.2	0.0	2.0	0.2
	Settlement	0.1	0.0	0.0	0.6	0.8	0.0
	Shrubs/farms	15.7	0.0	4.5	0.1	6.4	0.2
	Mining areas	0.2	0.1	0.1	0.0	0.5	0.8

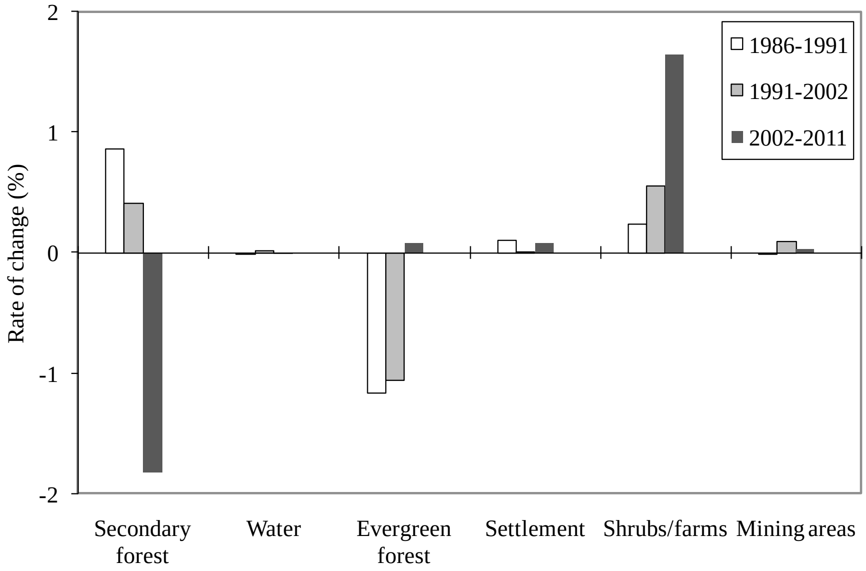

Figure 3.3: **Annual rate of land cover changes**

Table 3.4 further shows that forest thinning from evergreen to secondary[5] was higher between 1986 to 1991 (11.7%) and between 1991 and 2002 (13.5%) than between 2002 and 2011 (3.5%), while transition from secondary forests to shrubs/farms was higher (16%) between 2002 and 2011 than the other periods: i.e 3% between 1986 and 1991 and 6% between 1991 and 2002. The transition from evergreen to secondary forest occurred with an annual rate of reduction of 1.2% between 1986 and 1991 and 1.1% between 1991 and 2002, but during the period 2002-2011, the transition to secondary forest stopped (Figure 3.3). During the period 2002-2011, transition from secondary forest to shrubs/farms occurred, with the highest annual rate (1.8%) of reduction in secondary forest, confirming an overall reduction in secondary forest (Figure 3.3).Using FAO's definition of forests(FAO, 2010), the evergreen and secondary forest areas (Table 3.3) were merged into one class. Therefore, annual deforestation in the Bonsa catchment, defined as the overall conversion of forest areas to other land cover types per year, ranged from 0.3% between 1986 and 1991, 0.7% between 1991 and 2002 and 2% between 2002 and 2011(Table 3.5).

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[5] The phrase "forest thinning from evergreen to secondary" has replaced the phrase "transition from evergreen forest to secondary forest" in the published paper

Table 3.5: Annual deforestation rates for Bonsa catchment

Period	change in area	% change (total change)	% change (annual)
1986-1991	-23.3	-1.7	-0.3
1991-2002	-106.0	-7.7	-0.7
2002-2011	-232.8	-18.4	-2.0

Table 3.4 also demonstrates that forest recovery in the Bonsa catchment occurred from the re-growth of shrubs/farms and secondary forests. The re-growth from secondary forest to evergreen forest was similar for all the periods: i.e 6% between 1986 and 1991, 5% between 1991 and 2002 and 7% between 2002 and 2011. Re-growth from shrubs/farms to secondary forest was also similar for the three periods: i.e 2% between 1986 and 1991, 3% between 1991 and 2002 and 2% between 2002 and 2011. However, the re-growth between 2002 and 2011 is marginally higher than the other two periods.

3.5 Discussion

3.5.1 Land Cover and the Drivers of Changes

The results of the study indicate that deforestation in the Bonsa catchment is widespread, confirming the previous land cover study by Kusimi (2008). The present study shows that between 1986 and 2011, evergreen forest and secondary forest reduced by 25% and 28%, respectively, while mining areas increased over two-fold and settlements and shrubs/farms increased more than three and four-fold, respectively (Table 3.3). The increasing deforestation rate (0.3% per year between 1986 and 1991, 0.7% per year between 1991 and 2002 and 2% per year between 2002 and 2011), recorded in this study(Table 3.5), is consistent with the 2% per year deforestation rate for Ghana, estimated by the FAO (2010), which is also consistent with trends in deforestation in Africa between 1990 and 2000 (1.1 million ha) and between 2000 and 2005 (2.7 million ha) (FAO and JRC, 2012).The results further show that, although the deforestation rate has been increasing with time, more than 50% of the land cover in the Bonsa catchment remained unchanged between 1986 and 2011. Evergreen forest represented the largest stable class (55% between 1986 and 1991, 45% between 1991 and 2002 and 42%

between 2002 and 2011), while secondary forest and shrubs/farm were the most fragmented classes (Table 3.4). The recorded land cover changes indicate that some areas which were originally covered by either evergreen forests or secondary forests have been converted to other cover types, and the recovery of the original vegetation (reforestation) during the three periods is small, compared to the overall deforestation.

The land cover/use changes in the Bonsa catchment can be attributed to anthropogenic drivers, which can be grouped into two broad categories, namely global and local factors. The global factors include globalization of agriculture, urbanization, international trade regimes and global politics, while the local factors include population growth, urbanization, immigration, economic development and government policy (Sage, 1994; Barbier, 2000; Meyfroidt *et al.*, 2013). The recorded deforestation in the Bonsa catchment was influenced by local population growth (Ghana Statistical Service, 2005; Kusimi, 2008; Ghana Statistical Service, 2013), agricultural extensification (Kusimi, 2008; Sutton and Kpentey, 2012), timber logging (Asante, 2005; Kusimi, 2008) and increased surface mining activities (Akabzaa and Darimani, 2001) since 1986, when the implementation of the structural adjustment programme of the World Bank, liberalized Ghana's economy (Barbier, 2000) and increased foreign direct investment in the mining, timber and agricultural industries. Kusimi (2008) provided a discussion on how these driving forces have influenced land use changes within and around the Bonsa catchment.

In addition, population growth and per capita income are the two main drivers of settlement expansion (Sage, 1994). As the number of people in a community increases, there is the need to provide social infrastructure in transportation, housing, sanitation, health, education and recreation, which are mostly built on agricultural or forested lands. Hence, increases in a country's Gross Domestic Product (GDP), which result in higher per capita incomes, coupled with higher population growth rates, can lead to higher urbanization rates. In the Western region of Ghana, where the Bonsa catchment is located, the total urban population increased from 22.6% in 1984 to 42.4% in 2010 (Ghana Statistical Service, 2013) and correlates well with the expansion of settlements, recorded in this study, and is not surprising, considering that Ghana's GDP has increased from \$8 billion in 1984 to \$32 billion in 2010 (Kwakye, 2012). Therefore, for settlements, especially in the Tarkwa urban area, three main drivers namely (i) population growth (both natural growth and immigration), (ii) increase in per capita income and (iii) increases in mining activities, jointly influenced its expansion. According to Kusimi (2008) mining influenced population growth and urbanization by attracting people from other towns and cities in search of mining-based jobs. The expansion of settlements, puts further pressure on the surrounding rural areas to produce more food to feed urban dwellers and more cash crops to pay for the importation of foreign products, which are associated with urban populations (Sage, 1994). The increased demand from urban settlements further causes the conversion of more forested lands into food and cash crop farms, thereby increasing the rates of deforestation. International trade and rising per capita incomes of the developed world and the emerging markets, also reinforces deforestation in the developing world through higher demands for natural resources and commodities (Sage, 1994; Meyfroidt *et al.*, 2013). This phenomenon, which results in volatility in prices of commodities such as, cocoa, rubber and gold, has also influenced deforestation in the Bonsa catchment.

Despite the increasing deforestation rate, the results of the study also indicate that concurrent vegetation regeneration is taking place in the Bonsa catchment. Vegetation regeneration occurred mainly because of programmes implemented by the Forestry Commission of Ghana, as well as some mining companies, maturing of rubber trees and the restrictions placed on the timber industry; banning exportation of round logs (Sutton and Kpentey, 2012) and the criminalization of chainsaw operations. The Forestry Commission of Ghana embarked on reforestation programmes in 2000 to reforest about 4000 km^2 of degraded forests, at a rate of 200 km^2/year (FAO, 2010), but had only replaced 25 km^2/year by 2012 (Sutton and Kpentey, 2012). Mining companies in the Bonsa catchment have also carried out limited reforestation programmes in mined out areas (Tetteh, 2010). However, the results of this study show that, compared to deforestation, vegetation regeneration is less significant in the Bonsa catchment.

Anthropogenic land cover changes are caused by both proximate and global drivers, while the impacts are largely felt at the local scale. Therefore, in addition to mapping and identifying the drivers of the changes, there is also the need to identify the potential impacts of any changes in land use, in order to plan and manage land use effectively. Thus, the remainder of the discussion is focused on identifying the potential impacts of land cover/land use changes and discussing the need for further research.

3.5.2 Potential Impacts of the Land Cover Changes

The impacts of land cover changes can have substantial socio-economic, environmental and health impacts on communities, especially in poor countries. The impacts include change in hydrological regimes, reduced biodiversity, reduced soil organic carbon leading to poor fertility, pollution of surface and groundwater and changes in the albedo and the microclimate (Meyer and Turner II, 1994) and the invasion by alien species. Other impacts include emission of atmospheric trace gases (Penner, 1994), which contribute to climate changes. Impacts on hydrology and water resources are one of the most significant impacts of land cover changes. Land cover changes have impacts on water flows through changes in the partitioning of rainfall into the components of the hydrological cycle (Costa *et al.*, 2003; D'Orgeval and Polcher, 2008). Land cover changes that increases imperviousness, such as surface mining and urbanization for example, reduce infiltration and increase the velocity and volumes of runoff, which can lead to floods, soil erosion and sedimentation, and pollution of rivers. Reduced infiltration can also lead to less groundwater recharge and less baseflows and drying of rivers, during low flow periods (Rogers, 1994; Randolph, 2012). Therefore, in the long-term, as population size and water use in the Bonsa catchment increases, if land cover changes are not controlled, deforestation and urbanization, could further lead to scarcity of water (Rogers, 1994).

Additionally, conversion of more forested lands to agriculture can increase soil erosion and loss of soil fertility, thereby making it more difficult to produce enough food and cash crops to meet the demands of the growing population in Bonsa catchment. Land degradation and the loss of soil fertility has the potential to reinforce more land cover changes through the extensification of agriculture (Barbier, 2000). Since agriculture in the Bonsa catchment is of the low-input type, the only means to increase production will be to increase the area under cultivation, which can further cause changes in land cover. Soil erosion, as well as the use of fertilizers and other chemicals, can also cause pollution of water bodies, destroy aquatic habitats and reduce aquatic biodiversity, if proper agricultural practices are not adopted. The removal of forests, also leads to loss of indigenous plant species, the destruction of animal habitats and reduction in biodiversity of the forest ecosystem. Planting rubber trees and other non-native tree species for example, can reduce groundwater recharge and baseflows significantly, because exotic plants consume more water than the native species.

Apart from deforestation and soil erosion, mining activities in the Bonsa catchment have the potential to cause heavy metal pollution of the water sources and increases in respiratory diseases, caused by dust pollution, resulting from blasting of rocks and movement of heavy duty mining equipment. Akabzaa *et al.* (2009) concluded that heavy metals, such as mercury, copper and nickel of concentrations above World Health Organisation (WHO) maximum allowable limits for drinking water, have been released into streams and groundwater systems by mines within the Ankobra basin. Similarly, Armah *et al.* (2012), concluded that the pH, COD and turbidity levels of groundwater in the Tarkwa mining area are above WHO standards. Further, between 1998 and 2006, eight (8) spillages of cyanide were reported in the Tarkwa area (Tsuma, 2009). Impacts of both urbanization and surface mining also include changes in land surface albedo and the microclimate, which can create urban heat islands (UHI). UHI[6] can result in increased energy consumption of buildings. UHI is a phenomenon that results in higher temperatures in urban areas than the surrounding rural areas (Jensen, 2000), which is due to the presence of less vegetation/heat absorbing surfaces in urban/bare land areas.

According to Klocking and Haberlandt (2002), it is difficult to draw generalised, quantitative conclusions about impacts of land cover/use changes, without a specific local study. For example, Mahe *et al.* (2005), Boulain *et al.* (2009) and Warburton *et al.* (2012) among others, showed that the hydrological responses to land cover changes, depend on the scale of the changes, the land cover type, the climate and the location of the changes within a catchment. It is therefore imperative that locally relevant studies, consistent with the objectives of planning and development, within a specific basin, are undertaken.

3.5.3 Further Research

The population of people living in urban areas around the world is expected to grow from 3.15 billion in 2008 to 7.2 billion by 2050 (Randolph, 2012). The population pressure will make it difficult to provide services to people living in urban areas and many people in the developing world will not have access to portable water, sanitation and safe living environments, as urbanization increases. It is estimated that half of the people living in the

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[6] The phrase“cause skin cancer” has been removed from document, compared to the published paper.

developing world lack access to these services already (Randolph, 2012). The increasing rate of deforestation in Africa (FAO and JRC, 2012) for example, will have negative impacts on the livelihoods of people, who primarily depend on the natural resources for their development, while the goods and services provided by the natural environment will be reduced. The need to therefore plan and manage land use and water resources effectively in Africa and the rest of the developing world cannot be overemphasized.

In addition to the current land cover/land use changes, in the near future, the population of the Bonsa catchment in Ghana, is expected to grow at an average of 2% per annum (Ghana Statistical Service, 2005), mining activities will be intensified, as more mining leases are approved (Figure 3.4). Urbanization will also increase, as a result of both natural population increase and immigration to mining towns, and deforestation will increase. Therefore, in order to carryout effective land use planning, the impacts of both the current and the potential future land cover changes need to be quantified. Unfortunately, few studies of this type have been carried out and of these studies, all focus on impacts of surface mining on either groundwater pollution or surface water pollution (Kortatsi, 2003; Akabzaa *et al.*, 2009; Armah *et al.*, 2012), and airborne particulate matter pollution (Bansah and Amegbey, 2012). Although previous studies have mapped land cover changes between 1986 and 2002 of different sections of the catchment (Kusimi, 2008; Schueler *et al.*, 2011; Kumi-Boateng *et al.*, 2012), none assessed the impacts on the environment. The land cover change impacts on the hydrological flows, biodiversity and soil fertility are not known. Quantifying these impacts will provide the necessary information to protect life and property, protect the environment and ensure sustainable utilization of the natural resources of the catchment. In evaluating the impacts, the derived land cover information, as well as projected changes in the land cover, will be key variables. The potential drivers, identified in this study, will be vital in projecting future changes in the land cover. Therefore, further research will need to focus on modelling future changes in the land cover and quantification of the impacts of both historical and potential future changes in land cover on hydrology of Bonsa catchment. Additionally, future research will need to assess the impacts of climate change and land cover changes jointly.

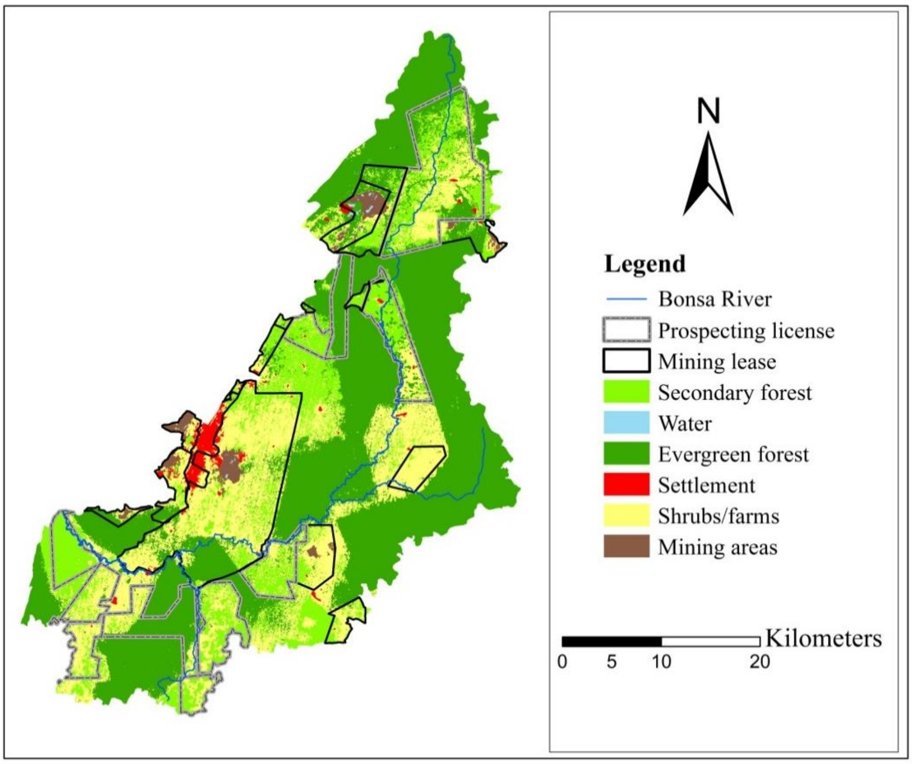

Figure 3.4: **Land cover (2011) and approved mining leases and prospecting licenses in the Bonsa catchment. Adapted from (Bourke *et al.*, 2007; Gold Fields Limited, 2012b, a; Castle Peak Mining Ltd, 2013)**

3.6 Conclusion

Land cover mapping and change detection for the Bonsa catchment was executed successfully with Kappa statistics ranging between 72 and 87%, using the maximum likelihood classification algorithm. The study has generated multi-temporal land cover data from 1986 to 2011, which shows that the Bonsa catchment is predominantly covered by forests, which are currently reducing at the rate of 2% per year, implying that the ongoing re-afforestation programmes undertaken by stakeholders in the catchment is occurring at a lower rate, compared to the deforestation. The study further indicates that the potential drivers of the land cover changes are both local and global, which include international trade, local population growth, agriculture extensification and urbanization. The study highlights the value of a multi-temporal land cover mapping approach to provide data to guide effective land use planning and water resources management, especially in data poor regions.

3.7 Acknowledgement

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3.8 References

Abuelgasim, AA, Ross, WD, Gopal, S and Woodcock, CE. 1999. Change Detection Using Adaptive Fuzzy Neural Networks: Environmental Damage Assessment after the Gulf War. *Remote Sensing of Environment* 70(2)**:**208-223.

Aduah, MS and Aabeyir, R. 2012. Land Cover Dynamics in Wa Municipality, Upper West Region of Ghana. *Research Journal of Environmental and Earth Sciences* 4(6)**:**658-664.

Akabzaa, T and Darimani, D. 2001. Impact of Mining Sector Investment in Ghana: A Study of the Tarkwa Mining Region - draft report, . SAPRIN.

Akabzaa, TM, Jamieson, HE, Jorgenson, N and Nyame, K. 2009. The Combined Impact of Mine Drainage in the Ankobra River Basin, SW Ghana. *Mine Water and the Environment* 28(1)**:**50-64.

Armah, FA, Luginaah, I and Ason, B. 2012. Water Quality Index in the Tarkwa Gold Mining Area in Ghana. *The Journal of Transdisciplinary Environmental Studies (TES)* 11(2)**:**1-15.

Asante, MS. 2005. *Deforestation in Ghana: Explainining the chronic failure of forest preservation policies in a developing Country,* University Press of America,Maryland, USA.

Atkinson, PM and Tatnall, ARL. 1997. Introduction Neural networks in remote sensing. *International Journal of Remote Sensing* 18(4)**:**699-709.

Bansah, KJ and Amegbey, N. 2012. Ambient Particulate Matter Monitoring - A Case Study at Tarkwa. *Research Journal of Environmental and Earth Sciences* 4(4)**:**419-423.

Barbier, EB. 2000. Links between economic liberalization and rural resource degradation in the developing regions. *Agricultural Economics* 23(3)**:**299-310.

Boulain, N, Cappelaere, B, Séguis, L, Favreau, G and Gignoux, J. 2009. Water balance and vegetation change in the Sahel: A case study at the watershed scale with an eco-hydrological model. *Journal of Arid Environments* 73(12)**:**1125-1135.

Bourke, P, Arthur, J, Marshall, N, MacIntyre, J, Wasel, SM and Urbaez, E. 2007. Technical Report, First time disclosure of mineral reserves, Hwini-Butre and Benso properties, Southwest Ghana. Golden Star Resources Ltd, Denver, Colorado, USA.

Braimoh, AK and Vlek, PLG. 2004. Land-Cover Change Analyses in the Volta Basin of Ghana. *Earth Interactions* 8(21)**:**1-17.

Braimoh, AK and Vlek, PLG. 2005. Land-cover change trajectories in Northern Ghana. *Environmental Management* 36(3)**:**356-373.

Campbell, JB. 2002. *Introduction to Remote Sensing,* Taylor and Francis,London, United Kingdom.

Castle Peak Mining Ltd. 2013. Strategic Gold Project in Ghana's Ashanti Belt, Apankrah Deposit Next Steps[Online]. Castle Peak Mining Ltd. Vancouver, BC, Canada: Available:http://edg1.precisionir.com/companyspotlight/NA019419/CAP-Presentation_Nov2013.pdf [Accessed 9th April 2014].

Cohen, B. 2004. Urban Growth in Developing Countries: A Review of Current Trends and a Caution Regarding Existing Forecasts. *World Development* 32(1)**:**23-51.

Congalton, RG. 1991. A review of Assessing the Accuracy of Classification of Remotely Sensed Data. *Remote Sensing of Environment* 37(1991)**:**35-46.

Coppin, P, Jonckheere, I, Nackaerts, K, Muys, B and Lambin, E. 2004. Digital change detection methods in ecosystem monitoring: a review. *International Journal of Remote Sensing* 25(9)**:**1565-1596.

Costa, MH, Botta, A and Cardille, JA. 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. *Journal of Hydrology* 283(1–4)**:**206-217.

D'Orgeval, T and Polcher, J. 2008. Impacts of precipitation events and land-use changes on West African river discharges during the years 1951-2000. *Climate Dynamics* 31(2-3)**:**249-262.

Dwomo, O and Dedzoe, CD. 2010. Oxisol (ferralsol) development in two agro-ecological zones of Ghana: A preliminary evaluation of some profiles. *Journal of Science and Technology, Kwame Nkrumah University of Science and Technology (KNUST)* 30(2)**:**11-28.

FAO. 2010. Global Forest Resources Assessment 2010, Country Report, Ghana. *In:* Affum-Baffoe, K (ed.). Food and Agricultural Organisation (FAO), Rome, Italy.

FAO and JRC. 2012. Global forest land - use change 1990 - 2005. *In:* Lindquist, EJ, D'annunzio, R, Gerrand, A, Macdicken, K, Achard, F, Beuchle, R, Brink, A, Eva, HD, Mayaux, P, San-Miguel-Ayanz, J and Stibig, H-J (eds.) *FAO Forestry Paper No. 169.* Food and Agriculture Organization of the United Nations and European Commission Joint Research Centre, Rome, FAO.

Foody, GM. 2002. Status of land cover classification accuracy assessment. *Remote Sensing of Environment* 80(2002)**:**185-201.

Frazier, AE and Wang, L. 2011. Characterizing spatial patterns of invasive species using sub-pixel classifications. *Remote Sensing of Environment* 115(8)**:**1997-2007.

Geneletti, D and Gorte, BGH. 2003. A method for object-oriented land cover classification combining Landsat TM data and aerial photographs. *International Journal of Remote Sensing* 24(6)**:**1273-1286.

Ghana Statistical Service. 2005. 2000 Population and Housing Census, Analysis of District Data and implications for Planning, Western Region, Ghana. *In:* Twum-Baah, KA, Kumekpor, TKB and Addae-Mensah, I (eds.). Ghana Statistical Service, Accra, Ghana.

Ghana Statistical Service. 2013. 2010 Population & housing census, National analytical report. *In:* Awusabo-Asare, K (ed.). Ghana Statistical Service, Accra, Ghana.

Gold Fields Limited. 2012a. Damang Gold Mine, Technical Short Form Report. Gold Fields Limited, South Africa.

Gold Fields Limited. 2012b. Tarkwa Gold Mine, Technical Short Form Report. Gold Fields Limited, South Africa.

Hu, Q, Willson, GD, Chen, X and Akyuz, A. 2005. Effects of climate and landcover change on stream discharge in the Ozark Highlands, USA. *Environmental Modeling & Assessment* 10(1)**:**9-19.

Huang, C, Davis, LS and Townshend, JRG. 2002. An assessment of support vector machines for land cover classification. *International Journal of Remote Sensing* 23(4)**:**725-749.

Jensen, JR. 2000. *Remote Sensing of the Environment: an Earth Resource Perspective*, Prentice-Hall,New Jersey, USA.

Klocking, B and Haberlandt, U. 2002. Impact of land use changes on water dynamics-a case study in temperate meso and macroscale river basins. *Physics and Chemistry of the Earth* 27(9-10)**:**619-629.

Kortatsi, BK. 2003. Acidifcation of Groundwater and its Implication on Rural Water Supply in the Ankobra Basin, Ghana. *West African Journal of Applied Ecology* 4(2003)**:**35-47.

Kumi-Boateng, B, Mireku-Gyimah, D and Duker, AA. 2012. A Spatio-Temporal Based Estimation of Vegetation Changes in the Tarkwa Mining Area of Ghana. *Research Journal of Environmental and Earth Sciences* 4(3)**:**215-229.

Kusimi, JM. 2008. Assessing land use and land cover change in the Wassa West District of Ghana using remote sensing. *GeoJournal* 71(2008)**:**249-259.

Kwakye, JK. 2012. Ghana’s middle-income reality check part I: The economic dimension. The Institute of Economic Affairs (IEA), Accra, Ghana.

Lambin, EF and Ehrlich, D. 1997. Land-cover changes in sub-Saharan Africa (1982-1991): Application of a change index based on remotely sensed surface temperature and vegetation indices at a continental scale. *Remote Sensing of Environment* 61(2)**:**181-200.

Lambin, EF, Geist, HJ and Lepers, E. 2003. Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources* 28(2003)**:**205-241.

Landis, JR and Koch, GG. 1977. The measurement of observer agreement for categorical data. *Biometrics* 33(1)**:**159-174.

Laurin, GV, Liesenberg, V, Chen, Q, Guerriero, L, Del Frate, F, Bartolini, A, Coomes, D, Wilebore, B, Lindsell, J and Valentini, R. 2013. Optical and SAR sensor synergies for forest and land cover mapping in a tropical site in West Africa. *International Journal of Applied Earth Observation and Geoinformation* 21(2013)**:**7-16.

Lu, D, Mausel, P, Brondizio, E and Moran, E. 2004. Change Detection Techniques. *International Journal of Remote Sensing,* 25(12)**:**2365 - 2407.

Lu, D and Weng, Q. 2007. A survey of image classification methods and techniques for improving classification performance. *International Journal of Remote Sensing* 28(5)**:**823-870.

Mahe, G, Paturel, JE, Servat, E, Conway, D and Dezetter, A. 2005. The impact of land use change on soil water holding capacity and river flow modelling in the Nakambe River, Burkina-Faso. *Journal of Hydrology* 300(1-4)**:**33-43.

Meyer, WB and Turner II, BL. 1994. *Changes in Land Use and Land Cover: A Global Perspective,* Cambridge University Press,Cambridge, United Kingdom.

Meyfroidt, P, Lambin, EF, Erb, K-H and Hertel, TW. 2013. Globalization of land use: distant drivers of land change and geographic displacement of land use. *Current Opinion in Environmental Sustainability* 5(5)**:**438-444.

Narumalani, S, Hlady, JT and Jensen, JR. 2002. Information extraction from remotely sensed data *In:* Bossler, JD, Campbell, JB, Mcmaster, RB and Rizos, C (eds.) *Manual of Geospatial Science and Technology.* First Edition ed. Taylor and Francis, London, United Kingdom.

Nichol, JE, Wong, MS, Corlett, R and Nichol, DW. 2010. Assessing avian habitat fragmentation in urban areas of Hong Kong (Kowloon) at high spatial resolution using spectral unmixing. *Landscape and Urban Planning* 95(1–2)**:**54-60.

Penner, JE. 1994. Atmospheric Chemistry and Air Quality. *In:* Meyer, WB and Turner Ii, BL (eds.) *Changes in Land Use and Land Cover: A Global Perspective.* Cambridge University Press, Cambridge, United Kingdom.

Platt, RV and Rapoza, L. 2008. An evaluation of an object-oriented paradigm for land use/land cover classification. *Professional Geographer* 60(1)**:**87-100.

Randolph, J. 2012. *Environmental Land Use Planning and Management,* Island Press,Washington, USA.

Richards, JA and Jia, X. 2006. *Remote Sensing Digital Image Analysis, An Introduction,* Springer,Berlin Heidelberg, Germany.

Rogers, P. 1994. Hydrology and Water Quality. *In:* Meyer, WB and Turner Ii, BL (eds.) *Changes in Land Use and Land Cover: A Global Perspective.* Cambridge University Press, Cambridge, United Kingdom.

Sage, C. 1994. Population and Income. *In:* Meyer, WB and Turner Ii, BL (eds.) *Changes in Land Use and Land Cover: A Global Perspective.* Cambridge University Press, Cambridge, United Kingdom.

Schueler, V, Kuemmerle, T and Schroeder, H. 2011. Impacts of Surface Gold Mining on Land Use Systems in Western Ghana. *Ambio* 40(5)**:**528-539.

Song, C, Woodcock, CE, Seto, KC, Lenney, MP and Macomber, SA. 2001. Classification and Change Detection Using Landsat TM Data: When and How to Correct Atmospheric Effects? *Remote Sensing of Environment* 75(2)**:**230-244.

Stavrakoudis, DG, Theocharis, JB and Zalidis, GC. 2011. A multistage genetic fuzzy classifier for land cover classification from satellite imagery. *Soft Computing* 15(12)**:**2355-2374.

Suresh Babu, V and Viswanath, P. 2009. Rough-fuzzy weighted k-nearest leader classifier for large datasets. *Pattern Recognition* 42(9)**:**1719-1731.

Sutton, J and Kpentey, B. 2012. *An enterprise map of Ghana,* International Growth Centre,London, United Kingdom.

Tetteh, EN. 2010. Evaluation of land reclamation practices at Anglogold Ashanti, Iduapriem mine Ltd, Tarkwa. Unpublished MSc Thesis, Department of Agroforestry, Faculty of Renewable Natural Resources, Kwame Nkrumah University of science and technology, Kumasi,Ghana.

Tsuma, W. 2009. *Gold Mining in Ghana, Actors, Alliances and Power,* LIT Verlag,Berlin, Germany.

Van Coillie, FMB, Verbeke, LPC and De Wulf, RR. 2007. Feature selection by genetic algorithms in object-based classification of IKONOS imagery for forest mapping in Flanders, Belgium. *Remote Sensing of Environment* 110(4)**:**476-487.

Verhoeye, J and De Wulf, R. 2002. Land cover mapping at sub-pixel scales using linear optimization techniques. *Remote Sensing of Environment* 79(1)**:**96-104.

Warburton, ML, Schulze, RE and Jewitt, GPW. 2012. Hydrological impacts of land use change in three diverse South African catchments. *Journal of Hydrology* 414-415(2012)**:**118-135.

Wasige, JE, Groen, TA, Smaling, E and Jetten, V. 2013. Monitoring basin-scale land cover changes in Kagera Basin of Lake Victoria using ancillary data and remote sensing. *International Journal of Applied Earth Observation and Geoinformation* 21(2013)**:**32-42.

Youngentob, KN, Roberts, DA, Held, AA, Dennison, PE, Jia, X and Lindenmayer, DB. 2011. Mapping two Eucalyptus subgenera using multiple endmember spectral mixture analysis and continuum-removed imaging spectrometry data. *Remote Sensing of Environment* 115(5)**:**1115-1128.

3.9 Appendix

Appendix 4.A: Confusion Matrix for 1986 land cover map

Reference Data (No. of points)

	Land cover	Secondary forest	Water	Evergreen forest	Settlement	Shrubs/ farms	Mining area	Total
1986 Land cover map	Secondary forest	32	0	1	0	0	0	**33**
	Water	0	29	0	0	0	0	**29**
	Evergreen forest	2	0	52	0	0	0	**54**
	Settlement	0	0	0	35	2	8	**45**
	Shrubs/farms	1	0	0	1	33	2	**37**
	Mining area	2	0	0	4	1	27	**34**
	Total	**37**	**29**	**53**	**40**	**36**	**37**	**232**

Overall accuracy = 208/232 *100% = 89.66%

kappa= 87.49%

Land cover	Producer's accuracy (%)		User's accuracy (%)	
Secondary forest	32/37=	86.49	32/33=	96.97
Water	29/29=	100.00	29/29=	100.00
Evergreen forest	52/53=	98.11	52/54=	96.30
Settlement	35/40=	87.50	35/45=	77.78
Shrubs/farms	33/36=	91.67	33/37=	89.19
Mining area	27/37=	72.97	27/37=	79.41

Appendix 4.B: Confusion Matrix for 1991 land cover map

Reference Data (No. of points)

	Land cover	Secondary forest	Water	Evergreen forest	Settlement	Shrubs/ farms	Mining area	Total
1991 Land cover map	Secondary forest	26	0	2	0	0	0	**28**
	Water	0	27	0	0	0	1	**28**
	Evergreen forest	3	3	62	0	0	0	**68**
	Settlement	0	0	0	57	4	2	**63**
	Shrubs/farms	17	0	0	0	26	0	**43**
	Mining area	0	4	0	24	0	48	**76**
	Total	**46**	**34**	**64**	**81**	**30**	**51**	**306**

Overall accuracy = 246/306*100%= 80.39%

kappa =76.09%

Land cover	Producer's accuracy (%)		User's accuracy (%)	
Secondary forest	26/46=	56.52	26/28=	92.86
Water	27/34=	79.41	27/28=	96.43
Evergreen forest	62/64=	96.88	62/68=	91.18
Settlement	57/81=	70.37	57/63=	90.48
Shrubs/farms	26/30=	86.67	26/43=	60.47
Mining area	48/51=	94.12	48/76=	63.16

Appendix 4.C: Confusion Matrix for 2002 land cover map

Reference Data (No. of points)

	Land cover	Secondary forest	Water	Evergreen forest	Settlement	Shrubs/ farms	Mining area	Total
2002 Land cover map	Secondary forest	64	0	1	0	0	0	**65**
	Water	0	51	0	0	0	0	**51**
	Evergreen forest	11	1	61	0	0	0	**73**
	Settlement	0	0	0	70	1	6	**77**
	Shrubs/farms	19	0	0	0	46	0	**65**
	Mining area	0	3	0	2	5	73	**83**
	Total	**94**	**55**	**62**	**72**	**52**	**79**	414

Overall accuracy =
365/414*100% = 88.16%

kappa = 85.76%

Land cover	Producer's accuracy (%)		User's accuracy (%)	
Secondary forest	64/94=	68.09	64/65=	98.46
Water	51/55=	92.73	51/51=	100.00
Evergreen forest	61/62=	98.39	61/73=	83.56
Settlement	70/72=	97.22	70/77=	90.91
Shrubs/farms	46/52=	88.46	46/65=	70.77
Mining area	73/79=	92.41	73/83=	87.95

Appendix 4.D: Confusion Matrix for 2011 land cover map

Reference Data (No. of points)

	Land cover	Secondary forest	Water	Evergreen forest	Settlement	Shrubs/ farms	Mining area	Total
2011 Land cover map	Secondary forest	44	0	0	0	2	0	**46**
	Water	0	36	0	4	0	0	**40**
	Evergreen forest	6	0	34	0	12	0	**52**
	Settlement	0	1	2	36	1	6	**46**
	Shrubs/farms	26	0	1	0	67	0	**94**
	Mining area	0	9	0	7	0	50	**66**
	Total	**76**	**46**	**37**	**47**	**82**	**56**	**344**

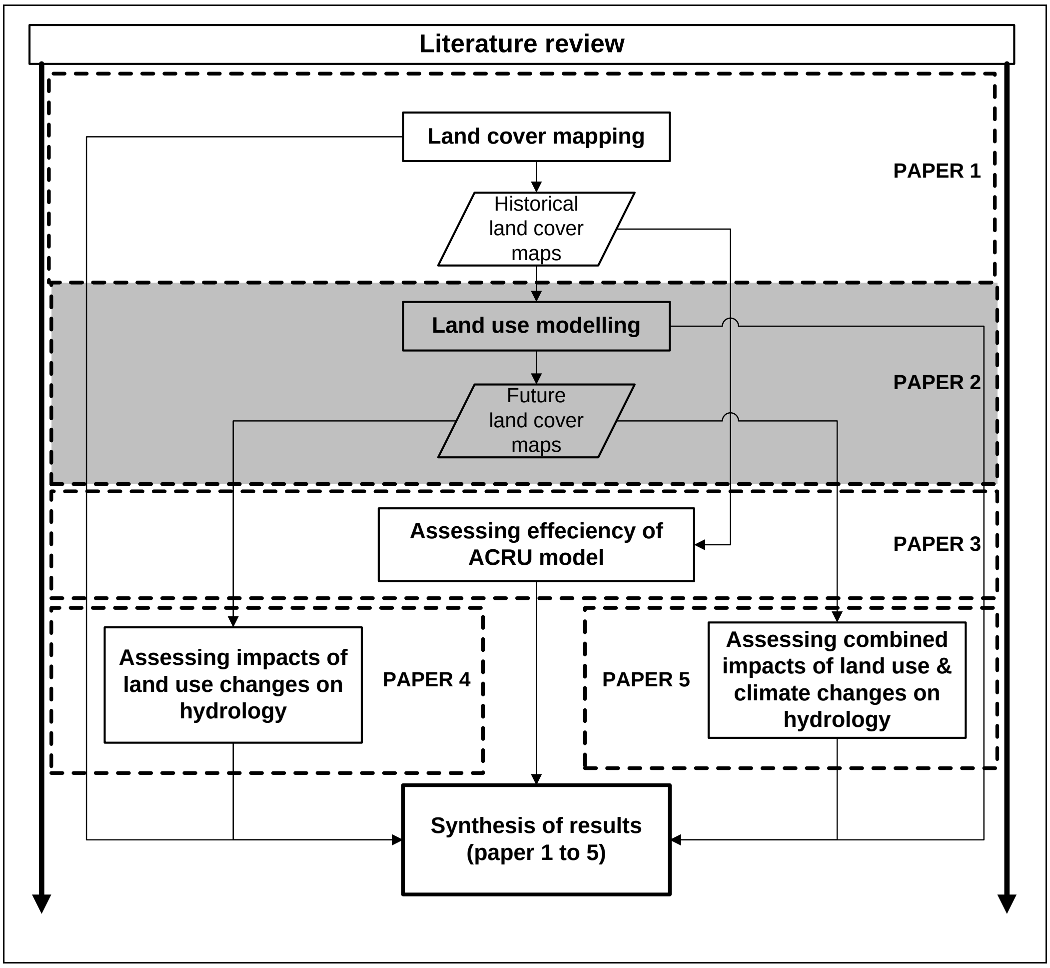
Overall accuracy =
267/344 *100% = 77.62 %

kappa = 72.84%

Land cover	Producer's accuracy (%)		User's accuracy (%)	
Secondary forest	44/77=	57.89	44/46=	95.65
Water	36/46=	78.26	36/40=	90.00
Evergreen forest	34/37=	91.89	34/52=	65.38
Settlement	36/47=	76.60	36/46=	78.26
Shrubs/farms	67/82=	81.71	67/94=	71.28
Mining area	50/56=	89.29	50/66=	75.76

Preface to Chapter 4

With increasing population and changing economic structures worldwide, it is expected that West African countries will continue to witness extensive land use changes in the near future and these changes, as is the case with current and historical changes will have significant impacts on water resources and the environment across scales. However, the only way to determine the potential future impacts of land use changes is to determine the future land use, which is the main objective of Chapter 4 (as shown in shaded region in figure below). The determination of future land use also requires current and historical land use and the understanding of the potential drivers (information obtained from Chapter 1 above).



CHAPTER 4 : MODELLING LAND USE CHANGES IN THE BONSA CATCHMENT, ANKOBRA BASIN, GHANA[7]

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4.1 Abstract

The Bonsa catchment in the Ankobra basin of Ghana, West Africa, has undergone significant deforestation and urbanisation since the 1980s. Identifying the significant drivers and understanding the process of change is vital for effective land use planning and environmental management. In this study, logistic regression, Markov chain and the Dyna-CLUE models were combined to simulate historical and future land use patterns to produce information for land use planning and academic purposes. The historical model validation produced relative operating characteristics (ROC) statistics above 0.69; indicating a significant relationship between the driving factors and the land cover types, and a Kappa statistic of 54%, indicating a moderate agreement between observed and simulated land use. The statistics of the historical model were used to simulate three plausible future land use scenarios, for the period 2012 to 2070. The historical simulation revealed that increases in population density, proximity to roads and expansion of mines were the major drivers that significantly increased the probability of settlement expansion and deforestation. Model simulations of future land use showed that settlement expansion and deforestation increased by similar margins for all scenarios, but the increase in secondary forests was higher for the economic growth and reforestation (EGR) scenario, compared to the economic growth (EG) and the business-as-

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[7] Aduah, MS, Warburton Toucher, ML and Jewitt, GPW. (submitted). Modelling land use changes in the Bonsa catchment, Ankobra Basin, Ghana. *Land Use Policy.*

usual (BAU) scenarios. The mining areas more than doubled between 2012 and 2070 for all the scenarios, while shrubs/farms increased in the BAU scenario, but reduced marginally in the EG and the EGR scenarios. The results of this study can be used to infill historical data gaps, support effective land use planning and provide a means to evaluate the impacts of different future development pathways.

Key words: Bonsa catchment, deforestation, driving factors, land use, Dyna-CLUE.

4.2 Introduction

A country's land cover/land use patterns over a period of time are determined by demographic, economic and environmental driving factors (Verburg *et al.*, 1999; Castella *et al.*, 2007) both at a national and global scale. An understanding of the patterns and the processes of land cover/land use changes is vital for effective land use planning (Dietzel and Clarke, 2006; Kamusoko *et al.*, 2009) and sustainable natural resources management (Castella *et al.*, 2007). In Sub-Saharan African countries, such as Ghana, the majority of economic activities are centred on the exploitation of natural resources, which has resulted in rapid degradation of the natural environment over the past several decades. The Gross Domestic Product (GDP) of Ghana increased from $8 billion in 1984 to $32 in 2010 (Kwakye, 2012). The increase in GDP has mainly resulted from growth in mining, oil and the agriculture sectors, including cocoa, tuber and fruit production, which have caused substantial land cover changes in Ghana.

Although several land use mapping (Braimoh and Vlek, 2004; Kusimi, 2008; Attua and Fisher, 2010; FAO, 2010b; Ruelland *et al.*, 2010; Aduah and Aabeyir, 2012; Laurin *et al.*, 2013; Aduah *et al.*, 2015) and a few land use modelling studies (Mertens and Lambin, 2000; Braimoh and Vlek, 2005; Judex *et al.*, 2006; Houessou *et al.*, 2013) have been conducted in West Africa; in Ghana there is still a considerable knowledge gap on land use change processes, patterns and their driving forces at the local scale. In Ghana, only one study (Braimoh and Vlek, 2005) has attempted a quantitative explanation of the land use change processes in relation to their driving forces for the northern savannah ecological zones. To the best of our knowledge, there is a lack of deeper understanding of the land use change processes in the rainforest regions of Ghana. Studies in rainforest regions of Ghana have mainly quantified the land use changes (Attua and Fisher, 2010; Schueler *et al.*, 2011; Aduah *et al.*, 2015), none attempted to gain a quantitative and deeper understanding of the processes of changes in relation to their driving forces. Several case studies worldwide (Verburg and Veldkamp, 2004; Judex *et al.*, 2006; Kamusoko *et al.*, 2009; Verburg and Overmars, 2009; Vermeiren *et al.*, 2012), show that there is a potential for a deeper understanding of the land use change processes in relation to their driving forces at the local scale, through spatially distributed land use modelling, using easily accessible data.

Land cover/use models provide a means to generate multi-temporal land cover maps from which the dynamism in land cover can be ascertained. During the past three decades, models have been used to establish quantitative relationships between land cover changes and their driving factors, in order to generate an understanding of the change processes and to simulate dynamic land cover/land use (Verburg *et al.*, 1999; Hu and Lo, 2007), which can be used for the assessment of impacts of either future changes or impacts of different scenarios of changes (Robinson *et al.*, 1994; Dietzel and Clarke, 2006). The application of dynamic land cover/land use in impact studies ensure that extreme and unrealistic assumptions of land use changes, such as complete deforestation, re-forestation or urbanization, which are common in impact and scenario studies (Legesse *et al.*, 2010; Moradkhani *et al.*, 2010; Mango *et al.*, 2011), are avoided. Land use models also contribute to effective planning by allowing the evaluation of different development scenarios (Dietzel and Clarke, 2006; Vermeiren *et al.*, 2012). This is especially important for data scarce regions, such as the Bonsa catchment in Ghana, where there is limited satellite images and aerial photographs, to derive land cover maps at regular time intervals.

Land cover models can be classified as stochastic or deterministic (Park *et al.*, 2011b). The stochastic models include Markov Chains (MC), logistic regression (LR) and Cellular Automata (CA), while the deterministic models include Agent Based Models (ABM) (Dietzel and Clarke, 2006; Matthews *et al.*, 2007; Bakker and van Doorn, 2009; Le *et al.*, 2012) and models based on Geographical Information Systems (GIS). Though stochastic models incorporate biophysical, demographic and economic driving factors to simulate land use changes, they have difficulty in incorporating agents (Bakker and van Doorn, 2009; Arsanjani *et al.*, 2013). Agents include factors that are based on human decisions and activities. Purely statistical models also have a limitation in terms of dynamic modelling of the competition between different land uses (Verburg *et al.*, 2002; Dietzel and Clarke, 2006).

The Dynamic Conversion of Land Use and its Effects (Dyna-CLUE) model, however, combines features of both deterministic and stochastic modelling, as well as estimation of land use demands, based on a Markov chain or any other appropriate technique (Verburg *et al.*, 1999; Verburg *et al.*, 2002; Verburg and Veldkamp, 2004; Verburg and Overmars, 2009; Chu *et al.*, 2010; Park *et al.*, 2011a; Hu *et al.*, 2013). The advantage of using the CLUE family of models is that they can model the dynamic competition between multiple land use types (Verburg *et al.*, 1999; Verburg *et al.*, 2002; Verburg and Veldkamp, 2004; Verburg and Overmars, 2009). Other models such as the SLEUTH (Dietzel and Clarke, 2007),'SimAmazonia'(Soares-Filho *et al.*, 2006), Fore-SCE (Sohl *et al.*, 2007) and LTM (Pijanowski *et al.*, 2006) use integrated modelling as well. However, SLEUTH and LTM were developed for urban simulations, while 'SimAmazonia' was developed for deforestation modelling in the Amazon basin and Fore-SCE was developed for the great plains of the United States. Additionally, although ABM models account for human actors and their interactions on the environment (Parker *et al.*, 2003; Dietzel and Clarke, 2006), they are complex (Bakker and van Doorn, 2009) and they require extensive datasets (Park *et al.*, 2011b), which are not available for data scarce catchments.

This study aims to extend the knowledge on spatial patterns of land use changes in relation to their driving forces in West Africa, by conducting an empirical spatially distributed land use modelling, using the Bonsa catchment in southern Ghana as a study site and it builds on a previous land use change analysis study by Aduah *et al.* (2015). The Bonsa catchment is one of the forested catchments in Ghana, which has undergone significant land cover changes in the past three decades (Aduah *et al.*, 2015), following the liberalization of Ghana's economy. The potential impacts of the rapid land cover changes, have substantial negative socio-economic, environmental and health impacts on the communities in the catchment. Studies have shown that over the years, both surface and groundwater quality in the catchment has decreased (Akabzaa and Darimani, 2001; Kortatsi, 2003; Akabzaa *et al.*, 2009; Armah *et al.*, 2012), while air pollution by airborne particulates from surface mines is increasing (Akabzaa and Darimani, 2001; Bansah and Amegbey, 2012). However, a deeper understanding of the quantitative relationships between the land cover types and their socio-economic and biophysical driving forces, which is necessary for effective land use planning, is non-existent in the Bonsa catchment. This study was therefore specifically conducted to determine the significant driving forces of land use changes and to simulate land use maps for historical, as well as future time slices for the Bonsa catchment, using logistic regression, Markov chain and the Dyna-CLUE models. The future land use maps were based on three plausible scenarios: i) the business-as-usual (BAU) scenario, where the current economic and environmental objectives persist, ii) the economic growth scenario (EG), where economic development is assumed to be promoted through expansion in mining operations, as well as increased rubber production and (iii) the economic growth and reforestation, which is similar to the EG, but prescribes higher rates of forest rehabilitation. Each of the scenarios cover the time slice from 2012 to 2070. The data generated can be used to gain a deeper insight into land use change processes, as well as guide effective land use planning and enables assessment of the impacts of land use changes on the environment.

4.3 Description of Study Area

The Bonsa catchment, a sub-catchment of the Ankobra River basin in Ghana, West Africa (Figure 4.1), is located between longitudes 1° 41´ and 2° 13´ West and latitudes 5° 4´and 5° 43´ North. The catchment straddles the intersection of four districts, namely: Twifo-Heman Lower Denkyira to the north, Tarkwa Nsuaem and the Prestea-Huni Valley to the west and Mpohor Wassa East to the east. The population of the large towns in the catchment, such as Tarkwa and Abosso, more than doubled in 30 years (Figure 4.2), with annual growth rate of approximately 2% (Ghana Statistical Service, 2005). The catchment has a generally low relief, with the elevations ranging between 30 and 340 m above mean sea level and it drains an area of 1482 km^2.The rainfall regime is bimodal and ranges between 1578 mm and 1982 mm per annum and the annual average minimum and maximum temperatures are 22ºC and 32ºC, respectively. Predominant land cover consists of thick evergreen and secondary forests, with scattered shrubs and farms. During the past 26 years, (i.e between 1986 and 2011), evergreen and secondary forest reduced by 25% and 28%, respectively and mining areas increased over two-fold, while settlements and shrubs/farms increased more than three and four-fold, respectively. This resulted in an annual deforestation rate of 0.33% between 1986 and 1991, 0.70% between 1991 and 2002 and 2% between 2002 and 2011(Aduah *et al.*, 2015). The basin’s geology is characterized by Birimian and Tarkwaian rock systems (Akabzaa et al., 2009), while the soil is composed mostly of Ferric Acrisols, according the Food and Agricultural Organisations’ (FAO) soil classification system and forest oxysols (Dwomo and Dedzoe, 2010), according to the Ghana soil classification system. Major economic activities in the catchment include open-pit gold mining, rubber cultivation and small-scale cocoa and food crop production.

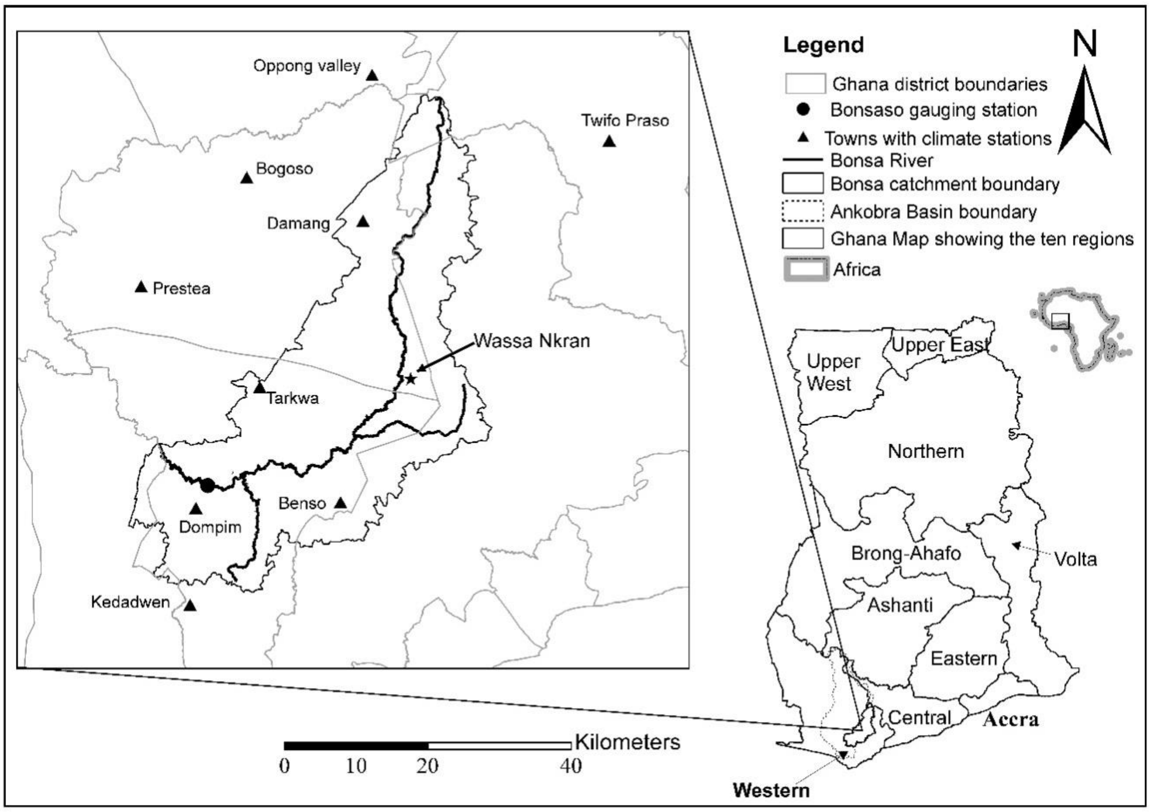


Figure 4.1: Map of the Bonsa catchment of the Ankobra basin, Ghana

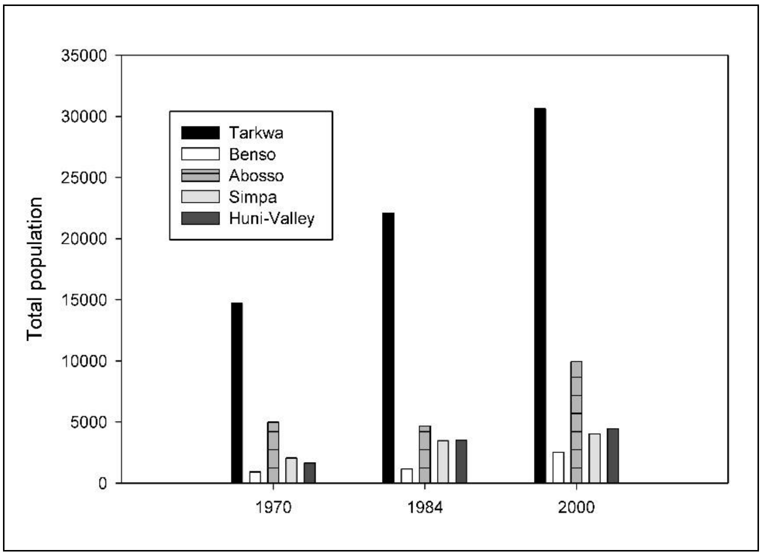


Figure 4.2: Population of major towns in Bonsa catchment from 1970 to 2000 (Ghana Statistical Service, 2013)

4.3 Model Details

4.3.1 Dyna-CLUE Model

The dynamic Conversion of Land Use and its Effects modelling frame work (Dyna-CLUE), was developed by the Institute of Environment at the University of Wageningen, Netherlands, to simulate land use change (Verburg *et al.*, 1999; Verburg *et al.*, 2002; Verburg and Veldkamp, 2004). The model uses empirical relations between land use, its driving factors, as well as dynamic modelling of the competition between land use types. Dyna-CLUE has two modules, (i) the non-spatial and (ii) the spatial allocation module. The non-spatial module calculates predicted land use change areas (demand) for each land use type, while the spatial module allocates the predicted (demand) land use areas spatially in the study region. Land use demand is the area per land use type and it is associated with both potential and actual land use. The land use demand is predicted outside of the Dyna-CLUE model, using trend analysis, econometric or Markov chain models, based on historical land use changes. The spatial allocation module in Dyna-CLUE uses the output of the non-spatial module (i.e. area of each land use type/year), spatial policy restrictions, the land use type conversion sequence matrices and land use location suitability to predict the new location of land use types. Figure 4.3 shows how the inputs of the Dyna-CLUE model are used to simulate land use maps.

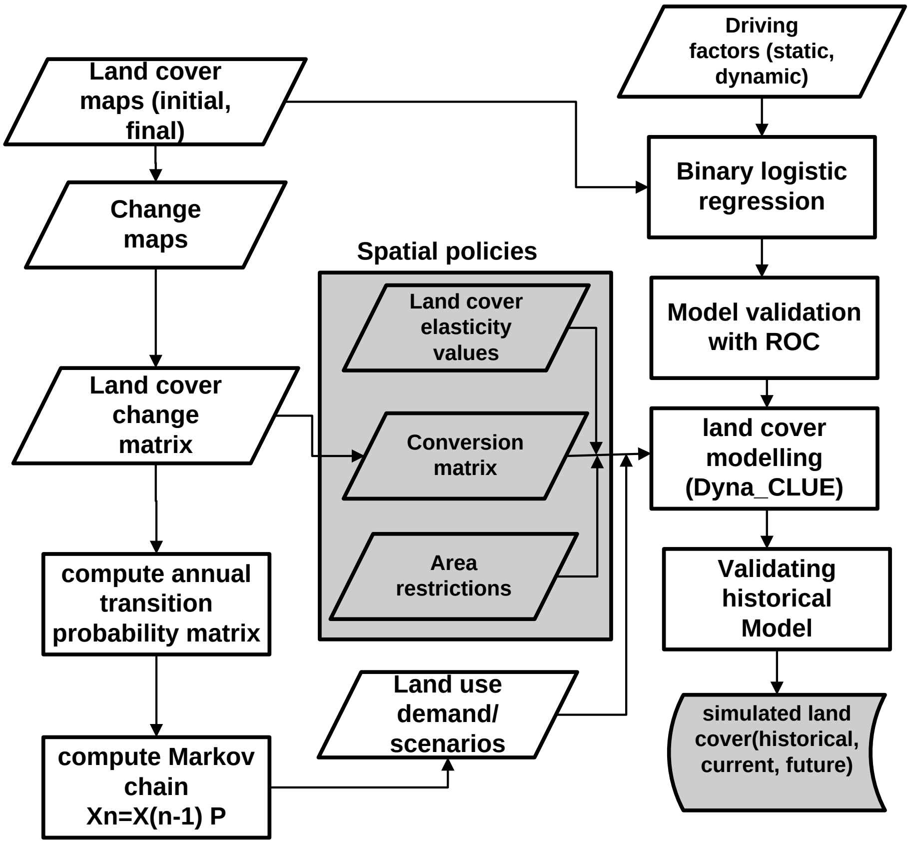


Figure 4.3: **Land use/land cover modelling procedure**

4.3.2 Estimation of Land Use Demand

The land use demand areas or scenarios for land use change areas in this study were calculated based on data from historical land use changes. The demand area for each land use type was estimated on a yearly basis starting from the initial (baseline) year (2002) to the final year (2011). Considering that land cover change is generally stable over short time slices (Robinson *et al.*, 1994; Hu *et al.*, 2013), the application of a Markov chain (Equation 4.1) to estimate the yearly land cover demand area was considered reasonable. A Markov chain as shown by Equation (4.1), is a memoryless model, where the area under a given land use type in next future time step is only dependent on the current land use.

$$X_n = X_{(n-1)}P \tag{4.1}$$

Where X_n is the computed land use demand, $X_{(n-1)}$ is the initial land use demand (the land use map of 2002) and P is the transition probability matrix, which is derived from the land use transition probability (R_{mn}). R_{mn}, calculated with Equation (4.2), is the probability of land use class m in initial year to change to class n in the final year(Flamenco-Sandoval *et al.*, 2007).

$$R_{mn} = a_{mn}/a_m \tag{4.2}$$

Where a_{mn} is the area of the land use class m during initial year (2002) and covered by land use class n during the final year (2011), a_m is the area of land use class during the initial year. The probability R_{mn} for more than one land use type between the initial and the nth year is given by the probability matrix, P. The P is calculated because of the lack of yearly land cover maps to generate annual probability matrices (Takada *et al.*, 2010). Hence, to estimate the probability matrix at annual time scales, in order to capture more accurately the dynamics in land use changes, the P matrix was converted to annual probability matrix using Equation (4.3) (Mertens and Lambin, 2000).

$$T_{ij=expm^{\frac{1}{n}logmP_{ij}^{n}}} \tag{4.3}$$

Where T_{ij} is the annual transition probability matrix, *expm* is the matrix exponential, *logm* is the matrix logarithm, P_{ij} is the transition probability matrix between the initial and the final year for more than one land use type and n is the number of years. Takada's software (Takada *et al.*, 2010), based on Equation (4.3), was used to calculate the annual transition probability matrix (Table 4.1),which was applied in Equation (4.1) to estimate the annual land use demand from the selected initial year (2002) to the final year (2011).

Table 4.1: Annual transition probability matrix (2002 to 2011)

		From 2002					
	Land cover	Secondary forest	Water	Evergreen forest	Settlements	Shrubs/farms	Mining areas
	Secondary forest	0.86	0.00	0.01	0.00	0.06	0.00
	Water	0.00	0.83	0.00	0.00	0.00	0.01
To 2011	Evergreen forest	0.03	0.03	0.98	0.01	0.02	0.01
	Settlements	0.00	.000	0.00	0.96	0.01	0.01
	Shrubs/farms	0.11	0.00	0.01	0.03	0.89	0.02
	Mining areas	0.00	0.16	0.00	0.00	0.01	0.94

4.3.3 Spatial Policies

Spatial policy restrictions deal with the constraints placed on the land use change processes (Verburg and Veldkamp, 2004). In Dyna-CLUE, three spatial policy restrictions namely (i) area restrictions, (ii) conversion sequences (matrix) and (iii) conversion elasticity can be used. The area restrictions deal with demarcation of protected areas (e.g. national parks or forest reserves), where certain land use changes are not allowed. Two area restriction maps were used in this study – i.e. one that allowed land use changes within the whole study area and another, which allowed land cover conversions to urban and mining areas in only certain parts of the study area. For mining, the area restriction map was extracted from the lease and prospecting license boundaries (Bourke *et al.*, 2007; Gold Fields Limited, 2012b, a; Castle Peak Mining Ltd, 2013), while for the settlements, the map was based on historical land cover trends. Land use conversion matrix is used to indicate land use transition sequences (Verburg and Veldkamp, 2004) during simulations and it is created based on historical land cover/land use maps. In this study, the transition sequences were derived by inspecting the land use change matrix between 2002 and 2011. Table 4.2 shows the conversion matrix used in this study, where 1 indicates that transition is allowed, while 0 mean no transition is allowed.

Furthermore, the land use conversion elasticity indicates the reversibility of land cover changes (Verburg and Veldkamp, 2004) and ranges from 0 for land cover types, which are easily changed, to 1 for those that are not easily changed. For example, the elasticity value to change settlement area to shrubs/farms is very high, compared to the elasticity value to convert secondary forest to shrubs/farms. The competition between the land uses, calculated by the Dyna-CLUE model, is controlled by the area restrictions, transition sequences/matrix, the elasticity and the location suitability, which is derived from binary logistic regression analysis.

Table 4.2: Conversion matrix for 2002 to 2011 land use simulations

		From 2002					
	Land cover	Secondary forest	Water	Evergreen forest	Settlements	Shrubs/farms	Mining areas
To 2011	Secondary forest	1	0	1	0	0	0
	Water	0	1	0	0	0	0
	Evergreen forest	0	0	1	0	0	0
	Settlements	0	0	0	1	1	0
	Shrubs/farms	1	0	0	0	1	0
	Mining areas	0	0	0	0	0	1

4.3.4 Land Use Location Suitability

Land use changes depend on proximate and distant factors. The distant factors include international trade, globalization of agriculture and international politics, while the proximate factors include local government policies, urbanization, agriculture and economic development (Sage, 1994; Barbier, 2000; Meyfroidt *et al.*, 2013). Regarding the proximate factors, biophysical variables such as accessibility to land and resources (e.g. distance to roads, rivers and urban centres), landscape characteristics such as elevation, slope, soil and geology play a critical role in how the land cover changes. Therefore, the biophysical factors can be used as proxies to understand how local land use changes. Regarding the distant drivers, they are underlying factors that influence government policies and socio-economic conditions, which successively determines where and how land use changes. For example, in many mining districts in Ghana, economic liberalization, favourable mining tax regimes and regulations, and increases in gold prices on the world market drives conversion of huge tracts of forest land into mining areas (Akabzaa and Darimani, 2001), while increases in prices of cocoa (Sutton and Kpentey, 2012) and rubber, as well as government support, drives conversion of forested lands into cocoa and rubber farms.

The predictors of land use change are therefore dependent on accessibility measures, demographics and the economic policies in a catchment. In this study, the land use driving factors adopted, based on previous case studies (Verburg *et al.,* 1999; Verburg *et al.,* 2002; Verburg and Veldkamp, 2004; Hu and Lo, 2007; Chu *et al.*, 2010; Park *et al.*, 2011a; Vermeiren *et al.*, 2012), are accessibility measures and demographics (total population density)(Table 4.3). The factors were classified as either static or dynamic. The accessibility measures were classified as static, while population density was classified as dynamic. The dynamic population was estimated, based on statistical projections (2% growth/year) for the Western Region of Ghana, obtained from Ghana Statistical Service (2005).Other important drivers, such as economic measures (global prices of gold, government tax regime and per capita income) were not included due to a lack of available data. In order to model expansion of mining areas, a driving factor, namely distance from mining concessions/mines, was included instead of geology. This is because when geology was used, the regression statistics were not significant. Soil was not included as a driving factor because the catchment has only one FAO soil class, Ferric Acrisols, which could be due to the low resolution of the soil map (1:250 000) obtained from the Soil Research Institute of Ghana (Boateng *et al.*, 1999). The individual land use types, as well as the land use change driving factors, which were converted to raster maps, using a spatial resolution of 50 m, were imported to IBM SPSS statistical software using the Dyna-CLUE data converter, to perform binary logistic regression Equation (4.4), in order to estimate the probability of each land use type given the driving factors.

$$Log\left(\frac{P_i}{1-P_i}\right)= \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n \qquad (4.4)$$

Where P_i is the probability of occurrence of a land use class in location i, X is the location factor and β is the logistic regression coefficient. The regression coefficients resulting from the above calculations were input in the Dyna-CLUE model, together with the other variables estimated in previous sections, to simulate land cover/land use.

Table 4.3: Land use change driving factors

Data	Description	Source
Population density	population density (person/sq. Km)	Ghana Statistical Service,2000, 2013
Distance from centre of towns	Euclidean distance from centre of all towns	Survey of Ghana
Distance from roads	Euclidean distance from roads	Survey of Ghana
Distance from Tarkwa	Euclidean distance from major urban area (Tarkwa)	Survey of Ghana
Elevation	elevation derived from 50 feet contour interval (50m)	Survey of Ghana
Distance from rivers	Euclidean distance from main rivers	Survey of Ghana
Aspect	Aspect derived from 50 m digital elevation model	Survey of Ghana
Slope	Slope derived from 50m digital elevation model (%)	Survey of Ghana
Distance from outskirts of towns	Euclidean distance from outskirts of all towns	Survey of Ghana
Easting coordinates	interpolation of all easting coordinates	Survey of Ghana
Northing coordinates	interpolation of all northing coordinates	Survey of Ghana
Distance from mining concessions	Euclidean distance from centre of concessions	Mining Companies

All Euclidean distances and coordinates are measured in metres

4.4 Model Validation and Future Land Use Scenarios

Uncertainties in land cover modelling emanate from several sources, such as model structure, initial land cover data and input socio-economic and biophysical data. Therefore, assessing uncertainties of the models is complex. However, since the results represent all the uncertainties associated with a model, location-based metrics, such as overall accuracy of the error matrix and Kappa statistic, have become the common methods for uncertainty assessment of predicted land use maps (Park *et al.*, 2011a; Park *et al.*, 2011b; Zhang *et al.*, 2011; Tong *et al.*, 2012; Zhou *et al.*, 2012; Arsanjani *et al.*, 2013). The relative operating characteristics (ROC) statistic is also commonly used for validating models based on logistic regression (Verburg and Veldkamp, 2004; Hu and Lo, 2007; Park *et al.*, 2011b). The model validation in this study was executed using the ROC and the Kappa statistics. The ROC statistic determines the quality of deterministic and probabilistic relations (Park *et al.*, 2011b) between driving factors and the different land uses, while the Kappa statistic is a multivariate technique, used in accuracy assessment of categorical data and it is designed to take chance into consideration. The Kappa statistic was based on the formula provided by Congalton (1991), as shown in Equation (3.1) in Chapter 3. Historical land cover maps for the period from 2003 to 2010 were not available for model validation. Thus, only the observed land cover map of 2011 (Aduah *et al.*, 2015) was used as the reference to estimate the Kappa for the modelled land cover map of 2011.

After validating the Dyna-CLUE model for the historical land use simulation, three scenarios/demands of land use changes were created to guide simulation of potential future land use changes in the Bonsa catchment, using Equation 4.1, the 2011 land cover map as initial land use and the annual transition probability matrix obtained in Equation 4.3 (for the historical period 2002 to 2011), with a time step of one year. The future land use scenarios are described below.

4.4.1 Business-as-usual (BAU) Scenario

This is a scenario where the historical trend of land use changes persists (similar to trends between 2002 and 2011). In this scenario, the evergreen forest is protected by the Ghana Government through restrictions on the timber industry, such as a ban on exportation of round logs and prosecution of illegal chainsaw operators. The area under surface mining increases, as mining companies are allowed to expand existing operations within their concessions, but new mining leases are not granted. In this scenario, the area of shrubs/farms increases due to increasing population (2%/year), as more farms are created and abandoned after few years of continuous cropping, thereby reducing areas which are in the secondary forest category located outside forest reserves.

4.4.2 Economic Growth (EG) Scenario

In this scenario, it was assumed that population growth (2%/year) will continue to affect the expansion of settlements as in the BAU scenario, however, shrubs/farm areas will reduce, due to maturing of rubber plantations (young rubber trees were captured as part of shrubs/farms) into secondary forest and the expansion of mines and urban areas into farm areas. The scenario also assumes that the area of evergreen forest will reduce, because new mining leases will be granted and existing leases will be activated (Figure 4.4) for new surface mines to start operating. Some of the forest reserves (evergreen forest areas) fall within some of the new and existing mining leases (Figure 4.4). It is also assumed that, under this scenario, timber logging will be allowed, especially within the mining concessions, which will further reduce the size of the evergreen forest. Therefore in this scenario, the area of mines will increase and all land use types can be converted to mines. It was further assumed that existing mining areas will increase up to 2040, which is around the time the longest lease (Tsuma, 2009; Gold Fields Limited, 2012b) for the existing mines will expire. After 2040 only the new mine areas will increase, based on the historical trend.

4.4.3 Economic Growth and Reforestation (EGR) Scenario

The scenario is the same as the EG scenario with an enhanced reforestation, in line with the plans by the Ghana Forestry Commission (FC) (FAO, 2010a; Ghana Forestry Commission, 2013) to rehabilitate 200 km^2 of degraded forests per year for the country. This means, proportionally 12.43 km^2 of forests need to be rehabilitated per decade for the 1482.2 km^2 Bonsa catchment, according to the FC’s plans for Ghana. Therefore, in this land use scenario, the secondary forests were increased by 1.243 km^2 per year, while the shrubs/farms were reduced by a similar amount. The secondary forest in this scenario was assumed to be a combination of rubber and indigenous tree species.

The three scenarios were created using, census data (Ghana Statistical Service, 2005, 2013), reports from mining companies (Bourke *et al.*, 2007; Gold Fields Limited, 2012b, a; Castle Peak Mining Ltd, 2013) and literature on land use modelling. Land use demands were calculated for each scenario (starting from 2011 and ending in 2070), which were subsequently used as input in the Dyna-CLUE model together with previously determined statistics, to simulate potential future land use distribution.

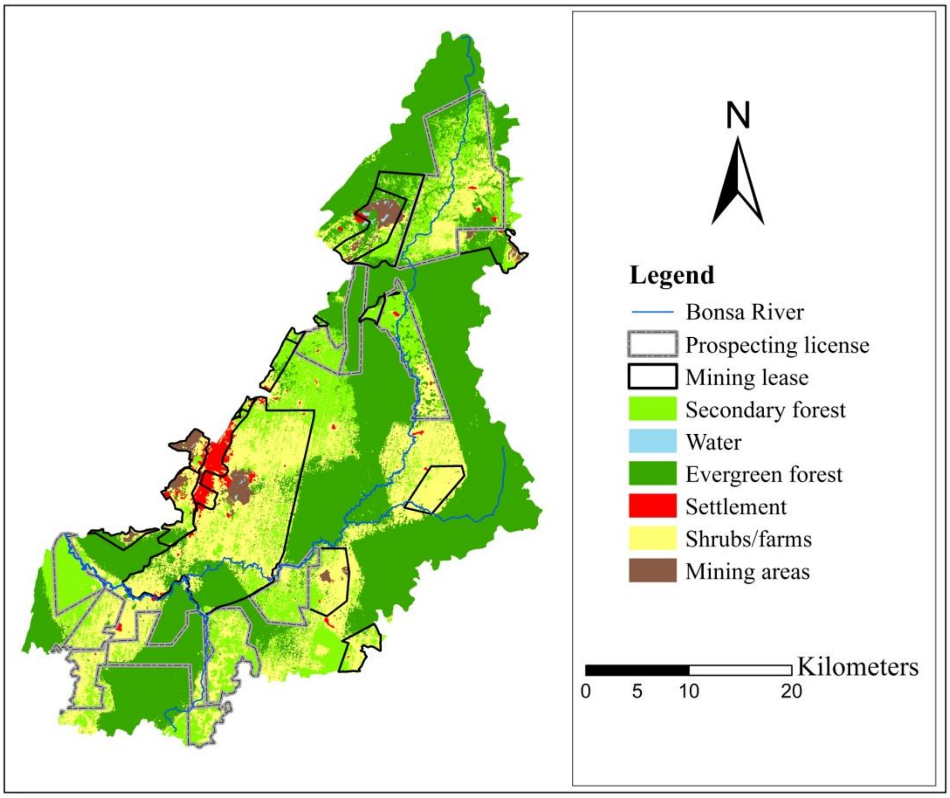


Figure 4.4: **2011 land cover and approved mining leases and prospecting licenses in the Bonsa catchment (Aduah *et al.*, 2015)**

4.5 Results

4.5.1 Model Validation and Simulated Land Use Maps

The logistic regression results are shown in Table 4.4 for the eleven independent driving factors and the six land cover types in the Bonsa catchment. The ROC statistics ranged from 0.69 for the secondary forest to 0.98 for the settlements and mining areas. The regression coefficients, as well as the constants, were significant at the 95% confidence level, indicating that the logistic regression model is capable of predicting the probability of occurrence of the land covers in the catchment. The positive coefficients show that the probability of observing the land covers increase for the independent factors, while the negative coefficients show the opposite. Table 4.4 shows that with increasing population density, the probability of occurrence of secondary forest and evergreen forest; reduces, while the probability increases for settlements and shrubs/farms. This indicates that population growth contributes to deforestation, as a result of increasing area of shrubs/farms and settlements in the catchment.

Table 4.4: Binary logistic regression statistics of 2011 land cover and driving factors

	Secondary forest	Water	Evergreen forest	Settlement	Shrubs/farms	Mining areas
Factor	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient
Population density	-0.006		-0.0191	0.0078	0.0051	
Distance from centre of towns	0.0002		-0.0001	-0.0009	-0.00001	
Distance from roads	-0.0003		0.0005	-0.0019	-0.0004	
Distance from Tarkwa	-0.00001		-0.0001	0.00004	0.00003	
Elevation	0.0018	0.0263	0.0013	-0.011	-0.0009	0.0161
Distance from rivers	0.0001		0.0001	0.00002	-0.0001	
Aspect			0.0001	-0.0007		
Distance from outskirts of towns	-0.00001		0.0001	-0.0032	-0.0002	
Easting coordinates	-0.0001		0.00002	0.00001	0.00002	
Northing coordinates	0.00003		0.00003		-0.0001	
Distance from mining concessions		-0.0014				-0.002
Constant	14.0627	-5.4279	-29.0138	-5.5325	21.2753	-0.2289
ROC statistic	0.6908	0.9746	0.8247	0.9844	0.7881	0.982

All coefficients significant at $p < 0.05$

Furthermore, the probability of observing settlements and shrubs/farms increases with proximity to centre of towns, roads and outskirts of towns, but increasing elevation has the opposite effect. This observation suggests that the local people, who engage in farming, prefer to locate their farms on relatively lowlands close to their homes and accessible by roads, which is not surprising since lowlands are mostly preferred for agriculture, because of their generally good soil fertility. With regards to settlements, the results demonstrate that people prefer to build their homes in relatively low lying areas, accessible by roads and close to towns. Building close to towns and roads provide easy access to services and social amenities such as schools, hospitals, markets/shops, lorry stations and playing fields, which are usually located in centre of towns/villages.

Additionally, the regression model shows that while proximity to rivers decreases the probability of occurrence of secondary forest, evergreen forest and settlements, it increases the probability of occurrence of shrubs/farms. In terms of mining and water (mainly mining tailings dams), the probability of their occurrence increased with elevation, but decreased with distance from mining concessions. According to Akabzaa and Darimani (2001) many ridges within the catchment, ranging from an elevation of 160 m to 340 m, have huge deposits of gold and manganese and will be turned into huge craters after surface mining is completed. The mining concessions contain the existing mines (Anglogold Ashanti Ltd, Iduaprem mine, Ghana Manganese Company Ltd, Nsuta, Gold fields Ghana Ltd, Tarkwa and Damang and Golden Star Resources Ltd, Wassa mines), with additional mines planned for the future, in areas where leases have been approved as well as in locations still under exploration (Figure 4.4).

Figure 4.5 and Table 4.5 shows the simulated spatial land use changes for the historical period between 2002 and 2011. The maps show that the settlement areas increased gradually from 2002 to 2011, while the secondary forest areas reduced over the period. Shrubs/farms areas also increased substantially between 2002 and 2011, but evergreen forest remained relatively the same for the entire simulation period. Validation of the historical model indicated that the simulation corresponded well with the historical land use, resulting in a Kappa statistic of 54%, after comparing the observed and the simulated land use map of 2011(Figure 4.6).

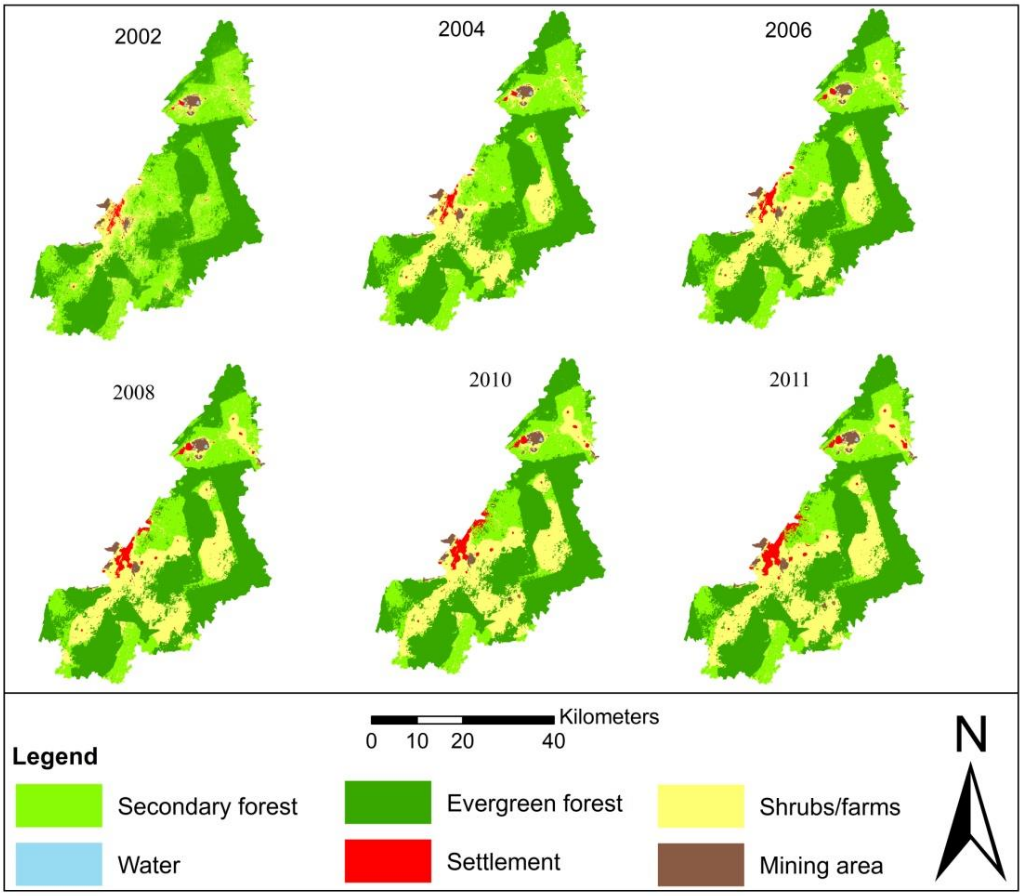


Figure 4.5: **Simulated historical land cover/land use distribution in the Bonsa catchment and observed 2002 land cover**

Table 4.5: Observed land cover proportions for 2002 and 2011, as well as demand and modelled land cover proportions for 2007, 2009 and 2011

		2007		2009		2011		
	Observed 2002	Demand	Modelled	Demand	Modelled	Demand	Modelled	Observed 2011
Land cover	area (km^2)	area (km^2)	area (km^2)	area (km^2)	area (km^2)	area (km^2)	area (km^2)	area (km^2)
Secondary forest	578.9	349.3	352.8	315.9	320.1	293.1	297.5	280.3
Water	1.6	1.8	1.6	1.8	1.6	1.8	1.6	1.4
Evergreen forest	739.5	743.9	739.5	743.9	739.5	743.9	739.5	755.2
Settlement	11.4	22.7	20.2	28.6	25.4	36.2	36.6	22.4
Shrubs/farms	133.9	344.4	348.1	370.8	374.3	384	385	398.8
Mining areas	17	20.2	20.1	21.1	21.3	23.2	22.1	24.2

According to Landis and Koch (1977), a Kappa of 54% demonstrates that the model's predictive power is moderate. The moderate performance of the model in the Bonsa catchment can be attributed to inadequate data and lack of information on land use decisions of individuals and organisations. Population is a highly significant driver of land cover change in the catchment (Table 4.4), however the population data used in this study is incomplete. Apart from the 2000 census data, the rest of the population density was based on projections (Ghana Statistical Service, 2005, 2013). There was a census in 2010, but at the time of writing this paper, detailed data at the community level was unavailable. Data on the development of the catchment's road network is also lacking. Road and elevation data used in this study is a combination of a 2003 1:5 000 urban map of Tarkwa and a Survey of Ghana (SOG) topographic map series produced in 1974. In terms of mining areas, data on driving factors that influenced the expansion of mining areas was not available as mining expansion is influenced by government policies, international financial and trade regimes, which are difficult to predict and to incorporate in Dyna-CLUE. Generally, information on the land use plan in the catchment was not available, even though this type of information is necessary for projecting changes in the land cover/land use (Verburg *et al.*, 2002). Furthermore, the land use maps of 2002 and 2011 also introduced uncertainties into the modelling. This is because the discrimination between secondary forest and shrubs/farms was poor (Chapter 3, Appendix 4.B to 4.D), although the overall mapping accuracies of the land use maps were acceptable.

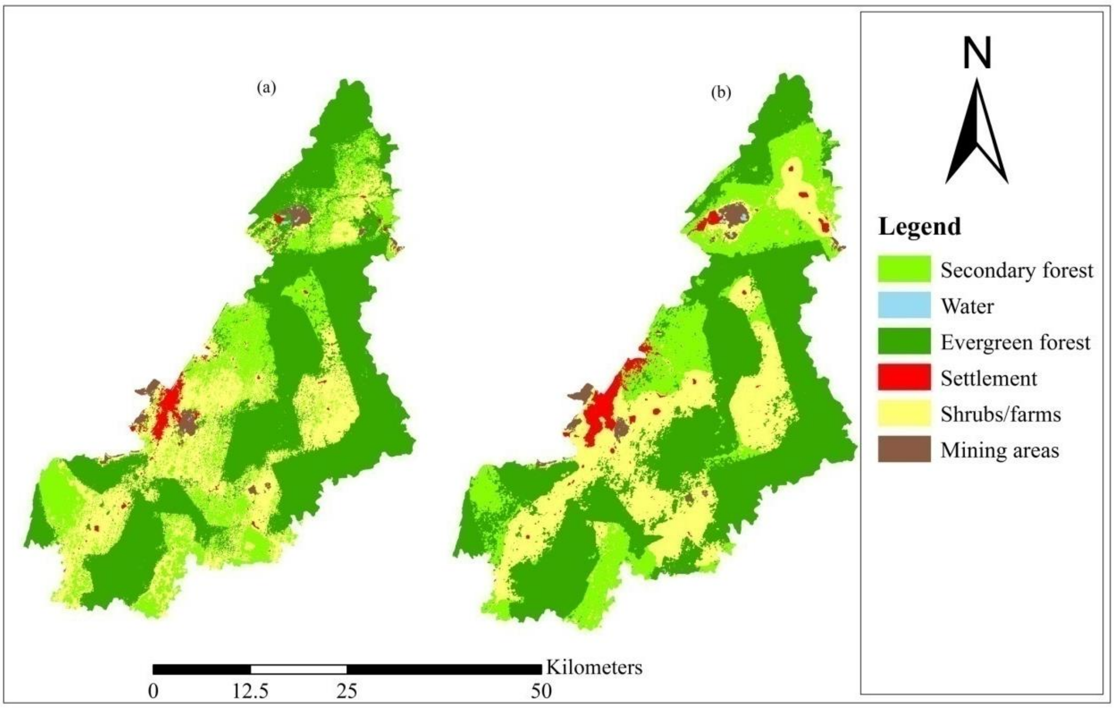


Figure 4.6: Observed (a) and simulated (b) land cover maps for 2011

4.5.2 *Potential Future Land Cover/Land Use Maps*

After demonstrating that the Dyna-CLUE model performs moderately in simulating historic land use, it was applied to simulate future land use, based on the BAU scenario, where the historical trend persist and the economic growth (EG) scenario, which calls for rapid expansion of mines, rubber plantations and settlement/urban areas, as well as the economic growth and reforestation (EGR) scenario, which is similar to the EG, but with higher rate of tree plantation. The logistic regression statistics obtained during model training for the historical data were applied to the future simulations. Figure 4.7 and 4.8, as well as Table 4.6, 4.7 and 4.8 show the results of future land use projections. The figures and tables show that the settlement areas in the scenarios increased by almost the same margin, while secondary forests decreased in the BAU scenario, it increased in the EG and the EGR scenarios, with higher increases in the EGR than the EG.

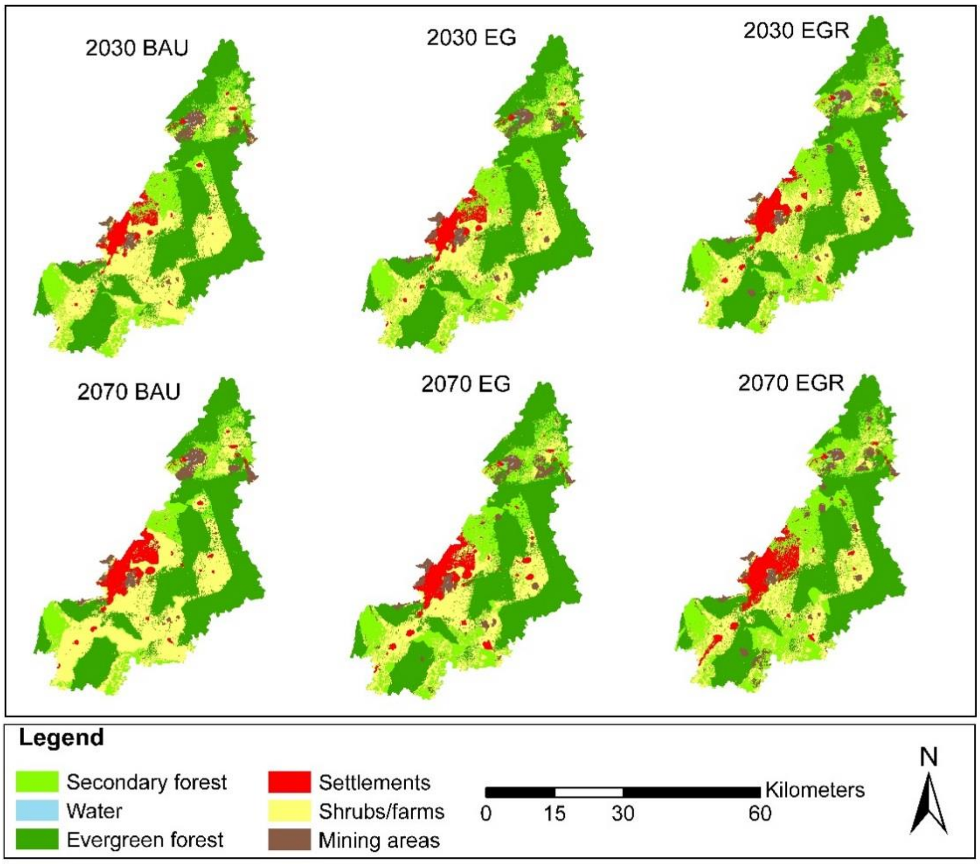


Figure 4.7: Potential future land cover maps for three future scenarios

The EGR had higher increase in secondary forest because the scenario assumed higher rates of forest rehabilitation, compared to the EG scenario. The three scenarios resulted in relatively the same decreases in the evergreen forest class. However, under the BAU scenario, shrubs/farms increased marginally up to 33% of study area in 2070, but in the EG and the EGR scenarios, it remained relatively stable, although the area of the EGR was slightly lower than that of the EG. Furthermore, mining areas increased in the scenarios, but the EG and EGR scenarios had higher increases, compared to the BAU scenario. Figure 8 demonstrates that population growth in the Bonsa catchment will result in increasing settlement areas and shrubs/farms areas, but decreases in evergreen, as well as secondary forest resources.

Table 4.6: BAU scenario: simulated land cover proportions compared with 2011 land cover

	2011		2030		2040		2050		2060		2070	
Land cover	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%
Secondary forest	280.3	18.9	215.5	14.5	200.2	13.5	188.4	12.7	178.7	12.1	171.0	11.5
Water	1.4	0.1	1.4	0.1	1.4	0.1	1.4	0.1	1.4	0.1	1.4	0.1
Evergreen forest	754.6	50.9	728.1	49.1	717.9	48.4	708.6	47.8	699.7	47.2	683.6	46.1
Settlement	22.4	1.5	63.7	4.3	72.2	4.9	79.9	5.4	85.4	5.8	91.3	6.2
Shrubs/farms	399.4	26.9	425.3	28.7	439.8	29.7	451.2	30.4	464.2	31.3	482.1	32.5
Mining areas	24.2	1.6	48.3	3.3	50.8	3.4	52.7	3.6	52.8	3.6	52.8	3.6
Total	1482	100	1482	100	1482	100	1482	100	1482	100	1482	100

Table 4.7: EG scenario: simulated land cover proportions compared with 2011 land cover

	2011		2030		2040		2050		2060		2070	
Land cover	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%
Secondary forest	280.3	18.9	283.9	19.2	286.1	19.3	289.4	19.5	293.1	19.8	294.7	19.9
Water	1.4	0.1	1.4	0.1	1.4	0.1	1.4	0.1	1.4	0.1	1.4	0.1
Evergreen forest	754.6	50.9	733.6	49.5	725.8	49	711.1	48	697.1	47	689.4	46.5
Settlement	22.4	1.5	68.8	4.6	82.8	5.6	87.6	5.9	93.7	6.3	95.7	6.5
Shrubs/farms	399.4	26.9	340.1	22.9	325	21.9	329.7	22.2	331.1	22.3	335	22.6
Mining areas	24.2	1.6	54.3	3.7	61.1	4.1	63.1	4.3	65.9	4.4	66	4.5
Total	1482	100	1482	100	1482	100	1482	100	1482	100	1482	100

Table 4.8: EGR scenario: simulated land cover proportions compared with 2011 land cover

	2011		2030		2040		2050		2060		2070	
Land cover	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%
Secondary forest	280.3	18.9	303.8	20.5	314.8	21.2	326.4	22.0	338.1	22.8	350.1	23.6
Water	1.4	0.1	1.4	0.1	1.4	0.1	1.4	0.1	1.4	0.1	1.4	0.1
Evergreen forest	754.6	50.9	716.0	48.3	703.8	47.5	691.8	46.7	680.4	45.9	667.7	45.0
Settlement	22.4	1.5	66.6	4.5	77.0	5.2	90.9	6.1	93.1	6.3	100.6	6.8
Shrubs/farms	399.4	26.9	340.2	23.0	320.4	21.6	307.3	20.7	304.4	20.5	295.4	19.9
Mining areas	24.2	1.6	54.3	3.7	64.8	4.4	64.4	4.3	64.8	4.4	67.2	4.5
Total	1482	100	1482	100	1482	100	1482	100	1482	100	1482	100

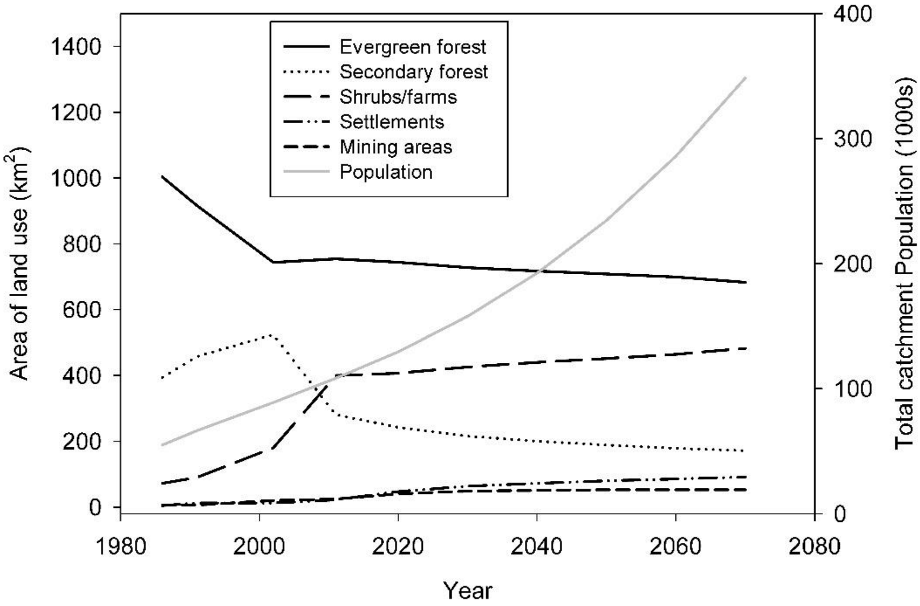


Figure 4.8: **Total projected population of Bonsa catchment from 1986 to 2070, land use areas from 1986 to 2011 (observed) and simulated land use areas from 2020 to 2070 for the BAU scenario**

4.6 Discussion

This study has demonstrated a moderately successful modelling of land cover changes for both historical and future scenarios, using a combination of logistic regression, Markov chain and the Dyna-CLUE models. Logistic regression modelling was able to determine successfully, the probabilities of occurrence of the land use types, using independent driving factors, which were selected based on a literature review. However, the limitation of the logistic regression model is that it lacks the ability to quantify the amount of changes (area) or demand, as well as to allocate the changes (Hu and Lo, 2007; Arsanjani *et al.*, 2013). Therefore, the outputs of Markov chain models were used to estimate the demand for the scenarios of land cover changes and the spatial allocation executed with the Dyna-CLUE model. Although the Dyna-CLUE model is unable to estimate the relationship between the driving factors and to quantify the demand (Verburg and Overmars, 2009), it was able to allocate spatially, the changes, by modelling the dynamic competition between the land use types. The dynamic competition was controlled by the statistics of the regression model, the demand, the change matrix (transition sequences) and the elasticity of the land cover (Verburg and Overmars, 2009). Hence using Dyna-CLUE ensured that multiple land use types, as well as dynamic simulation were executed successfully.

The Dyna-CLUE model predicted the trend in land use changes, observed on the actual land cover maps for 2002 and 2011(Figure 4.5and Table 4.5). When the simulated land cover of 2011 was compared with the observed land cover of 2011, secondary forest and settlements were overestimated, while evergreen forest, shrubs/farms and mining areas, were underestimated (Figure 4.6 and Table 4.5). However, the model was able to allocate the demand correctly most of the time. Therefore, the major hindrance to the overall model performance is the accuracy of the initial land use maps, demand calculations as well as the driving factors. According to Verburg *et al.* (2002), Verburg and Veldkamp (2004) and Verburg and Overmars (2009), the CLUE family of models are very sensitive to the demand. It is therefore not surprising that the model validation achieved only a Kappa of 54%, representing a moderate agreement in simulation of the observed land cover, due to inadequate input data which include lack of information on how individuals and communities/the Government make land use decisions. However, since the overall trend in land cover changes is well simulated and the purpose of the modelling was to provide plausible pathways of land cover changes, the generated model statistics were assumed to be valid for the future land cover scenarios. This approach is consistent with previous studies (Chu *et al.*, 2010; Park *et al.*, 2011a; Park *et al.*, 2011b).

Furthermore, the results of this study provide evidence of the existence of the Sahel Syndrome (Petschel-Held *et al.*, 1999) in the southern part of Ghana, where the ever increasing poor population of Bonsa catchment, who have no other livelihoods, converted forested lands into agriculture, thereby contributing significantly to degradation of the environment. With regards to influence of population size on deforestation, results of this study are similar to those for the Eastern province of Cameroon (Mertens and Lambin, 2000) and the West Biosphere reserve in Northern Benin (Houessou *et al.*, 2013), but contradict that of Braimoh and Vlek (2005), where population did not contribute significantly to deforestation in the northern Savannah of Ghana. Braimoh and Vlek (2005) noted that during the early stages of the economic recovery programme in Ghana, large parcels of land in the north were converted into irrigated rice fields, which explains why population size did not contribute significantly to deforestation. However, in terms of the influence of accessibility factors on deforestation, the results of this study are similar those of Mertens and Lambin (2000), Braimoh and Vlek (2005) and Houessou *et al.* (2013).

The future scenarios of land cover changes, consisting of the BAU, the EG, as well as the EGR scenarios, indicate that in both the near and far future, there may be extensive land cover/land use changes in Bonsa catchment, through population growth and increased surface mining activities (Figure 4.7 and 4.8 and Table 4.6, 4.7 and 4.8). In future, settlement area is projected to increase, with all three scenarios projected to have relatively the same area. The settlement expansion may occur mainly in the Tarkwa area, as well as in towns and villages along the major roads. It is important to note that higher settlement expansion rates will exacerbate impacts, such as increased stormflows, runoff, soil erosion, sedimentation of rivers and the pollution of water bodies. For evergreen forests, all scenarios show substantial changes. In the BAU scenario, although the forest reserves were strictly protected, after 2002 (Sutton and Kpentey, 2012) (Figure 4.8), the authorization of mining near forest reserves for the existing mines, as well as expansion of agriculture, mainly rubber and cocoa cultivation, may inevitably lead to encroaching into the evergreen forests, located mostly in forest reserves. In the EG and the EGR scenarios, the decrease in evergreen forest is due to increased mining activities, as new mining leases (Figure 4.4) may be approved for mining to start in various parts of the catchment, including forest reserves. It is also expected that once mining is allowed in the forest reserves, timber logging will likely take place in those mining concessions. Moreover, increases in mining areas, resulting in a decrease in evergreen forests, will also negatively impact the environment. The biodiversity of the ecosystem will reduce; runoff volumes and speed may increase leading to soil erosion, sedimentation and pollution of water bodies. The increased mining activities also have the potential to pollute both surface and groundwater, with heavy metals, such as mercury and arsenic, resulting from processing gold ores.

For the shrubs/farms, the scenarios show contrasting futures. While there is an increase in the BAU scenario, as a result of population growth and expansion in agriculture, there is a decrease in the EG and the EGR scenarios, which is a result of the combined expansion in settlements, mining areas and secondary forests. Increased shrubs/farms areas under the BAU scenario, at the expense of evergreen and secondary forest, call for implementation of farming technologies that maintain soil fertility, farming practices that encourage less encroachment of forested areas, as well as protect the water sources from pollution. The reduction of shrubs/farm areas under EG and the EGR scenarios, calls for measures to intensify production for food security, by using modern agricultural technologies, as well as diversifying the local economy, in order to provide the local communities with sources of livelihood. Hence the extensification of rubber and indigenous tree plantations, which is represented by an increase in secondary forests in the EG and the EGR scenarios, can contribute to providing the local communities with a source of livelihood, as a larger portion of their farm lands may be taken for settlements and mining operations. Under the BAU scenario, secondary forest is projected to decrease, which means lands currently (2011) being used as secondary forests, are not protected, unlike the EG and the EGR scenarios. In the EG and the EGR scenarios, it is anticipated that even if new mining leases are granted and settlement expansion is allowed to occur at the current rate, the protection of the secondary forests or encouragement of rubber cultivation will partly offset the potential negative effects that reduction in evergreen forest and shrubs/farms areas will have on both the local communities and the environment.

It is important to state that the maps generated under both historical and future scenarios of land cover/land use changes in this study do not represent real land cover changes. The maps are only a projection of different development pathways for the catchment. The predicted maps are intended to be used to support the formulation and revision of land use policies in the medium to long-term time slices. It is also acknowledged that even though the land use modelling, using Dyna-CLUE was moderately successful in terms of the Kappa statistic in simulating the 2011 land cover, there were some limitations. These include the inability of the Dyna-CLUE model to incorporate actor decisions, such as preference of individuals and communities, government policy, globalization of economics, as well as inadequate input data. Thus, the set of driving factors used were local; distant and underlying factors were excluded. Due to lack of data, it was also difficult to separate correlation from causality of land cover changes during the modelling process, as noted by Mertens and Lambin (2000) and Tran Van *et al.* (2012) in previous studies. Consequently, the regression statistics generated for the different land cover types were assumed to be valid for the future time slices, used for the two scenarios, as was the case in previous studies elsewhere (Sohl *et al.*, 2007; Chu *et al.*, 2010; Park *et al.*, 2011a; Tran Van *et al.*, 2012).

It must also be mentioned that Dyna-CLUE model cannot simulate changes such as introduction of new land use types, due to lack of historical precedence (Verburg *et al.*, 1999). However, the land cover maps generated in this study provide an avenue to explore the implications of the different development scenarios on the environment. The study has demonstrated that spatial modelling of land use change is the best way to provide data to infill data gaps as a result of lack of satellite or aerial imagery to generate land cover maps, especially in data scarce regions. In West Africa for example, the historical record of satellite or aerial imagery is limited mainly due to cloud cover, hence spatial land use modelling adopted in this study is vital to provide the best estimate of the distribution of land use for the periods where there are no satellite or aerial imagery to derive land cover. In future, further studies should improve the modelling results, by acquiring more data and identifying techniques to incorporate human actor information. It is also recommended for future studies to refine the scenarios used in this study, as land use planning information in the catchment becomes available. Further studies should also be conducted to quantify the impacts of the predicted land cover/land use changes on environmental goods and services.

4.7 Conclusion

The study has demonstrated a successful combination of logistic regression, Markov chain and the Dyna-CLUE models to simulate land cover/land use changes in the Bonsa catchment, Ghana, West Africa. The study has identified eleven driving factors, which significantly influence land cover changes in the Bonsa catchment and has generated land cover maps for both the historical, as well as future time slices. The results of the study reveal that increases in population density, proximity to roads and increase in surface mining activities are the major drivers of deforestation and settlement expansion in the catchment. It is therefore suggested that in order to promote sustainable development, land use planning in the Bonsa catchment should not be for the urban areas alone, as is the case in many districts in Ghana, but for the entire catchment and should incorporate protection of forests and promotion of sustainable mining operations. This will require effective collaboration between the planning agencies (Town and Country Planning, Environmental Protection Agency, Water Resources Commission), the Minerals and the Forestry Commissions of Ghana on how to integrate the activities of all organisations within their ambit to promote economic development, without compromising the current and future environmental quality. Although the accuracy of the simulation for the 2011 land cover was only moderate, it can be said that spatially explicit and dynamic simulation of multiple land cover changes is a far more realistic way to generate potential future land use data than the use of extreme assumptions of land changes. The dynamic land use simulation accounts for both biophysical and socio-economic driving forces, as well as enforcement of known trends of land cover changes within the study area in a spatially explicit manner. Therefore the maps and statistics generated in this study can be used to support effective land use planning, as well as assess the impacts of historical and potential future land cover changes on the environment.

4.8 References

Aduah, MS and Aabeyir, R. 2012. Land Cover Dynamics in Wa Municipality, Upper West Region of Ghana. *Research Journal of Environmental and Earth Sciences* 4(6)**:**658-664.

Aduah, MS, Warburton, ML and Jewitt, G. 2015. Analysis of land cover changes in the Bonsa catchment, Ankobra Basin, Ghana. *Applied Ecology and Environmental Research* 13(4)**:**935-955.

Akabzaa, T and Darimani, D. 2001. Impact of Mining Sector Investment in Ghana: A Study of the Tarkwa Mining Region - draft report, . SAPRIN.

Akabzaa, TM, Jamieson, HE, Jorgenson, N and Nyame, K. 2009. The Combined Impact of Mine Drainage in the Ankobra River Basin, SW Ghana. *Mine Water and the Environment* 28(1)**:**50-64.

Armah, FA, Luginaah, I and Ason, B. 2012. Water Quality Index in the Tarkwa Gold Mining Area in Ghana. *The Journal of Transdisciplinary Environmental Studies (TES)* 11(2)**:**1-15.

Arsanjani, JJ, Helbich, M, Kainz, W and Boloorani, AD. 2013. Integration of logistic regression, Markov chain and cellular automata models to simulate urban expansion. *International Journal of Applied Earth Observation and Geoinformation* 21265-275.

Attua, EM and Fisher, JB. 2010. Historical and Future Land-Cover Change in a Municipality of Ghana. *Earth Interactions* 15(9)**:**1-26.

Bakker, MM and van Doorn, AM. 2009. Farmer-specific relationships between land use change and landscape factors: Introducing agents in empirical land use modelling. *Land Use Policy* 26(3)**:**809-817.

Bansah, KJ and Amegbey, N. 2012. Ambient Particulate Matter Monitoring - A Case Study at Tarkwa. *Research Journal of Environmental and Earth Sciences* 4(4)**:**419-423.

Barbier, EB. 2000. Links between economic liberalization and rural resource degradation in the developing regions. *Agricultural Economics* 23(3)**:**299-310.

Boateng, E, Ayamga, T, Chidley, T, John Elgy, J, David Savory, D and van Velthuizen, H. 1999. Land suitabilty analysis: Geo-spatial modelling for agro-ecological assessments and decision support for development planning. *Ghana environmental resource management project (GERMP).* Ghana Soil Research Institute, Accra, Ghana.

Bourke, P, Arthur, J, Marshall, N, MacIntyre, J, Wasel, SM and Urbaez, E. 2007. Technical Report, First time disclosure of mineral reserves, Hwini-Butre and Benso properties, Southwest Ghana. Golden Star Resources Ltd, Denver, Colorado, USA.

Braimoh, AK and Vlek, PLG. 2004. Land-Cover Change Analyses in the Volta Basin of Ghana. *Earth Interactions* 8(21)**:**1-17.

Braimoh, AK and Vlek, PLG. 2005. Land-cover change trajectories in Northern Ghana. *Environmental Management* 36(3)**:**356-373.

Castella, J-C, Pheng Kam, S, Dinh Quang, D, Verburg, PH and Thai Hoanh, C. 2007. Combining top-down and bottom-up modelling approaches of land use/cover change to support public policies: Application to sustainable management of natural resources in northern Vietnam. *Land Use Policy* 24(3)**:**531-545.

Castle Peak Mining Ltd. 2013. Strategic Gold Project in Ghana's Ashanti Belt, Apankrah Deposit Next Steps[Online]. Castle Peak Mining Ltd. Vancouver, BC, Canada: Available:http://edg1.precisionir.com/companyspotlight/NA019419/CAP-Presentation_Nov2013.pdf [Accessed 9th April 2014].

Chu, H-J, Lin, Y-P, Huang, C-W, Hsu, C-Y and Chen, H-Y. 2010. Modelling the hydrologic effects of dynamic land-use change using a distributed hydrologic model and a spatial land-use allocation model. *Hydrological Processes* 24(18)**:**2538-2554.

Congalton, RG. 1991. A review of Assessing the Accuracy of Classification of Remotely Sensed Data. *Remote Sensing of Environment* 37(1991)**:**35-46.

Dietzel, C and Clarke, K. 2006. The effect of disaggregating land use categories in cellular automata during model calibration and forecasting. *Computers Environment and Urban Systems* 30(1)**:**78-101.

Dietzel, C and Clarke, KC. 2007. Toward Optimal Calibration of the SLEUTH Land Use Change Model. *Transactions in GIS* 11(1)**:**29–45.

Dwomo, O and Dedzoe, CD. 2010. Oxisol (ferralsol) development in two agro-ecological zones of Ghana: A preliminary evaluation of some profiles. *Journal of Science and Technology, Kwame Nkrumah University of Science and Technology (KNUST)* 30(2)**:**11-28.

FAO. 2010a. Global Forest Resources Assessment 2010, Country Report, Ghana. *In:* Affum-Baffoe, K (ed.). Food and Agricultural Organisation (FAO), Rome, Italy.

FAO. 2010b. Global Forest Resources Assessment 2010: Main report. Food and Agriculture Organization of the United Nations, Rome, Italy.

Flamenco-Sandoval, A, Martinez Ramos, M and Raul Masera, O. 2007. Assessing implications of land-use and land-cover change dynamics for conservation of a highly diverse tropical rain forest. *Biological Conservation* 138(1-2)**:**131-145.

Ghana Forestry Commission. 2013. Draft Ghana forest plantation strategy: 2015 - 2040. Ghana Forestry Commission, Accra, Ghana.

Ghana Statistical Service. 2005. 2000 Population and Housing Census, Analysis of District Data and implications for Planning, Western Region, Ghana. *In:* Twum-Baah, KA, Kumekpor, TKB and Addae-Mensah, I (eds.). Ghana Statistical Service, Accra, Ghana.

Ghana Statistical Service. 2013. 2010 Population & housing census, National analytical report. *In:* Awusabo-Asare, K (ed.). Ghana Statistical Service, Accra, Ghana.

Gold Fields Limited. 2012a. Damang Gold Mine, Technical Short Form Report. Gold Fields Limited, South Africa.

Gold Fields Limited. 2012b. Tarkwa Gold Mine, Technical Short Form Report. Gold Fields Limited, South Africa.

Houessou, LG, Teka, O, Imorou, IT, Lykke, AM and Sinsin, B. 2013. Land Use and Land-Cover Change at “W” Biosphere Reserve and Its Surroundings Areas in Benin Republic (West Africa). *Environment and Natural Resources Research* 3(2)**:**87-101.

Hu, Y, Zheng, Y and Zheng, X. 2013. Simulation of land-use scenarios for Beijing using CLUE-S and Markov composite models. *Chinese Geographical Science* 23(1)**:**92-100.

Hu, ZY and Lo, CP. 2007. Modeling urban growth in Atlanta using logistic regression. *Computers Environment and Urban Systems* 31(6)**:**667-688.

Judex, M, Thamm, H-P and Menz, G. 2006. Modelling of land-use changes in a West African catchment. *In:* Kerle, N and Skidmore, AK, eds. *ISPRS Mid-term symposium: From pixels to processes*. ISPRS.

Kamusoko, C, Aniya, M, Adi, B and Manjoro, M. 2009. Rural sustainability under threat in Zimbabwe – Simulation of future land use/cover changes in the Bindura district based on the Markov-cellular automata model. *Applied Geography* 29(3)**:**435-447.

Kortatsi, BK. 2003. Acidifcation of Groundwater and its Implication on Rural Water Supply in the Ankobra Basin, Ghana. *West African Journal of Applied Ecology* 4(2003)**:**35-47.

Kusimi, JM. 2008. Assessing land use and land cover change in the Wassa West District of Ghana using remote sensing. *GeoJournal* 71(2008)**:**249-259.

Kwakye, JK. 2012. Ghana’s middle-income reality check part I: The economic dimension. The Institute of Economic Affairs (IEA), Accra, Ghana.

Landis, JR and Koch, GG. 1977. The measurement of observer agreement for categorical data. *Biometrics* 33(1)**:**159-174.

Laurin, GV, Liesenberg, V, Chen, Q, Guerriero, L, Del Frate, F, Bartolini, A, Coomes, D, Wilebore, B, Lindsell, J and Valentini, R. 2013. Optical and SAR sensor synergies for forest and land cover mapping in a tropical site in West Africa. *International Journal of Applied Earth Observation and Geoinformation* 21(2013)**:**7-16.

Le, QB, Seidl, R and Scholz, RW. 2012. Feedback loops and types of adaptation in the modelling of land-use decisions in an agent-based simulation. *Environmental Modelling & Software* 27–28(2012)**:**83-96.

Legesse, D, Abiye, TA, Vallet-Coulomb, C and Abate, H. 2010. Stream flow sensitivity to climate and land cover changes: Meki River, Ethiopia. *Hydrology and Earth System Science* 14(2010)**:** 2277-2287.

Mango, LM, Melesse, AM, McClain, ME, Gann, D and Setegn, SG. 2011. Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: results of a modeling study to support better resource management. *Hydrology and Earth System Science* 15(2011)**:**2245-2258.

Matthews, R, Gilbert, N, Roach, A, Polhill, JG and Gotts, N. 2007. Agent-based land-use models: a review of applications. *Landscape Ecology* 22(10)**:**1447-1459.

Mertens, B and Lambin, EF. 2000. Land-cover-change trajectories in southern Cameroon. *Annals of the Association of American Geographers* 90(3)**:**467-494.

Meyfroidt, P, Lambin, EF, Erb, K-H and Hertel, TW. 2013. Globalization of land use: distant drivers of land change and geographic displacement of land use. *Current Opinion in Environmental Sustainability* 5(5)**:**438-444.

Moradkhani, H, Baird, RG and Wherry, SA. 2010. Assessment of climate change impact on floodplain and hydrologic ecotones. *Journal of Hydrology* 395(3-4)**:**264-278.

Park, JY, Park, MJ, Joh, HK, Shin, HJ, Kwon, HJ, Srinivasan, R and Kim, SJ. 2011a. Assessment of MIROC3.2 HIRES climate and CLUE-S land use change impacts on watershed hydrology using SWAT. *Transactions of the Asabe* 54(5)**:**1713-1724.

Park, S, Jeon, S, Kim, S and Choi, C. 2011b. Prediction and comparison of urban growth by land suitability index mapping using GIS and RS in South Korea. *Landscape and Urban Planning* 99(2)**:**104-114.

Parker, DC, Manson, SM, Janssen, MA, Hoffmann, MJ and Deadman, P. 2003. Multi-agent systems for the simulation of land-use and land-cover change: A review. *Annals of the Association of American Geographers* 93(2)**:**314-337.

Petschel-Held, G, Block, A, Cassel-Gintz, M, Kropp, J, Lüdeke, MKB, Moldenhauer, O, Reusswig, F and Schellnhuber, HJ. 1999. Syndromes of Global Change: a qualitative modelling approach to assist global environmental management. *Environmental Modeling & Assessment* 4(4)**:**295-314.

Pijanowski, BC, Alexandridis, KT and Mueller, D. 2006. Modelling urbanization patterns in two diverse regions of the world. *Journal of Land Use Science* 183-108.

Robinson, J, Brush, S, Douglas, I, Gradel, TE, Graetz, D, Hodge, W, Liverman, D, Melillo, J, Moss, R, Naumov, A, Njiru, G, Penner, J, Rogers, P, Ruttan, J and Sturdevant, J. 1994. Land-Use and Land-Cover Projections: Report of Working Group C. *In:* Meyer, WB and Turner Ii, BL (eds.) *Changes in Land Use and Land Cover: A Global Perspective.* Cambridge University Press, Cambridge, United Kingdom.

Ruelland, D, Levavasseur, F and Tribotté, A. 2010. Patterns and dynamics of land-cover changes since the 1960s over three experimental areas in Mali. *International Journal of Applied Earth Observation and Geoinformation* 12, Supplement 1(0)**:**S11-S17.

Schueler, V, Kuemmerle, T and Schroeder, H. 2011. Impacts of Surface Gold Mining on Land Use Systems in Western Ghana. *Ambio* 40(5)**:**528-539.

Soares-Filho, BS, Nepstad, DC, Curran, LM, Cerqueira, GC, Garcia, RA, Ramos, CA, Voll, E, McDonald, A, Lefebvre, P and Schlesinger, P. 2006. Modelling conservation in the Amazon basin. *Nature* 440(2006)**:**520-523.

Sohl, TL, Sayler, KL, Drummond, MA and Loveland, TR. 2007. The FORE-SCE model: a practical approach for projecting land cover change using scenario-based modeling. *Journal of Land Use Science* 2(2)**:**103-126.

Sutton, J and Kpentey, B. 2012. *An enterprise map of Ghana,* International Growth Centre,London, United Kingdom.

Takada , T, Miyamoto, A and Hasegawa, SF. 2010. Derivation of a yearly transition probability matrix for land-use dynamics and its applications. *Landscape Ecology* 25(2010)**:**561-572.

Tong, STY, Sun, Y, Ranatunga, T, He, J and Yang, YJ. 2012. Predicting plausible impacts of sets of climate and land use change scenarios on water resources. *Applied Geography* 32 (2012)**:**477 - 489.

Tran Van, T, Sunada, K, Ichikawa, Y and Oishi, S. 2012. Scenario-based Impact Assessment of Land Use/Cover and Climate Changes on Water Resources and Demand: A Case Study in the Srepok River Basin, Vietnam-Cambodia. *Water Resources Management* 26(5)**:**1387-1407.

Tsuma, W. 2009. *Gold Mining in Ghana, Actors, Alliances and Power,* LIT Verlag,Berlin, Germany.

Verburg, P and Veldkamp, A. 2004. Projecting land use transitions at forest fringes in the Philippines at two spatial scales. *Landscape Ecology* 19(1)**:**77-98.

Verburg, PH, de Koning, GHJ, Kok, K, Veldkamp, A and Bouma, J. 1999. A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. *Ecological Modelling* 116(1)**:**45-61.

Verburg, PH and Overmars, KP. 2009. Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. *Landscape Ecology* 24(9)**:**1167-1181.

Verburg, PH, Soepboer, W, Veldkamp, A, Limpiada, R, Espaldon, V and Mastura, SSA. 2002. Modeling the spatial dynamics of regional land use: The CLUE-S model. *Environmental Management* 30(3)**:**391-405.

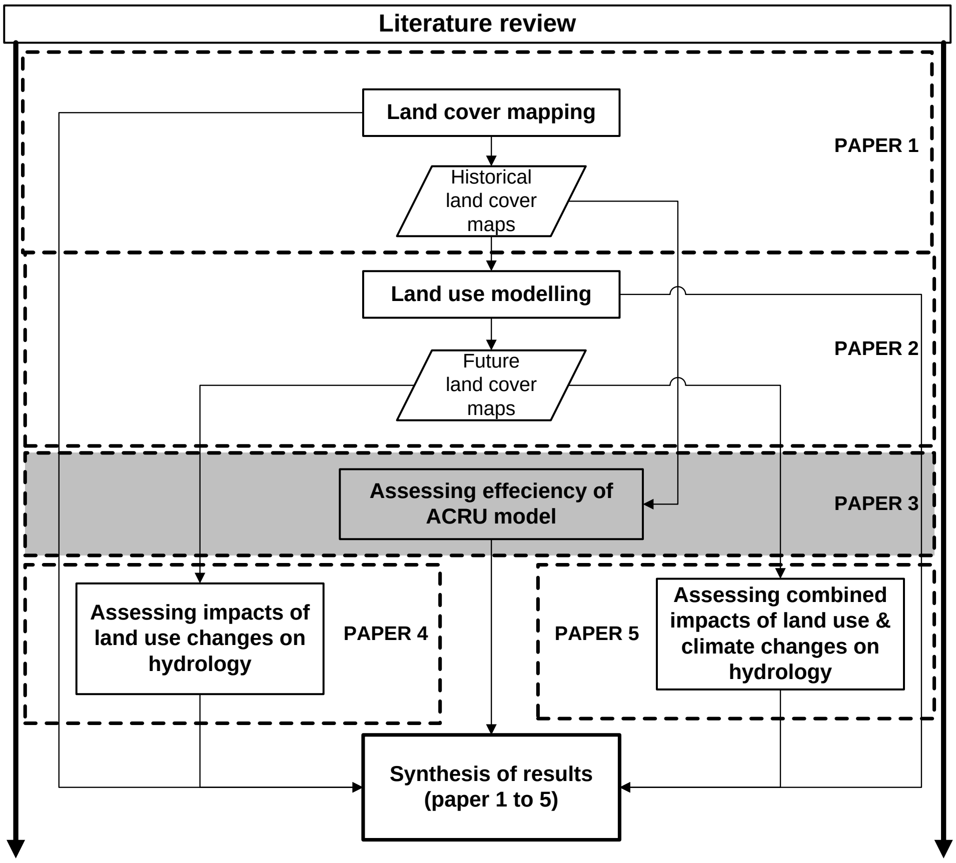
Vermeiren, K, Van Rompaey, A, Loopmans, M, Serwajja, E and Mukwaya, P. 2012. Urban growth of Kampala, Uganda: Pattern analysis and scenario development. *Landscape and Urban Planning* 106(2)**:**199-206.

Zhang, RQ, Tang, CJ, Ma, SH, Yuan, H, Gao, LL and Fan, WY. 2011. Using Markov chains to analyze changes in wetland trends in arid Yinchuan Plain, China. *Mathematical and Computer Modelling* 54(3-4)**:**924-930.

Zhou, D, Lin, Z and Liu, L. 2012. Regional land salinization assessment and simulation through cellular automaton-Markov modeling and spatial pattern analysis. *Science of The Total Environment* 439(0)**:**260-274.

Preface to Chapter 5

Understanding impacts of Global Changes on hydrology and consequent river ecological alterations requires the application of hydrological model capable of describing adequately the hydrological process of a catchment under consideration. In a data scarce region the use of limited data and sensitivity analysis is one method used to gain understanding of the hydrological process, as the major parameters influencing hydrology can be determined for effective modelling. The objective of Chapter 5 (shown in shaded portion of figure below) is to use sensitivity analysis to select parameters of the ACRU model and to conduct hydrological modelling for the Bonsa catchment, which is a representative lowland rainforest catchment in West Africa. Afterwards, the calibrated ACRU model can be used to simulate hydrology under historical, current and potential future land use, as well as climate changes, with confidence. The historical land use was obtained from Chapter 1 above.



CHAPTER 5 : ASSESSING SUITABILITY OF THE ACRU HYDROLOGICAL MODEL IN A RAINFOREST CATCHMENT IN WEST AFRICA[8]

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5.1 Abstract

Hydrological modelling is a challenge in the rainforest dominated Bonsa catchment (1482 km^2) in Ghana, West Africa, because of data scarcity and rapidly changing land uses, which makes it difficult to generate urgently needed reliable hydrological information for effective water resources management and land use planning. The objective of this study was to assess the suitability of the daily time step physical-conceptual ACRU model for hydrological modelling in the Bonsa catchment. Since the catchment is data poor, model calibration was conducted using a careful parameterization and sensitivity analysis, using initial values obtained from literature and field observations, as well as climate data for the period 1987 to 1999 and 1991 land use. The model performance during calibration was satisfactory, with a monthly Nash-Sutcliffe efficiency index and R^2 of 0.6 and 0.7, respectively. The model simulated the rise and the recession of the hydrograph well, but the accumulated monthly streamflows were underestimated by 5%. The main conclusion from this study is that the ACRU hydrological model is suitable for exploring basic hydrological responses to land use and climate in the Bonsa catchment. However, several challenges encountered during the modelling exercise are discussed and recommendations to assist modelling exercises in similar poorly gauged basins are provided.

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Key words: **data scarcity, hydrological modelling, poorly gauged basins, West Africa**

5.2 Introduction

Many catchments in West Africa are undergoing rapid land cover changes, as a result of rapid population growth, increased rural-urban immigration, urbanization, agricultural intensification and extensification, as well as expansion in surface mining (Schueler *et al.*, 2011). Modifications in land use alter the energy and water balance of the soil-vegetation-atmosphere system (Breuer *et al.*, 2009), which control hydrological responses and impacts negatively on the socio-economic wellbeing of people. Climate change also has the potential to alter hydrological flow regimes with negative consequences for the ecology, environment and the economy. In West Africa, climate change has already manifested (Conway *et al.*, 2009) in the form of erratic rainfall, high temperatures, frequent droughts and floods and reduced productivity of crops (Jalloh *et al.*, 2013). Mean annual rainfall is reported to have reduced by more than 20% and mean annual temperatures have increased by 2°Cbetween 1901 and 1995(Hulme *et al.*, 2001).According to the Intergovernmental Panel on Climate Change, IPCC (2007), temperatures will continue to rise in West Africa in the 21stcentury.

Effective planning of land use and water resources management in a catchment requires understanding of the interactions between climate and land use, as well as impacts of their changes on local hydrological components (Choi *et al.*, 2003). However, in data scarce regions such as West Africa, the assessment of climate change and land use change impacts on hydrology is a challenge because of a lack of adequate data and calibrated hydrological models. For this region the need to use process-based tools to derive as much information as possible from the limited data (Li *et al.*, 2009) can therefore not be overemphasized, as it is a key method for predictions in ungauged or poorly gauged basins, as recommended by the International Association of Hydrological Sciences' (IAHS) initiative on a decade of Predictions in Ungauged Basins (Parajka *et al.*, 2013). In this light, the use of hydrological models, which directly link model parameters to physically measurable catchment characteristics (Bastola *et al.*, 2008; Li *et al.*, 2009), to assess impacts is essential to understand the hydrology of a data scarce catchment, such as the Bonsa, an important rainforest dominated catchment in southwestern Ghana, West Africa.

The economy of the Bonsa catchment largely depends on mining and agriculture, but the majority of the population are employed in agriculture (Ghana Statistical Service, 2013). As the land cover changes through slash and burn agriculture and encroachment of farms by other users, agricultural productivity is likely to reduce, which can result in entrenchment of poverty. Availability of water may also be constrained, as rainfall has become erratic in the last four decades (Gyau-Boakye and Tumbulto, 2006; Lacombe *et al.*, 2012). Therefore, assessing the impacts of the land cover and climate changes on the hydrology of the catchment is important for the sustainable utilization of the natural resources, in order to protect life and property, empower the local people economically and to promote effective planning for the future. However, to assess impacts of land use and climate changes on hydrology, a suitable hydrological model is required. Literature (Jewitt and Schulze, 1999; Schulze, 2000; Jewitt *et al.*, 2004; Schmidt *et al.*, 2009; Warburton *et al.*, 2010; Forbes *et al.*, 2011; Mugabe *et al.*, 2011; Kienzle *et al.*, 2012) shows that the Agricultural Catchments Research Unit (ACRU) hydrological model is a suitable tool for hydrological modelling, as well as for the assessment of impacts of land use changes and climate changes on hydrology in catchments with diverse climates and land uses.

The ACRU model uses hydrological responses units to simulate catchment hydrology, similar to models such as the Soil and Water Assessment Tool (SWAT) and the Precipitation Runoff Modelling System (PRMS). However, the advantage of using the ACRU model in data scarce regions is that it is relatively less data intensive, compared to other physically-based semi-distributed models. The model also enables multi-level inputs and outputs, where information can be input and output depending on data availability or user requirement. However, the performance of the ACRU model for the data scarce rainforest catchments in West Africa, is not well known, as case studies in the region are rare. In West Africa only one study (Bekoe, 2005) applied the model in the Densu basin, West of Accra, Ghana. The study by Bekoe (2005) had several limitations including the use of very short record length (four years) of runoff and climate data. Also, the land use data (of 1990) applied in the study was more than fifteen years out of phase with the climate and runoff data (1968-1972). The objective of this study was therefore to assess whether the ACRU model can adequately simulate streamflows of the Bonsa catchment in Ghana, a representative lowland rainforest catchment in West Africa.

5.3 Methodology

5.3.1 Description of Study Area

The Bonsa catchment, a sub-catchment of the Ankobra River basin in Ghana, West Africa(Figure 5.1), is located between longitudes 1° 41´ and 2° 13´ West and latitudes 5° 4´and 5° 43´ North. The catchment straddles the intersection of four administrative districts, namely: Twifo-Heman Lower Denkyira to the north, Tarkwa Nsuaem and the Prestea-Huni Valley to the west and MpohorWassa East to the east. The population of the large towns in the catchment, such as Tarkwa and Abosso, has more than doubled in the past 30 years (Figure 5.2), with an annual growth rate of approximately 2% (Ghana Statistical Service, 2013). The catchment has a generally low relief, with the elevations ranging between 30 and 340 m above mean sea level draining an area of 1482 km^2.The rainfall regime is convective (Jackson *et al.*, 2009)and bimodal, with the major peak season from March/April to July and the minor peak from August/September to November. The annual rainfall ranges between 1500 mm and 2150 mm (Yidana *et al.*, 2007), while the annual average temperatures ranges from a minimum of 23ºC to a maximum of 31ºC.Predominant land cover consists of thick evergreen and secondary forests, with scattered shrubs and farms. The basin’s geology is characterized by Birimian and Tarkwaian rock systems (Akabzaa *et al.*, 2009), while the soil is composed mostly of Ferric Acrisols. Major economic activities in the catchment include open-pit gold mining, rubber cultivation, cocoa and food crop production.

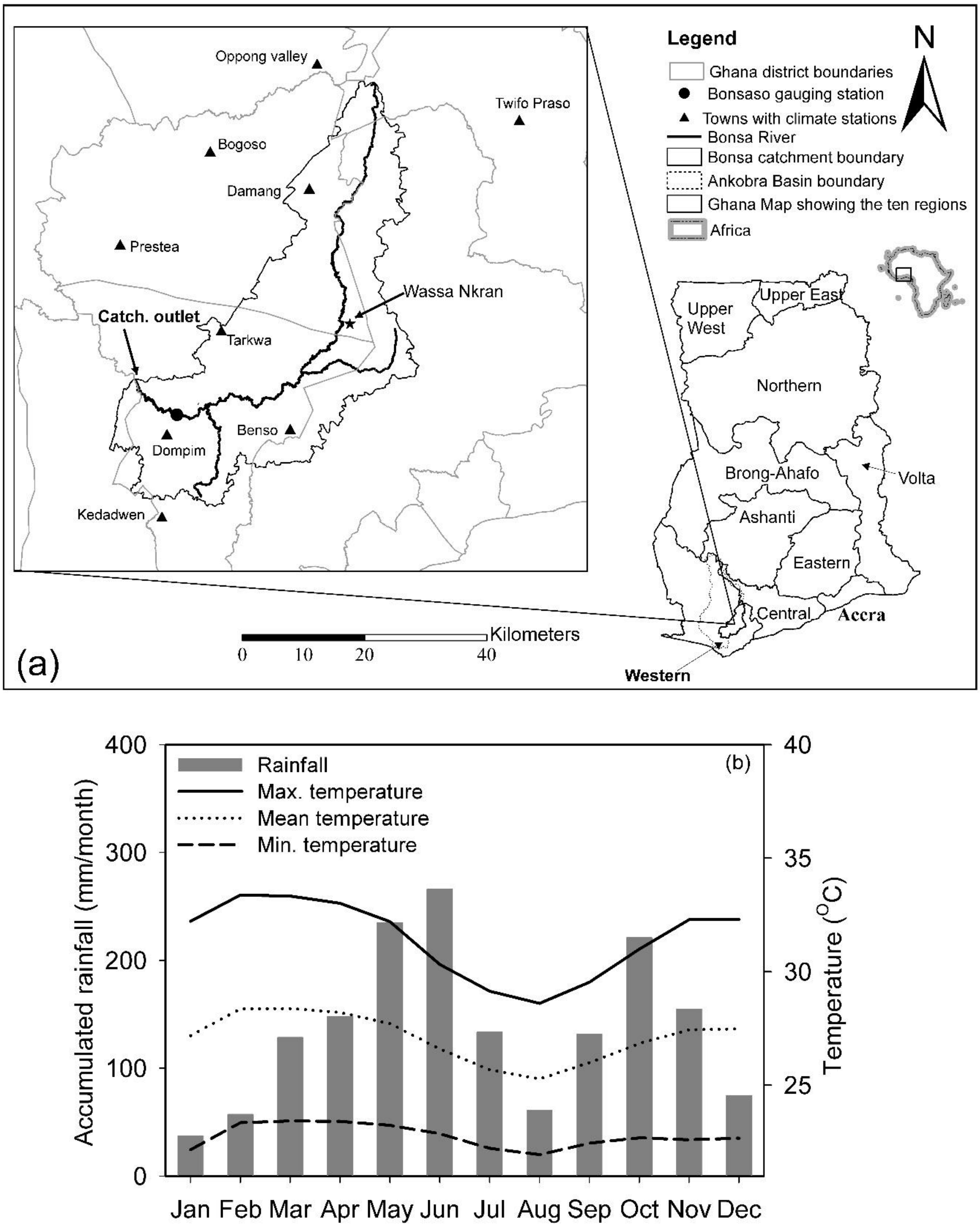


Figure 5.1: **Map of the Bonsa catchment in the Ankobra basin of Ghana (a) and a graph showing mean monthly climate between 1990 and 2009 for Tarkwa (b)**

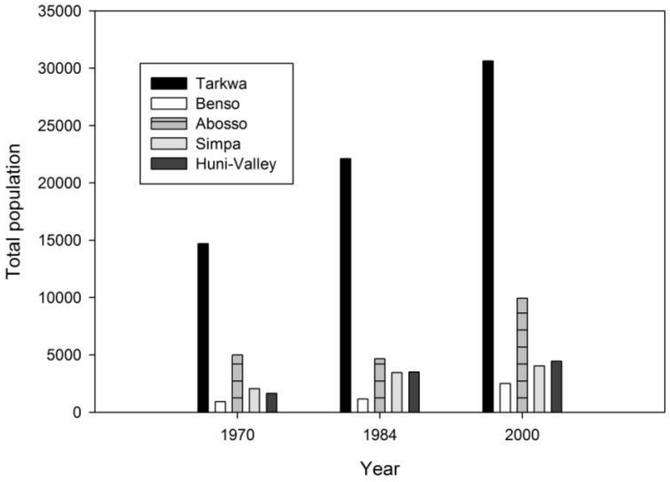


Figure 5.2: Population of major towns in Bonsa catchment from 1970 to 2000

5.3.2 Hydrological Modelling using ACRU

The ACRU Model (Schulze, 1995) is a daily time step physical-conceptual agro-hydrological model developed by the former School of Bioresources Engineering and Environmental Hydrology of the University of KwaZulu-Natal, South Africa to simulate catchment hydrological responses to land management. It is a multi-purpose model (Figure 5.3) that can be used for catchment water resources assessment, design floods, assessment of land use change and climate change impact (Schulze, 1995). The ACRU model is not considered a parameter optimising model, but rather uses variables derived from catchment physical properties (Schulze, 1995; Schulze, 2005; Warburton *et al.*, 2010).

The core module of the ACRU model is a multi-layer soil water budget based on total evaporation (Figure 5.3). The model is sensitive to climate and land cover/land use changes and is able to simulate their impacts on water flows. The land use component in the ACRU model is modelled, using canopy interception losses, total evaporation and soil water extraction by plant roots (Schulze, 1995; Warburton *et al.*, 2010). It is a multi-level model, with options for calculating water balance depending on the available data and the required outputs. Additionally, the model can operate as a point model or as a lumped small catchments model (Schulze, 1995). In large catchments with complex soils and land uses, the model can be used as a distributed cell-type model, where each cell is a sub-catchment. The sub-catchments can further be divided into hydrological response units (HRUs). Streamflow is modelled using a modified SCS curve number method; infiltration is computed with the Green-Ampt method and reference PET is obtained from A-pan observations or one of the reference PET methods, e.g. Penman (Chin, 2006), Hargreaves (Hargreaves *et al.*, 1985), Linacre (Schulze, 1995), or Blaney-Criddle (Schulze, 1995). One main disadvantage of the model for application in other regions is that its default values are based on soil information from Southern Africa (Schulze, 1995). Apart from the numerous successful application of the model in Southern Africa (Jewitt and Schulze, 1999; Warburton *et al.*, 2010; Mugabe *et al.*, 2011), the ACRU model has also been applied in Canada (Forbes *et al.*, 2011; Kienzle *et al.*, 2012), New Zealand (Kienzle and Schmidt, 2008; Schmidt *et al.*, 2009), Eritrea (Ghile, 2004) and Ghana (Bekoe, 2005).

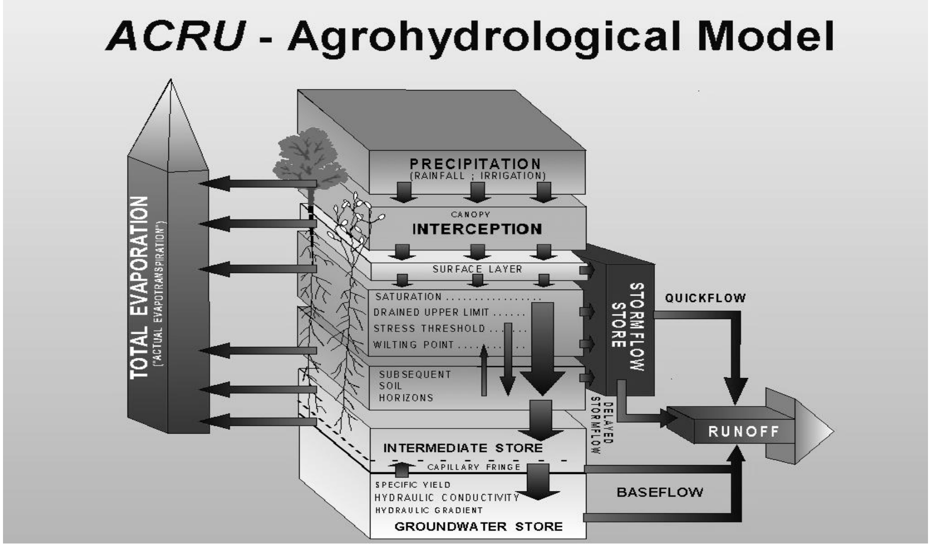


Figure 5.3: **Representation of hydrological processes in the ACRU model (Schulze, 1995)**

5.4 Model Parameterization and Data

5.4.1 Subcatchments and HRU Delineation

The Bonsa catchment was divided into 103 sub-catchments (Figure 5.4), using a contour and river courses map obtained from Survey of Ghana. The hydrological response units (HRUs) for each sub-catchment were delineated based on land cover types, since the catchment is relatively flat and has only one generalised soil class (i.e. forest oxysol), under the generalised soil classification system for Ghana (Dwomo and Dedzoe, 2010). The land cover data (Figure 5.4) was obtained from analysis of land cover changes in the Bonsa catchment (Aduah *et al.*, 2015). The sub-catchments and the HRUs (Figure 5.5) were based on the river courses, such that their streamflows cascaded into each other in a logical sequence representative of the river.

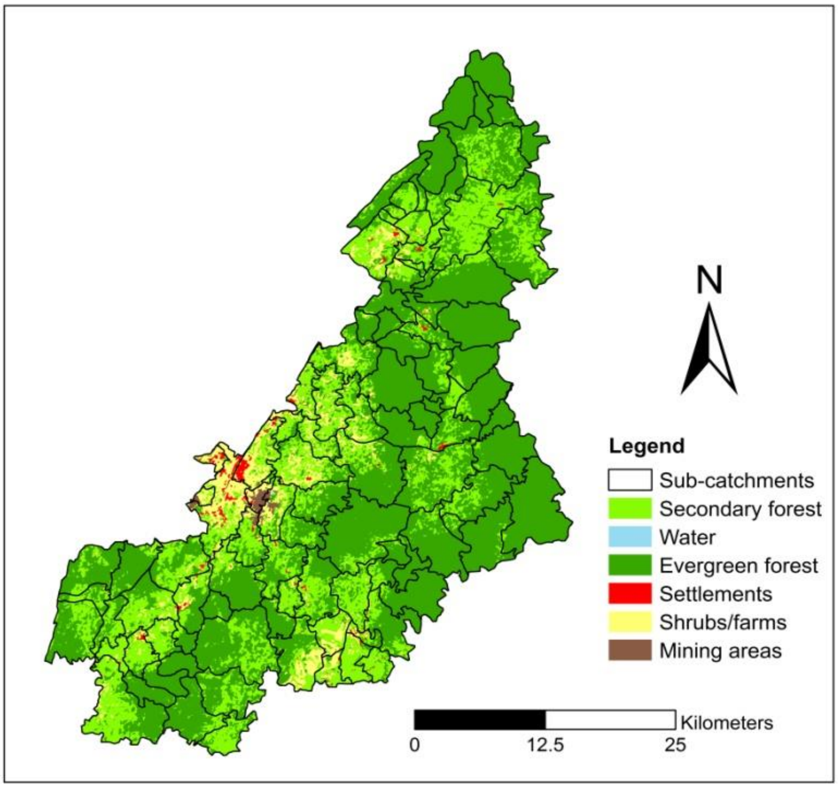


Figure 5.4: Land use/land cover of 1991 and subcatchments of Bonsa catchment

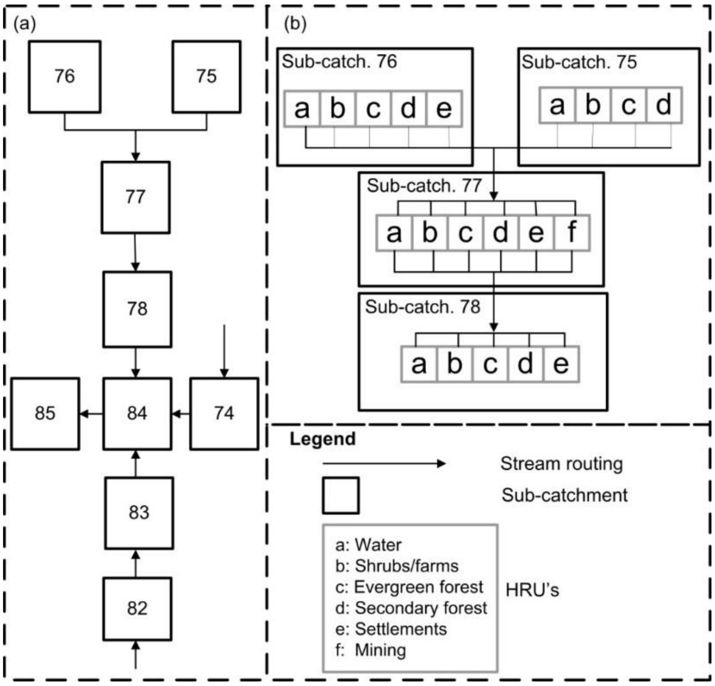


Figure 5.5: Example of subcatchment (a) and HRU streamflow configuration (b), for Bonsa catchment, showing the cascading of water flow from HRU's to subcatchments

5.4.2 Hydrometeorological Data

Daily streamflow records between 1970 and 2010 for the Bonsaso gauging station (Figure 5.1), were obtained from the Hydrological Services Department of Ghana. The streamflows records had missing data, ranging from a few days upto six months for many years. However, since there were no nearby gauging stations within the catchment, streamflow infilling was not done. For climate data, daily rainfall, daily maximum and minimum temperature records for four stations inside the Bonsa catchment and six neighbouring stations (Figure 5.1), were obtained from the Ghana Meteorological Agency (GMA) and Goldfields Ghana Ltd at Damang, Western region. Missing temperature data were estimated with the: (1) within-station technique (Allen and DeGaetano, 2001), which uses average values in the preceding or subsequent time steps of the same station and (2) linear regression (Allen and DeGaetano, 2001), using data from nearby stations. Erroneous rainfall values were identified by plotting graphs of the rainfall records and comparing the patterns of near-by stations (CWC, 1999).

The days with rainfall records significantly higher than those of near-by stations were suspected to be erroneous, since storm cells in the region are noted to be fairly large, with a mean area of more than 500 km^2(Jackson *et al.*, 2009). The suspected erroneous records were further investigated and confirmed by identifying them using the outlier identification procedure in the IBM SPSS software. Since daily rainfall data is positively skewed, a Box-Cox transformation (Makhuvha *et al.*, 1997), was used to transform the records into approximately normally distributed data. Overall, only a few days' rainfall records per year were identified as erroneous, which were recorded mainly during the rainy seasons. Outliers were removed because they are observations that do not follow the pattern of the majority of the observations and they exert disproportionate influence on any model (Schulze, 1995), which uses such observations.

For both the erroneous and the missing rainfall records, linear regression, using records from the highest correlated climate station and the station under consideration, was used for infilling. Further, in order to convert point rainfall to areal rainfall, which maintains the spatial variability of the sub-catchments/HRUs rainfall, monthly rainfall correction factors were generated and applied in the ACRU model, using the driver station method (Schulze, 1995Forbes *et al.*, 2011).The driver station method generates monthly rainfall correction factors using ratio of median monthly rainfall surfaces to the gauged median monthly rainfall. In this study the median monthly rainfall surfaces were created using a spline interpolation of 20 year median monthly rainfall records for climate stations in and around the study area.

Additionally, the Hargreaves and the Samani method (Hargreaves *et al.*, 1985) was used to compute reference evapotranspiration by the ACRU model, as this method required only monthly temperatures.

5.4.3 Soil data

A digital soil map for the Bonsa catchment was obtained from the Soil Research Institute (SRI) of Ghana. According to the SRI map, the Bonsa catchment is made up of three FAO soil classes, namely Ferric Acrisols (91.5%), Dystric Fluvisols (2.9%) and Plinthic Ferralsols (5.6%). According to Dwomo and Dedzoe (2010), the soils are also grouped under the forest oxysols, following the generalised soil classification system for Ghana. The forest oxysol parameters (Table 5.1) used in this study were obtained from Adjei-Gyapong and Asiamah (2002) and Dwomo and Dedzoe (2010). The ACRU model requires the depths of the topsoil (A horizon; DEPAHO) and the subsoil (B horizon; DEPBHO), the soil texture and permanent wilting points, field capacities and porosities for both topsoil and the subsoil. To obtain the soil water content at permanent wilting point (WP) and the soil water content at drained upper limit (field capacity) for the top- and subsoil horizons, the pedotransfer functions developed by Schulze *et al.* (1995), shown in Equation (5.1), were applied.

$$PWPA = 0.0572 + 0.00322 * Cl\%$$
$$DULA = 0.1506 + 0.00365 * Cl\%$$
$$PWPB = 0.0520 + 0.00322 * Cl\%$$
$$DULB = 0.1567 + 0.00365 * Cl\% \quad (5.1)$$

Where PWPA and DULA are the soil water content at permanent wilting point and drained upper limit, respectively, for the topsoil, while PWPB and DULB are the soil water contents for the subsoil. The Cl% is the percentage clay content in the soil.

Furthermore, the ACRU model requires porosities of the top- and subsoil horizons, as well as the surface properties of soils (e.g. crusting and cracking) and soil redistribution rates. In this study the soil surface properties were inferred from the soil textural classes, but for the soil porosities and the redistribution rates, values published by Schulze *et al.* (1995) were used, since no published records existed for the study area.

Table 5.1: Forest oxysols of the high rain forest zone, southwest Ghana (Dwomo and Dedzoe, 2010)

			Proportion (%)			
Soil series	**Horizon**	**Depth (cm)**	**Sand**	**Silt**	**Clay**	**Texture**
Ankasa	Ah1	0-5	66	14	20	Sandy loam
	Ah2	5-12	64	14	22	Sandy clay loam
	BA	12-36	59	13	28	Sandy clay loam
	Bts1	36-72	39	14	47	Clay
	Bts2	72-110	28	21	51	Clay
	Bt	110-150	30	23	47	Clay

5.4.4 Land Use Information

The land cover information required by the ACRU hydrological model are monthly values of the average crop coefficient for the pervious land cover (CAY), the fraction of effective root system in the soil (ROOTA), the mean value of leaf area index (ELAIM) and the interception loss by vegetation (VEGINT; mm.rain day^{-1}). The ACRU model converts the monthly vegetation parameter values into daily values, using Fourier analysis. The model also allows the use of either ELAIM or VEGINT for computing interception. The values of the initial land use parameters applied in this study are shown in Table 5.2. The initial parameter values were obtained from previous studies (Schulze, 1995; Bekoe, 2005; Warburton *et al.*, 2010). For water bodies, since field observations showed that they were mainly water contained in mining tailings dams, they were considered as closed storages, where there is no inflow from upstream or outflow to the downstream catchment. The only change was through increase in volume of water by discharge of mining waste and rainfall and loss of water by evaporation. The parameter value of the coefficient of initial abstraction (COIAM) for evergreen forest was obtained from a study by Poncea and Shetty (1995), who collated data on water abstraction by various vegetation types including those in the tropics. Maximum evaporation from soil surface can be suppressed by land surface cover such as leaf litter and mulch and their values vary with time. For the Bonsa catchment, the percentage surface covers (PCSUCO) for evergreen, secondary and shrubs/farms were estimated, based on field observations. The values for settlements and mining areas were, however, set to zero, since they are mostly bare lands.

Table 5.2: Initial land use parameters**

Land use	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Shrubs/farms	VEGINT(mm.rain/day)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ROOTA	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
	CAY	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7
	COIAM	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	*PCSUCO	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Evergreen and secondary forests	VEGINT(mm.rain/day)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	ROOTA	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	CAY	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8
	COIAM	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	*PCSUCO (Evergreen)	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
	*PCSUCO (secondary)	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Settlements and mining areas	VEGINT(mm.rain/day)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	ROOTA	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
	CAY	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7
	COIAM	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	*PCSUCO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Values obtained from field observations, **adapted from Schulze (1995), Bekoe (2005) and Warburton (2012).

5.4.5 Streamflow Simulation Control Variables

The ACRU model uses streamflow simulation control variables to determine the amount of rainfall that becomes part of streamflow and groundwater store. Typical values of streamflow simulation control variables obtained from Schulze (1995) were used for the simulation. The fraction of saturated soil water to be redistributed daily from the topsoil into the subsoil (ABRESP) and the fraction of saturated soil water to be redistributed daily from the subsoil into ground water store (BFRESP) were set to 0.1, which is a typical value for clay soils, while the soil depth from which stormflow takes place (SMDDEP) was set at 0.4 m, which is also a typical value for high rainfall catchments. A baseflow response fraction of 0.009, which is also typical value, was set to control amount of groundwater that becomes part of streamflow in a day. Quickflow response fraction (QFRESP), the fraction of rainfall that becomes streamflow during a rain day for each land use type was input in the ACRU model. For the evergreen, secondary and shrubs/farms, QFRESP of 0.1, 0.2 and 0.36 were used, respectively. The values were selected based on an assumption arising out of a study by Asomaning (1992), who obtained 0.36 as total runoff coefficient for a degraded forested catchment in southern Ghana. Furthermore, QFRESP of 0.7 was used for the settlements

(California EPA, 2011), which is a typical value, while a value of 0.5 was used for the mining areas, with the assumption that they are more pervious than settlement areas.

5.5 Sensitivity Analysis

According to Schulze (1995), a model's performance is only truly acceptable after a sensitivity analysis has been conducted. The sensitivity analysis builds confidence in the model structure and enables the modeller to understand the association between the model and the dominant physical processes taking place in a catchment (Atkinson *et al.*, 2002). Because of the lack of well-known measured data for the Bonsa catchment, a sensitivity analysis was conducted to determine the most sensitive parameters to streamflow simulation. Ten parameters namely QFRESP, ABRESP, BFRESP, SMDDEP, DEPAHO, DEPBHO, CAY, COIAM, VEGINT and ROOTA were selected to test their sensitivity to simulation of total streamflows by using the procedure outlined in Schulze (1995). The initial input parameter values (Table 5.2) for the ACRU model were increased/decreased iteratively for each simulation and computing the change in total streamflow as a result of the change in a particular parameter. The change in parameter value was computed using Equation (5.2), which was provided by Schulze (1995).

$$\Delta O\% = (o - o_{base})/(o_{base}) * 100\% \tag{5.2}$$

Where $\Delta o\%$ is the percentage change in total streamflow, o_{base} is the base value of streamflow corresponding to the initial parameter and o is the output streamflow after change in parameter value. Furthermore, the sensitivity of the parameters were ranked according to the criteria provided by Schulze (1995), which is shown in Table 5.3. Based on Table 5.3, the most sensitive, as well as the least sensitive parameters were identified, to aid further simulations.

Table 5.3: Ranking of sensitivities of ACRU model, adapted from Schulze (1995)

Sensitivity class	**Description**
Extremely sensitive	$\Delta O\% > 200\%\ \Delta I$
Highly sensitive	$200\%\ \Delta I > \Delta O\% > \Delta I\%$
Moderately sensitive	$\Delta I\% > \Delta O\% > 50\%\ of\ \Delta I$
Slightly sensitive	$50\%\ \Delta I > \Delta O\% >10\%\ \Delta I$
insensitive	$\Delta O\% < 10\%\ \Delta I$

$\Delta I\ is\ change\ in\ input\ parameter$

5.6 Model Calibration

The ACRU hydrological model was calibrated by carefully varying the sensitive parameters, iteratively within their physical limits, until the simulated streamflows compared well with the observed streamflows. The model performance was evaluated using the coefficient of determination (R^2) and the Nash-Sutcliffe efficiency index (NSE) (Moriasi *et al.*, 2007), by comparing the simulated and observed streamflows at the Bonsaso gauge (Figure 5.1), which has 85 upstream subcatchments. The calibration target was R^2 and NSE greater than 0.5, which indicates a model with satisfactory performance. The simulation was carried out using observed climate records for the period from 01-01-1987 to 31-12-1999 and 1991 land use data. The period from 01-01-1987 to 31-12-1989 was used as a warm-up period and was not used in model calibration.

5.7 Results

5.7.1 *Sensitivity Analysis*

The results of sensitivity analysis, which are presented in Table 5.4 and Figure 5.6, indicate that the insensitive parameters to streamflow simulation in the Bonsa catchment were the QFRESP, ABRESP and BFRESP, SMDDEP and COIAM, while DEPAHO, DEPBHO, CAY and VEGINT were slightly sensitive and only ROOTA was moderately sensitive, when the parameters were increased iteratively by 10%. On the other hand, when the parameters were decreased iteratively by 10%, QFRESP, BFRESP, SMDDEP, ROOTA and COIAM were insensitive, while DEPAHO, DEPBHO and CAY were moderately sensitive, but VEGINT was slightly sensitive. Thus CAY, DEPAHO, DEPBHO, ROOTA and VEGINT were the most sensitive parameters in the Bonsa catchment. Table 5.5 shows the final model parameters used in this study, as they reproduced the best correspondence between observed and simulated streamflows.

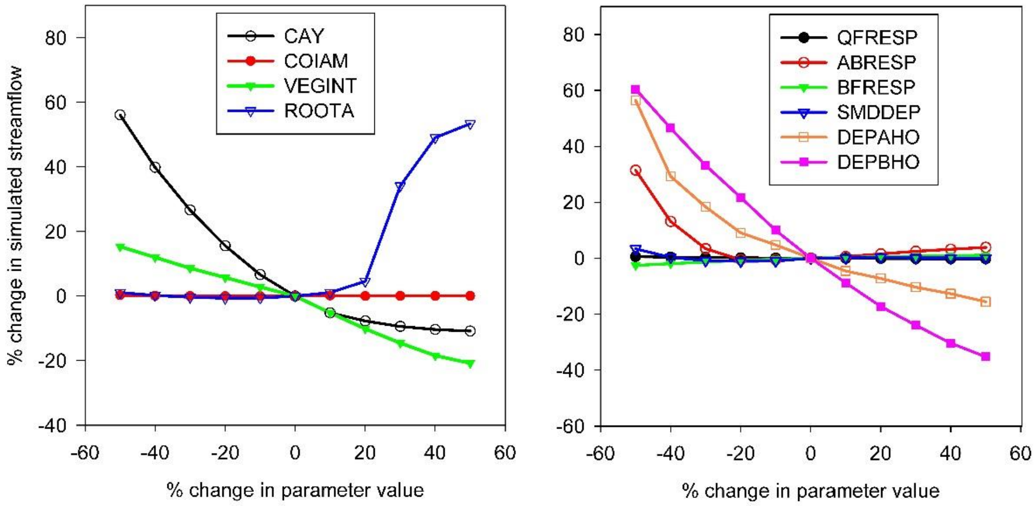


Figure 5.6: Sensitivity of streamflows as a result of change in parameters in Bonsa catchment

Table 5.4: Sensitivity ranking of streamflow simulation parameters in Bonsa catchment

Parameter	Sensitivity when parameter is		
	Increased	Reduced	Remarks
QFRESP	I	I	
DEPAHO	S	M	
DEPBHO	S	M	DEPBHO more sensitive than DEPAHO
ABRESP	I	S	
BFRESP	I	I	
SMDDEP	I	I	
CAY	S	M	
VEGINT	S	S	
ROOTA	M	I	
COIAM	I	I	

I=insensitive; Slightly sensitive (S); moderately sensitive (M); highly sensitive (H)

Table 5.5: Final land use parameters used for simulation

Land use	**Variable**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Shrubs/farms	VEGINT (mm.rain/day)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	CAY	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
	COIAM	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	PCSUCO	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00
Evergreen forest	VEGINT (mm.rain/day)	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
	ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	CAY	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	COIAM	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
	PCSUCO	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00
Secondary forests	VEGINT (mm.rain/day)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	CAY	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	COIAM	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
	PCSUCO	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00
Mining areas	VEGINT (mm.rain/day)	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
	ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	CAY	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
	COIAM	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	PCSUCO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Settlements	VEGINT (mm.rain/day)	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
	ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	CAY	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
	COIAM	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	PCSUCO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

5.7.2 Model Calibration

Using the final parameters, the calibrated ACRU model was used to simulate the hydrology of the Bonsa catchment. Model validation was not done as there was no independently available observed streamflows. Table 5.6 shows the statistics of model performance at the monthly time step during calibration, while Figure 5.7 presents a graph of observed and simulated streamflows plotted together with rainfall at the Benso climate station as well as mean annual streamflow map. It can be observed from the statistics in Table 5.6 that the model performance corresponded fairly well with the observed streamflows for the period 1990 to 1999. Monthly NSE of 0.6 and R^2 of 0.7 were obtained, which is within the range suggested by Moriasi *et al.* (2007) for satisfactory model performance. From Figure 5.7, it is evident that the model simulated low flows well, but overestimated high flows and the percentage difference between the standard deviations of total observed and simulated streamflows (28%) was rather large. However, the rising and the recession of the hydrograph were simulated well. The model also underestimated the accumulated monthly streamflows by 5% (Table 5.6). Calibration based on the daily time step, however, did not generate satisfactory NSE. The model calibration method applied in this study is similar to traditional model calibration, however, the advantage of using ACRU model is that the calibration in this study was physically meaningful. The calibration relied on relatively less data, which is physically meaningful and readily available for most data scarce regions. Since the calibration was executed successfully by varying the model parameters within their physical limits in the Bonsa catchment and the ACRU model is not a parameter optimising model, but rather depend mainly on physical catchment variables (Schulze, 1995), we suggest that the model is useful for exploring basic hydrological responses to land use and climate in the Bonsa catchment, although it is not validated. Further, the mean annual streamflow map (Figure 5.7c) shows that subcatchments in the west and middle sections of the Bonsa catchment, which have settlements, mining and shrubs/farms land uses (Figure 5.4) generated the highest streamflows, while those in the northern, eastern and south which have forest land uses generated the lowest streamflows; indicating that the ACRU model generally simulates the Bonsa catchment’s water balance well. Since the observed streamflow records had severe data gaps, it was not possible to compare simulated and observed flow duration curves.

Table 5.6: **Statistics of performance of ACRU model at the Bonsa catchment outlet: Comparison of monthly observed and simulated values**

1990-1999	Bonsa catchment
Total Observed flows (mm)	1877.5
Total Simulated flows (mm)	1788.8
Av. Error in flows (mm/month)	-0.8
Mean Observed flows (mm/month)	17.9
Mean Simulated flows (mm/month)	17
% Difference between means	4.7
Std. Deviation of observed flows (mm)	14.4
Std. Deviation of simulated flows (mm)	18.4
% Difference between std. Deviations	-27.8
Correlation Coefficient: Pearson's R	0.9
Regression Coefficient (slope)	1.1
Regression Intercept	-2.6
Coefficient of Determination: R^2	0.7
Nash-Sutcliffe Efficiency Index (NSE)	0.6

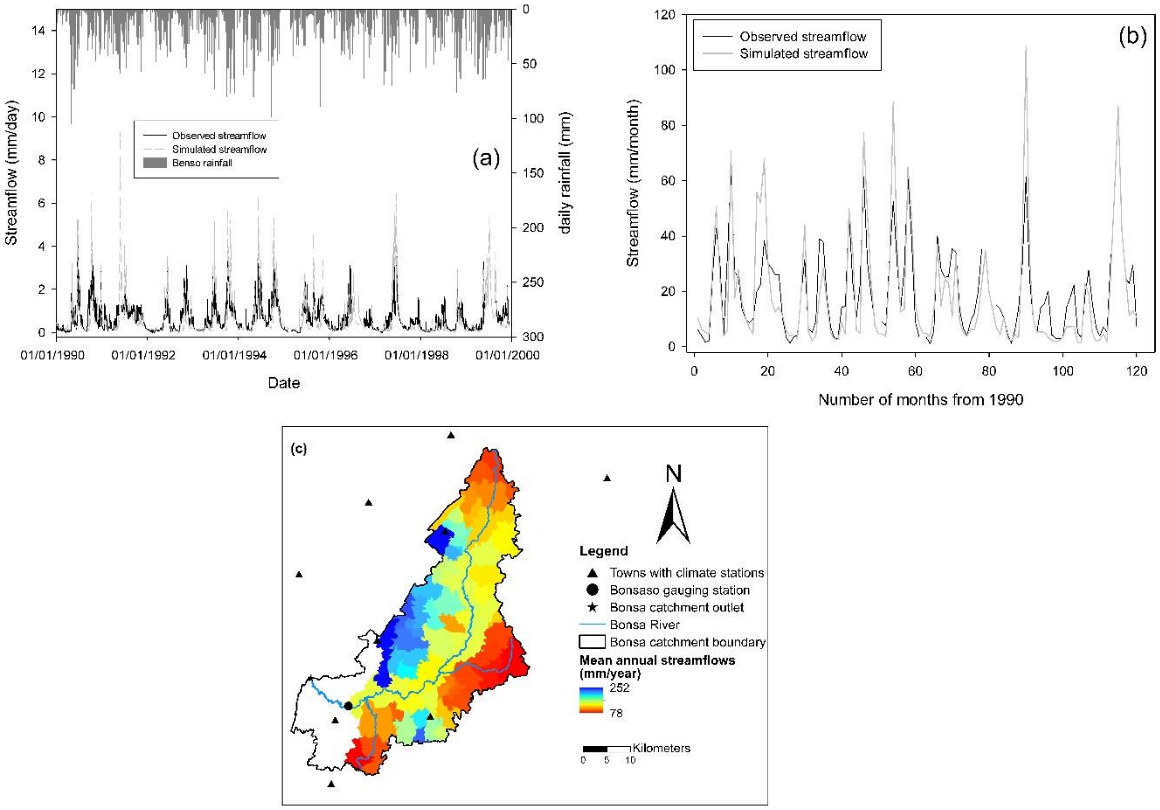


Figure 5.7: **Observed and simulated (a) daily and (b) monthly streamflows at the Bonsaso gauging station, as well as rainfall at Benso climate station from January 1990 to December 1999. (c) mean annual (1990-1999) streamflow map for subcatchments upstream of Bonsaso gauging station**

5.8 Discussion

5.8.1 Sensitivity Analysis

The sensitivity of the ACRU model parameters for the Bonsa catchment obtained in this study clearly show that CAY, VEGINT and the soil depths are the most significant parameters that need more attention in order to estimate their values accurately. Since VEGINT is the amount of rainfall intercepted by vegetation, its value depends on the canopy storage capacity and the leaf area index (Bulcock and Jewitt, 2012b), as well as on the density of the vegetation. Hence a reliable estimate of VEGINT should be based on the vegetation types as shown by Bulcock and Jewitt (2012a). VEGINT (interception loss) has previously been found to be significant in a humid tropical catchment in Puerto Ricoand the KwaZulu Natal province in South Africa by Schellekensa *et al. (*1999) and Bulcock and Jewitt (2012a), respectievly. Bekoe (2005) also concluded that VEGINT is a sensitive parameter for the Densu basin in southern Ghana. The studies by Schellekensa *et al. (*1999), Bulcock and Jewitt (2012a) and Bekoe (2005) were conducted in catchments with high frequency of low intensity rainfall events. Hence it is not surprising that interception loss is significant in the Bonsa catchment as there is a high frequency of low intensity rainfall events in the catchment. Furthermore, soil depths affect processes such as evaporation, transpiration, soil moisture status, baseflow and groundwater storage, which together control streamflow. Since each of these processes is significant in the hydrological cycle of a humid tropical forest region, reliable estimates of the topsoil and the subsoil horizon depths is also vital in determining reliable streamflows. Concerning CAY and ROOTA, their values are also related to land cover types. While CAY is crop coefficient of a land cover type, ROOTA depends on the distribution of the root system within the topsoil horizon. CAY and ROOTA are significant controlling factors of evaporation and transpiration; hence their values need to be known accurately in order to reliably simulate streamflows in a catchment.

The results of sensitivity analysis of streamflows to ACRU model parameters in this study confirms those obtained by Bekoe (2005) for the Densu, a coastal Savanah basin in southern, Ghana. The identified sensitive parameters provide important information to guide data collection and hydrological modelling in similar lowland rainforest catchments, especially in West Africa. The lowland rainforests of West Africa, have similar rainfall patterns (bimodal regime) and vegetation types, which is likely to result in similar hydrological regimes. It may therefore be possible to transfer some of the parameters generated in one catchment to other physically similar catchments, based on the similarity (climate, catchment and runoff) of physical properties approach of regionalisation (Wagener *et al.*, 2013). In the current study, CAY, VEGINT and ROOTA which are the most sensitive parameters in the Bonsa catchment will be more transferable to other catchments, compared to the soil depths. The reason is that VEGINT, CAY and ROOTA are based on vegetation types, which are similar in all lowland/Guinean rainforests in West Africa. Therefore, future modelling exercises in West African rainforest regions should benefit from this study by paying more attention to the VEGINT, CAY, soil depths and ROOTA. The other parameters are also important in achieving reliable hydrological modelling, using the ACRU model; however, this study has shown that their values can be estimated based on literature, without incurring much error in model outputs.

5.8.2 Model Calibration

Physically meaningful model calibration with a NSE of 0.6 and R^2 of 0.7 (Moriasi *et al.*, 2007) is an indication that the ACRU model can be used to explore basic hydrological responses in the Bonsa catchment. The errors in the simulated streamflows are the result of inadequate data inputs, including lack of information on the amount of water withdrawals and discharges by mining companies, located upstream of the Bonsaso gauging station and poor knowledge of the water use of the vegetation, as well as the lack of detailed soil information. The results are however comparable to those of a previous study in Ghana (Bekoe, 2005). However, with only a satisfactory calibration at the monthly time step and no formal validation against independent data, we suggest that the model can only be used for exploring basic streamflow responses to land use and climate for long term water management in the Bonsa catchment. The results of the hydrological modelling in this study are a reflection of the capabilities of semi-distributed, physically-based conceptual models such as the ACRU, to provide information for long term water resources management in data scarce catchments. Although the majority of the data applied in this study were poorly known, the success of the physically meaningful calibration justifies the application of the ACRU model in data scarce regions, as it is capable of reproducing the basic hydrological patterns, using relatively less data.

The major drivers of hydrological regimes, such as climate and land use, are uncertain for future time periods - and given that other variables which influence model performance play less critical roles in long term hydrological regimes, a model successfully calibrated using physically meaningful parameters and validated for the historical time period in a diverse range of catchments is the best tool available for assessment of potential future impacts of global changes. In poorly gauged or ungauged basins, real-time model validation, using data assimilation techniques, can also be applied to progressively ascertain the reliability of models used to study potential future hydrological impacts.

5.8.3 Challenges to Hydrological Modelling in Bonsa Catchment

The challenge to hydrological modelling in the Bonsa catchment is that some of the variables/parameters were either poorly known or unknown and only one streamflow gauge was available. The rainfall and the soil data was of poor quality, while there was lack of data on vegetation parameters, as well as streamflow simulation control variables. Other challenges to successful hydrological modelling was the lack of data on water withdrawals/discharges for domestic, mining and agricultural purposes, as well as rapid land use changes, during the period used for model calibration. The only data that was considered adequate was the static land use data, derived from a 30 m resolution Landsat image.

The poor quality of the rainfall data is the result of many missing, as well as erroneous rainfall records. Attempts were made to complement the observed rainfall station data with satellite-based rainfall estimates, however, two sources, viz.: TAMSAT and CHIRPS (not included in this paper), drastically underestimated rainfall for the catchment, hence they were not considered suitable. It is suggested that the correspondence between observed and simulated streamflows would have been better if the rain gauge network distribution and density was optimal, especially because of the convective nature of the rainfall in the catchment. Most of the current rain gauges in the Bonsa catchment are concentrated in the settlement and mining areas, with no rain gauges located in the forested areas. To obtain a more representative areal rainfall for the entire catchment, it is suggested that more rain gauges are installed especially in the forest reserves within the catchment area.

The lack of adequate soil information also affected model accuracy, as the soil map was coarse (scale of 1:250 000) and the soil physical properties were not known for the Bonsa catchment. The soil physical properties required by the ACRU model included the depth of the top and sub-soil horizons, the permanent wilting points and the field capacity, as well as porosities. Because of the lack of these soil parameters for the catchment, published values for the entire high rainforest region of Ghana (Adjei-Gyapong and Asiamah, 2002; Dwomo and Dedzoe, 2010), were used. Since the soil map was coarse, it had only one soil type for the entire 1482 km^2 catchment. The use of a generalised soil map and soil properties, which were not specifically determined for the catchment as well as the use of Southern African rainfall-intensity curves to disaggregate daily rainfall for calculation of infiltration within the ACRU model code (Schulze, 1995) are some of the reasons why the model performance did not correspond well with the daily observed streamflows.

Furthermore, there was no information on the vegetation parameters of the catchment. These included the CAY, COIAM, VEGINT, ROOTA, ROOTB and PCSUCO. The initial values used in the model are those from previous studies (Schulze, 1995; Bekoe, 2005; Warburton, 2012). However, the COIAM for the dominant land cover, evergreen forest, was obtained from a study that compared water abstraction by different tropical forests (Poncea and Shetty, 1995). The final parameters for the model were obtained after smoothly varying the parameters within their physical limits iteratively and each time the simulated and the observed streamflows were compared. The PCSUCO, however, was based on visual inspection of the evergreen and the secondary forest floors, during field visits and then successively reducing it for the less vegetated land covers, resulting in settlements and mining areas having zero percentage surface cover, since they are mostly bare lands.

The lack of information on the streamflow simulation control variables also affected the accuracy of simulation. Typical values of SMDDEP, ABRESP and BFRESP for high rainfall regions and clay soils obtained from Schulze (1995), were used. QFRESP and baseflow (fraction of soil water that becomes part of groundwater daily) response fractions were also assumed based on typical values provide by Schulze (1995), as well as values from Bekoe (2005) and Warburton *et al.* (2010). Higher QFRESP response fractions were assumed for the settlements, mining areas and shrubs/farms, because these land covers have higher runoff coefficients, while relatively lower values were selected for the secondary and the evergreen forests. For the baseflow response fraction, all the land uses were assigned the same value, since it is controlled largely by the soil type, which is mostly clay for the entire catchment. Field measurements of the streamflow control variables provides the most reliable values, however, it was not possible to conduct field surveys in this study due to lack of funds. However, based on the sensitivity analysis, these variables were not very sensitive in the Bonsa catchment, hence it was assumed that errors in estimating their values contributed less to the overall model uncertainties.

The lack of data on water withdrawals/discharges in the catchment also played a role in the poor correspondence between observed and simulated daily streamflows. The Ghana water company draws water upstream of the Bonsaso gauge for domestic purposes. Contacts were made with the company, but no records of the volumes of water withdrawals were available, as the company only measures the water level in the river. According to the mining companies (AngloGold Ashanti, 2013; Gold Fields Limited, 2013) in the catchment, groundwater, as well as surface water (drawn from tributaries of the Bonsa River) is used for their operations. However, only aggregated volumes of water for a particular mine per year were available and there were no indications of the locations from which water withdrawals were made, especially for the surface water. From field visits it was also observed that water is discharged from abandoned underground mines in the Tarkwa Township, to control mine flooding and this water forms part of the streamflows. However, data on the volumes of water discharged were not available for this study.

Studies elsewhere show that hydrological modelling performance is sensitive to land use changes (Mahe *et al.*, 2005). The use of 1991 land cover to simulate 1990 to 1999 streamflows, in a catchment undergoing rapid changes, limited the modelling accuracy, as land use changes between 1991 and 1999 were not accounted for, during the simulation. For a catchment that is undergoing rapid land use changes, dynamic land use data is more appropriate in order to simulate the hydrology accurately (Tarboton and Schulze, 1995). The quality of the observed streamflows can also reduce the correspondence between observed and simulated streamflows. Streamflows at the Bonsaso gauge were estimated by the Ghana Hydrological Services Department, using water levels under a bridge. The estimation is based on a rating curve (Personal Communication, Mr. Mawuli Lumor: Ankobra Basin Officer, Water resources Commission of Ghana). A wrong or outdated rating curve, has the potential to generate inaccurate streamflows. Overtopping of the river gauge is also another contributing factor to poor streamflow observations. In the Bonsa catchment, the large number of missing records during the peakflow seasons is an indication of overtopping of the stream gauge (Figure 5.7). The use of only one streamflow gauge is also a major challenge to successful hydrological modelling, especially in understanding the hydrology of the interior of a catchment. According to Wi *et al.* (2015) using multisite streamflow gauges within the interior parts of a catchment improves modelling accuracies, however, there was only one gauge available for model calibration in the Bonsa catchment.

5.8.4 Recommendations to Assist Future Modelling in Similar Basins

Based on the identified challenges to hydrological modelling in the Bonsa catchment, the recommendations below are presented to support future studies to progressively improve the quality of simulation. The recommendations are as follows:

- Values of three parameters namely VEGINT, CAY and ROOTA, applied in this study can be used to simulate catchment hydrology in similar lowland high rainforest catchments in West Africa, since they have relatively similar land uses, topography and rainfall regime,
- Values of QFRESP, ABRESP, BFRESP, SMDDEP and COIAM can be estimated based on literature for streamflow simulation in lowland rainforests in West Africa, without much error,
- Field methods should be employed to estimate the water use of the different vegetation types,
- Rainfall data should be screened for outliers since rainforest catchments often receive high intensity localised storms, which can exert disproportionate influence on streamflow simulation if not corrected for,
- Detailed soil surveys need to be conducted to provide adequate hydrological soil information in order to achieve accurate streamflow simulation for rainforest catchments in West Africa,
- The number of rain gauges need to be increased, especially in the forested areas, in order to capture the spatially variability of rainfalls,
- In order to be able to make long-term plans for water management downstream, several weirs need to be constructed on the Bonsa River. A weir should be constructed upstream of the intake point of the Ghana water treatment plant at Bonsa and another

weir(Figure 5.1) near Wassa Nkran (south of Damang climate station) to measure inflows from upstream areas, which drain mining, natural and agricultural land uses. A weir should also be located at the middle portion of the main river, where the main eastern tributary joins the main river and west of the Subiri forest reserve (largest forest reserve in Ghana). This weir can be used to measure inflows from the Subiri forest reserve. Finally, a weir should be constructed at the outlet of the catchment, downstream of the current gauge at Bonsaso. The installation of gauges in the interior parts of the catchment has the potential to improve future hydrological modelling accuracies and will be vital in making reliable streamflow projections under climate change, since calibration of models, using multisite streamflow gauges is far more accurate than using only gauges at basin outlets (Wi *et al.*, 2015).

- The sensitivity analysis in the ACRU model should be automated to make it more applicable in ungauged or poorly gauged basins, since the current manual technique is time consuming and makes it difficult to carryout simulation in ungauged or poorly gauged basins. To adapt the ACRU model to West Africa, the rainfall intensity curves which are used to disaggregate daily rainfall in the model should be replaced with those for West Africa.

5.9 Conclusion

This study has identified the significant model parameters in the Bonsa catchment through a sensitivity analysis, which has enabled successful hydrological modelling for the catchment, using the ACRU model. This study indicates that the ACRU model is suitable for simulating streamflows in the Bonsa catchment, has identified several challenges associated with modelling in a data scarce catchment and suggested ways to improve hydrological modelling in the catchment, as well as in similar basins.

5.10 References

Adjei-Gyapong, T and Asiamah, RD. 2002. The interim Ghana soil classification system and its relation with the World Reference Base for Soil Resources. 2002 ed. FAO, Rome, Italy.

Aduah, MS, Warburton, ML and Jewitt, G. 2015. Analysis of land cover changes in the Bonsa catchment, Ankobra Basin, Ghana. *Applied Ecology and Environmental Research* 13(4)**:**935-955.

Akabzaa, TM, Jamieson, HE, Jorgenson, N and Nyame, K. 2009. The Combined Impact of Mine Drainage in the Ankobra River Basin, SW Ghana. *Mine Water and the Environment* 28(1)**:**50-64.

Allen, RJ and DeGaetano, AT. 2001. Estimating missing daily temperature extremes using an optimized regression approach. *International Journal of Climatology* 21(11)**:**1305-1319.

AngloGold Ashanti. 2013. Carbon Disclosure Project : CDP 2013 Water Disclosure, 2013 Information Request[Online]. AngloGold Ashanti. Available: http://www.anglogoldashanti.com/en/sustainability/CarbonDisclosureProject/WaterSubmissions/CDPWaterDisclosure2013.pdf [Accessed 6th March 2015].

Asomaning, G. 1992. Groundwater resources of the Birim basin in Ghana. *Journal of African Earth Sciences (and the Middle East)* 15(3–4)**:**375-384.

Atkinson, SE, Woods, RA and Sivapalan, M. 2002. Climate and landscape controls on water balance model complexity over changing timescales. *Water Resources Research* 38(12)**:**1314.

Bastola, S, Ishidaira, H and Takeuchi, K. 2008. Regionalisation of hydrological model parameters under parameter uncertainty: A case study involving TOPMODEL and basins across the globe. *Journal of Hydrology* 357(3–4)**:**188-206.

Bekoe, EO. 2005. Application of a hydrological model in a data-poor tropical West African catchment: a case study of the Densu Basin of Ghana. Unpublished PhD Thesis, Institute of Water and Environment, Cranfield University at Silsoe, UK.

Breuer, L, Huisman, JA, Willems, P, Bormann, H, Bronstert, A, Croke, BFW, Frede, HG, Gräff, T, Hubrechts, L, Jakeman, AJ, Kite, G, Lanini, J, Leavesley, G, Lettenmaier, DP, Lindström, G, Seibert, J, Sivapalan, M and Viney, NR. 2009. Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM). I: Model intercomparison with current land use. *Advances in Water Resources* 32(2)**:**129-146.

Bulcock, HH and Jewitt, GPW. 2012a. Field data collection and analysis of canopy and litter interception in commercial forest plantations in the KwaZulu-Natal Midlands, South Africa. *Hydrology and Earth System Sciences* 16(10)**:**3717-3728.

Bulcock, HH and Jewitt, GPW. 2012b. Modelling canopy and litter interception in commercial forest plantations in South Africa using the Variable Storage Gash model and idealised drying curves. *Hydrology and Earth System Sciences* 16(12)**:**4693-4705.

California EPA. 2011. Guidance compendium for watershed monitoring and assessment, Section 5.0 - Measurements taken in a watershed, section 5.1.3- Runoff coefficient fact sheet[Online]. California EPA. California, USA: Available:

http://www.waterboards.ca.gov/water_issues/programs/swamp/docs/cwt/guidance/513.pdf [Accessed 30th March 2015].

Chin, DA. 2006. *Water Resources Engineering,* Pearson Education Limited,New Jersey, USA.

Choi, J, Engel, BA, Muthukrishnan, S and Harbor, J. 2003. GIS based long term hydrologic impact evaluation for watershed urbanization. *Journal of the American Water Resources Association* 39(3)**:**623-635.

Conway, D, Persechino, A, Ardoin-Bardin, S, Hamandawana, H, Dieulin, C and Mahé, G. 2009. Rainfall and Water Resources Variability in Sub-Saharan Africa during the Twentieth Century. *Journal of Hydrometeorology* 10(1)**:**41-59.

CWC. 1999. How to correct and complete rainfall data, Hydrology Project, World Bank & Government of The Netherlands funded[Online]. India Central Water Commission. New Delhi, India:Available: http://www.cwc.gov.in/main/HP/download/10%20How%20to%20correct%20and%20complete%20rainfall%20data.pdf [Accessed 8th December 2014].

Dwomo, O and Dedzoe, CD. 2010. Oxisol (ferralsol) development in two agro-ecological zones of Ghana: A preliminary evaluation of some profiles. *Journal of Science and Technology, Kwame Nkrumah University of Science and Technology (KNUST)* 30(2)**:**11-28.

Forbes, KA, Kienzle, SW, Coburn, CA, Byrne, JM and Rasmussen, J. 2011. Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada. *Climatic Change* 105(3-4)**:**555-576.

Ghana Statistical Service. 2013. 2010 Population & housing census, National analytical report. *In:* Awusabo-Asare, K (ed.). Ghana Statistical Service, Accra, Ghana.

Ghile, YB. 2004. An adaptation of the SCS-ACRU hydrograph generating technique for application in Eritrea,. Unpublished MSc, School of Bioresources Engineering and Environmental Hydrology, University of Natal, South Africa.

Gold Fields Limited. 2013. CDP Water Disclosure 2013[Online]. Gold Fields Limited. Available: https://www.goldfields.co.za/pdf/water_disclosure/cdp_water_2013.pdf [Accessed 6th March 2015].

Gyau-Boakye, P and Tumbulto, JW. 2006. Comparison of rainfall and runoff in the humid south-western and the semiarid northern savannah zone in Ghana. *African Journal of Science and Technology* 7 (1)**:**64–72.

Hargreaves, G, Hargreaves, G and Riley, J. 1985. Agricultural Benefits for Senegal River Basin. *Journal of Irrigation and Drainage Engineering* 111(2)**:**113-124.

Hulme, M, Doherty, R, Ngara, T, New, M and Lister, D. 2001. African climate change: 1900-2100. *Climate Research* 17(2)**:**145-168.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *In:* Solomon, S, Qin, D, Manning, M, Chen, Z, Marquis, M, Averyt, KB, Tignor, M and Miller, HL (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jackson, B, Nicholson, SE and Klotter, D. 2009. Mesoscale Convective Systems over Western Equatorial Africa and Their Relationship to Large-Scale Circulation. *Monthly Weather Review* 137(4)**:**1272-1294.

Jalloh, A, Faye, MD, Roy-Macauley, H, Sérémé, P, Zougmoré, R, Thomas, TS and Nelson, GC. 2013. Overview. *In:* Jalloh, A, Nelson, G. C., Thomas,T. S., Zougmoré,R. And Roy-Macauley, H. (ed.) *West African Agriculture and Climate Change: A Comprehensive Analysis.* International Food Policy Research Institute(IFPRI), Washington, DC, USA.

Jewitt, GPW, Garratt, JA, Calder, IR and Fuller, L. 2004. Water resources planning and modelling tools for the assessment of land use change in the Luvuvhu Catchment, South Africa. *Physics and Chemistry of the Earth* 29(2004)**:**1233–1241.

Jewitt, GPW and Schulze, RE. 1999. Verification of the ACRU model for forest hydrology applications. *Water Sa* 25(4)**:**483-489.

Kienzle, SW, Nemeth, MW, Byrne, JM and MacDonald, RJ. 2012. Simulating the hydrological impacts of climate change in the upper North Saskatchewan River basin, Alberta, Canada. *Journal of Hydrology* 412–413(2012)**:**76-89.

Kienzle, SW and Schmidt, J. 2008. Hydrological impacts of irrigated agriculture in the Manuherikia catchment, Otago, New Zealand. *Journal of Hydrology (Wellington North)* 47(2)**:**67-84.

Lacombe, G, McCartney, M and Forkuor, G. 2012. Drying climate in Ghana over the period 1960-2005: evidence from the resampling-based Mann-Kendall test at local and regional levels. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 57(8)**:**1594-1609.

Li, Z, Liu, W, Zhang, X and Zheng, F. 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology* 377(2009)**:**35-42.

Mahe, G, Paturel, JE, Servat, E, Conway, D and Dezetter, A. 2005. The impact of land use change on soil water holding capacity and river flow modelling in the Nakambe River, Burkina-Faso. *Journal of Hydrology* 300(1-4)**:**33-43.

Makhuvha, T, Pegram, G, Sparks, R and Zucchini, W. 1997. Patching rainfall data using regression methods.: 1. Best subset selection, EM and pseudo-EM methods: theory. *Journal of Hydrology* 198(1–4)**:**289-307.

Moriasi, DN, Arnold, JG, Van Liew, MW, Bingner, RL, Harmel, RD and Veith, TL. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the Asabe* 50(3)**:**885-900.

Mugabe, FT, Chitata, T, Kashaigili, J and Chagonda, I. 2011. Modelling the effect of rainfall variability, land use change and increased reservoir abstraction on surface water resources in semi-arid southern Zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C* 36(14–15)**:**1025-1032.

Parajka, J, Andreassian, V, Archfield, SA, Bardossy, A, Blöschl, G, Chiew, F, Duan, Q, Gelfan, A, Hlavcova, K, Merz, R, McIntyre, N, Oudin, L, Perrin, C, Rogger, M, Salinas, JL, Savenije, HHG, Skoien, JO, Wagener, T, Zehe, E and Zhang, Y. 2013. Prediction of runoff hydrographs in ungauged basins. *In:* Blöschl, G, Sivapalan, M, Wagener, T, Viglione, A and Savenije, HHG (eds.)

Runoff prediction in ungauged basins. Synthesis across processes, places and scales. . Cambridge University Press, Cambridge, UK.

Poncea, VM and Shetty, AV. 1995. A conceptual model of catchment water balance: 2. Application to runoff and baseflow modeling. *Journal of Hydrology* 173(1–4)**:**41-50.

Rosbjerg, D and Madsen, H. 2005. Concepts of hydrologic modeling. *Encyclopedia of hydrological sciences.* John Wiley and Sons, Chichester, England.

Schellekensa, J, Scatenab, FN, Bruijnzeela, LA and Wickela, AJ. 1999. Modelling rainfall interception by a lowland tropical rain forest in northeastern Puerto Rico. Journal of Hydrology 225(1999):168-184.

Schmidt, J, Kienze, SW and Srinivasan, MS. 2009. Estimating increased evapotranspiration losses caused by irrigated agriculture as part of the water balance of the Orari catchment, Canterbury, New Zealand. *Journal of Hydrology (Wellington North)* 48(2)**:**73-94.

Schueler, V, Kuemmerle, T and Schroeder, H. 2011. Impacts of Surface Gold Mining on Land Use Systems in Western Ghana. *Ambio* 40(5)**:**528-539.

Schulze, RE. 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System,* Water Research Commission,Pretoria, South Africa.

Schulze, RE. 2000. Modelling hydrological responses to land use and climate change: A southern African perspective. *Ambio* 29(1)**:**12-22.

Schulze, RE. 2005. Selection of a Suitable Agrohydrological Model for Climate Change Impact Studies over Southern Africa. *In:* Schulze, RE (ed.) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation.* Water Research Commission, Pretoria, RSA.

Schulze, RE, Angus, GR and Guy, RM. 1995. Soils. *In:* Schulze, RE (ed.) *Hydrology and Agrohydrology, A text to accompany the ACRU 3.00 Agrohydrological Modelling System.* Water Research Commission, Pretoria, South Africa.

Tarboton, KC and Schulze, RE. 1995. An application of the dynamic input option for hydrolgical modelling with land use over time. *In:* Schulze, RE (ed.) *Hydrology and Agrohydrology, A text to accompany the ACRU 3.00 Agrohydrological Modelling System.* Water Research Commission, Pretoria, South Africa.

Wagener, T, Blöschl, G, Goodrich, DC, Gupta, HV, Sivapalan, M, Tachikawa, T, Troch, PA and Weiler, M. 2013. A synthesis framework for runoff prediction in ungauged basins. *In:* Blöschl, G, Sivapalan, M, Wagener, T, Viglione, A and Savenije, HHG (eds.) *Runoff prediction in ungauged basins. Synthesis across processes, places and scales.* Cambridge University Press, Cambridge, UK.

Warburton, ML. 2012. Challenges in modelling hydrological responses to impacts and interactions of land use and climate change. Unpublished PhD, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

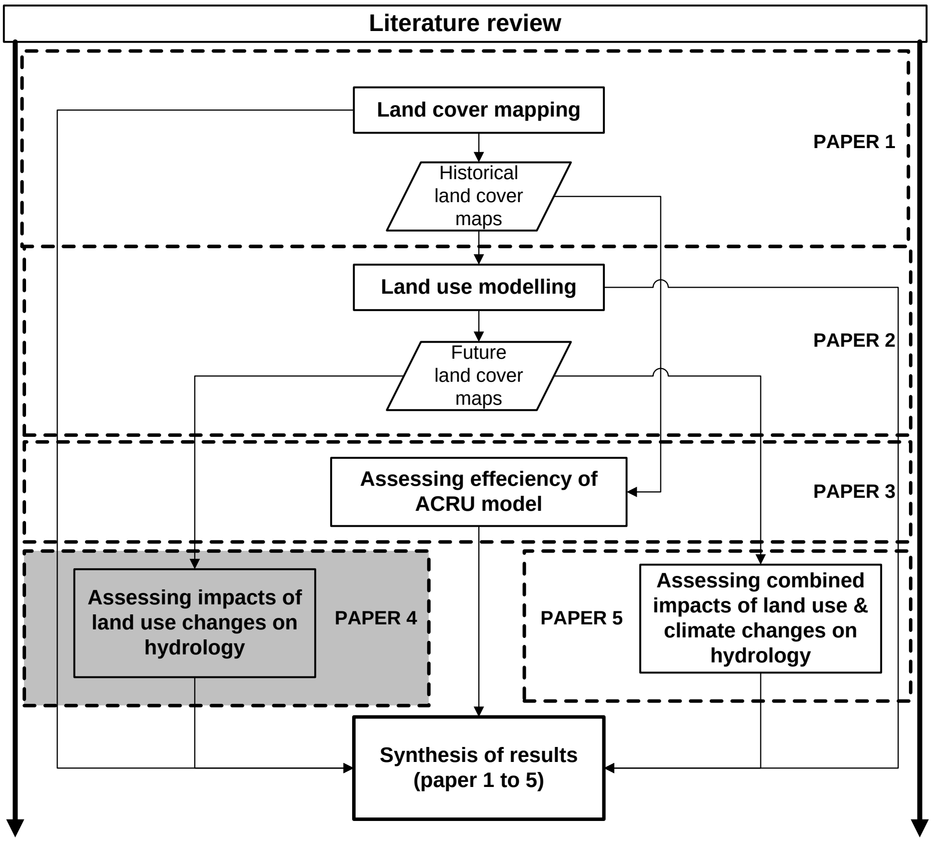
Warburton, ML, Schulze, RE and Jewitt, GPW. 2010. Confirmation of ACRU model results for applications in land use and climate change studies. *Hydrology and Earth System Sciences* 14(2010)**:**2399-2414.

Wi, S, Yang, YCE, Steinschneider, S, Khalil, A and Brown, CM. 2015. Calibration approaches for distributed hydrologic models in poorly gaged basins: implication for streamflow projections under climate change. *Hydrol. Earth Syst. Sci.* 19(2015)**:**857-876.

Yidana, SM, Ophori, D and Banoeng-Yakubo, B. 2007. Irrigation water resource management for sustainable agriculture - The Ankobra basin, Ghana. *Journal of Irrigation and Drainage Engineering-Asce* 133(6)**:**609-615.

Preface to Chapter 6

Hydrological changes which result in floods, soil erosion, sedimentation of rivers, droughts, increased evaporation and scarcity of water are some of the major impacts of Global Changes, which affect society and the environment. Understanding how Global Changes affect hydrological changes is therefore necessary in effective management of the environment to protect life and property, as well as promote sustainable economic development. In this chapter (shaded portion in Figure below) the impacts of historical and potential future land use change on hydrology and the consequent potential river ecological alteration in the Bonsa catchment of Ghana is assessed. The chapter relies on the verified ACRU hydrological model from Chapter 5 and historical and potential future land use data from Chapters 3 and 4, respectively.



CHAPTER 6 : ASSESSING IMPACTS OF LAND USE CHANGES ON THE HYDROLOGY OF A LOWLAND RAINFOREST CATCHMENT IN WEST AFRICA

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6.1 Abstract

Impact assessments of actual and potential land use (LU) changes on hydrology is vital in land use planning, which is a prerequisite for effective water resources management. In this study, impacts of actual, as well as potential LU changes on the hydrology of the Bonsa catchment (1482 km^2), Ghana, West Africa, were assessed using the ACRU hydrological model. Baseline, current and potential future LU maps for three scenarios *viz.*, business-as-usual (BAU), economic growth (EG) and economic growth and reforestation (EGR), as well as observed climate between 1990 and 2009, were used for the study. Richter's range of variability analysis, using the indicators of hydrologic alteration software, was used to assess the current, as well as the potential future ecological impacts of LU changes. The results indicate that peak and dry season streamflows have increased by 21% and 37%, respectively, under the current land use in comparison to the baseline due to a decrease in evergreen and secondary forests by 18% and 39% respectively, and an increase in settlements, mining areas and shrubs/farms by 81%, 310% and 343% respectively, between 1991 and 2011,. The potential future LU scenarios suggested that there may be further increases in streamflows, but the historical land use changes between 1991 and 2011 were so substantial that they continued to impact streamflow changes in any of the future land use scenarios. The study also showed that variability of streamflow changes at the catchment scale was lower than at the subcatchment scale and the current land use changes has created the potential for changes in river ecology, with further potential alterations expected under the future LU scenarios. For the scenarios of potential future LU changes, the BAU shows the highest potential alterations in river ecology, as well as increases in streamflows, while the EGR shows the least. Policy interventions for effective management of the catchment are recommended.

Key words: Bonsa catchment, Ghana, hydrology, land use scenarios, ecological alterations

6.2 Introduction

Rapid population growth, rural-urban migration, urbanization, agricultural intensification and extensification, as well as expansion in surface mining are some of the major causes of land use changes in West Africa (Braimoh and Vlek, 2005; Kusimi, 2008; FAO, 2010b; Schueler *et al.*, 2011). According to FAO (2010b), about 32 million ha of forest were converted to other land uses between 1990 and 2010 alone in West and Central Africa. Land use changes modify the balance between precipitation and the other components of the hydrological cycle, which can impact negatively on the environment and socio-economic wellbeing of people. Therefore, to effectively manage water resources in a catchment, the historical and present, as well as the potential future impacts of land use changes need to be assessed (Choi *et al.*, 2003). As these results are vital in efficient land use planning, which is prerequisite for effective water resources management.

The impacts of land cover/land use changes on hydrology have been assessed during the past several decades, using (i) field-based data driven statistical methods, based on single catchments or paired catchments (Brown *et al.*, 2005; Lane *et al.*, 2005) and (ii) hydrological modelling (Warburton *et al.*, 2010; Gosling *et al.*, 2011; Park *et al.*, 2011). Hydrological modelling using physically-based tools, are reported to provide reasonable representation of observed hydrological processes for large areas and also enable rapid evaluation of catchment development scenarios (Li *et al.*, 2007), using relatively less time and resources than field studies. Modelling also allows extrapolation of field measurements over large areas and the projection of future hydrological conditions. Therefore, for regions with less data in addition to challenges with financial and technical resources, the use of physically-based tools to derive maximum information from limited data, has been recommended (Li *et al.*, 2009). Thus, hydrological models, which link model parameters to physically measurable catchment parameters, to assess impacts of land use changes on hydrology, have received much attention in literature (Legesse *et al.*, 2003; Seguis *et al.*, 2004; Mahe *et al.*, 2005; Bossa *et al.*, 2012; Warburton *et al.*, 2012; Cornelissen *et al.*, 2013). The use of physically-based models is underpinned by the fact that the models integrate heterogeneity of landscape processes, which has been found to be useful in the simulation of hydrological components for ungauged basins (Hrachowitz *et al.*, 2013).

In West Africa, both field-based studies and hydrological modelling has been used to assess impacts of land use changes on hydrology at various scales (Giertz and Diekkruger, 2003; Valentin *et al.*, 2004; Giertz *et al.*, 2005; Mahe *et al.*, 2005; Li *et al.*, 2007; Leblanc *et al.*, 2008; Van de Giesen *et al.*, 2011). However, in the rainforest regions of the south, where the majority of West African populations live, there remains a lack of knowledge on the hydrological impacts of land use changes at the local scale, although land use changes have been significant during the past three decades (FAO, 2010b; Aduah *et al.*, 2015). Previous land use change impact studies on hydrology in West Africa have been mainly undertaken in the semi-arid areas and the Sahel parts of the region (Giertz and Diekkruger, 2003; Valentin *et al.*, 2004; Giertz *et al.*, 2005; Mahe *et al.*, 2005; Li *et al.*, 2007; Leblanc *et al.*, 2008; Van de Giesen *et al.*, 2011; Bossa *et al.*, 2012; Cornelissen *et al.*, 2013; Bossa *et al.*, 2014). These regions have vastly different vegetation and climate, compared to the rainforest regions of the south. Previous studies in the savannah and Sahel regions (Li *et al.*, 2007) also relied on limited data, including extreme and unrealistic land use scenarios (e.g. 100% deforestation/afforestation). Thus, there is a need for studies that use realistic land use scenarios that account for simultaneous removal and regeneration of vegetation, as well as gradual changes in impervious surface areas, for both historical and future time slices. Beyond this, literature provides evidence of the importance of locally relevant studies. For example, several studies (Klocking and Haberlandt, 2002; Mahe *et al.*, 2005; Boulain *et al.*, 2009; Warburton *et al.*, 2012) have shown that impacts of land use change on hydrology depend on a variety of local factors including climate, vegetation and the location of the land use within a catchment, making it unrealistic to arrive at generalised conclusions about land use change impacts on hydrology.

In the southern rainforest Bonsa catchment of the Ankobra River basin in Ghana, West Africa, land uses have changed significantly during the past three decades. Mining areas have increased over two-fold, while settlements and shrubs/farms increased more than three and four-fold, respectively, leading to overall annual deforestation rates of 0.3% between 1986 and 1991, 0.7% between 1991 and 2002 and 2% between 2002 and 2011 (Aduah *et al.*, 2015). It is also expected that in the near future, rates of land use changes may be substantially higher than the current rates. There is lack of understanding of the impacts of these land use changes and potential future changes on the hydrological regimes and biodiversity. Prior studies have mainly focused on impacts of mining on water quality (Kortatsi, 2003; Akabzaa *et al.*, 2009; Armah *et al.*, 2012) and pollution by airborne particulate matter (Bansah and Amegbey, 2012). With the substantial land use changes in the past and the potential for higher rates in the future, it is important to understand how these changes will impact on the local hydrology to allow for effective land use planning, environmental management, as well as sustainable utilization of the natural resources. Conclusions of such a study will be useful to understanding impacts of similar lowland rainforest catchments of West Africa, informing further studies, as well as the management and development of those catchments.

Thus this study seeks to understand how lowland rainforest catchments in West Africa have responded hydrologically to historical land use changes and how they will respond to land use changes in the future under three development scenarios, using the Bonsa catchment of Ghana as a representative study site. In addition to a baseline land use scenario, three future land use scenarios developed in a previous study (Aduah *et al., under review*, Chapter 4), namely (i) the business-as-usual (BAU), (ii) the economic-growth (EG) and (iii) the economic growth and reforestation (EGR) scenarios. This study builds on a companion paper in Chapter 5, which has demonstrated that the ACRU hydrological model (Schulze, 1995) is a suitable tool for modelling the hydrology of Bonsa catchment. Several studies have also applied the ACRU model successfully to assess the impacts of land use changes on the hydrology of catchments with diverse land uses and climates (Schulze, 2000; Jewitt *et al.*, 2004; Warburton *et al.*, 2012), demonstrating the sensitivity of the model to land uses and changes thereof. The study investigates the hydrological impacts, as well as the consequent potential ecological alterations in the environment. Unlike previous studies in West Africa, this study analyses the entire range of streamflows, using flow duration curves, seasonal and annual streamflows, to account for both extreme and median flow conditions, which are important for water supply management, flood protection, as well as environmental protection. The study also investigates the spatial variability of streamflow changes, in response to land use changes, which has been ignored in all but one previous study (Bossa *et al.*, 2014) in West Africa.

6.3 Methods and Materials

6.3.1 Study Area Description

The Bonsa catchment of the Ankobra River basin in Ghana, West Africa (Figure 6.1), is located between longitudes 1° 41´ and 2° 13´ West and latitudes 5° 4´and 5° 43´ North. The Bonsa River, which provides many local communities with water for domestic as well as industrial purposes, flows in a south-westly direction to join the Ankobra River, which flows in a north-south direction and joins the Atlantic Ocean at Axim. The population of the large towns in the catchment, such as Tarkwa and Abosso, has more than doubled in the past 30 years, with an annual growth rate of approximately 2% (Ghana Statistical Service, 2013). The catchment has a low relief, with the elevations ranging between 30 and 340 m above mean sea level and it drains an area of 1482 km^2.The catchment has a convective rainfall regime (Jackson *et al.*, 2009) with two peak rainfall seasons, the major peak from March/April to July and the minor peak from August/September to November (Figure 6.1). The mean rainfall ranges between 1500 mm and 2150 mm per annum (Yidana *et al.*, 2007), while the annual average minimum and maximum temperatures are 23ºC and 31ºC, respectively. Dominant land cover consists of evergreen and secondary forests, shrub lands and farms, while the geology is mostly Birimian and Tarkwaian rock systems (Akabzaa *et al.*, 2009) and the soil is mostly Ferric Acrisols. The economic activities in the catchment include open-pit gold mining (small and large scale), rubber plantations (small and large scale) and cocoa and food crop cultivation.

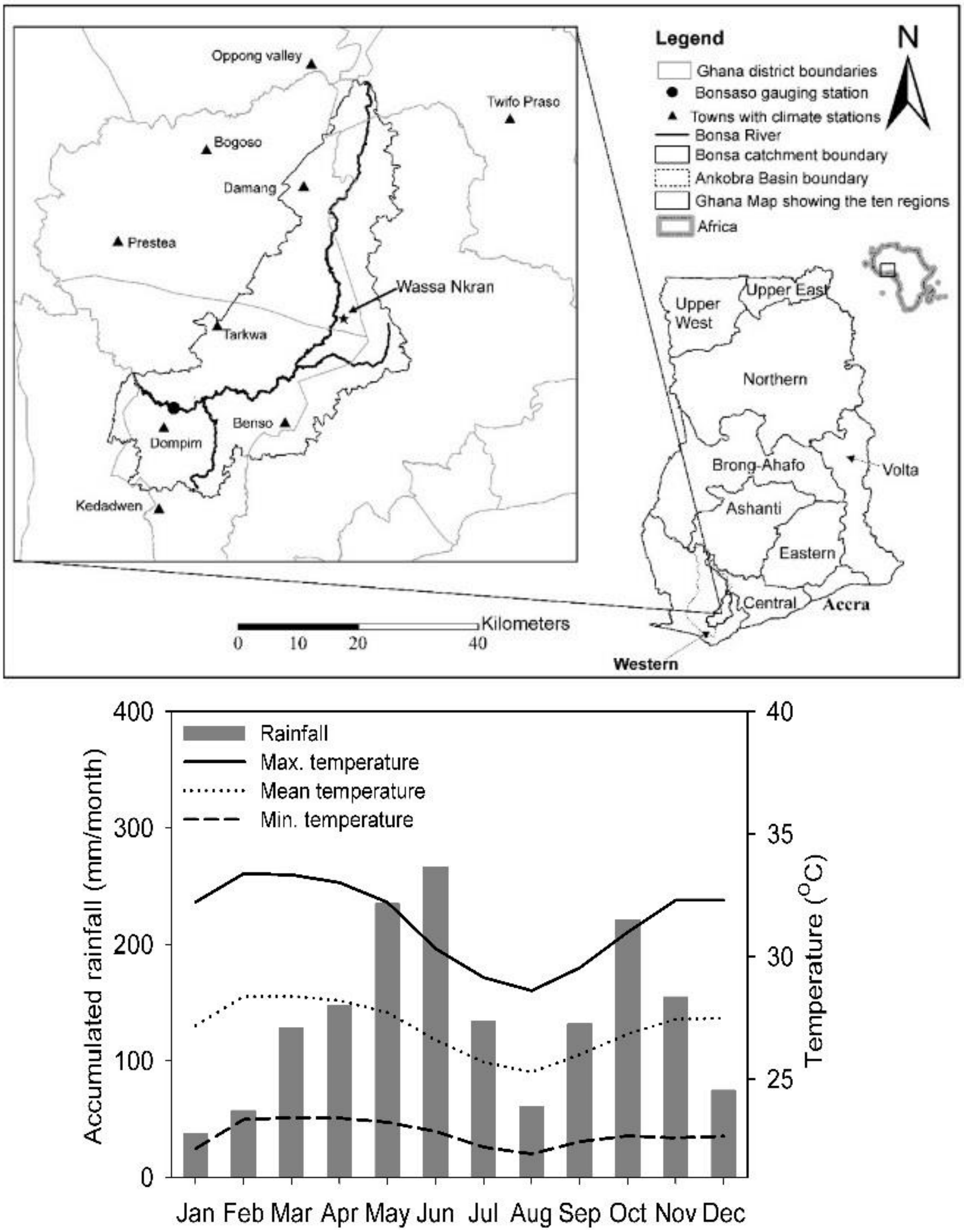


Figure 6.1: **Map of the Bonsa catchment in the Ankobra basin of Ghana (top) and a graph showing mean monthly climate between 1990 and 2009 for Tarkwa (bottom)**

6.3.2 The ACRU Hydrological Model

The ACRU Model (Schulze, 1995) is a daily time step physical-conceptual agro-hydrological model developed by the former School of Bioresources Engineering and Environmental Hydrology of the University of KwaZulu-Natal, South Africa to simulate catchment hydrological responses to land management. It is a multi-purpose model (Figure 6.2) that can be used for catchment water resources assessment, design floods, irrigation water planning, assessment of land use change and climate change impacts(Schulze, 1995). A detailed description of the model is available in Schulze (1995). The ACRU model was selected as a satisfactory monthly NSE of 0.6 and R^2 of 0.7 were obtained after a physically-based calibration study undertaken for the catchment (Chapter 5) and because the model has been applied successfully in a variety of catchments (Ghile, 2004; Warburton *et al.*, 2010; Forbes *et al.*, 2011), with a wide range of climates and land uses.

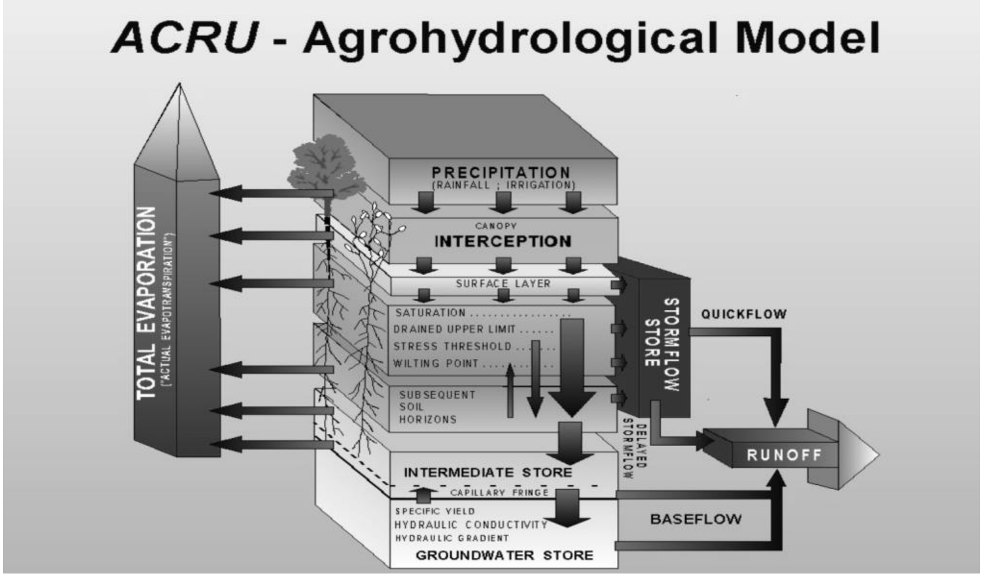


Figure 6.2: Representation of hydrological processes in the ACRU model (Schulze, 1995)

6.3.3 Data Acquisition and Model Configuration

6.3.3.1 Hydrological Model Configuration

The Bonsa catchment was delineated and sub-divided into 103 subcatchments, using digitized river courses and contour maps, obtained from the Survey of Ghana (SOG). The subcatchments were further sub-divided into hydrological response units (HRUs), based on the catchment land uses (Figure 6.4), in order to provide a more homogeneous land use area for hydrological simulation. The subcatchments and HRUs were configured such that their streamflows cascade (route) into each other in a logical sequence representative of river flow. An example of the flow sequence of subcatchments is shown in Figure 6.3. The land use parameters (Appendix A) used in this study were the same as those used in the companion paper in Chapter 5, which were obtained after a sensitivity analysis in the Bonsa catchment. The assumption made was that the land use types remained the same, however the area and distribution changed depending on land use scenario (Figure 6.4; Table 6.1). The streamflow simulation control variables which determine the amount of rainfall that becomes groundwater and streamflow during a day, were also the same as those applied in Chapter 5.
Similarly, the soils information and parameters (Appendix A) were those used in the verification study (Chapter 5), which were obtained from a generalised soil map from the Soil Research Institute (SRI) of Ghana and Dwomo and Dedzoe (2010), as well as computation of soil water content at permanent wilting point and drained upper limit, using their clay proportions in the pedotranfer equations developed by Schulze (1995). Climate records were obtained from the Ghana Meteorological Agency (GMA) for the period 1980 to 2011. Due to data gaps and outliers in the rainfall records, the data was pre-processed before using it in the ACRU model as described in Chapter 5. Reference potential evaporation was calculated using the Hargreaves and Samani method (Hargreaves *et al.*, 1985).

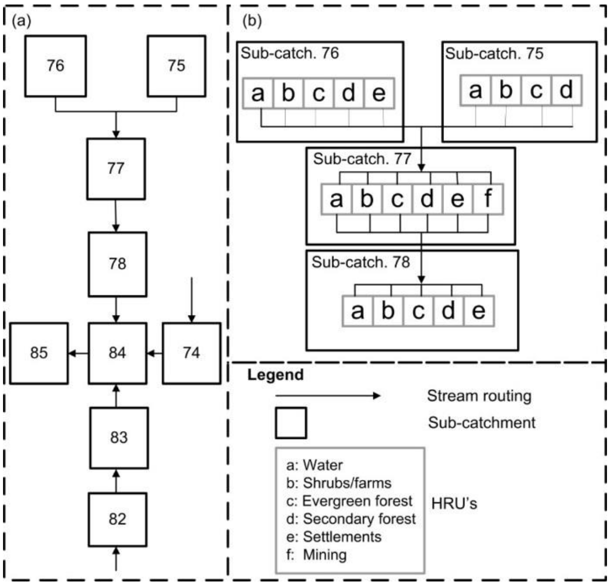


Figure 6.3: **Example of subcatchment (a) and HRU streamflow configuration (b), for Bonsa catchment, showing the cascading of water flow from HRU's to subcatchments**

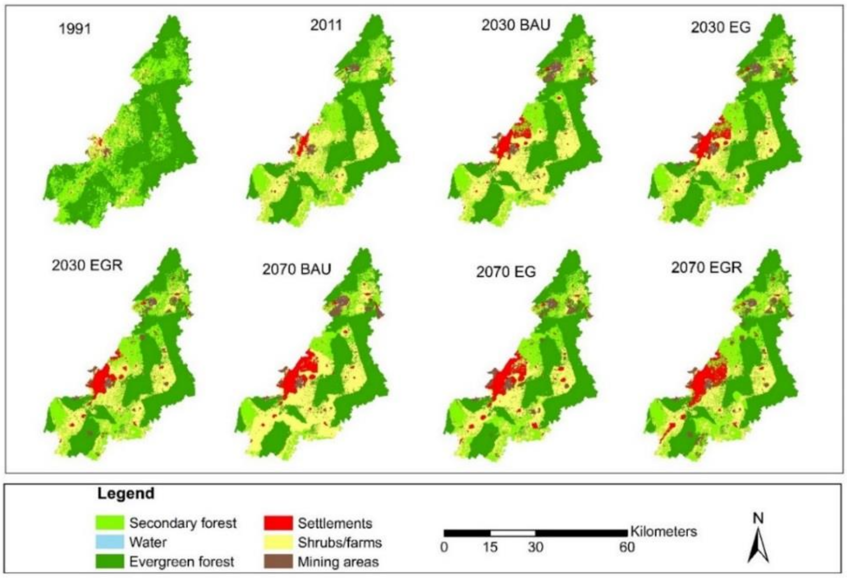


Figure 6.4: **Maps for baseline land use (1991), current (2011) land use and future land use scenarios in the Bonsa catchment, generated from mapping and land use simulation (Aduah *et al.*, *under review*, Chapter 4)**

Table 6.1: Land uses proportions for the Bonsa catchment for the baseline (1991), current (2011) and future scenarios

			Land cover						
Scenario	Time slice	Unit	Secondary forest	Water	Evergreen forest	Settlements	Shrubs/farms	Mining areas	Total
Baseline	1991	area (km^2)	457.3	0.2	916.5	12.4	90.0	5.9	1482.3
		%	30.8	0.0	61.8	0.8	6.1	0.4	100.0
Current	2011	area (km^2)	280.3	1.4	754.6	22.4	399.4	24.2	1482.3
		%	18.9	0.1	50.9	1.5	26.9	1.6	100.0
BAU	2030	area (km^2)	215.5	1.4	728.1	63.7	425.3	48.3	1482.2
		%	14.5	0.1	49.1	4.3	28.7	3.3	100.0
	2070	area (km^2)	171.0	1.4	683.6	91.3	482.1	52.8	1482.2
		%	11.5	0.1	46.1	6.2	32.5	3.6	100.0
EG	2030	area (km^2)	283.9	1.4	733.6	68.8	340.1	54.3	1482.1
		%	19.2	0.1	49.5	4.6	22.9	3.7	100.0
	2070	area (km^2)	294.7	1.4	689.4	95.7	335.0	66.0	1482.2
		%	19.9	0.1	46.5	6.5	22.6	4.5	
EGR	2030	area (km^2)	303.8	1.4	716.0	66.6	340.2	54.3	1482.2
		%	20.5	0.1	48.3	4.5	22.9	3.7	100.0
	2070	area (km^2)	350.1	1.4	667.7	100.6	295.4	67.2	1482.2
		%	23.6	0.1	45.0	6.8	19.9	4.5	100.0

To determine the impacts of land use changes on hydrology, the calibrated ACRU model was used to simulate the streamflow for the Bonsa catchment using the 1991 land use map and climate records from 1990 to 2009. This was considered the baseline scenario against which the simulated streamflows under the current (2011) and future (2030, 2070) land use scenarios (Figure 6.4) were compared.

The 1991 land use was selected as the baseline land use as it represents a period prior to substantial land use changes in the catchment. It is assumed to be close to the natural land use conditions of the Bonsa catchment, thus it is assumed that the streamflows simulated under the 1991 land use are relatively close to the natural flow regime of the Bonsa River. The future land use scenarios were derived in Aduah *et al.*(*under review*, Chapter 4), using census data from the Ghana Statistical Service (2013), policy documents on forest plantations from the Forestry Commission of Ghana (FAO, 2010a; Ghana Forestry Commission, 2013), information from mining companies (Bourke *et al.*, 2007; Gold Fields Limited, 2012b, a; Castle Peak Mining Ltd, 2013), as well as guidelines on land use simulation from literature (Verburg *et al.*, 1999; Verburg and Overmars, 2009). In order to attribute hydrological changes to changes in land uses the climate records from 1990 to 2009 were used for the simulation of each of the land use scenarios, and the soils and the streamflow control variables were held constant. The method of assessing land use change impacts on hydrology, used in this study, was adapted from several studies including Li *et al.* (2007), Park *et al.* (2011), Cornelissen *et al.* (2013) and Bossa *et al.* (2014). The effect of climate was removed by averaging streamflows over the period of simulation.

6.3.3.2 Assessment of Ecological Impacts of Hydrological Changes

To assess the potential ecological impacts of the hydrological changes in the Bonsa catchment, the Indicators of Hydrological Alteration (IHA) software developed by The Nature Conservancy (2009), was used to analyse simulated streamflows from all the scenarios in addition to the baseline. The analysis was executed in pairs using the Richter's Range of Variability Approach (RVA) which is implemented in the IHA software, using the baseline 1991 simulation results (for the period 1990-2009) as pre-impact streamflows and streamflows from the 2011, as well as the future land use scenarios (2030 and 2070 BAU, EG and EGR) as post-impact streamflows. The RVA target limits were calculated using the median ±17%.

The RVA approach is aimed at providing information for conservation of native aquatic biodiversity as it is used to quantify the degree of alteration in hydrologic characteristics such as timing, frequency, duration, magnitudes and rates of changes, which are critical to the sustenance of aquatic ecosystems (Richter *et al.*, 1996; Hillman *et al.*, 2012; Homa *et al.*, 2013). The approach uses analysis of hydrological data from either observed records or model generated data. Hydrologic data for RVA analysis is categorized into pre-impact and post-impact time frames. The pre-impact hydrologic time frame represents period with little to no change from natural hydrologic regimes, while the post-impact hydrologic data represents period after the ecosystem has changed mainly due to human influence. The hydrologic characteristics assessed under the RVA approach have been categorised into 5 groups of 32 parameters which statistically describe hydrologic variation within each year. The RVA approach relates the measure of the changes in the hydrologic parameters between the pre-impact and the post-impact times frames to the degree of alteration in the aquatic ecosystem, hence provides data that can be used to support restoration or management of aquatic ecosystems.

The RVA (IHA) parameter groups 1 to 5 were selected to assess the probable ecological impacts of the hydrological regime changes, as they provide the full range of flow conditions necessary to sustain aquatic and riparian ecosystems (The Nature Conservancy, 2009; Richter *et al.*, 1996) and it is assumed that alteration of flows from pre-impact conditions can be used to measure ecological changes. Non-parametric statistics were selected to implement the RVA calculations, since the streamflow records are positively skewed.

6.4 Results

The temporal changes in streamflows across the selected land use scenarios are described using tables and figures, while maps are used to explore the spatial variability of streamflow responses to the current, as well as future land use (LU) scenarios. The section also describes the potential ecological implications for the streamflow changes, with respect to the current (2011) and potential future land use scenarios.

6.4.1 Temporal Analysis of Impacts of Current and Future Land use Changes

LU changes between 1991 and 2011, in the form of deforestation and urbanization, in the Bonsa catchment have resulted in increased inter-annual, dry season, major and minor peak season streamflows (Table 6.2). The highest increase in streamflows of 37% (i.e. an increase from 590 m^3 to 808 m^3) occurred in the dry season, while the major peak season had the lowest increase of 21% (i.e. 2524 m^3 to 3055 m^3). The current (2011) LU changes also resulted in increased high, median and low simulated flows (Figures 6.5 and 6.6). The streamflows simulated under the potential future LU change scenarios (BAU, EG and EGR) followed the same trend as those for the current (2011) LU, but with higher magnitudes of change, which increased with time. The dry season streamflows showed the highest increases regardless of the LU scenario or time slice (Table 6.2). The high, median and low flows also increased under the future LU scenarios (Figures 6.5 and 6.6). The differences between streamflows simulated under the different future LU scenarios were however, small, but the streamflow increases simulated under the BAU LU scenarios were the highest, while those of the EGR were the lowest, irrespective of the time slice. Under all the land use scenarios (current and potential future), streamflow increases for the low flows were relatively higher than the increases in the high flows (Figure 6.6).

Table 6.2: **Increased streamflows relative to the baseline (1991 land use) scenario for the current (2011) and three future land use scenarios (BAU, EG and EGR) simulated using climate data from 1990-2009**

Scenario		Annual (%)	Dry season (%)	Major peak season (%)	Minor peak season (%)
2011		23.3	36.9	21.0	23.9
BAU					
	2030	32.1	48.0	30.1	33.1
	2070	39.0	57.9	36.8	40.2
EG					
	2030	27.9	40.7	26.7	28.9
	2070	32.2	46.1	31.3	33.4
EGR					
	2030	28.1	41.2	26.8	28.9
	2070	31.2	44.0	30.5	32.3

The simulated increases in streamflows between 1991 and 2011 may be attributable to the extensive deforestation which occurred during the period, where evergreen and secondary forests reduced by 18% (917-755 km^2) and 39% (457-280 km^2), respectively. During the same period settlements areas increased by 81%, while shrubs/farms (90-399 km^2) and mining areas (6-24 km^2) increased three fold. The substantial increase in streamflows in the current (2011) scenario is largely because of the over 300% increase in shrubs/farms area between 1991 and 2011.

Streamflows simulated under the potential future land use scenarios were higher than those of the baseline and current land uses because of a further land degradation. For example, mining, shrubs/farms and settlements in the BAU scenario increased by eight fold (6-53 km^2), four fold (90-482 km^2) and six fold (12-91 km^2) between 1991 and 2070 (Table 6.1), respectively, while the evergreen and secondary forests reduced drastically.

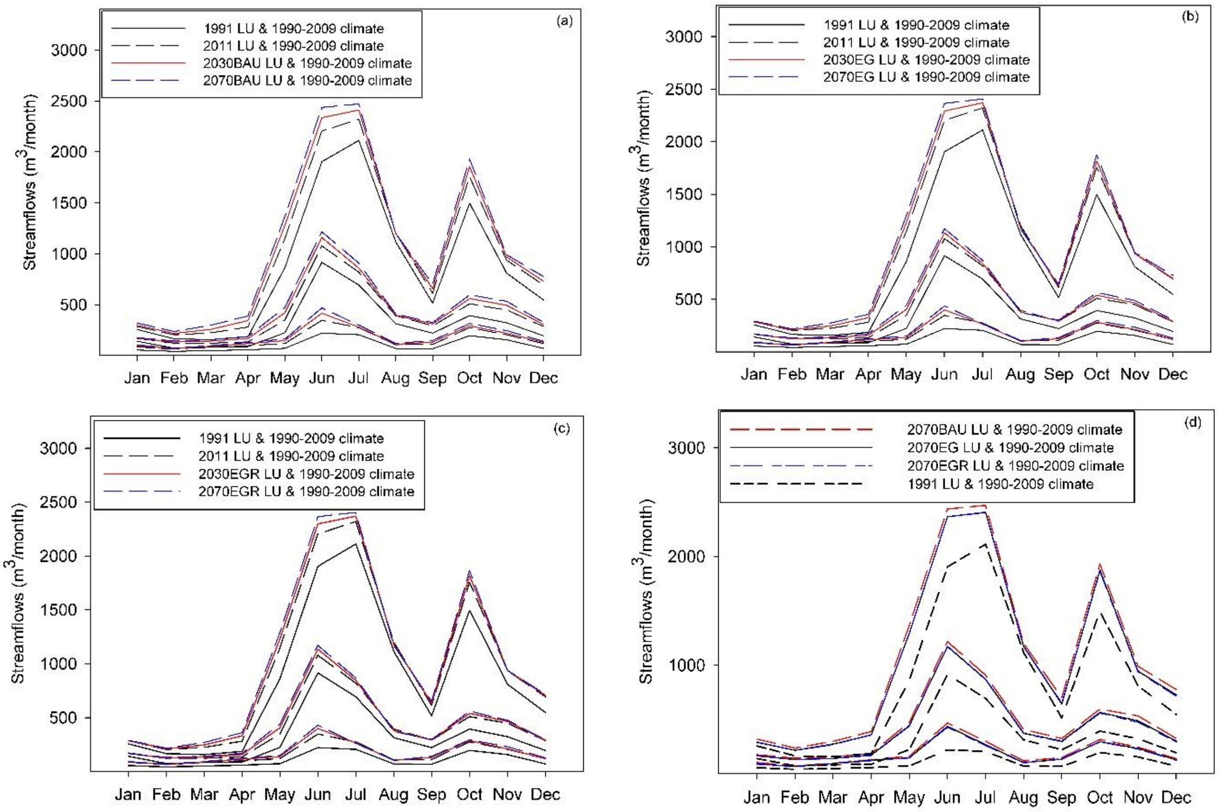


Figure 6.5: Monthly 90th (1 in 10 year high), 50th (median flows) and 10th (1 in 10 year low) percentile streamflows for baseline, 2011 land use and (a) BAU, (b) EG, (c) EGR and (d) 2070 BAU, EG and EGR land uses

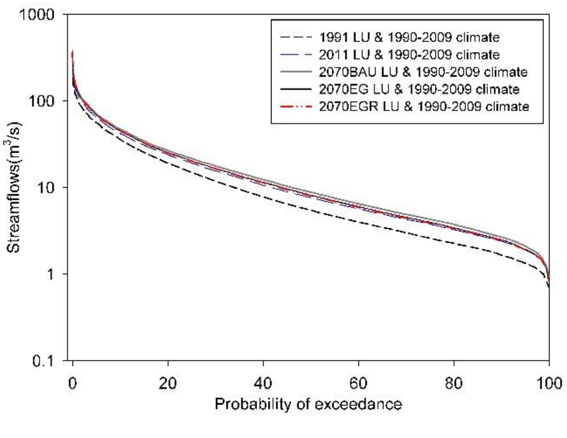


Figure 6.6: Flow duration curves (FDCs) for 2070 future, baseline (1991) and current (2011) land use scenarios

Streamflow responses simulated under the future land uses were generally similar because the proportion of land uses in the scenarios were relatively similar. Nonetheless, the slightly lower streamflows for the EG and the EGR scenarios, compared to the BAU land uses, is because of the higher overall forested areas (secondary and evergreen forest), lower shrubs/farm areas and higher mining areas in the EG and EGR scenarios (Table 6.1). The large difference between streamflow responses of the baseline and the EGR scenarios is an indication that rehabilitation of catchment vegetation through an increase in secondary forests (25% between 2011 and 2070), is not sufficient to restore the baseline flows of the Bonsa catchment.

6.4.2 Spatial Analysis of the Hydrological Impacts of Land Use Changes

The spatial pattern of changes in streamflows due to land use change is similar across the land use scenarios, however the magnitude of change in streamflow varies (Figure 6.7). Due to the conversion of mainly secondary forests in 1991 to shrubs/farms in 2011, subcatchments along the main stem of the river showed increases in streamflow of between 15-25% (Figure 6.7a). While the subcatchments in the northern, south western and the eastern part of the Bonsa catchment which have remained evergreen forests between 1991 and 2011 showed no changes in streamflows. The highest increases in streamflows (45-65%) between the baseline and current land use scenario occurred in the south eastern part of Bonsa (subcatchment 54 and surrounding areas) due to the reduction of evergreen and secondary forests in 2011, increased settlement area and the introduction of shrubs/farms. The only decreases in streamflows (5 - 20%) were those that occurred in the subcatchments on the outskirts of Damang in the northwest. These decreases are due to the maturation of secondary to evergreen forests between 1991 and 2011, and the conversion of patches of shrubs/farms to secondary forests (Figure 6.4). This conversion is possibly due to the abandonment of farms when mining leases were granted to mining companies in the early 1990s.

Under the 2030 land use scenarios (Figure 6.7b), changes of between 25 and 35% in streamflow relative to the baseline were evident for subcatchments along the main stem of the Bonsa River for the BAU scenario. Under the EG and EGR scenarios the streamflow increases were lower towards the northern part of the main stem (15 - 25%), while in the south eastern part of the main stem the streamflow increases (between 25 and 35%) were similar to those under the BAU scenario. These increases are attributable to the predominantly secondary forests along the main river stem in 1991 being converted to shrubs/farms, mining areas and settlements in the future scenarios (Figure 6.4). The lower increases in streamflows in the north under the EG and EGR scenarios in comparison to the BAU scenario is due to the larger areas of shrubs/farms in BAU scenario. In the west central part of the Bonsa catchment increases in streamflow were evident in all future 2030 scenarios with larger increases evident under the BAU LU scenario. These increases were due to increasing areas of settlements, shrubs/farms and mining areas. The largest increases in streamflow under the 2030 land use scenarios were evident in subcatchment 54 and its surrounding subcatchments to the northwest and southwest (Figure 6.7b), with increases of 55 – 75% under the BAU scenario and increases of 55 - 65% under the EG and EGR scenarios. These changes were due to the conversion of mainly evergreen and secondary forests in 1991 to shrubs/farms, mining and settlement areas in the future LU scenarios (Figure 6.4), with the conversion to shrubs/farms being greatest in the BAU scenario. For those subcatchments in the northern, middle and the eastern part of Bonsa catchment, where the evergreen forest remained under the future LU scenarios, no changes in streamflows were evident.

Under the 2070 LU scenarios, the streamflow changes followed the same trend as those simulated under the 2030 LU scenarios, except that the magnitude of increases was greater (Figure 6.7b) due to the larger mining, settlement and shrubs/farms areas (Figure 6.4). For example, in the west central subcatchments near Tarkwa, the streamflow increases ranged from 35 to more than 75% for the 2070 LU scenarios, while under the 2030 LU scenarios the increases were below 35%.

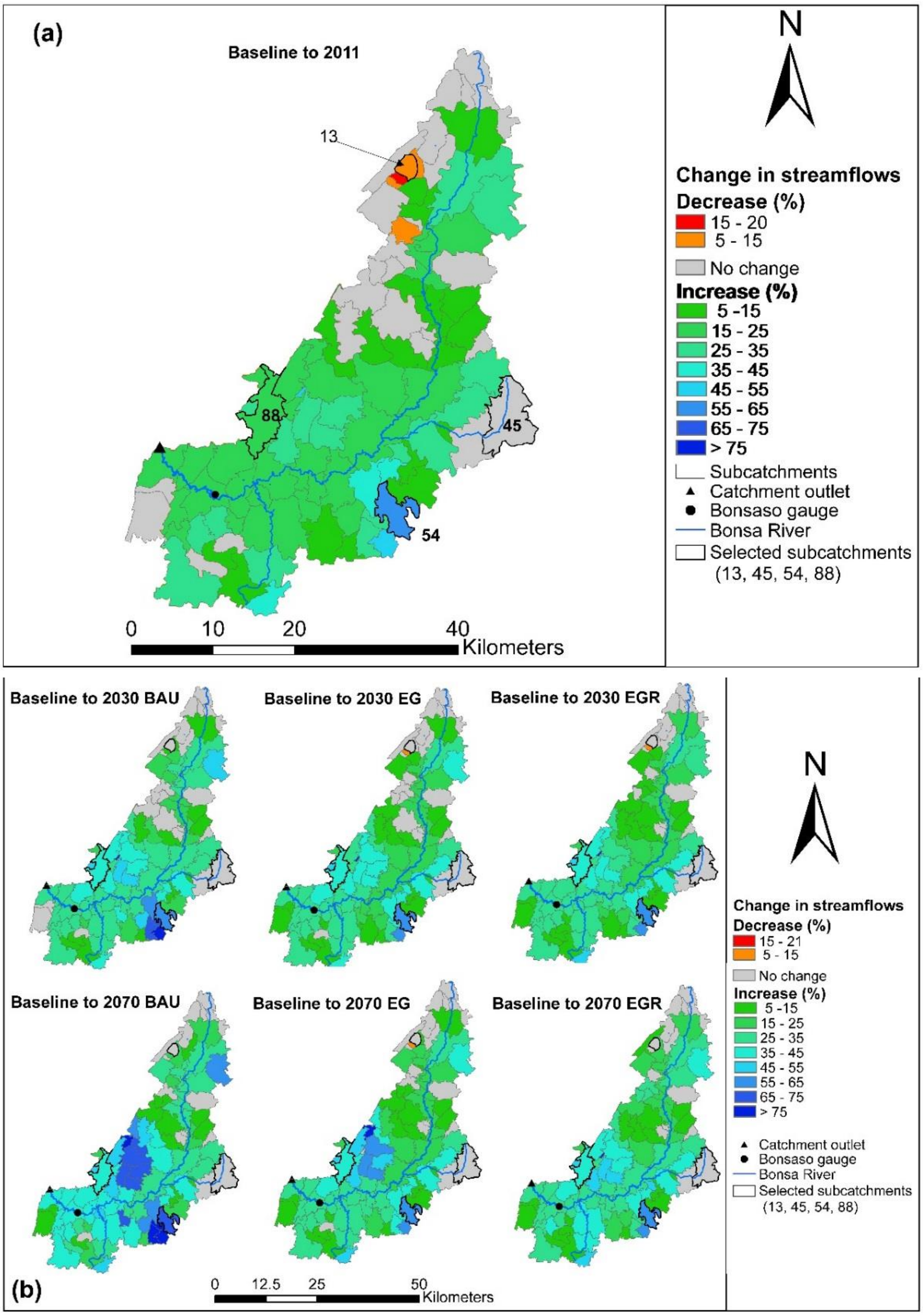


Figure 6.7: Changes in mean annual accumulated streamflows relative to the baseline (1991 land use) streamflows for (a) 2011 land use as well as (b) the potential future land use scenarios. Numbers in maps represents subcatchments

6.4.3 Potential Ecological Impacts of Land Use Changes

The results of the RVA analysis for the streamflows of the baseline (1991), current (2011) and the potential future land use scenarios are summarised in Table 6.3. The RVA analysis showed that the median monthly streamflows (parameter group 1) resulting from the current (2011) land use were greater than those of the pre-impact 1991 median monthly streamflows, however the flows were within the pre-impact RVA lower and upper limits. The magnitude and duration of the extreme streamflow conditions (parameter group 2, 4 and 5) were also greater than the pre-impact conditions and above the pre-impact RVA limits, however the timing of occurrence (parameter group 3) of the extreme streamflow conditions did not change.

Similarly, under the potential future land use scenarios, the monthly median streamflows were greater than the baseline flows but within the pre-impact RVA limits, except for the BAU scenario where most of the monthly median streamflows were above the pre-impact RVA limits. The extreme flows under the potential future land use scenarios had similar trend as the current (2011) land scenario, where the magnitudes and durations of the streamflows have mostly increased beyond those of the pre-impact 1991 and the RVA limits. Nonetheless, the BAU land use scenario had relatively higher changes in the magnitudes and duration of the extreme streamflows, while the EGR land use had the lowest.

The RVA analysis for the current land use suggests that the Bonsa catchment might have experienced ecological changes relative to the baseline 1991 ecology, as streamflows have generally increased in the catchment. This can affect the habitats of both aquatic and riparian life. Higher floods may also cause changes in the channel morphology, increased frequency of flooding in riparian areas and can lead to invasion by alien plants, reducing biodiversity in the long term. The RVA analysis for the potential future land use scenarios show that there may be more extreme flows in the future, with similar effects, but higher in magnitudes, compared to the current land use change effects. The BAU scenario may have the highest ecological impacts, while the EGR may have the lowest impacts in the future. Since the timing of occurrence of the extreme streamflows has not changed for both the current and the potential future land use scenarios, the seasonal pattern of streamflows has not changed and may not change in the future, indicating that the life cycle of wildlife has not been affected currently and may not be affected in the future.

Table 6.3: **Hydrological alteration of daily simulated streamflows for pre-impact baseline 1991 land use and post-impact land use scenarios, using 20 years observed climate data (1990 to 2009)**

	Pre-impact 1991 streamflows			Post-impact streamflows for land use scenarios			
Parameters		RVA Limits					
Parameter Group #1 (m^3/s)	Median	Low	High	2011	2070EGR	2070EG	2070BAU
January	0.087	0.067	0.129	0.123	0.116	0.121	0.138
February	0.068	0.052	0.096	0.092	0.090	0.092	0.102
March	0.064	0.057	0.075	0.085	0.089	0.089	0.095
April	0.068	0.056	0.080	0.092	0.100	0.099	0.109
May	0.144	0.107	0.240	0.202	0.285	0.289	0.310
June	0.852	0.504	1.230	1.004	1.065	1.072	1.079
July	0.538	0.402	0.863	0.634	0.573	0.582	0.628
August	0.202	0.097	0.344	0.252	0.237	0.239	0.261
September	0.150	0.119	0.270	0.186	0.189	0.189	0.200
October	0.257	0.140	0.788	0.320	0.366	0.366	0.384
November	0.305	0.182	0.433	0.424	0.416	0.431	0.464
December	0.141	0.117	0.216	0.203	0.200	0.203	0.228
Parameter Group #2							
Extreme flows (m^3/s)							
7-day minimum	0.045	0.035	0.052	0.060	0.060	0.061	0.066
90-day minimum	0.076	0.059	0.089	0.111	0.124	0.127	0.140
7-day maximum	2.257	1.824	2.646	2.706	2.954	2.970	3.093
90-day maximum	0.871	0.658	0.996	1.038	1.091	1.103	1.146
Parameter Group #3							
Date of minimum (Julian day)	127.500	119.000	161.400	127.500	123.000	123.000	125.000
Date of maximum (Julain day)	191.000	175.000	227.900	188.000	188.000	189.000	189.000
Parameter Group #4							
Low pulse count	7.000	5.930	9.000	7.000	8.500	8.000	5.000
Low pulse duration (days)	7.000	5.000	9.400	4.000	3.000	3.000	3.000
High pulse count	6.000	5.930	9.070	11.000	16.500	16.000	15.500
High pulse duration (days)	4.000	2.000	8.070	3.000	2.000	2.000	2.000
Parameter Group #5							
Rise rate (m^3/s)	0.052	0.043	0.067	0.108	0.150	0.155	0.165
Fall rate (m^3/s)	-0.009	-0.010	-0.007	-0.014	-0.019	-0.019	-0.020
Number of reversals	88.000	84.000	94.000	103.000	115.000	116.000	112.000
Key:	**below RVA**		**above RVA**				

6.5 Discussion

The objective of this study was to confirm whether there has been significant hydrological alterations in the Bonsa catchment during the past three decades, as well as to investigate the plausible future impacts, to be able to provide information for catchment management and land use planning. The study also aimed at reducing the knowledge gap on how land use changes impacts hydrology and consequently alter the ecology of lowland rainforests in West Africa. The study used historical, current and potential future land use maps as inputs to a verified ACRU hydrological model to simulate hydrological regime for each land use scenario.

6.5.1 Historical and Potential Future Land Use Change Impacts on Hydrology

The results of the study has shown that the hydrology of the Bonsa catchment has been altered (Figure 6.5 and 6.6) from the selected baseline hydrological regime. The land use of the Bonsa catchment prior to the implementation of the economic liberalization programmes of the Ghana government in the late 1980s and early 1990s was mainly evergreen forests, but currently (2011), only 51% of it remains (Aduah *et al.*, 2015). Although the study shows a substantial alteration of the hydrology between the baseline (1991) and current (2011) land use scenarios, the seasonal patterns of the high and low flows have been maintained. However, the current hydrological regime (i.e. 2011 land use scenario), shows significantly higher peak and dry season flows relative to the baseline flows. The higher flows in the current hydrological regime is because of land degradation through deforestation and urbanization, as well as expansion in surface mines (Aduah *et al.*, 2015).

Deforestation has been the result of many activities including timber logging and increasing farming activities by the local people, as well as felling of trees for fuelwood. The creation of new and the expansion of existing mines in the eastern and the northern part of the study area also contributed to the increased streamflows. The mines are located close to the main stem and tributaries of the Bonsa River, thereby affecting the streamflows directly. The almost 81% increase in settlement areas between 1991 and 2011, especially around the Tarkwa town, which also has streams that link directly to the Bonsa River and the 3 fold increase in shrubs/farms and mining areas, as well as reduction of secondary forest by 39% (Table 6.1), contributed to the increased streamflows at the catchment outlet for the current

(2011) land use scenario. However, the increase in shrubs/farms of over 3 fold from 1991 to 2011 was the main reason why streamflows in 2011 were substantially higher than those in 1991. Areas currently occupied by shrubs/farms should therefore be the main focus of any vegetation rehabilitation efforts in Bonsa catchment.

The study has further shown that under future land use scenarios, simulated streamflows were higher relative to the baseline and their magnitudes increased with time. However, the difference between the outlet streamflows of the future land uses was not much due to the relatively similar proportion of different land use areas. The slightly higher streamflows for the BAU scenarios, compared to the EG and the EGR scenarios is because of the slightly smaller and larger areas occupied by shrubs/farms and forests, respectively, in those scenarios. The little difference between outlet streamflows of the future land use scenarios implies that striving towards any one of them for planning may not significantly influence the streamflow responses at the catchment outlet. This maybe because the catchment has already undergone significant land use changes (e.g. over 300% increase in shrubs/farms between 1991 and 2011).

The spatial pattern of streamflow increases is similar across all land use scenarios, but the increases become greater and more evident with time. The increases in streamflows were greatest in the central part of the catchment in and around Tarkwa, where there are settlements, shrubs/farms and mining areas. The increases in streamflows were however dampened towards the catchment outlet due to streamflow contributions from more forested areas. Overall, the variability of streamflow changes was highest for the BAU land use, while that of the EGR scenario was lowest. Catchment management under changing land uses may therefore be enhanced by taking into account outlet streamflows, as well as streamflows in the interior parts.

Although hydrological alteration does not indicate how a stream’s ecology is directly affected, the assumption that the ecology of a basin is adapted to the pristine streamflow regimes (Richter *et al.*, 1997; Hillman *et al.*, 2012), provides an opportunity to use hydrological alteration indices such as RVA to infer potential river ecological changes. This study supports the notion of river ecological changes following land use changes and is consistent with previous studies (Hillman *et al.*, 2012; Homa *et al.*, 2013). The study has shown that the changed hydrological regimes of the Bonsa catchment under the current and the potential future land use scenarios, have created the potential for change in the ecology of the river. The slight increase in monthly flows for the major and minor peak seasons, indicate that water availability for both terrestrial and aquatic organisms is not constrained and soil moisture for plants has increased. This means both animals and plant species are not significantly stressed under normal hydrological regimes (i.e. monthly flows). However, under extreme flow conditions, the current (2011) and the potential future hydrological regimes may be detrimental to the survival of some plants and animals. This is because maximum water flows and durations for the hydrological regimes are above the pre-impact water flows, as well as the RVA pre-impact limits. Although the timing of extreme flows does not change under any of the land use scenarios, the frequent and higher magnitude floods under the current (2011) and the potential future hydrological regimes can destroy habitats of organisms, as well as seeds of plants and thereby affect river biodiversity. Such impacts are more pronounced where sensitive species are concerned (Richter *et al.*, 1997).The study has also shown that under the three potential future land use scenarios, river ecological impacts may increase with time, but the impacts under the BAU scenario were greater than those of the EG and the EGR scenarios.

6.5.2 Dealing with Uncertainties in Land Use Change Impact Assessments

Several studies (Breuer *et al.*, 2009; Legesse *et al.*, 2010; Park *et al.*, 2011; Warburton *et al.*, 2012) have applied distributed models to study impacts of land use changes on hydrology as the models are able simulate the physical reality of the hydrological cycle, spatially and temporally, which is vital for effective land use planning and water management. The use of physically-based semi-distributed model such as ACRU, reduces the data requirements that would have been necessary for a fully-distributed model and justifies its application in a data scarce region such as the Bonsa catchment in Ghana, West Africa.

The poor spatial resolution (scale: 1: 250 000) of the applied soil map and the lack of land use parameters required by the ACRU model, determined specifically for the Bonsa catchment has contributed to reducing the simulation accuracies in the study. Shortcomings of this study also include the use of single streamflow gauge, as well as few rain gauges for ACRU model simulation. Model calibration and validation would have been more robust, if several streamflow (Wi *et al.*, 2015) and rainfall gauges were available, as the streamflows in the Bonsa catchment are more variable at the subcatchment than at the catchment scale. The study also assessed the potential for ecological changes of the Bonsa River, which need to be verified with field based surveys. The above mentioned uncertainties were minimized by using physically meaningful sensitivity analysis of the ACRU model parameters (Chapter 5) for the Bonsa catchment. The sensitivity analysis of the ACRU model was suitable for the data scarce Bonsa catchment, since the model uses relatively few parameters, which are also physically meaningful and measurable.

The use of actual land use data, as well as realistic land use scenarios generated from land use modelling for determining impacts on hydrology ensures that simulated responses are reasonable. Land use models generate land use distributions for each scenario, based on statistically significant socio-economic and biophysical driving factors and allows incorporation of gradual changes, as well as regeneration of land use types at different locations within a catchment, simultaneously. The challenge with modelled land use scenarios used in this study was the lack of adequate input data for estimation of the historical land use model parameters, which resulted in only a moderate land use simulation accuracy (see companion paper in Chapter 4). To quantify these uncertainties, this study used three land use scenarios (BAU, EG and EGR) based on three development pathways. The BAU scenario was based on recent historical (2002 to 2011) trends of land use changes and the EG scenario assumed increasing secondary forest area through rubber plantations. For the EGR land use scenario, the Ghana Forestry Commission (2013) policy to rehabilitate 200 km^2/year of forest in the country were implemented.

Land use impacts are also affected by climate changes (Dale, 1997; D'Orgeval and Polcher, 2008) and their joint impacts are nonlinear (Li *et al.*, 2009). Since climate change is an additional uncertainty, this study tried to reduce the uncertainty by assessing land use change impacts separately. However, in order to fully comprehend the magnitudes and reasons for hydrological changes in the Bonsa catchment in Ghana, West Africa, further studies are needed to assess the combined land use and climate change impacts on the Bonsa catchment.

6.5.3 Management of Bonsa and Similar Catchments in West Africa

As the major finding in this study is increased streamflows in the current (2011) hydrological regime and the fact that neither plantation of rubber (EG scenario) nor plantation of rubber in addition to indigenous tree species at higher rates (EGR scenario) in the future scenarios was enough to moderate the catchment streamflows, additional management measures are necessary. It is suggested that an integrated and adaptive management (Richter *et al.*, 1997; Homa *et al.*, 2013) should be adopted to manage the hydrology and the environment of the Bonsa and similar catchments in West Africa. Thus in the current land use scenario effective storm water management including the use of runoff delay techniques in settlement, shrubs/farms and mining areas are needed and going into the future intensive rather than extensive farming should be promoted. Forest rehabilitation should also be targeted in areas dominated by shrubs lands. Installation of additional streamflow and rain gauges and continuous environmental monitoring and evaluation should also be considered.

6.6 Conclusion

The objectives of this study were to quantitatively assess the impacts of land use changes from the historical period to potential future, using historical, as well as potential future land use scenarios and to determine the river ecological alterations, if any in the Bonsa catchment of Ghana, West Africa. The study clearly shows that current land use changes relative to the baseline land use have significantly increased peak and dry season flows. It has also been revealed that the potential future land use changes may increase streamflows, although the seasonal patterns are not expected to change. The spatial variability of streamflow changes has been shown to be higher at the subcatchment than at the catchment scale. The study has also indicated that the potential for the river ecology relative to the baseline to change have been created, and the future land use scenarios show the potential for further river ecological alterations, although some of the land use scenarios incorporate reforestation. The BAU and the EGR scenarios are expected to generate the highest and the lowest river ecological alterations, respectively. In order to manage the Bonsa catchment effectively, adaptive catchment-wide management strategies, including installation of equipment and data capturing, research, rehabilitation of degraded forests, implementation of ecologically friendly and effective stormwater management strategies for urbanized, farms and mining areas and conducting monitoring and evaluation of restoration efforts, are suggested.

6.7 References

Aduah, MS, Warburton, ML and Jewitt, G. 2015. Analysis of land cover changes in the Bonsa catchment, Ankobra Basin, Ghana. *Applied Ecology and Environmental Research* 13(4)**:**935-955.

Akabzaa, TM, Jamieson, HE, Jorgenson, N and Nyame, K. 2009. The Combined Impact of Mine Drainage in the Ankobra River Basin, SW Ghana. *Mine Water and the Environment* 28(1)**:**50-64.

Armah, FA, Luginaah, I and Ason, B. 2012. Water Quality Index in the Tarkwa Gold Mining Area in Ghana. *The Journal of Transdisciplinary Environmental Studies (TES)* 11(2)**:**1-15.

Bansah, KJ and Amegbey, N. 2012. Ambient Particulate Matter Monitoring - A Case Study at Tarkwa. *Research Journal of Environmental and Earth Sciences* 4(4)**:**419-423.

Bossa, AY, Diekkrueger, B and Agbossou, EK. 2014. Scenario-Based Impacts of Land Use and Climate Change on Land and Water Degradation from the Meso to Regional Scale. *Water* 6(10)**:**3152-3181.

Bossa, AY, Diekkrueger, B, Giertz, S, Steup, G, Sintondji, LO, Agbossou, EK and Hiepe, C. 2012. Modeling the effects of crop patterns and management scenarios on N and P loads to surface water and groundwater in a semi-humid catchment (West Africa). *Agricultural Water Management* 115(2012)**:**20-37.

Boulain, N, Cappelaere, B, Séguis, L, Favreau, G and Gignoux, J. 2009. Water balance and vegetation change in the Sahel: A case study at the watershed scale with an eco-hydrological model. *Journal of Arid Environments* 73(12)**:**1125-1135.

Bourke, P, Arthur, J, Marshall, N, MacIntyre, J, Wasel, SM and Urbaez, E. 2007. Technical Report, First time disclosure of mineral reserves, Hwini-Butre and Benso properties, Southwest Ghana. Golden Star Resources Ltd, Denver, Colorado, USA.

Braimoh, AK and Vlek, PLG. 2005. Land-cover change trajectories in Northern Ghana. *Environmental Management* 36(3)**:**356-373.

Breuer, L, Huisman, JA, Willems, P, Bormann, H, Bronstert, A, Croke, BFW, Frede, HG, Gräff, T, Hubrechts, L, Jakeman, AJ, Kite, G, Lanini, J, Leavesley, G, Lettenmaier, DP, Lindström, G, Seibert, J, Sivapalan, M and Viney, NR. 2009. Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM). I: Model intercomparison with current land use. *Advances in Water Resources* 32(2)**:**129-146.

Brown, AE, Zhang, L, McMahon, TA, Western, AW and Vertessy, RA. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* 310(1-4)**:**28-61.

Castle Peak Mining Ltd. 2013. Strategic Gold Project in Ghana’s Ashanti Belt, Apankrah Deposit Next Steps[Online]. Castle Peak Mining Ltd. Vancouver, BC, Canada: Available: http://edg1.precisionir.com/companyspotlight/NA019419/CAP-Presentation_Nov2013.pdf [Accessed 9th April 2014].

Choi, J, Engel, BA, Muthukrishnan, S and Harbor, J. 2003. GIS based long term hydrologic impact evaluation for watershed urbanization. *Journal of the American Water Resources Association* 39(3)**:**623-635.

Cornelissen, T, Diekkrueger, B and Giertz, S. 2013. A comparison of hydrological models for assessing the impact of land use and climate change on discharge in a tropical catchment. *Journal of Hydrology* 498(2013)**:**221-236.

D'Orgeval, T and Polcher, J. 2008. Impacts of precipitation events and land-use changes on West African river discharges during the years 1951-2000. *Climate Dynamics* 31(2-3)**:**249-262.

Dale, VH. 1997. The relationship between land-use change and climate change. *Ecological Applications* 7(3)**:**753-769.

Dwomo, O and Dedzoe, CD. 2010. Oxisol (ferralsol) development in two agro-ecological zones of Ghana: A preliminary evaluation of some profiles. *Journal of Science and Technology, Kwame Nkrumah University of Science and Technology (KNUST)* 30(2)**:**11-28.

FAO. 2010a. Global Forest Resources Assessment 2010, Country Report, Ghana. *In:* Affum-Baffoe, K (ed.). Food and Agricultural Organisation (FAO), Rome, Italy.

FAO. 2010b. Global Forest Resources Assessment 2010: Main report. Food and Agriculture Organization of the United Nations, Rome, Italy.

Forbes, KA, Kienzle, SW, Coburn, CA, Byrne, JM and Rasmussen, J. 2011. Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada. *Climatic Change* 105(3-4)**:**555-576.

Ghana Forestry Commission. 2013. Draft Ghana forest plantation strategy: 2015 - 2040. Ghana Forestry Commission, Accra, Ghana.

Ghana Statistical Service. 2013. 2010 Population & housing census, National analytical report. *In:* Awusabo-Asare, K (ed.). Ghana Statistical Service, Accra, Ghana.

Ghile, YB. 2004. An adaptation of the SCS-ACRU hydrograph generating technique for application in Eritrea,. Unpublished MSc, School of Bioresources Engineering and Environmental Hydrology, University of Natal, South Africa.

Giertz, S and Diekkruger, B. 2003. Analysis of the hydrological processes in a small headwater catchment in Benin (West Africa). *Physics and Chemistry of the Earth* 28(33-36)**:**1333-1341.

Giertz, S, Junge, B and Diekkrüger, B. 2005. Assessing the effects of land use change on soil physical properties and hydrological processes in the sub-humid tropical environment of West Africa. *Physics and Chemistry of the Earth, Parts A/B/C* 30(8–10)**:**485-496.

Gold Fields Limited. 2012a. Damang Gold Mine, Technical Short Form Report. Gold Fields Limited, South Africa.

Gold Fields Limited. 2012b. Tarkwa Gold Mine, Technical Short Form Report. Gold Fields Limited, South Africa.

Gosling, SN, Taylor, RG, Arnell, NW and Todd, MC. 2011. A comparative analysis of projected impacts of climate change on river runoff from global and catchment-scale hydrological models. *Hydrology and Earth System Sciences* 15(1)**:**279-294.

Hargreaves, G, Hargreaves, G and Riley, J. 1985. Agricultural Benefits for Senegal River Basin. *Journal of Irrigation and Drainage Engineering* 111(2)**:**113-124.

Hillman, B, Douglas, EM and Terkla, D. 2012. An analysis of the allocation of Yakima River water in terms of sustainability and economic efficiency. *Journal of Environmental Management* 103(2012)**:**102-112.

Homa, ES, Brown, C, McGarigal, K, Compton, BW and Jackson, SD. 2013. Estimating hydrologic alteration from basin characteristics in Massachusetts. *Journal of Hydrology* 503(2013)**:**196-208.

Hrachowitz, M, Savenije, HHG, Bloeschl, G, McDonnell, JJ, Sivapalan, M, Pomeroy, JW, Arheimer, B, Blume, T, Clark, MP, Ehret, U, Fenicia, F, Freer, JE, Gelfan, A, Gupta, HV, Hughes, DA, Hut, RW, Montanari, A, Pande, S, Tetzlaff, D, Troch, PA, Uhlenbrook, S, Wagener, T, Winsemius, HC, Woods, RA, Zehe, E and Cudennec, C. 2013. A decade of Predictions in Ungauged Basins (PUB)a review. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 58(6)**:**1198-1255.

Jackson, B, Nicholson, SE and Klotter, D. 2009. Mesoscale Convective Systems over Western Equatorial Africa and Their Relationship to Large-Scale Circulation. *Monthly Weather Review* 137(4)**:**1272-1294.

Jewitt, GPW, Garratt, JA, Calder, IR and Fuller, L. 2004. Water resources planning and modelling tools for the assessment of land use change in the Luvuvhu Catchment, South Africa. *Physics and Chemistry of the Earth* 29(15-18)**:**1233-1241.

Klocking, B and Haberlandt, U. 2002. Impact of land use changes on water dynamics-a case study in temperate meso and macroscale river basins. *Physics and Chemistry of the Earth* 27(9-10)**:**619-629.

Kortatsi, BK. 2003. Acidifcation of Groundwater and its Implication on Rural Water Supply in the Ankobra Basin, Ghana. *West African Journal of Applied Ecology* 4(2003)**:**35-47.

Kusimi, JM. 2008. Assessing land use and land cover change in the Wassa West District of Ghana using remote sensing. *GeoJournal* 71(2008)**:**249-259.

Lane, PNJ, Best, AE, Hickel, K and Zhang, L. 2005. The response of flow duration curves to afforestation. *Journal of Hydrology* 310(1-4)**:**253-265.

Leblanc, MJ, Favreau, G, Massuel, S, Tweed, SO, Loireau, M and Cappelaere, B. 2008. Land clearance and hydrological change in the Sahel: SW Niger. *Global and Planetary Change* 61(3-4)**:**135-150.

Legesse, D, Abiye, TA, Vallet-Coulomb, C and Abate, H. 2010. Stream flow sensitivity to climate and land cover changes: Meki River, Ethiopia. *Hydrology and Earth System Science* 14(2010)**:** 2277-2287.

Legesse, D, Vallet-Coulomb, C and Gasse, F. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *Journal of Hydrology* 275(1-2)**:**67-85.

Li, KY, Coe, MT, Ramankutty, N and De Jong, R. 2007. Modeling the hydrological impact of land-use change in West Africa. *Journal of Hydrology* 337(3-4)**:**258-268.

Li, Z, Liu, W, Zhang, X and Zheng, F. 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology* 377(2009)**:**35-42.

Mahe, G, Paturel, JE, Servat, E, Conway, D and Dezetter, A. 2005. The impact of land use change on soil water holding capacity and river flow modelling in the Nakambe River, Burkina-Faso. *Journal of Hydrology* 300(1-4)**:**33-43.

Park, JY, Park, MJ, Joh, HK, Shin, HJ, Kwon, HJ, Srinivasan, R and Kim, SJ. 2011. Assessment of MIROC3.2 HIRES climate and CLUE-S land use change impacts on watershed hydrology using SWAT. *Transactions of the Asabe* 54(5)**:**1713-1724.

Richter, BD, Baumgartner, JV, Powell, J and Braun, DP. 1996. A method for assessing hydrologic alteration within ecosystems *Conservation Biology* 10(4)**:**1163-1174.

Richter, BD, Baumgartner, JV, Wigington, R and Braun, DP. 1997. How much water does a river need? . *Freshwater Biology* 37(1997)**:**231-249.

Schueler, V, Kuemmerle, T and Schroeder, H. 2011. Impacts of Surface Gold Mining on Land Use Systems in Western Ghana. *Ambio* 40(5)**:**528-539.

Schulze, RE. 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System,* Water Research Commission,Pretoria, South Africa.

Schulze, RE. 2000. Modelling hydrological responses to land use and climate change: A southern African perspective. *Ambio* 29(1)**:**12-22.

Seguis, L, Cappelaere, B, Milesi, G, Peugeot, C, Massuel, S and Favreau, G. 2004. Simulated impacts of climate change and land-clearing on runoff from a small Sahelian catchment. *Hydrological Processes* 18(17)**:**3401-3413.

The Nature Conservancy. 2009. Indicators of Hydrologic Alteration Version 7.1, User's Manual.

Valentin, C, Rajot, JL and Mitja, D. 2004. Responses of soil crusting, runoff and erosion to fallowing in the sub-humid and semi-arid regions of West Africa. *Agriculture, Ecosystems & Environment* 104(2)**:**287-302.

Van de Giesen, N, Stomph, T-J, Ajayi, AE and Bagayoko, F. 2011. Scale effects in Hortonian surface runoff on agricultural slopes in West Africa: Field data and models. *Agriculture, Ecosystems & Environment* 142(1–2)**:**95-101.

Verburg, PH, de Koning, GHJ, Kok, K, Veldkamp, A and Bouma, J. 1999. A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. *Ecological Modelling* 116(1)**:**45-61.

Verburg, PH and Overmars, KP. 2009. Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. *Landscape Ecology* 24(9)**:**1167-1181.

Warburton, ML, Schulze, RE and Jewitt, GPW. 2010. Confirmation of ACRU model results for applications in land use and climate change studies. *Hydrology and Earth System Sciences* 14(2010)**:**2399-2414.

Warburton, ML, Schulze, RE and Jewitt, GPW. 2012. Hydrological impacts of land use change in three diverse South African catchments. *Journal of Hydrology* 414-415(2012)**:**118-135.

Wi, S, Yang, YCE, Steinschneider, S, Khalil, A and Brown, CM. 2015. Calibration approaches for distributed hydrologic models in poorly gaged basins: implication for streamflow projections under climate change. *Hydrol. Earth Syst. Sci.* 19(2015)**:**857-876.

Yidana, SM, Ophori, D and Banoeng-Yakubo, B. 2007. Irrigation water resource management for sustainable agriculture - The Ankobra basin, Ghana. *Journal of Irrigation and Drainage Engineering-Asce* 133(6)**:**609-615.

6.8 Appendices

Appendix A

Table A.1: Land use parameters used for simulation

Land use	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Shrubs/farms	VEGINT (mm.rain/day)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	CAY	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
	COIAM	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	PCSUCO	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00
Evergreen forest	VEGINT (mm.rain/day)	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
	ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	CAY	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	COIAM	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
	PCSUCO	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00
Secondary forests	VEGINT (mm.rain/day)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	CAY	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	COIAM	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
	PCSUCO	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00
Mining areas	VEGINT (mm.rain/day)	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
	ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	CAY	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
	COIAM	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	PCSUCO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Settlements	VEGINT (mm.rain/day)	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
	ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	CAY	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
	COIAM	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	PCSUCO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A.2: Soil information

			Proportion (%)			
Soil series	**Horizon**	**Depth (cm)**	**Sand**	**Silt**	**Clay**	**Texture**
Ankasa	Ah1	0-5	66	14	20	Sandy loam
	Ah2	5-12	64	14	22	Sandy clay loam
	BA	12-36	59	13	28	Sandy clay loam
	Bts1	36-72	39	14	47	Clay
	Bts2	72-110	28	21	51	Clay
	Bt	110-150	30	23	47	Clay

Appendix B

Table B.1: Post-impact hydrological alteration of daily simulated streamflows of BAU land use scenario (2030, 2050 and 2070) using 1991 baseline streamflows as pre-impact data and 20 years observed climate data (1990 to 2010)

	Pre-impact:Baseline 1991 land use			Post-impact: 2030 BAU land use scenario				Post-impact: 2050 BAU land use scenario				Post-impact: 2070 BAU land use scenario			
		RVA Limits			Hydrologic Alteration Factors				Hydrologic Alteration Factors				Hydrologic Alteration Factors		
Parameters	Medians	Low	High	Medians	High	Middle	Low	Medians	High	Middle	Low	Medians	High	Middle	Low
Parameter Group #1 (m^3/s)															
January	**0.084**	0.063	0.128	**0.128**	0.429	0.286	-0.714	**0.132**	0.571	0.286	-0.857	**0.136**	0.571	0.286	-0.857
February	**0.066**	0.050	0.093	**0.091**	0.429	0.429	-0.857	**0.094**	0.571	0.286	-0.857	**0.099**	0.714	0.143	-0.857
March	**0.065**	0.058	0.074	**0.089**	1.714	-0.857	-0.857	**0.094**	1.714	-0.857	-0.857	**0.096**	1.714	-0.857	-0.857
April	**0.067**	0.056	0.079	**0.101**	1.571	-0.714	-0.857	**0.103**	1.714	-0.714	-1.000	**0.105**	1.714	-0.714	-1.000
May	**0.142**	0.109	0.229	**0.258**	0.857	-0.143	-0.714	**0.283**	1.000	0.000	-1.000	**0.296**	1.000	0.000	-1.000
June	**0.787**	0.553	1.188	**0.967**	0.143	0.429	-0.571	**0.985**	0.286	0.286	-0.571	**0.994**	0.286	0.286	-0.571
July	**0.529**	0.312	0.816	**0.620**	0.143	0.000	-0.143	**0.616**	0.143	0.000	-0.143	**0.616**	0.143	0.000	-0.143
August	**0.190**	0.117	0.332	**0.231**	0.143	0.286	-0.429	**0.235**	0.143	0.286	-0.429	**0.239**	0.143	0.429	-0.571
September	**0.162**	0.120	0.282	**0.192**	0.429	0.000	-0.429	**0.196**	0.429	0.000	-0.429	**0.200**	0.429	0.000	-0.429
October	**0.268**	0.153	0.815	**0.397**	0.143	0.571	-0.714	**0.410**	0.143	0.571	-0.714	**0.411**	0.143	0.714	-0.857
November	**0.347**	0.190	0.461	**0.461**	0.571	0.000	-0.571	**0.469**	0.571	0.000	-0.571	**0.469**	0.571	0.000	-0.571
December	**0.144**	0.122	0.246	**0.242**	0.429	0.286	-0.714	**0.249**	0.571	0.143	-0.714	**0.258**	0.571	0.143	-0.714
Parameter Group #2															
Extreme flows (m^3/s)															
1-day minimum	**0.043**	0.032	0.050	**0.051**	0.714	0.143	-0.857	**0.051**	0.714	0.143	-0.857	**0.052**	0.857	0.000	-0.857
3-day minimum	**0.044**	0.034	0.051	**0.054**	0.857	0.000	-0.857	**0.054**	0.857	0.000	-0.857	**0.056**	0.857	0.000	-0.857
7-day minimum	**0.045**	0.036	0.052	**0.063**	1.000	-0.143	-0.857	**0.065**	1.000	-0.143	-0.857	**0.065**	1.000	-0.143	-0.857
30-day minimum	**0.050**	0.045	0.058	**0.077**	1.714	-0.857	-0.857	**0.079**	1.714	-0.857	-0.857	**0.081**	1.714	-0.857	-0.857
90-day minimum	**0.074**	0.060	0.088	**0.126**	1.714	-0.857	-0.857	**0.135**	1.714	-0.714	-1.000	**0.141**	1.857	-0.857	-1.000
1-day maximum	**3.086**	2.850	3.964	**4.662**	0.857	0.143	-1.000	**4.900**	1.000	0.000	-1.000	**5.060**	1.000	0.000	-1.000
3-day maximum	**2.556**	2.201	3.427	**3.482**	0.571	0.286	-0.857	**3.579**	0.571	0.429	-1.000	**3.650**	0.714	0.286	-1.000
7-day maximum	**2.165**	1.846	2.602	**2.875**	0.714	-0.286	-0.429	**2.971**	0.857	-0.286	-0.571	**3.046**	0.857	-0.143	-0.714
30-day maximum	**1.533**	1.179	1.715	**1.866**	0.571	0.143	-0.714	**1.915**	0.714	0.000	-0.714	**1.946**	0.714	0.000	-0.714
90-day maximum	**0.877**	0.702	0.988	**1.110**	1.000	-0.429	-0.571	**1.135**	1.000	-0.429	-0.571	**1.157**	1.000	-0.429	-0.571
Number of zero days	**0.000**	0.000	0.000	**0.000**		0.000		**0.000**		0.000		**0.000**		0.000	
Base flow index	**0.128**	0.106	0.142	**0.131**	-0.286	0.571	-0.286	**0.130**	-0.286	0.571	-0.286	**0.128**	-0.286	0.571	-0.286
Parameter Group #3															
Date of minimum (Julian day)	**127.000**	119.000	150.000	**127.000**	-0.286	0.000	0.333	**123.000**	-0.429	0.000	0.500	**123.000**	-0.429	0.000	0.500
Date of maximum (Julain day)	**192.000**	177.100	236.600	**189.000**	-0.143	0.143	0.000	**189.000**	-0.143	0.143	0.000	**189.000**	-0.143	0.143	0.000
Parameter Group #4															
Low pulse count	**7.000**	6.000	9.000	**7.000**	1.000	-0.417	0.333	**6.000**	1.333	-0.583	0.500	**6.000**	0.667	-0.500	0.667
Low pulse duration (days)	**7.000**	5.000	9.070	**3.000**	-1.000	-0.700	3.000	**3.000**	-1.000	-0.800	3.250	**3.000**	-1.000	-0.700	2.750
High pulse count	**7.000**	5.260	8.740	**14.000**	1.857	-0.857	-1.000	**15.000**	1.714	-0.714	-1.000	**16.000**	2.000	-1.000	-1.000
High pulse duration (days)	**5.000**	3.260	8.370	**2.000**	-1.000	-0.857	1.857	**2.000**	-1.000	-0.714	1.714	**2.000**	-1.000	-0.857	1.857
Parameter Group #5															
Rise rate (m^3/s)	**0.052**	0.044	0.066	**0.145**	2.000	-1.000	-1.000	**0.159**	2.000	-1.000	-1.000	**0.165**	2.000	-1.000	-1.000
Fall rate (m^3/s)	**-0.009**	-0.010	-0.007	**-0.018**	-1.000	-0.571	1.571	**-0.020**	-1.000	-0.571	1.571	**-0.020**	-1.000	-0.714	1.714
Number of reversals	**90.000**	86.520	94.000	**110.000**	2.800	-0.778	-1.000	**112.000**	3.200	-1.000	-1.000	**112.000**	3.200	-1.000	-1.000

Table B.2: **Post-impact hydrological alteration of daily simulated streamflows of EG land use scenario (2030, 2050 and 2070) using 1991 baseline streamflows as pre-impact data and 20 years observed climate data (1990 to 2010)**

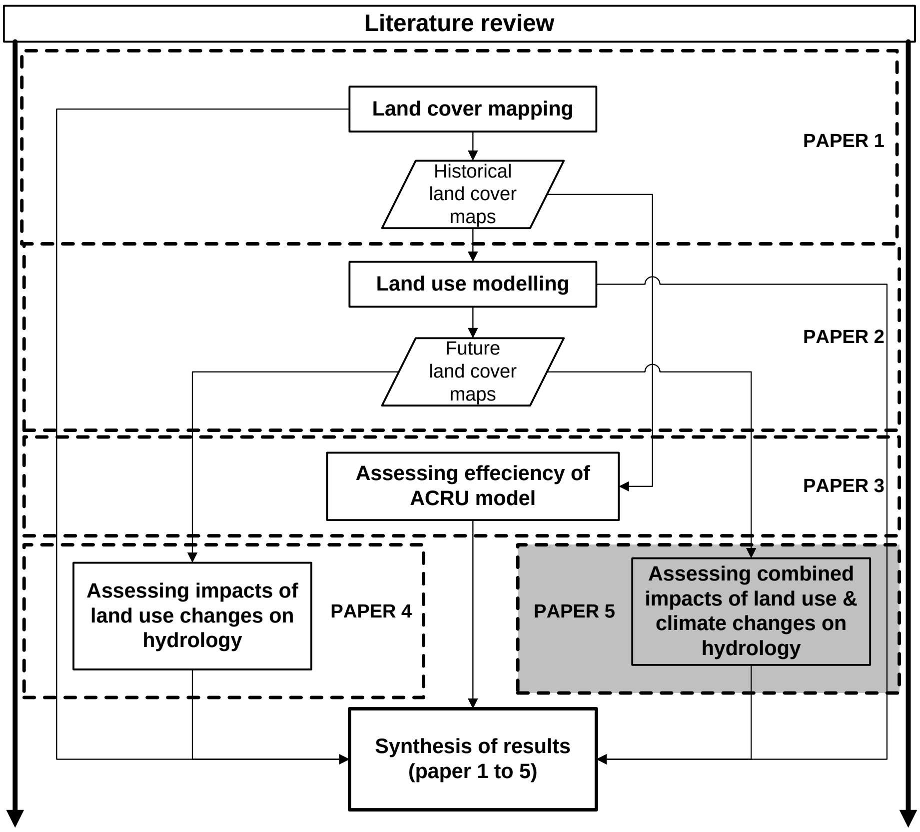
	Pre-impact:Baseline 1991 land use			Post-impact: 2030 EG land use scenario				Post-impact: 2050 EG land use scenario				Post-impact: 2070 EG land use scenario			
		RVA Limits			Hydrologic Alteration Factors				Hydrologic Alteration Factors				Hydrologic Alteration Factors		
Parameters	Medians	Low	High	Medians	High	Middle	Low	Medians	High	Middle	Low	Medians	High	Middle	Low
Parameter Group #1 (m^3/s)															
January	**0.084**	0.063	0.128	**0.115**	0.286	0.429	-0.714	**0.114**	0.286	0.429	-0.714	**0.116**	0.286	0.429	-0.714
February	**0.066**	0.050	0.093	**0.083**	0.429	0.429	-0.857	**0.083**	0.429	0.429	-0.857	**0.085**	0.429	0.429	-0.857
March	**0.065**	0.058	0.074	**0.087**	1.571	-0.714	-0.857	**0.088**	1.571	-0.714	-0.857	**0.089**	1.714	-0.857	-0.857
April	**0.067**	0.056	0.079	**0.093**	0.857	0.000	-0.857	**0.098**	1.429	-0.571	-0.857	**0.102**	1.571	-0.571	-1.000
May	**0.142**	0.109	0.229	**0.248**	0.714	0.000	-0.714	**0.261**	0.857	-0.143	-0.714	**0.274**	0.857	-0.143	-0.714
June	**0.787**	0.553	1.188	**0.965**	0.000	0.429	-0.429	**0.974**	0.143	0.429	-0.571	**0.980**	0.143	0.429	-0.571
July	**0.529**	0.312	0.816	**0.586**	0.143	-0.143	0.000	**0.575**	0.000	0.000	0.000	**0.570**	0.000	0.000	0.000
August	**0.190**	0.117	0.332	**0.219**	0.143	0.000	-0.143	**0.218**	0.143	0.000	-0.143	**0.220**	0.143	0.143	-0.286
September	**0.162**	0.120	0.282	**0.187**	0.429	0.000	-0.429	**0.188**	0.429	0.000	-0.429	**0.190**	0.429	0.000	-0.429
October	**0.268**	0.153	0.815	**0.371**	0.143	0.571	-0.714	**0.389**	0.143	0.571	-0.714	**0.397**	0.143	0.571	-0.714
November	**0.347**	0.190	0.461	**0.439**	0.429	0.143	-0.571	**0.444**	0.429	0.143	-0.571	**0.448**	0.429	0.143	-0.571
December	**0.144**	0.122	0.246	**0.219**	0.429	0.000	-0.429	**0.222**	0.429	0.000	-0.429	**0.227**	0.429	0.000	-0.429
Parameter Group #2															
Extreme flows (m^3/s)															
1-day minimum	**0.043**	0.032	0.050	**0.050**	0.429	0.429	-0.857	**0.051**	0.571	0.286	-0.857	**0.051**	0.571	0.286	-0.857
3-day minimum	**0.044**	0.034	0.051	**0.053**	0.571	0.286	-0.857	**0.053**	0.714	0.000	-0.714	**0.052**	0.714	0.143	-0.857
7-day minimum	**0.045**	0.036	0.052	**0.059**	0.857	0.000	-0.857	**0.060**	1.000	-0.143	-0.857	**0.061**	1.000	-0.143	-0.857
30-day minimum	**0.050**	0.045	0.058	**0.075**	1.286	-0.429	-0.857	**0.076**	1.429	-0.571	-0.857	**0.076**	1.429	-0.571	-0.857
90-day minimum	**0.074**	0.060	0.088	**0.122**	1.571	-0.714	-0.857	**0.128**	1.714	-0.857	-0.857	**0.130**	1.714	-0.857	-0.857
1-day maximum	**3.086**	2.850	3.964	**4.517**	0.857	0.000	-0.857	**4.733**	1.000	0.000	-1.000	**4.850**	1.000	0.000	-1.000
3-day maximum	**2.556**	2.201	3.427	**3.384**	0.429	0.286	-0.714	**3.447**	0.571	0.286	-0.857	**3.496**	0.571	0.429	-1.000
7-day maximum	**2.165**	1.846	2.602	**2.782**	0.714	-0.286	-0.429	**2.870**	0.714	-0.143	-0.571	**2.923**	0.857	-0.286	-0.571
30-day maximum	**1.533**	1.179	1.715	**1.838**	0.571	0.000	-0.571	**1.879**	0.571	0.000	-0.571	**1.898**	0.571	0.143	-0.714
90-day maximum	**0.877**	0.702	0.988	**1.088**	0.857	-0.429	-0.429	**1.103**	1.000	-0.429	-0.571	**1.114**	1.000	-0.429	-0.571
Number of zero days	**0.000**	0.000	0.000	**0.000**		0.000		**0.000**		0.000		**0.000**		0.000	
Base flow index	**0.128**	0.106	0.142	**0.130**	-0.286	0.429	-0.143	**0.127**	-0.286	0.429	-0.143	**0.126**	-0.286	0.429	-0.143
Parameter Group #3															
Date of minimum (Julian day)	**127.000**	119.000	150.000	**127.000**	-0.286	0.000	0.333	**123.000**	-0.286	-0.125	0.500	**123.000**	-0.286	-0.125	0.500
Date of maximum (Julain day)	**192.000**	177.100	236.600	**189.000**	-0.143	0.143	0.000	**189.000**	-0.143	0.143	0.000	**189.000**	-0.143	0.143	0.000
Parameter Group #4															
Low pulse count	**7.000**	6.000	9.000	**8.000**	2.000	-0.667	0.333	**8.000**	1.000	-0.417	0.333	**8.000**	1.333	-0.500	0.333
Low pulse duration (days)	**7.000**	5.000	9.070	**3.750**	-0.833	-0.400	2.250	**3.000**	-1.000	-0.400	2.500	**3.000**	-1.000	-0.500	2.750
High pulse count	**7.000**	5.260	8.740	**15.000**	1.714	-0.714	-1.000	**15.000**	1.857	-0.857	-1.000	**15.000**	2.000	-1.000	-1.000
High pulse duration (days)	**5.000**	3.260	8.370	**2.000**	-1.000	-0.714	1.714	**2.000**	-1.000	-0.857	1.857	**2.000**	-1.000	-0.857	1.857
Parameter Group #5															
Rise rate (m^3/s)	**0.052**	0.044	0.066	**0.139**	2.000	-1.000	-1.000	**0.141**	2.000	-1.000	-1.000	**0.155**	2.000	-1.000	-1.000
Fall rate (m^3/s)	**-0.009**	-0.010	-0.007	**-0.017**	-0.857	-0.714	1.571	**-0.019**	-1.000	-0.571	1.571	**-0.020**	-1.000	-0.714	1.714
Number of reversals	**90.000**	86.520	94.000	**112.000**	3.200	-1.000	-1.000	**116.000**	3.200	-1.000	-1.000	**116.000**	3.200	-1.000	-1.000

Table B.3: Post-impact hydrological alteration of daily simulated streamflows of EGR land use scenario (2030, 2050 and 2070) using 1991 baseline streamflows as pre-impact data and 20 years observed climate data (1990 to 2010)

	Pre-impact:Baseline 1991 land use			Post-impact: 2030 EGR land use scenario				Post-impact: 2050 EGR land use scenario				Post-impact: 2070 EGR land use scenario			
		RVA Limits			Hydrologic Alteration Factors				Hydrologic Alteration Factors				Hydrologic Alteration Factors		
Parameters	Medians	Low	High	Medians	High	Middle	Low	Medians	High	Middle	Low	Medians	High	Middle	Low
Parameter Group #1 (m^3/s)															
January	**0.084**	0.063	0.128	**0.116**	0.286	0.429	-0.714	**0.113**	0.286	0.429	-0.714	**0.112**	0.286	0.429	-0.714
February	**0.066**	0.050	0.093	**0.084**	0.429	0.429	-0.857	**0.085**	0.429	0.429	-0.857	**0.085**	0.429	0.429	-0.857
March	**0.065**	0.058	0.074	**0.088**	1.571	-0.714	-0.857	**0.088**	1.714	-0.857	-0.857	**0.089**	1.571	-0.714	-0.857
April	**0.067**	0.056	0.079	**0.094**	1.286	-0.429	-0.857	**0.095**	1.571	-0.714	-0.857	**0.098**	1.571	-0.714	-0.857
May	**0.142**	0.109	0.229	**0.240**	0.571	0.143	-0.714	**0.258**	0.857	-0.143	-0.714	**0.264**	0.857	-0.143	-0.714
June	**0.787**	0.553	1.188	**0.949**	0.143	0.286	-0.429	**0.967**	0.143	0.429	-0.571	**0.975**	0.143	0.429	-0.571
July	**0.529**	0.312	0.816	**0.587**	0.143	-0.143	0.000	**0.568**	0.143	-0.143	0.000	**0.561**	0.143	-0.143	0.000
August	**0.190**	0.117	0.332	**0.220**	0.143	0.143	-0.286	**0.218**	0.143	0.000	-0.143	**0.219**	0.143	0.000	-0.143
September	**0.162**	0.120	0.282	**0.187**	0.429	0.000	-0.429	**0.187**	0.429	0.000	-0.429	**0.189**	0.429	0.000	-0.429
October	**0.268**	0.153	0.815	**0.383**	0.143	0.571	-0.714	**0.393**	0.143	0.571	-0.714	**0.396**	0.143	0.571	-0.714
November	**0.347**	0.190	0.461	**0.440**	0.429	0.143	-0.571	**0.439**	0.429	0.143	-0.571	**0.437**	0.429	0.143	-0.571
December	**0.144**	0.122	0.246	**0.226**	0.429	0.000	-0.429	**0.224**	0.429	0.000	-0.429	**0.222**	0.429	0.000	-0.429
Parameter Group #2															
Extreme flows (m^3/s)															
1-day minimum	**0.043**	0.032	0.050	**0.052**	0.571	0.286	-0.857	**0.051**	0.571	0.286	-0.857	**0.051**	0.571	0.286	-0.857
3-day minimum	**0.044**	0.034	0.051	**0.054**	0.571	0.286	-0.857	**0.055**	0.571	0.143	-0.714	**0.055**	0.571	0.143	-0.714
7-day minimum	**0.045**	0.036	0.052	**0.059**	0.857	0.000	-0.857	**0.059**	0.857	0.000	-0.857	**0.059**	0.857	0.000	-0.857
30-day minimum	**0.050**	0.045	0.058	**0.075**	1.429	-0.571	-0.857	**0.075**	1.429	-0.571	-0.857	**0.076**	1.429	-0.571	-0.857
90-day minimum	**0.074**	0.060	0.088	**0.122**	1.571	-0.714	-0.857	**0.126**	1.714	-0.857	-0.857	**0.126**	1.714	-0.857	-0.857
1-day maximum	**3.086**	2.850	3.964	**4.503**	0.857	-0.143	-0.714	**4.708**	1.000	0.000	-1.000	**4.796**	1.000	0.000	-1.000
3-day maximum	**2.556**	2.201	3.427	**3.377**	0.429	0.286	-0.714	**3.440**	0.571	0.286	-0.857	**3.468**	0.571	0.286	-0.857
7-day maximum	**2.165**	1.846	2.602	**2.781**	0.714	-0.286	-0.429	**2.863**	0.714	-0.143	-0.571	**2.896**	0.714	-0.143	-0.571
30-day maximum	**1.533**	1.179	1.715	**1.839**	0.571	0.000	-0.571	**1.878**	0.571	0.000	-0.571	**1.894**	0.571	0.143	-0.714
90-day maximum	**0.877**	0.702	0.988	**1.090**	0.857	-0.429	-0.429	**1.099**	1.000	-0.429	-0.571	**1.104**	1.000	-0.429	-0.571
Number of zero days	**0.000**	0.000	0.000	**0.000**		0.000		**0.000**		0.000		**0.000**		0.000	
Base flow index	**0.128**	0.106	0.142	**0.130**	-0.286	0.429	-0.143	**0.126**	-0.286	0.429	-0.143	**0.123**	-0.286	0.429	-0.143
Parameter Group #3															
Date of minimum (Julian day)	**127.000**	119.000	150.000	**123.000**	-0.286	0.000	0.333	**123.000**	-0.286	-0.125	0.500	**123.000**	-0.286	-0.125	0.500
Date of maximum (Julain day)	**192.000**	177.100	236.600	**189.000**	-0.143	0.143	0.000	**189.000**	-0.143	0.143	0.000	**189.000**	-0.143	0.143	0.000
Parameter Group #4															
Low pulse count	**7.000**	6.000	9.000	**8.000**	1.667	-0.583	0.333	**8.000**	1.333	-0.500	0.333	**9.000**	2.000	-0.667	0.333
Low pulse duration (days)	**7.000**	5.000	9.070	**3.750**	-0.833	-0.400	2.250	**3.250**	-1.000	-0.400	2.500	**3.000**	-1.000	-0.400	2.500
High pulse count	**7.000**	5.260	8.740	**15.000**	1.857	-0.857	-1.000	**15.000**	1.857	-0.857	-1.000	**15.000**	2.000	-1.000	-1.000
High pulse duration (days)	**5.000**	3.260	8.370	**2.000**	-1.000	-0.714	1.714	**2.000**	-1.000	-0.857	1.857	**2.000**	-1.000	-1.000	2.000
Parameter Group #5															
Rise rate (m^3/s)	**0.052**	0.044	0.066	**0.128**	2.000	-1.000	-1.000	**0.142**	2.000	-1.000	-1.000	**0.154**	2.000	-1.000	-1.000
Fall rate (m^3/s)	**-0.009**	-0.010	-0.007	**-0.018**	-1.000	-0.571	1.571	**-0.019**	-1.000	-0.571	1.571	**-0.019**	-1.000	-0.571	1.571
Number of reversals	**90.000**	86.520	94.000	**112.000**	3.200	-1.000	-1.000	**116.000**	3.200	-1.000	-1.000	**116.000**	3.200	-1.000	-1.000

Preface to Chapter 7

Understanding of the combined, as well as the separate impacts of land use and climate changes on hydrology and ecology is important in preparing for future land use and climate changes, as the impacts affect society and the environment in many different ways. Understanding the impacts of Global Changes is necessary for effective water resources and environmental management and the information obtained from impact studies can guide effective data collection and monitoring programmes. This chapter (paper 5) analyses the potential future impacts of climate changes, as well as the combined impacts of potential future climate and land use changes on hydrology and the resultant river ecological alterations in the Bonsa catchment of Ghana, West Africa. The chapter use data obtained from Chapter 3 and 4, as well as the verified ACRU hydrological model from Chapter 5. Potential future climate change scenarios were downloaded from the climate information portal of the Climate Analysis Group of University of Cape Town, South Africa.



CHAPTER 7 : COMBINED IMPACTS OF LAND USE AND CLIMATE CHANGES ON THE HYDROLOGY OFA LOWLAND RAINFOREST CATCHMENT IN WEST AFRICA

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7.1 Abstract

This study analysed the separate and the combined impacts of climate and land use changes on hydrology, as well as the consequent potential river ecological alterations on the Bonsa catchment in Ghana, West Africa, using the ACRU hydrological model. The study used five RCP8.5 climate change scenarios (wet, 25th percentile, 75th percentile, dry and a multi-model median of nine GCMs) from the CMIP5 AR5 models for near (2020 – 2039) and far (2060 – 2079) future time slices. Change factors were used to downscale the GCM scenarios to the local scale, using observed climate data for the control period of 1990 to 2009. The land use of 1991 was used as the baseline land use and three future land use scenarios (BAU, EG, EGR) for two time slices (2030 and 2070) were used. Richter’s range of variability approach (RVA) was used to assess the potential river ecological impacts. The study showed that under all separate climate change scenarios, overall flows reduced, but under combined climate and land use changes, streamflows increased. Under the combined scenarios, streamflow responses due to the different future land use scenarios were not substantially different. Also, land use is the dominant controlling factor in streamflow changes in the Bonsa catchment under a dry climate change, but under a wet climate change, climate controls streamflow changes. The spatial variability of catchment streamflow changes under combined land use and climate changes were greater than the spatial variability of streamflow changes under climate change and the potential river ecological changes in the catchment followed trends similar to the streamflows, as they increased with time. The potential river ecological alterations resulting from combined climate change and land use changes were higher than those resulting from separate climate change impacts. The range of plausible future streamflows and potential river ecological changes derived in this study provides natural resources and environmental managers of the Bonsa catchment, the first ever and the most current information to develop suitable adaptation and mitigation strategies, to prepare adequately for climate and land use changes.

Key words: Bonsa catchment, change factors, climate changes, ecological changes, Ghana, land use changes, spatial variability

7.2 Introduction

Climate change has become a topical issue because of its far reaching impacts on economies, life, property and the environment. Climate change intensifies the hydrological cycle, with consequences such as increases in frequency and severity of droughts and floods. The impacts of climate change on hydrology influences agriculture, water supply, environmental sustainability and protection from floods and infrastructure. Therefore determination of the impacts of the climate change on hydrology at the local scale is urgently needed in order to promote sustainable development and the protection of life, property and the environment. Land use also plays an important role in the environment, as it partitions rainfall into the components of the hydrological cycle (Costa *et al.*, 2003; D'Orgeval and Polcher, 2008; Warburton *et al.*, 2010), such as evaporation, runoff and groundwater. Land use changes thus change the balance between the components of the hydrological cycle, which can lead to several challenges in water resources and environmental management. It has also been suggested (Buytaert *et al.*, 2010) that these challenges are more variable at the local and regional scale than at the global scale. Furthermore, since climatic changes can influence land use changes (Warburton *et al.*, 2012) and land use changes through vegetation dynamics can also feedback to impact regional climate (Xue, 1997; Wang and Eltahir, 2000), comprehensive understanding of land use change and climate change impacts on hydrology can only be gained from determination of both their combined and separate impacts. The combined effects of climate change and land use changes on hydrology and the environment can lead to severe water resources and environmental problems at the local scale.

In West Africa, during the past four decades, there has been extensive land use changes and intensification of climate change. For example, between 1990 and 2010, deforestation has resulted in the removal of about 32 million ha of forest (FAO, 2010) and during the twentieth century mean annual temperatures increased by 2^{0}C, while mean annual precipitation decreased by approximately 20% (Hulme *et al.*, 2001). According to the IPCC's assessment reports (IPCC, 2007, 2013), temperatures will continue to rise in the 21^{st} century, but there is no clear trend in precipitation for the region. It has been argued that the changes in the past four decades have largely been the result of the large scale drought in West Africa, between the 1970s and the early 1980s (L'Hote *et al.*, 2002; Leblanc *et al.*, 2008), agricultural expansion, as well as population increase and urbanization (Barbier, 2000; Jalloh *et al.*, 2013).

Despite the substantial changes in West Africa and the numerous studies that have been conducted (Ardoin-Bardin *et al.*, 2009; Bossa *et al.*, 2012; Ruelland *et al.*, 2012; Sood *et al.*, 2013; Bossa *et al.*, 2014), the responses to climate change and land use changes are still not understood well, especially in the southern rainforest catchments, where the majority of the population live. The companion paper in Chapter 6 concluded that land use changes have altered the hydrology and the ecology of the Bonsa catchment of Ghana, a representative rainforest catchment of West Africa, with both increases in peak and low flows. The future scenarios of land use change in the catchment point to higher increases in both peak and low flows and a higher potential for ecological alterations. However, since the study did not consider effects of climate, it is not known how climate change and the combined impacts of land use changes and climate changes will affect the hydrological cycle components and the ecology in the near and far future. Since land use and climate changes affect each other (Dale, 1997; D'Orgeval and Polcher, 2008) and their joint impacts are sometimes non-linear (Li *et al.*, 2009), it is necessary to determine both the joint and separate impacts on the hydrology of the catchment to improve knowledge and understanding of global change impacts in the region.

The aims of this study were to determine the impacts of climate changes, as well as the combined impacts of climate change and land use changes on the hydrology and the consequent river ecological alterations of the Bonsa catchment, which was selected to represent lowland rainforest catchments of West Africa. The study builds on a previous study (Chapter 6) and it uses the ACRU hydrological model, which has previously been calibrated in another study (Chapter 5) for the study area.

7.3 Methodology and Data Acquisition

7.3.1 Geographical Overview

The Bonsa catchment in Ghana, West Africa (Figure 7.1) is located between longitudes 1° 41´ and 2° 13´ West and latitudes 5° 4´and 5° 43´North. The catchment (1482 km^2) has a low relief, with elevation ranging between 30 and 340 m above mean sea level. The rainfall regime is bimodal, with the major season peaking in July and the minor season peaking in October. The annual rainfall ranges between 1500 mm and 2150 mm (Yidana *et al.*, 2007) and the annual average minimum and maximum temperatures are 23ºC and 31ºC, respectively. The catchment land cover consists mostly of evergreen and secondary forests and shrubs/farms. The geology is characterized by Tarkwaian and Birimian rock systems (Akabzaa *et al.*, 2009) and the soil is composed mostly of Ferric Acrisols. Major economic activities in the catchment include open-pit gold mining, rubber and small-scale cocoa and food crop cultivation.

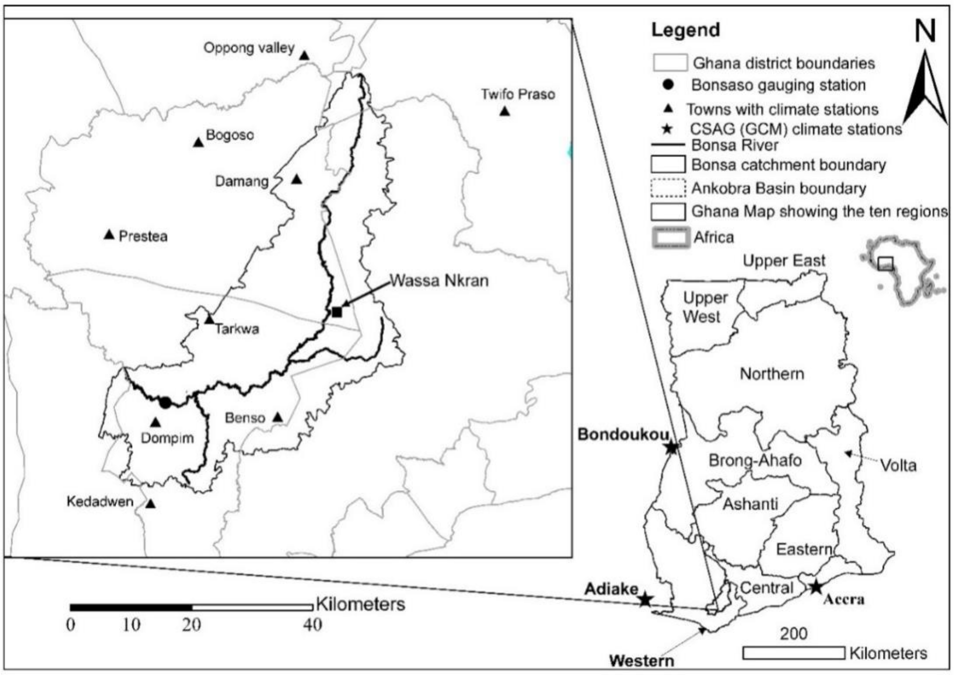


Figure 7.1: Map of study area showing the Bonsa catchment in the Ankobra basin, Ghana and the GCM (CSAG) as well as observed climate stations

7.3.2 *The ACRU Hydrological Model*

The ACRU Model (Schulze, 1995) is a daily time step physical-conceptual hydrological model developed by the University of KwaZulu-Natal, South Africa to simulate catchment hydrological responses. It is a multi-purpose and multi-layer model (Figure 7.2) that can be used for catchment water resources assessment, assessment of land use change (Schulze, 2000; Jewitt *et al.*, 2004; Schmidt *et al.*, 2009; Warburton *et al.*, 2012) and climate change impacts (Forbes *et al.*, 2011; Graham *et al.*, 2011; Kienzle *et al.*, 2012). A detailed description of the model is available in Schulze (1995). The ACRU model was selected for this study because a satisfactory monthly NSE of 0.6 and R^2 of 0.7 were obtained after a physically meaningful calibration study undertaken for the Bonsa catchment (Chapter 5) and because the model has also been applied successfully in a variety of catchments (Ghile, 2004; Warburton *et al.*, 2010; Forbes *et al.*, 2011), which has a wide range of land uses and climates.

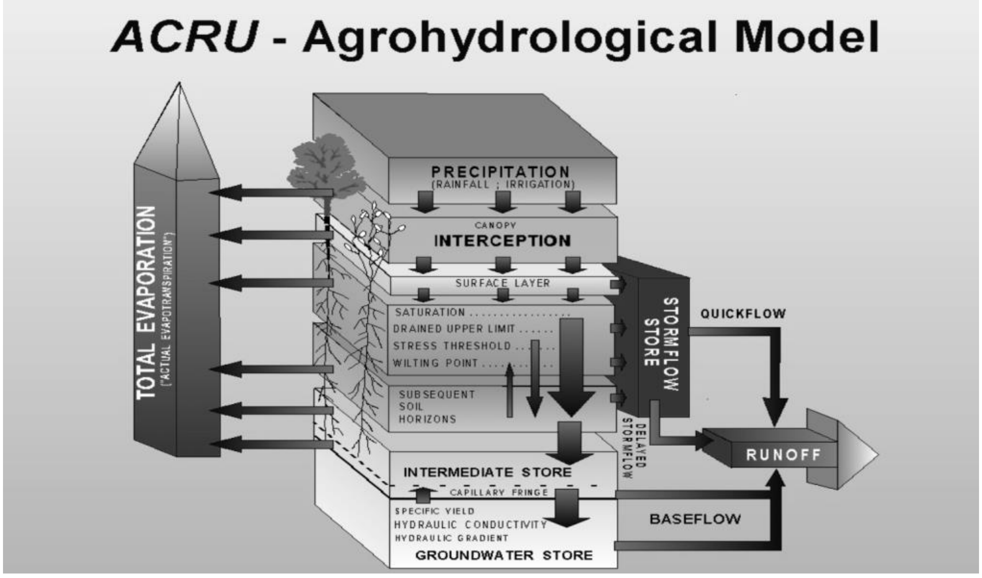


Figure 7.2: Representation of hydrological processes in the ACRU model (Schulze, 1995)

7.3.3 Model Data Acquisition and Preparation

A total of 103 subcatchments were created using digitized contour and river courses maps obtained from the Survey of Ghana (SOG). The associated hydrological response units (HRUs) were created based on catchment land uses. In order to define the flow path of the rivers, a catchment configuration network, using subcatchments, HRUs and the river courses, was created. The land use data, soil information and streamflow simulation control variables used in this study are the same as those used in the companion papers in Chapters 5 and 6.To determine the impacts of climate and land use change on the hydrological responses of the Bonsa catchment various simulations were performed. The verified ACRU hydrological model was run for the Bonsa catchment for the baseline scenario, using the baseline land use of 1991 and baseline observed climate data from 1990 to 2009.The separate impacts of climate changes on streamflows were determined by running the ACRU model for each selected climate change scenario and holding the land use as the baseline (1991) land use. Following this, the combined impacts of climate and land use change were determined by varying both the climate change and the land use scenarios.

7.3.3.1 Land use scenarios

Three land use scenarios (Figure 7.3 and Table 7.1), namely business-as-usual (BAU), economic growth (EG) and economic growth with enhanced reforestation (EGR), for two time slices (2030 and 2070) were used. The land use scenarios were simulated in a previous study (Aduah *et al., under review*, Chapter 4).

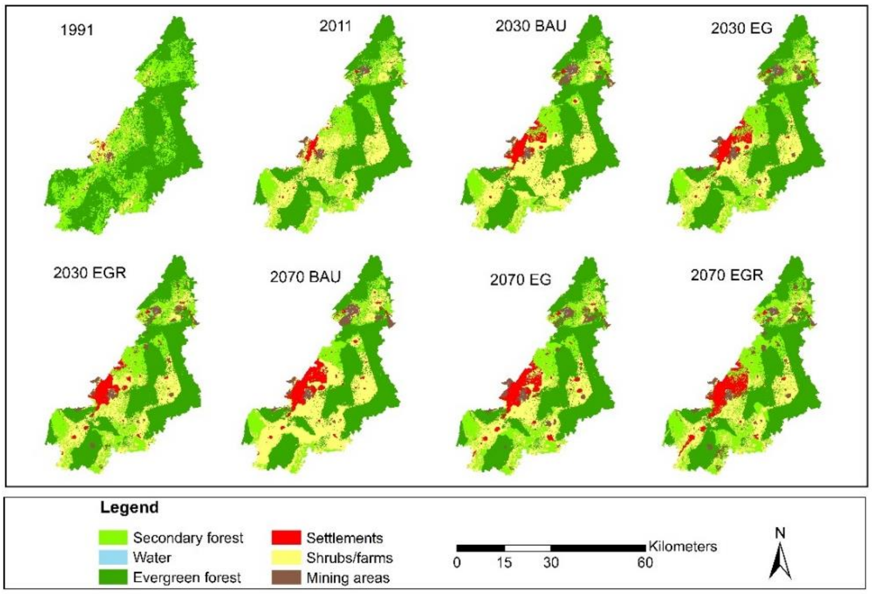


Figure 7.3: **Land use maps for baseline land use (1991), current (2011) land use and future land use scenarios in the Bonsa catchment, generated from mapping and land use simulation (Aduah *et al.*, *under review*, Chapter 4)**

Table 7.1: **Proportions of land uses for the Bonsa catchment for the baseline (1991), current (2011) and future scenarios (2030 and 2070)**

			Land cover						
Scenario	Time slice	Unit	Secondary forest	Water	Evergreen forest	Settlements	Shrubs/farms	Mining areas	Total
Baseline	1991	area (km^2)	457.3	0.2	916.5	12.4	90.0	5.9	1482.3
		%	30.8	0.0	61.8	0.8	6.1	0.4	100.0
Current	2011	area (km^2)	280.3	1.4	754.6	22.4	399.4	24.2	1482.3
		%	18.9	0.1	50.9	1.5	26.9	1.6	100.0
BAU	2030	area (km^2)	215.5	1.4	728.1	63.7	425.3	48.3	1482.2
		%	14.5	0.1	49.1	4.3	28.7	3.3	100.0
	2070	area (km^2)	171.0	1.4	683.6	91.3	482.1	52.8	1482.2
		%	11.5	0.1	46.1	6.2	32.5	3.6	100.0
EG	2030	area (km^2)	283.9	1.4	733.6	68.8	340.1	54.3	1482.1
		%	19.2	0.1	49.5	4.6	22.9	3.7	100.0
	2070	area (km^2)	294.7	1.4	689.4	95.7	335.0	66.0	1482.2
		%	19.9	0.1	46.5	6.5	22.6	4.5	
EGR	2030	area (km^2)	303.8	1.4	716.0	66.6	340.2	54.3	1482.2
		%	20.5	0.1	48.3	4.5	22.9	3.7	100.0
	2070	area (km^2)	350.1	1.4	667.7	100.6	295.4	67.2	1482.2
		%	23.6	0.1	45.0	6.8	19.9	4.5	100.0

7.3.3.2 Global Climate Model Scenario Selection and Downscaling

Global climate models (GCMs) are the most important tools for studying climate change impacts (Fowler *et al.*, 2007; Teng *et al.*, 2012). Substantial progress has been made in GCM modelling in the past several decades, including the use of finer resolutions and realistic parameterisation of vegetation and many physical processes (IPCC, 2007; Alo and Wang, 2010; IPCC, 2013). Unfortunately there are still numerous sources of uncertainties in GCM climate data, especially at the regional scale, due to the inability of the models to capture small scale processes accurately (Buytaert *et al.*, 2010), coarse spatial resolution (Quintana Segui *et al.*, 2010; Teng *et al.*, 2012), uncertain future emission scenarios (Kim *et al.*, 2013), inconsistent rainfall estimation (Moradkhani *et al.*, 2010) and biases in extreme events (Teng *et al.*, 2012). Thus GCM climate data is still unsuitable for hydrological modelling at the local scale (Buytaert *et al.*, 2010). For impact assessments, such as the current study, downscaling to a finer resolution (Liu *et al.*, 2008; Buytaert *et al.*, 2010) using either dynamic or statistical downscaling (SD) (Kunstmann *et al.*, 2004; Maurer and Hidalgo, 2008) is required.

Consequently, statically downscaled future climate records of the 8.5 Representative Concentration Pathway (RCP) scenario from four GCMs and a multi-model median of all available nine CMIP5 AR5 models were downloaded from CSAG (2015) and used for impact modelling. The selection of GCMs was based on changes in mean annual precipitation (MAP) (Table 7.3). Two GCMs representing the extremes (wettest:CNRM-CM5 and driest: MIROC-ESM) and two representing 75th (GFDL-ESM2M) and 25th (MIROC5) percentile changes in MAP as well as a multi-model median of available downscaled GCMs were used for the study. The selection of the wettest and driest GCMs was to account for hydrological extremes (Lutz *et al*., 2016) such as floods and droughts, while the selection of the 75th and the 25th percentiles of GCMs was to avoid possible outliers in the climate projections (Mendlik and Gobiet, 2016) to provide a more robust impact analysis. The use of the multi-model median of the GCMs for the study was to account for average hydrological conditions, which are also vital for sustainable water supply as well as proper functioning of the environment. The methods of selection of the GCMs (Moradkhani *et al.*,2010; Mango *et al.*, 2011; Forbes *et al.*, 2011; Kienzle *et al.*, 2012; Lutz *et al.*, 2016; Mendlik and Gobiet, 2016) was to support analysis of the full range of impacts, without using all available GCMs.

The selected GCMs were already downscaled to a few synoptic climate stations in Africa by CSAG (2015) as part of the World Climate Research Programme (WCRP) (Kim *et al.*,

2013) Coordinated Regional Climate Downscaling Experiment for Africa (CORDEX-Africa). The scenario datasets used for the study formed part of the Coupled-Model Inter-comparison Phase five (CMIP5) project, which were used for the Fifth Assessment Report (AR5) of the IPCC (IPCC, 2013).

Table 7.2: GCMs from IPCC CMIP5 AR5 used in this study

No.	GCM	Modelling Centre	Scenarios (from CSAG)
1	MIROC-ESM*	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	4.5/8.5RCP
2	CNRM-CM5*	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	4.5/8.5RCP
3	CanESM2	Canadian Centre for Climate Modelling and Analysis	4.5/8.5RCP
4	FGOALS-s2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	4.5/8.5RCP
5	BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University	4.5/8.5RCP
6	MIROC5*	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	4.5/8.5RCP
7	GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory, USA	4.5/8.5RCP
8	MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	4.5/8.5RCP
9	GFDL-ESM2M*	Geophysical Fluid Dynamics Laboratory, USA	4.5/8.5RCP

* denotes GCMs used for study

The RCP8.5 scenario was selected because it prescribes a continual global warming into the 21st century through increasing radiative forcing and greenhouse gas emissions (Moss *et al.*, 2010), which is consistent with historical climate trends in West Africa (Hulme *et al.*, 2001). Based on recent analysis (Jalloh *et al.*, 2013), this trend of environmental degradation and climate change may continue to 2100, increasing the greenhouse gas emissions from the region, making the RCP8.5 the most suitable climate scenario for the region.

Table 7.3: Selected GCMs based on changes in projected MAP in 2060 - 2079 relative to the 1990 - 2009 control period for Adiake, Bondoukou and Accra in West Africa

GCM	Change in MAP (%)	Variable lable
CNRM-CM5****	8.6	Wet
FGOALS-s2	6.6	
GFDL-ESM2M ***	5.4	75th percentile
CanESM2	5.2	
GFDL-ESM2G	1.8	
BNU-ESM	1.7	
MIROC5**	1.1	25th percentile
MIROC-ESM-CHEM	0.9	
MIROC-ESM*	-3.8	Dry

* denotes dry, ** 25th, ***75th and **** wet GCMs

Since the CSAG data had no downscaled climate stations within the Bonsa catchment, three nearby and surrounding synoptic climate stations (Figure 7.1) in Accra (Ghana), Adiake and Bondoukou (Ivory Coast), which had downscaled GCM climate records were selected and the monthly mean of rainfall, minimum and maximum temperatures were computed and used for further downscaling to the Bonsa catchment using the change factor method of statistical downscaling(Fowler *et al.*, 2007; Chen *et al.*, 2011; Forbes *et al.*, 2011; Park *et al.*, 2011). For the rainfall, the change factor was calculated by dividing the monthly mean of each selected GCM, as well as the multi-model median, for the near (2020-2039) and far (2060-2079) future by the corresponding monthly values for the control period (1990-2009). The change factor at the monthly time scale was then applied to the daily observed rainfall records of Bonsa catchment for the control period (1990-2009) to obtain climate change scenarios (Figure 7.4). For the minimum and maximum temperatures, the near and far future values were subtracted from their corresponding control period values and the difference was applied to the observed daily records. The change factor method of downscaling is the most widely used method for impact analysis (Chen *et al.*, 2011), however, its limitation is that it assumes that the variability of the future climate will be same as the control observed climate (Forbes *et al.*, 2011) and in applying the method relative climate changes are assumed to be more important than absolute changes. The change factor method is therefore limited as it does not account for possible changes in intensity, duration and frequencies of rainfall events (Ruelland *et al.*, 2012). Thus the results obtained in this study are only a contextualized scenario of the potential climate change impacts on long-term annual and seasonal hydrology. More suitable downscaling methods such as spatially disaggregated and random cascades (Sharma *et al.*, 2007; Groppelli *et al.*, 2011) and Regional Climate Modelling (Kim *et al.*, 2013) could have been used, but for lack of long-term predictor data and computational resources.

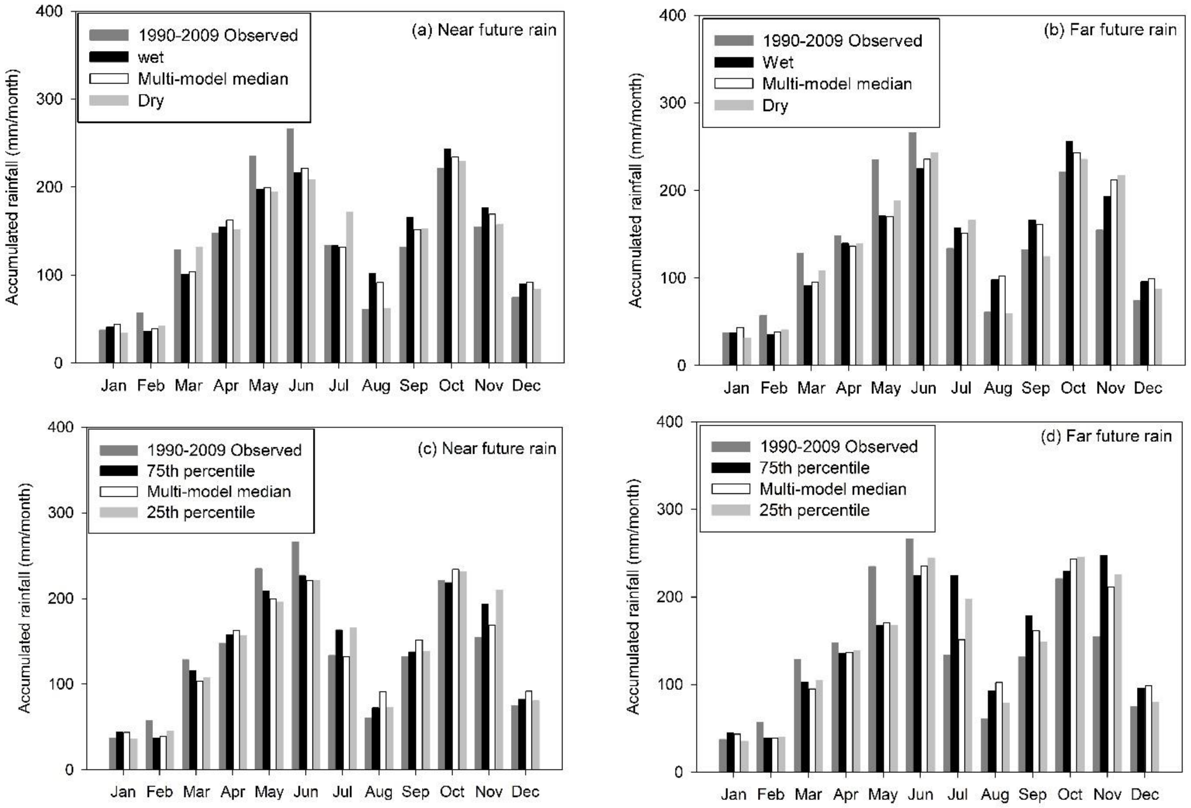


Figure 7.4: **Downscaled and observed monthly mean rainfall for Tarkwa climate station in Bonsa catchment**

7.3.4 Assessing the Ecological Impacts

To analyse the potential impacts of streamflows changes on the ecology, Richter's range of variability analysis (RVA) (Hillman *et al.*, 2012; Homa *et al.*, 2013; Richter *et al.*, 1996) was executed using the indicators of hydrological alteration (IHA) software (The Nature Conservancy, 2009). The IHA calculations were based on five (1 to 5) parameter groups (Table 7.4), which were used to assess the potential future ecological impacts of the hydrological changes relative to the pre-impact streamflow variability (RVA limits).

The IHA parameter groups 1 to 5 include the entire range of streamflow conditions for the sustenance of aquatic and riparian ecosystems (Richter *et al.*, 1996); hence their variations (lower and upper RVA limits) from pristine conditions can be used to describe ecological changes. As streamflows are statistically skewed, non-parametric statistics were used to execute the RVA analysis, using the baseline streamflows (resulting from land use of 1991 and observed climate between 1990 and 2009) as the pre-impact flows, while the streamflows resulting from the various scenarios were used as the post-impact streamflows. The use of the baseline (1991) land use and observed climate of 1990 to 2009 to generate the pre-impact streamflows, was based on the assumption that during the early 1990s, there was little land use modification (evergreen and secondary forests covered 93% of the catchment) (Aduah *et al.*, 2015). Hence, streamflows corresponding to the 1991 land use were assumed to be close to the pristine conditions.

Table 7.4: IHA Parameters and their ecological significance (adopted from The Nature Conservancy, 2009)

IHA parameter Group	Hydrologic Parameters	Ecosystem Influences
1. Magnitude of monthly water conditions	Mean or median value for each calendar month	Habitat availability for aquatic organisms Soil moisture availability for plants Availability of water for terrestrial animals Availability of food/cover for furbearing mammals Reliability of water supplies for terrestrial animals Access by predators to nesting sites Influences water temperature, oxygen levels, photosynthesis in water
2. Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means Number of zero-flow days	Balance of competitive, ruderal, and stress tolerant organisms Creation of sites for plant colinization Structuring of aquatic ecosystems by abiotic vs. biotic factors Structuring of river channel morphology & physical habitat Soil moisture stress in plants Dehydration in animals Anaerobic stress in plants Volume of nutrient exchanges between rivers and floodplains Distribution of plant communities in lakes, ponds, floodplains
3. Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum	Compatibility with life cycles of organisms Predictability/avoidability of stress for organisms Access to special habitats Spawning cues for migratory fish Evolution of life history strategies,
4. Frequency and duration of high and low pulses	Number of low pulses within each water year Mean or median duration of low pulses (days) Number of high pulses within each water year Mean or median duration of high pulses (days)	Frequency and magnitude of soil moisture stress for plants Frequency and duration of anaerobic stress for plants Availability of floodplain habitats for aquatic organisms Nutrient and organic matter exchanges between river and floodplain Soil mineral availability Access for waterbirds to feeding, resting, reproduction sites
5. Rate and frequency of water condition change	Rise rates: Mean or median of all positive differences between consecutive daily values Fall rates: Mean or median of all negative differences between consecutive daily values Number of hydrologic reversals	Drought stress on plants (falling levels) Entrapment of organisms on islands, floodplains (rising levels) Desiccation stress on low-mobility streamedge (varial zone) organisms

7.4 Results

7.4.1 Climate Change Impacts

Climate changes in the Bonsa catchment under the selected scenarios generally lead to increased temperatures. For rainfall, however, the changes were consistent but varied with seasons. Reductions in rainfalls were evident for the first half of the year, with increases evident for the second half of the year (Figure 7.4). Projections in rainfall for the GCM scenarios with the 25th and 75th percentile change in MAP were inconsistent, compared with the other scenarios as the differences between near future monthly rainfalls for the 25th and the 75th percentile scenarios were not much. The sections below describe the temporal dynamics, spatial variability and the potential ecological impacts of the selected climate change scenarios on streamflows of the Bonsa catchment.

7.4.1.1 Temporal Dynamics of Climate Change Impacts on Hydrology

Annual streamflows, monthly median flows and high flows generally reduced for the near future, but increased for the far future climate change scenarios (Table 7.5, Figures 7.5, 7.6 and 7.7). The major peak season flows reduced in all the time slices (Table 7.5) and resulted in reduced low flows (Figure 7.6). The wet scenarios generated the highest streamflows, while the dry scenarios produced the lowest. The results in Table 7.5b for the near future time slice are inconsistent, compared with those of Table 7.5a, as streamflow changes for the 75th percentile GCM were less than those of the 25th percentile GCM. However, for accumulated mean monthly streamflows, the trends for all the scenarios are similar (Figure 7.5).

The results generally appear to indicate longer dry seasons particularly for the far future and shorter wet seasons, despite the higher magnitudes of the peak season flows (Figure 7.5 and Figure 7.6). The lengthening of the dry season, shortening of the rainy season and increase in flows during the minor peak season could reduce agriculture productivity in the Bonsa catchment as the growing period may reduce and the risk of flooding during the minor peak season will be higher than it currently is. Hence, impacts of climate change could be a food security challenge in the catchment.

Table 7.5: **Change (%) in streamflows relative to the baseline (land use & climate) for all climate scenarios**

(a)

		Change in streamflows (%) from baseline climate			
Time slice	Climate scenario/GCM	Annual	Dry season	Major peak	Minor peak
2020-2039	Wet	13.2	34.1	-17.1	61.7
	Multi-model median	-4.8	6.9	-19.4	15.5
	Dry	-15.3	-12.9	-32.2	14.3
2060-2079	Wet	33.9	46.0	8.2	77.9
	Multi-model median	0.8	28.8	-24.1	33.5
	Dry	-13.6	2.6	-30.0	13.8

(b)

		Change in streamflows (%) from baseline climate			
Time slice	Climate scenario/GCM	Annual	Dry season	Major peak	Minor peak
2020-2039	75th percentile	-4.8	9.5	-21.4	17.3
	Multi-model median	-4.8	6.9	-19.4	15.5
	25th percentile	-4.7	17.0	-29.0	29.9
2060-2079	75th percentile	18.4	51.4	-17.4	62.2
	Multi-model median	0.8	28.8	-24.1	33.5
	25th percentile	4.8	20.9	-22.2	45.4

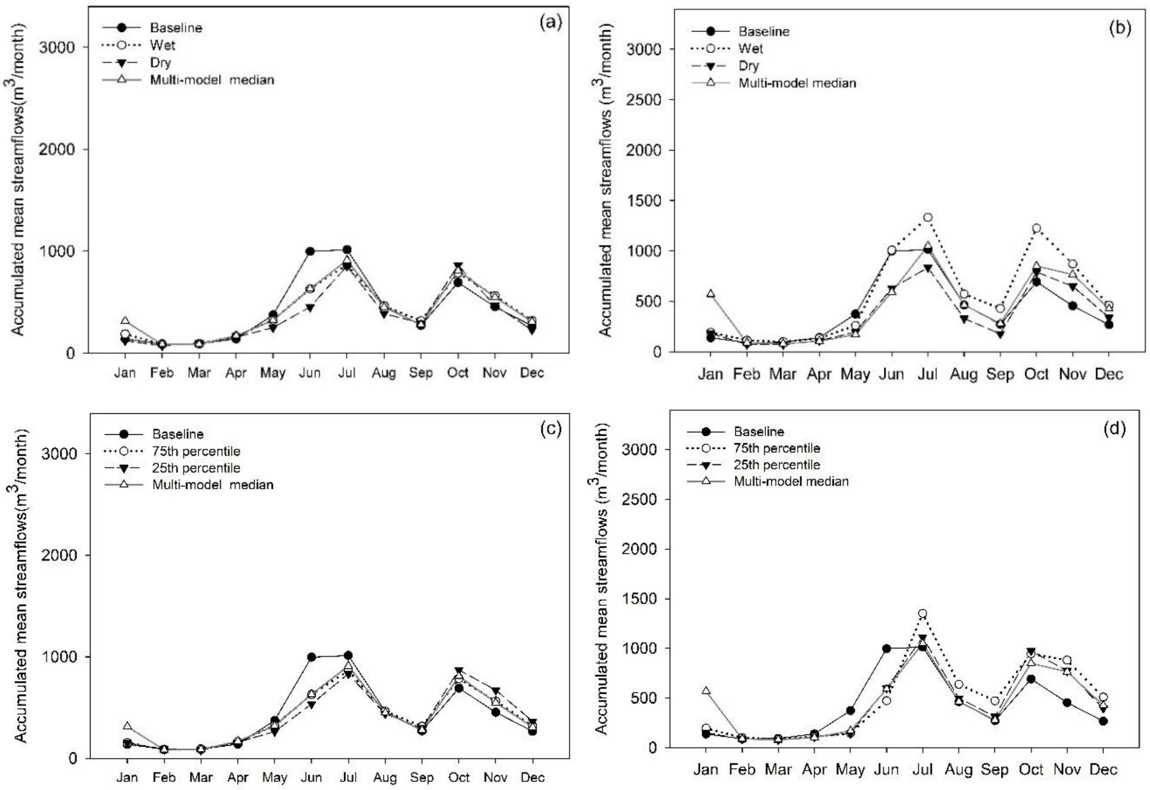


Figure 7.5: **Accumulated mean monthly streamflows for the selected climate change scenarios for the near future (2020 – 2039) (a, c) and far future (2060 – 2079) (b, d), compared with the baseline streamflows**

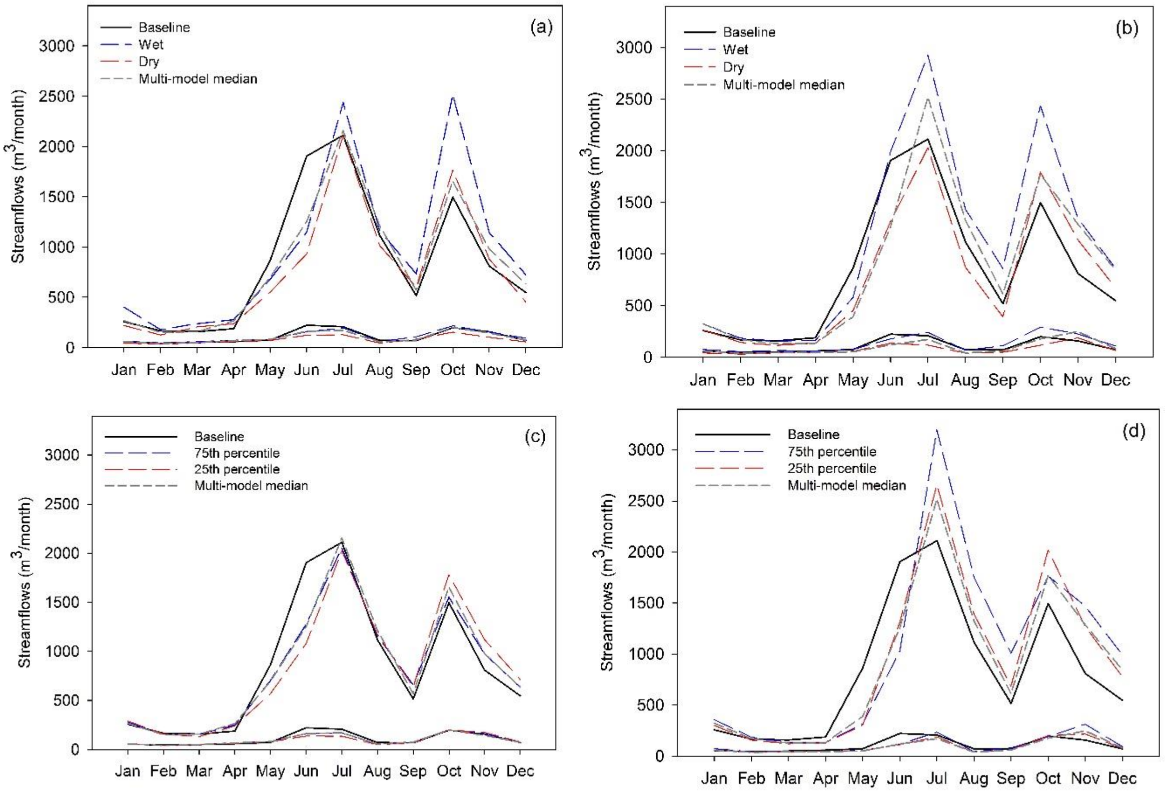


Figure 7.6: **Monthly 90th (1 in 10 year high) and 10th percentile (1 in 10 year low) streamflows for the selected climate scenarios for the near future (2020 – 2039) (a, c) and (b, d) far future (2060 – 2079), compared with the baseline streamflows**

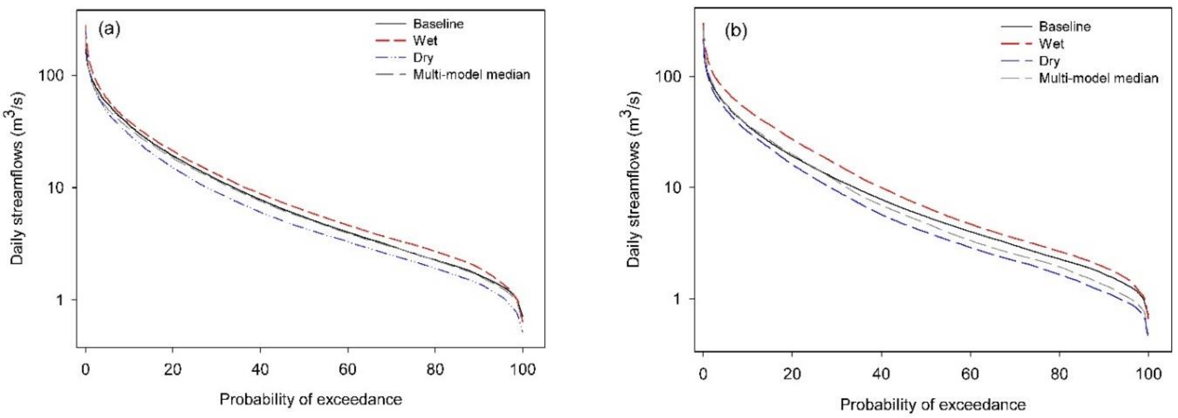


Figure 7.7: **Flow duration curves for the wet, dry and multi-model median climate change scenarios for two time slices (a) 2020 - 2039 and (b) 2060 – 2079, as well as the baseline FDCs**

7.4.1.2 Spatial Patterns of Climate Change Impacts on Hydrology

An example of how streamflow responses to climate changes are distributed within the Bonsa catchment under the near future (2020 - 2039) wet and dry GCM scenarios is shown in Figure 7.8. The results for the 75th and 25th percentiles GCM scenarios are not shown as the pattern of streamflow changes were similar in all the climate scenarios, with the exception of the near future streamflow projections for the 25th percentile GCM scenario (Table7.5b). For the wet scenario, the streamflow changes ranged from no change to a 5 - 25% increase, while for the dry GCM scenario there was 5 - 27% streamflow reduction. It is evident that subcatchments in the main stem of the river experienced similar change (+5 - 15%) in streamflows under the wet scenario, but under the dry scenario these subcatchments showed a 15-27% reduction in streamflow (Figure 7.8). These subcatchments constituted more than 50% of the catchment, hence they influenced the outlet streamflows in the respective scenarios.

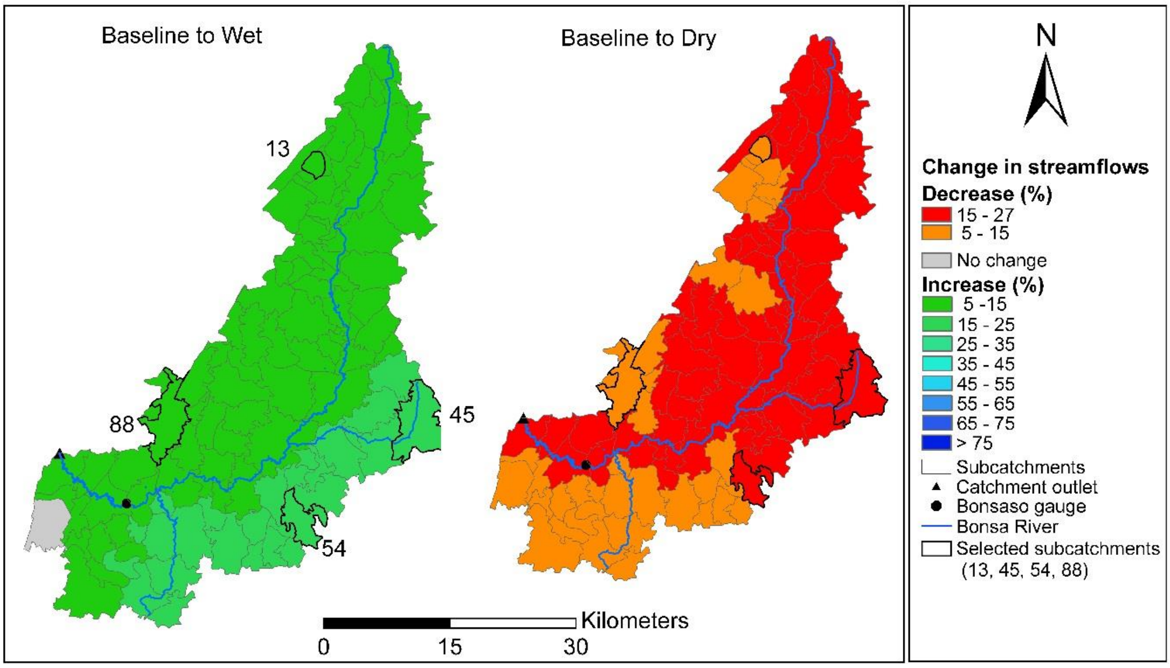


Figure 7.8: **Changes in mean annual streamflows relative to baseline (1991 land use and 1990-2009 climate) for 2020 - 2039 wet and dry climate change scenarios. Numbers in map indicate subcatchments**

7.4.1.3 Potential Ecological Impacts of Climate Changes

Figure 7.9 summaries the RVA analysis for the streamflows resulting from separate impacts of wet and dry climate change in the Bonsa catchment. Results for the 25th and 75th percentile GCMs are not shown as the pattern of changes in streamflows were similar for all the projections, with the exception of the near future streamflows of the 25th percentile scenario (Table7.5b). For the near future (2020 - 2039) climate scenarios, the post-impact monthly streamflows (IHA parameter group 1, Table 7.4) under the wet scenario were above those under the pre-impact baseline flows and were mostly above the RVA limits. On the average, monthly streamflows during the low flow season (December, January, February and March) increased by approximately 51%; during the major peak season (April, May, June, July)flows reduced by approximately 15% and for the minor peak season (September, October, November) there was an increase of approximately 54%, relative to the forested 1991 baseline. The minimum flows (IHA parameter group 2) increased by 10 - 12% and the maximum flows reduced by13 -28%. The Julian date for the occurrence of maximum and minimum streamflows (IHA parameter group 3), occurred later than the pre-impact dates. The low pulse duration and count reduced by 14%, but the high pulse duration (IHA parameter group 4) reduced by 6% and the high pulse count increased by 8%. The rise and the fall rates (IHA parameter group 5) increased by 29% and 24%, respectively, but there were no flow reversals.

Under the dry scenario, the IHA parameters mostly showed reductions, except the low flow season which had an average of 14% increase in monthly streamflows and the high pulse count and duration which increased by 17 and 38%, respectively. Under the near future multi-model median GCM scenario, monthly streamflows in the major peak season reduced by 16%, while the minor peak season streamflows increased by an average of 12% relative to the baseline. However, the extreme flow conditions (minimum and maximum), remained relatively similar to those under the forested 1991 baseline except that the Julian date of the maximum flows occurred much later. For the far future (2060 - 2079), the trend in streamflows followed a similar pattern as the near future scenarios, but the magnitudes of changes were higher than those in the near future (2020 - 2039) scenarios. The overall trend, with the exception of the low flow and minor peak seasons in the wet climate scenario, is a drying of the Bonsa catchment, which can affect soil moisture availability for plants, water availability for aquatic life, as well as increased stress for wildlife.

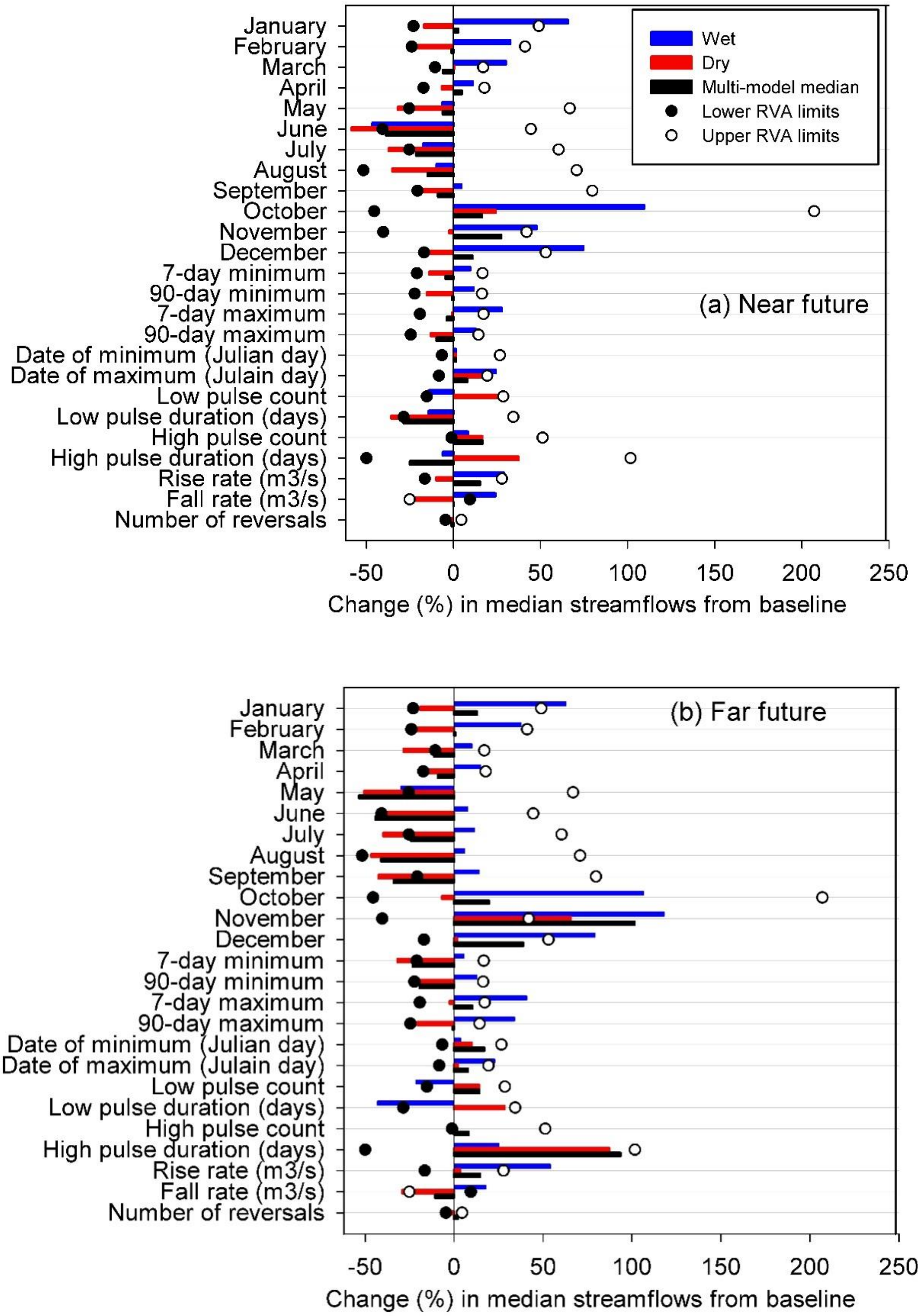


Figure 7.9: Change (%) in IHA parameters (1 to 5) relative to the baseline pre-impact streamflows for the wet and dry climate change impacts (a: 2020-2039, b: 2060-2079), as well as the lower and upper pre-impact RVA streamflow limits

7.4.2 Combined Impacts of Climate and Land use Changes

7.4.2.1 Temporal Dynamics of Combined Future Climate/Land Use Change Impacts

The annual, seasonal as well as high, median and low flows of the Bonsa catchment increased under the combined future land use and climate change scenarios (Table 7.6, Figures 7.10 and 7.11). The differences in streamflows associated with the future land use scenarios were small, with larger differences between the climate change scenarios (Figure 7.12). The streamflows associated with the BAU combined land use and climate change scenarios were slightly higher than those associated with the EG and EGR scenarios. The combined scenarios associated with the wet climate change scenario generated the highest streamflows, while those associated with the dry climate change scenarios generated the lowest streamflows, regardless of the time slice and land use involved (Table 7.6, Figures 7.10, 7.11 and 7.12). Minor reductions (up to 8%) in streamflows occurred in the major peak season (Table 7.6) with higher increases in flows occurring in the minor peak season.

Under wet scenarios, the combined impacts had higher increases in annual streamflows than those under the separate land use change impacts, but under a dry climate scenario, the combined impacts were lower than those under separate land use changes, regardless of the time slice (Table 7.6). As a result of inconsistent rainfall projections, the near future streamflow changes (values in parentheses) for the 25th percentile GCM were lower than those of the 75th percentile GCM. The results also indicate that the combined impacts of land use and climate change in the Bonsa catchment are additive of the separate impacts. For example, the change in annual streamflows for the BAU land use scenario of 32.1% and the corresponding impacts under the multi-model climate change scenario (2020-2039) of -4.8%, sum closely to the annual change in combined impacts under the multi-model 2020-2039 and BAU land use of 27.7 (Table 7.6).

Table 7.6: Changes in streamflows relative to the baseline (1990-2009) for combined climate change/land use change scenarios as well as change in annual streamflows for separate land use and climate change impacts. Values in parentheses are for the 25th and 75th percentile GCMs

Land use		Climate change		A: Change in streamflows (%)				B: Change in streamflows (%)	
Scenario	Time slice	Time slice	Scenario/GCM	Annual	Dry season	Major peak	Minor peak	LUC (Annual)	CC (Annual)
BAU	2030	2020-2039	Wet (75th)	47.7 (27.6)	88.7 (54.8)	12.0 (7.1)	102.4 (54.8)	32.1	13.2 (-4.8)
			Multi-model	27.7	54	9.5	52.5		-4.8
			Dry (25th)	16.0 (27.8)	34.0 (61.1)	-5.4 (-1.5)	50.7 (70.0)		-15.3 (-4.7)
	2070	2060-2070	Wet (75th)	76.5 (60.2)	100.5 (108.6)	44.8 (14.7)	132.7 (119.1)	39	33.9 (18.4)
			Multi-model	40.7	85.2	8.2	85.4		0.8
			Dry (25th)	24.2 (44.0)	53.0 (71.0)	2.4 (9.7)	61.6 (98.0)		-13.6 (4.8)
EG	2030	2020-2039	Wet (75th)	43.2 (23.5)	80.2 (47.5)	8.7 (4.0)	97.2 (50.1)	27.9	
			Multi-model	23.5	46.5	6.3	47.8		
			Dry (25th)	12.0 (23.6)	26.9 (53.7)	-8.3 (-4.5)	46.0 (65.0)		
	2070	2060-2070	Wet (75th)	69.2 (53.1)	88.1 (95.1)	39.6 (10.4)	123.4 (109.6)	32.2	
			Multi-model	34	72.3	3.8	77		
			Dry (25th)	17.9 (37.5)	41.5 (59.2)	-2.0 (5.4)	54.0 (89.3)		
EGR	2030	2020-2039	Wet (75th)	43.4 (23.7)	80.7 (48.0)	8.8 (4.1)	97.3 (50.2)	28.1	
			Multi-model	23.7	47.1	6.5	47.9		
			Dry (25th)	12.2 (23.8)	27.3 (54.4)	-8.2 (-4.4)	46.1 (65.1)		
	2070	2060-2070	Wet (75th)	68.1 (52.1)	86.3 (93.2)	38.9 (9.8)	122.0 (108.2)	31.2	
			Multi-model	33	70.3	3.2	75.7		
			Dry (25th)	17.0 (36.5)	39.6 (57.5)	-2.7 (4.8)	52.8 (88.0)		

A: combined impacts, B: separate impacts, LUC : land use change , CC: climate change

Values in parentheses are for the 25th and 75th percentile GCMs

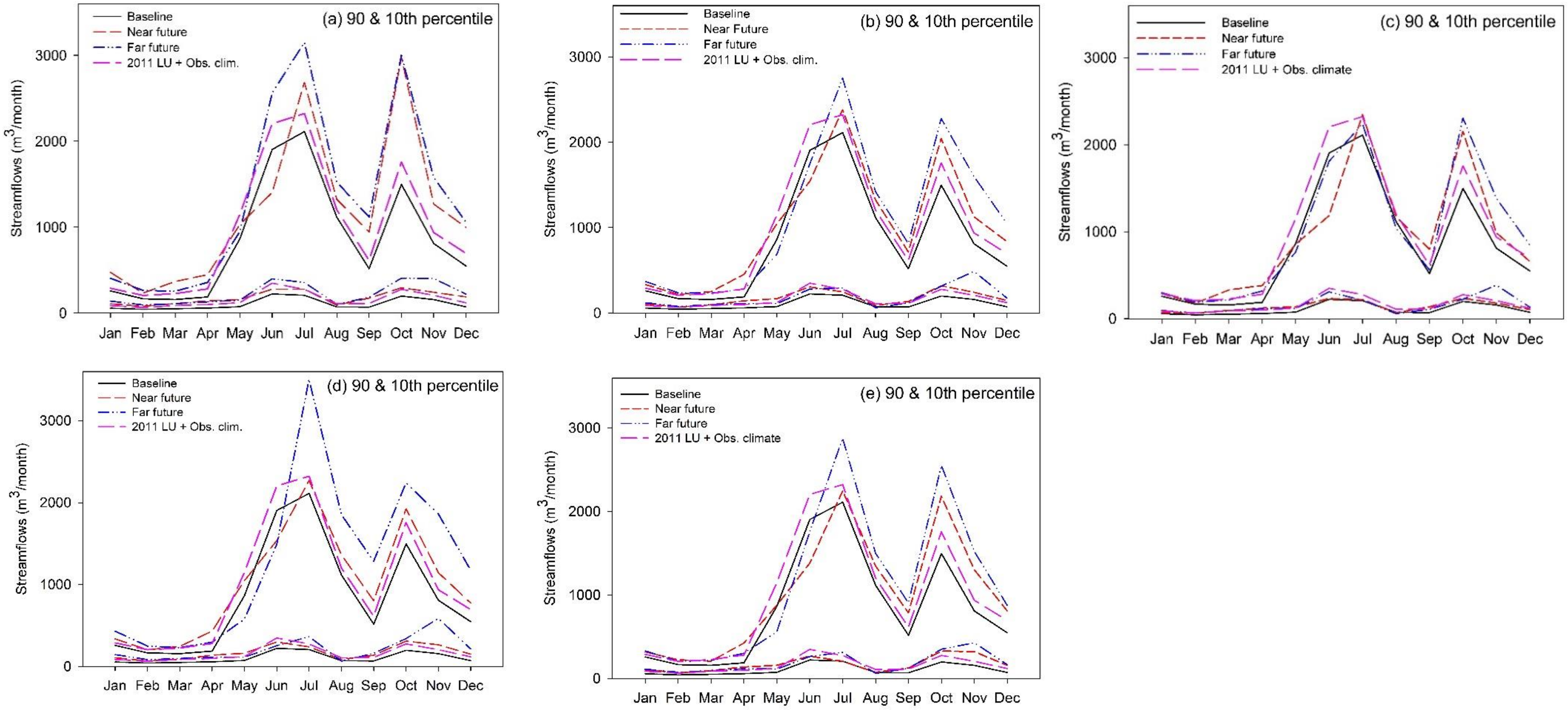


Figure 7.10: Monthly 90th (1 in 10 year high) and 10th (1 in 10 year low) percentile streamflows for combined (a) BAU+ wet, (b) BAU+ multi-model median, (c) BAU+ dry climate change scenarios, (d) BAU + 75th percentile GCM scenario and (e) BAU+25th percentile GCM scenario, as well as baseline (1991) and 2011 Land use (LU) +Observed climate (1990-2009)

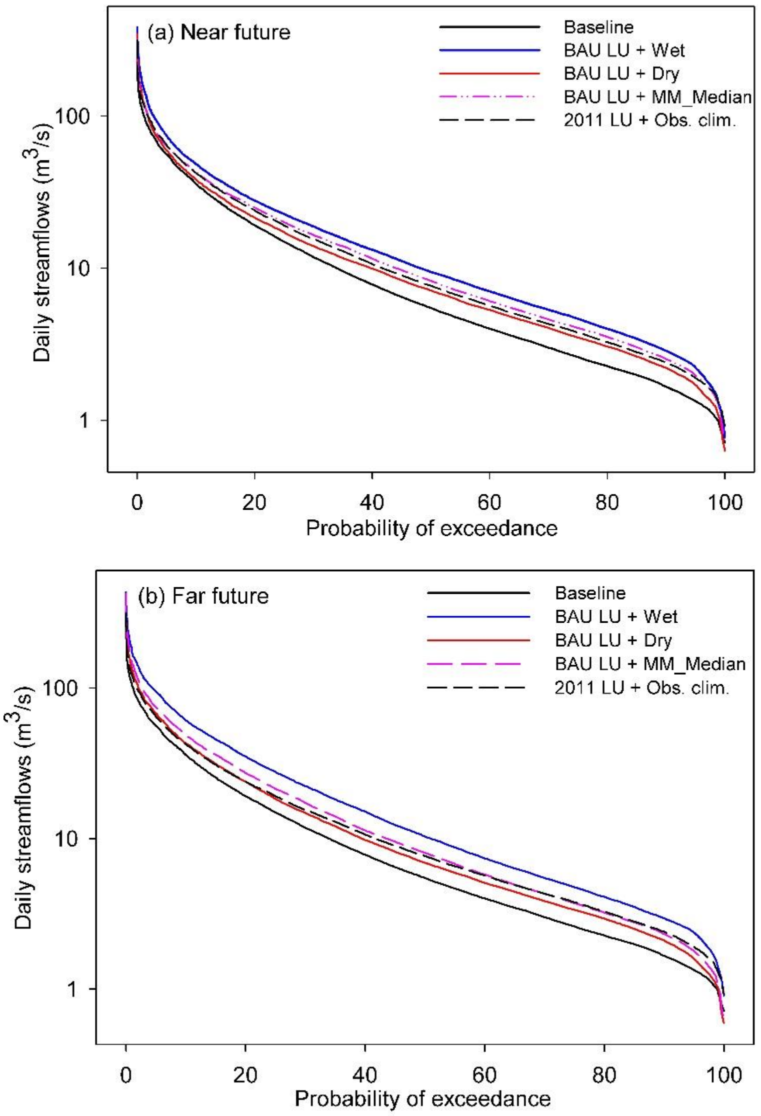


Figure 7.11: **FDCs for combined near future (a) 2020 - 2039 and far future (b) 2060 – 2079 GCM climate scenarios and the BAU land use scenario, compared to those of the baseline and current (2011) FDCs**

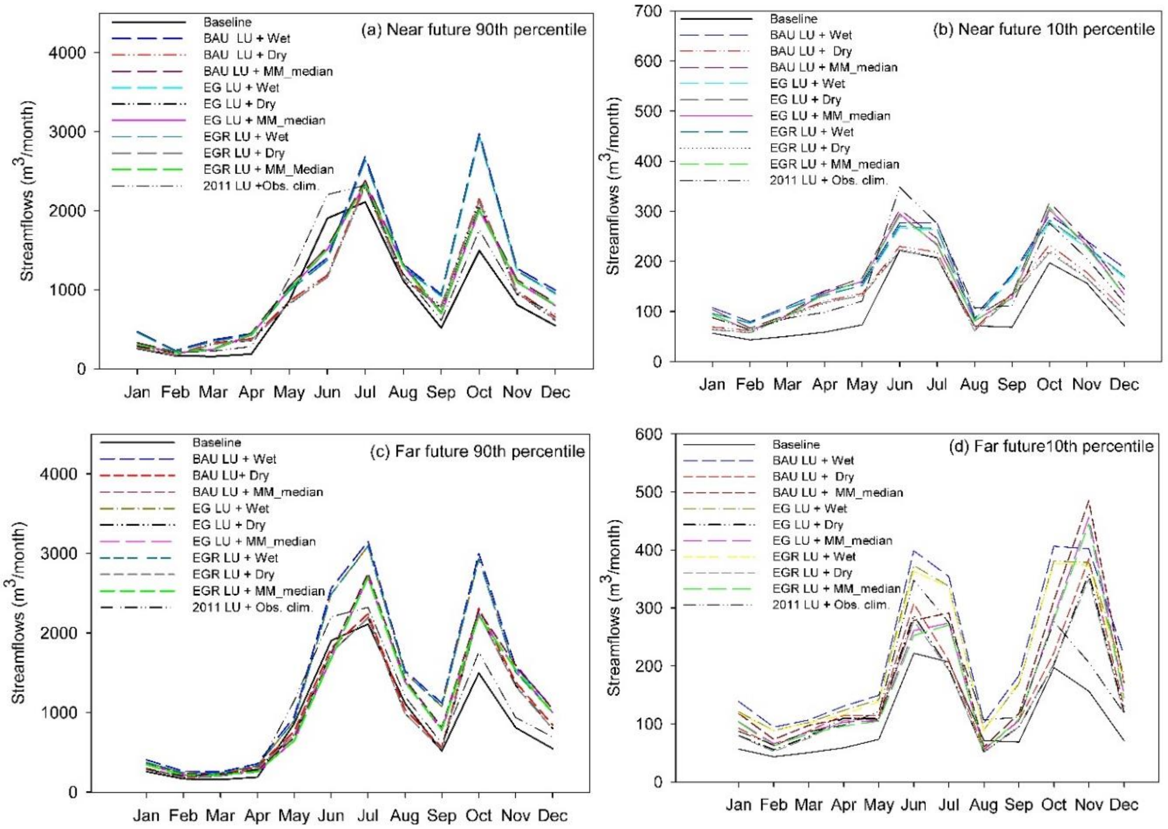


Figure 7.12: **Streamflows for combined impacts of land uses (BAU, EG, EGR) and wet, multi-model median (MMM) and dry climate change scenarios for (a) 90th percentile near future, (b) 10th percentile near future, (c) 90th percentile far future and (d) 10th percentile far future climate change scenarios. Figures also show the 90th and 10th percentile streamflows for the baseline and 2011 land use (LU) + Observed climate (1990-2009)**

7.4.2.2 Spatial Patterns of Combined Climate/Land Use Change Impacts

The spatial response to combined land use and climate change for the near future time slice under a wet and a dry climate scenario is shown in Figure 7.13. The use of the wet and dry scenarios is to demonstrate how the availability of water affect the spatial distribution of combined land use and climate change impacts in Bonsa catchment as the wet and dry scenarios can represent spatial patterns in streamflow changes similar to the rest of the combined scenarios. Under the BAU, EG and the EGR land uses and wet climate scenario, subcatchments along the main stem of the Bonsa River experienced streamflow changes between 5 - >75% for the northern and 40-55% for the southern areas. The increase in streamflows along the main stem of the river is because the land use changed from secondary forests in 1991 to shrubs/farms in the future land use scenarios (Figure 7.3). For subcatchment 88 and its surrounding areas in the west central part of the catchment, streamflow increases ranged from 45-65% under the BAU, EG and the EGR scenarios with the wet climate. The large increase in streamflows in this west central part of the catchment was due to the expansion of the settlements (Tarkwa), mining areas (east and west of Tarkwa) and increased shrubs/farms in the future scenarios, compared to the baseline 1991 land use (Figure 7.3).

For those subcatchments in the southwest, the middle and the northern parts of the catchment, which remain as evergreen forest in the future land use scenarios (Figure 7.3), there was 5-25% increase in simulated streamflows under the scenarios of future land use and a wet climate. There was also a 5-15% increase in streamflows (Figure 7.13) in the eastern tip, north western tip and the northern tip of the catchment in subcatchments which were mostly covered by evergreen forests in both the historical land use and the future land uses (Figure 7.3). In all the scenarios involving the wet climate, subcatchment 54 and its surrounding areas had the highest overall increases in streamflows. The outlet streamflows with respect to the BAU and wet climate scenario increased between 45-55%, while those with respect to the EG and the EGR increased by between 35-45% only (Figure 7.12). The difference between the land use scenarios under wet climate change is that the BAU show higher magnitudes of increases in streamflows for subcatchments 88, 54 and their surrounding areas, compared to the EG and the EGR land uses.

Figure 7.13 also show that the various land use scenarios under the dry climate change exhibited similar patterns as the streamflow changes under the wet climate change, except that there were streamflow reductions (between 5-26%) in subcatchments which either experienced no changes or reductions, under the wet climate and land use scenarios. The streamflow increases along the main stem of the river under the dry climate also appear to dampen towards the outlet of Bonsa catchment. It can therefore be deduced from Figure 7.13 that the variability of streamflow changes within the subcatchments increased as land use and climate changes occurred simultaneously, but the variability of the streamflow changes at the outlet of the catchment does not experience significant changes under combined land use and climate changes.

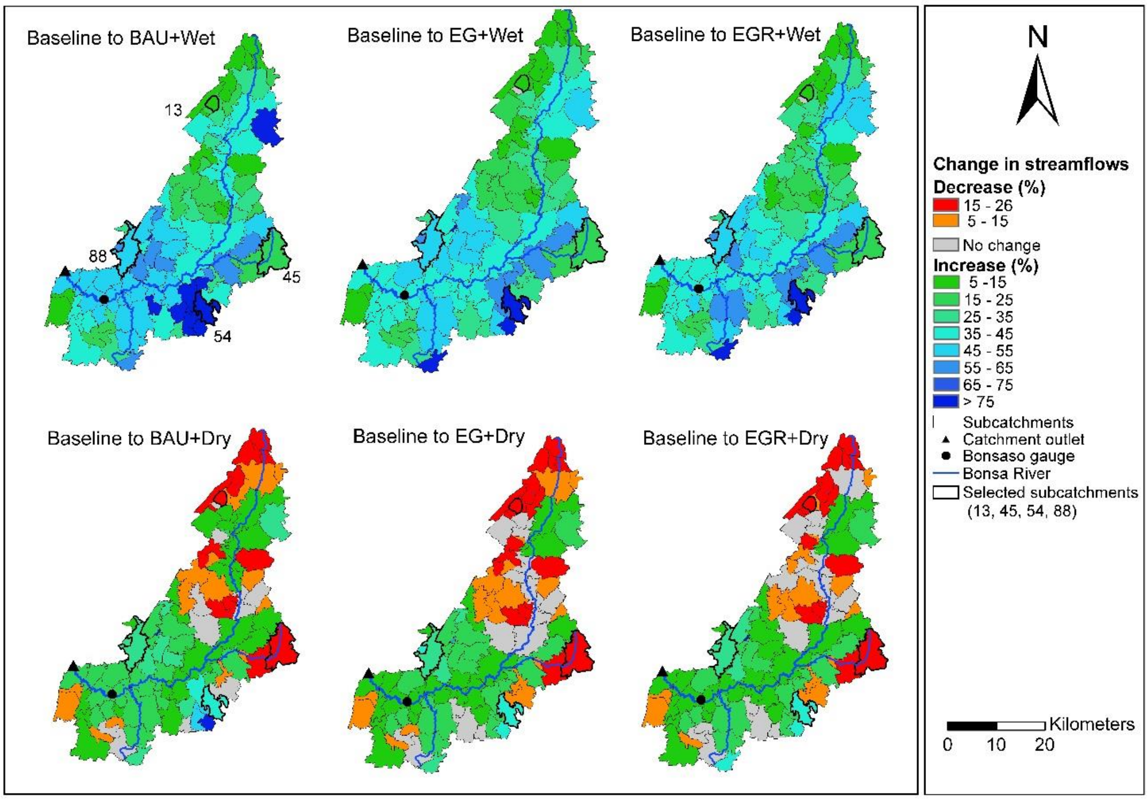


Figure 7.13: Changes in mean annual streamflows relative to baseline (1990 - 2009) for combined land use change (2030) and 2020 - 2039 wet and dry climate change scenarios. Numbers in map indicate selected subcatchments

7.4.2.3 Potential Ecological Impacts of Combined Climate and Land Use Changes

Figure 7.14 summaries results of RVA analysis of streamflows based on the BAU land use scenario, wet and dry climate change scenarios. RVA analysis of streamflows from the combined scenarios (land use and climate) involving the 25th (MIROC5) and 75th (GFDL-ESM2M) percentile GCMs were not used in the RVA analysis, as the trends in streamflow changes were similar to those for the wet, multi-model median and dry climate scenarios, with the exception of the MIROC5 scenario for the near future time slice (Table7.5b).

Furthermore, only the BAU scenario was used to illustrate an example river ecological impacts in the Bonsa catchment as the differences in ecological impacts between the scenario, the EG and the EGR scenarios were small. The combined BAU 2030 land use and the wet climate scenario for the near future (Figure 7.14a) shows that median monthly flows (parameter group 1), the magnitude and duration of extreme flows (parameter group 2, 4 and 5), have increased beyond the pre-impact range of variability (RVA) limits. The Julian date of the timing of maximum flows also occurred later than those of the pre-impact RVA limits. For example the average monthly low flow season (December, January, February, March) streamflows increased by 100% relative to the baseline, while those of the major and minor peak seasons increased by 29%and 122%, respectively. The 7 and 90 day maximum flows increased by an average of 51%. For the BAU LU + multi-model median, as well as the BAU2030 LU + dry climate change, although the IHA parameters changed following similar trends as those of the combined BAU2030 LU + wet climate scenario, the magnitudes were slightly lower, with the scenario involving the multi-model median being slightly higher than that of the dry climate scenario.

Under the far future (2060 - 2079) climate scenarios (wet, multi-model medain and dry) and the BAU 2070 land use (Figure 7.14b), the trend of streamflow changes were slightly different from those under the near future (2020 - 2039) climate change and the BAU 2030 land use (Figure 7.14a). For the far future scenario, the monthly streamflows for the low flow season, as well as the minor peak season and June to July of major peak season, were generally higher than those of the corresponding near future scenario values. However, the minimum flows (7 and 90 day flows) were generally lower than the corresponding flows in the near future scenario. For the maximum flows, they were generally higher than their corresponding near future scenario values, but the Julian date of their occurrence was earlier. The median parameter values for the combined scenarios involving the EG and the EGR LU were not included here because they were relatively similar to those of the BAU, although they followed similar trend as Figure 7.14, they were slightly lower than those involving the BAU LU.

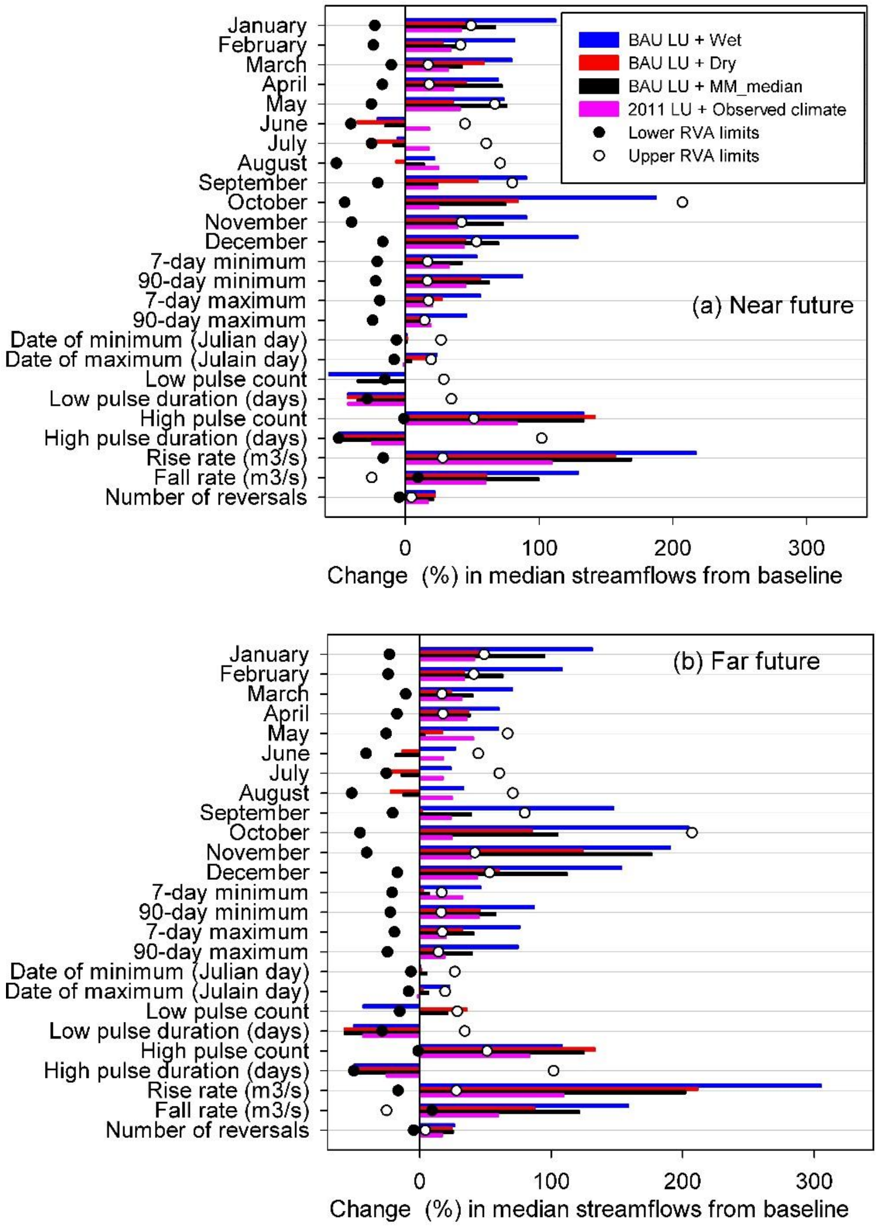


Figure 7.14: **Change (%) in IHA parameters (1 to 5) relative to the baseline pre-impact streamflows for (a) 2030 BAU land uses (LU) and 2020-2039 climate and b) 2070 BAU LU and 2060-2079 climate scenarios, as well as the current (2011), lower and upper pre-impact RVA streamflow limits**

7.5 Discussion

7.5.1 Combined Climate and Land Use Change Impacts on Hydrology

The study analysed the separate impacts of climate change, as well as the combined impacts of climate and land use change on the hydrology of the Bonsa catchment, Ghana, West Africa, which to the authors' knowledge is the first time such a study has been conducted in the catchment. The study revealed that the effects of climate change for both the near and far future suggests an overall drying trend in the catchment, regardless of the scenario. The results also indicate a lengthening of the dry season in the Bonsa catchment in the far future, which can affect water availability for domestic, industrial and environmental flows.

On the other hand, streamflow increases due to combined land use and climate changes were higher than the forested 1991 baseline flows. During high flow periods, combined impacts analysis shows that high flow magnitudes generally increased beyond both baseline and current (2011) levels as did the low flows, regardless of the land use and climate scenario. The combined scenarios involving the wet, 25th percentile, 75th percentile and multi-model median climate scenarios showed slightly different patterns of changes in the length of the dry and major peak seasons. In the near future the duration and the onset of the dry season and the major peak season did not change for the wet, the 25th percentile, the 75th percentile and the multi-model median climate scenarios, but in the far future the dry season length increased, while the major peak season length reduced for the 25th percentile, the 75th percentile and the multi-model median climate scenarios (Figure 7.10). For the combined scenarios involving the dry climate scenario, there was a small shift in both the dry and major peak season lengths, as well as their onsets.

The streamflow responses for the combined scenarios involving the different land use scenarios (BAU, EG and EGR) were not very different, although the scenarios involving the BAU had slightly higher streamflows than the rest. This is mainly because although the secondary forest areas in the potential future land uses were different, the proportion of the shrubs/farms, which is the dominant land use in terms of both area and runoff generation, were not substantially different between the scenarios. Given the significant land use changes that already occurred between 1991 and 2011, the land use changes in the future in comparison will not significantly alter outlet streamflows assuming land cover changes as predicted by the model.

The study showed that the combined impact of land use and climate changes are additive of the separate impacts, unlike studies such as Li *et al*., 2009 where the joint impacts were non-linear. The study further shows that when there is substantial increase in rainfall (under the wet climate scenario), climate largely controls streamflow changes, but when there is less rain (under dry climate scenario), land use controls streamflow changes. This is because under the wet climate and land use change, the impacts were higher than those under separate land use change, but under a dry climate and land use change, the impacts were higher than those under separate land use change (Table 7.6). Furthermore, the study revealed that the variability of climate change impacts at the catchment and subcatchment scales were also almost the same (Figure 7.8 and Table7.5), as the streamflow changes at the two scales did not differ much. The study reveals that variability of streamflow changes was greater at the subcatchment than at the catchment scale under simultaneous land use and climate change. Hence, it is relevant to not only focus on the outlet streamflows when considering Global change impacts and basing catchment management plans on outlet streamflow changes alone can result in less effective adaptation measures.

These results contradict those of previous studies in West Africa, where Bossa *et al.* (2014) concluded that streamflow responses to combined impacts of climate change and land use changes were higher than climate change impacts, but less than separate land use change impacts. Bossa *et al.* (2012), also concluded that climate was the dominant factor in streamflow changes in a savannah dominated catchment in Benin Republic. Hence, the effects of Global changes revealed in this study (rainforest catchment) and others (mainly savannah catchments) in West Africa, portray within-region differences of hydrological impacts under changing conditions and provides a platform for further studies. The results of this study also disproves the hypothesis that joint impacts of land use and climate changes are non-linear (Li *et al*., 2009).

This study demonstrated that there may be ecological changes in the Bonsa River, relative to the baseline stream ecology due to climate, land use or combined land use and climate change impacts. Under separate climate changes, there is a general trend towards a drying of the Bonsa catchment which may reduce soil moisture for plants and reduce water availability for both terrestrial and aquatic life (Figure 7.9 and Table 7.4). Drying can also lead to invasion by alien plants. However, under all combined climate and land use change scenarios streamflows generally increase in the near and far future relative to the forested baseline

(1991) streamflows (Figure 7.14). This potential increase in streamflows may lead to the occurrence of more high flows and fast flowing water, which can wash away habitats of sensitive and slow moving aquatic organisms. The frequent occurrence of fast flowing waters may also erode and change the channel morphology of the Bonsa River, eventually disrupting the spawning habitats of aquatic life and increase invasion by alien plants.

7.5.2 Uncertainties in Assessing Land Use and Climate Change Impacts

Semi-distributed hydrological models are the most widely used tools for studying the impacts of climate change and land use change on hydrology, separately and jointly in regions with diverse land uses and climates (Breuer *et al.*, 2009; Legesse *et al.*, 2010; Forbes *et al.*, 2011; Park *et al.*, 2011; Warburton *et al.*, 2012). This is because semi-distributed models simulate the hydrological cycle physically, spatially and temporally, to generate information for effective land use planning and water management decisions. The use of the physical-conceptual and semi-distributed ACRU model in this study hinged on the fact that it is sensitive to both land use and climate changes (Schulze, 1995), as well as being able to generate hydrological responses both at the subcatchment and catchment scales.

Apart from the uncertainties with hydrological models, the uncertainties with climate change and land use input data also affects the impact assessments. Previous studies (Buytaert *et al.*, 2010; Thompson *et al.*, 2013) show that the uncertainties associated with GCM climate change scenarios are greater than those related to hydrological models. In West Africa, the rainfall estimation by climate models is particularly problematic, as some models predict increases in the coastal areas and decreases in the semi-arid, others predict the opposite (Ardoin-Bardin *et al.*, 2009). Since rainfall is the major driver of the hydrology of humid regions and is the most sensitive parameter in the ACRU model, the future rainfall estimates, as well as the use of the change factor downscaling method, constitute the most significant source of uncertainty in the simulated streamflows in this study. However, as the study used five GCM climate scenarios (wet, 25th percentile, 75th percentile, dry and multi-model median) to quantify the uncertainties with climate changes, a contextualised scenario of alternative futures, upon which different catchment planning scenarios can be evaluated, have been provided. Another source of uncertainty with this study is the modelled future land uses. Since the land use modelling was based on historical land use data, the far future (2070) land use scenarios, are more uncertain, compared to the near (2030) future land uses. Although the use of modelled future land use introduces uncertainties into the simulated streamflows, land use modelling is the most realistic method to provide plausible future land use scenarios, as it relies on statistically significant socio-economic and biophysical driving factors. Land use modelling also ensures that gradual changes, including simultaneous regeneration and removal of land use types at different locations within a catchment, are accounted for. This ensures that realistic change processes, previously witnessed in a catchment are applied. This study used three land use scenarios (BAU, EG and EGR), which provide alternative development pathways for the catchment, to quantify the uncertainties with the land use.

Furthermore, uncertainties have also been introduced due to the use of a coarse resolution soil map (scale: 1: 250 000) and the lack of locally measured soil hydrological properties, as well as lack of vegetation parameters for the Bonsa catchment. These uncertainties have been minimized in this study since the sensitivity analysis and the hydrological modelling in the companion paper in Chapter 5 resulted in satisfactory calibration, making it possible to provide a first estimate of global change impacts on hydrology in the Bonsa catchment in this chapter.

7.6 Conclusions

This study has shown that in the Bonsa catchment under climate change, streamflows generally reduced, compared to the forested (1991) baseline conditions. Under combined land use and climate change scenarios, streamflow increases relative to the forested (1991) baseline, were higher, compared to the climate change scenarios, irrespective of the time slice. The impacts of simultaneous land use and climate changes on streamflows are higher than those under separate land use changes when there is considerable increase in rainfall, but lower when there less rainfall. This means climate will control streamflow changes when there is substantial increase in rainfall, but land use will control the streamflows changes if rainfall reduces. The streamflow responses in the combined scenarios with respect to the different future land use (LU) scenarios were however, not substantially different, for a particular LU scenario to be selected over the other. In terms of spatial variability of Global change impacts, the streamflow changes had similar patterns especially along the main stem of the river. When land use and climate changes occur simultaneously, the streamflow increase were higher and the spatial variability of streamflow changes was higher than when only climate changes are considered.

The study has shown that separate climate change impacts may impact on wildlife. Under combined impacts of climate change and land use changes the potential river ecological alterations may increase through increase of magnitudes and durations of higher flows, which can destroy habitats of sensitive and slow moving aquatic organisms. The frequent occurrence of fast flowing waters may also disrupt the spawning habitats of aquatic life. The increased high flows may also result in colonisation by invasive plants, with negative consequences for the indigenous wildlife.

The use of both multiple future land uses and climate change scenarios in the impact assessments has provided a range of first stage estimation of potential Global change impacts on the hydrology and river ecology, which policy makers can use for land use and environmental planning, as the various scenarios can be evaluated against a set of planning objectives for the catchment.

7.7 References

Aduah, MS, Warburton, ML and Jewitt, G. 2015. Analysis of land cover changes in the Bonsa catchment, Ankobra Basin, Ghana. *Applied Ecology and Environmental Research* 13(4)**:**935-955.

Akabzaa, TM, Jamieson, HE, Jorgenson, N and Nyame, K. 2009. The Combined Impact of Mine Drainage in the Ankobra River Basin, SW Ghana. *Mine Water and the Environment* 28(1)**:**50-64.

Alo, CA and Wang, G. 2010. Role of dynamic vegetation in regional climate predictions over western Africa. *Climate Dynamics* 35(5)**:**907-922.

Ardoin-Bardin, S, Dezetter, A, Servat, E, Paturel, JE, Mahe, G, Niel, H and Dieulin, C. 2009. Using general circulation model outputs to assess impacts of climate change on runoff for large hydrological catchments in West Africa. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 54(1)**:**77-89.

Barbier, EB. 2000. Links between economic liberalization and rural resource degradation in the developing regions. *Agricultural Economics* 23(3)**:**299-310.

Bossa, AY, Diekkrueger, B and Agbossou, EK. 2014. Scenario-Based Impacts of Land Use and Climate Change on Land and Water Degradation from the Meso to Regional Scale. *Water* 6(10)**:**3152-3181.

Bossa, AY, Diekkrueger, B, Giertz, S, Steup, G, Sintondji, LO, Agbossou, EK and Hiepe, C. 2012. Modeling the effects of crop patterns and management scenarios on N and P loads to surface water and groundwater in a semi-humid catchment (West Africa). *Agricultural Water Management* 115(2012)**:**20-37.

Breuer, L, Huisman, JA, Willems, P, Bormann, H, Bronstert, A, Croke, BFW, Frede, HG, Gräff, T, Hubrechts, L, Jakeman, AJ, Kite, G, Lanini, J, Leavesley, G, Lettenmaier, DP, Lindström, G, Seibert, J, Sivapalan, M and Viney, NR. 2009. Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM). I: Model intercomparison with current land use. *Advances in Water Resources* 32(2)**:**129-146.

Buytaert, W, Vuille, M, Dewulf, A, Urrutia, R, Karmalkar, A and Celleri, R. 2010. Uncertainties in climate change projections and regional downscaling in the tropical Andes: implications for water resources management. *Hydrology and Earth System Sciences* 14(7)**:**1247-1258.

Chen, J, Brissette, FP and Leconte, R. 2011. Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. *Journal of Hydrology* 401(3-4)**:**190-202.

Costa, MH, Botta, A and Cardille, JA. 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. *Journal of Hydrology* 283(1–4)**:**206-217.

CSAG. 2015. Future climate projections [Online]. Climate System Analysis Group, University of Cape Town. Cape Town, South Africa: Available: http://cip.csag.uct.ac.za/webclient2/datasets/africa-merged-cmip5/#nodes/cmip5-anomalies?folder_id=33&extent=99799 [Accessed 24th August 2015].

D'Orgeval, T and Polcher, J. 2008. Impacts of precipitation events and land-use changes on West African river discharges during the years 1951-2000. *Climate Dynamics* 31(2-3)**:**249-262.

Dale, VH. 1997. The relationship between land-use change and climate change. *Ecological Applications* 7(3)**:**753-769.

FAO. 2010. Global Forest Resources Assessment 2010: Main report. Food and Agriculture Organization of the United Nations, Rome, Italy.

Forbes, KA, Kienzle, SW, Coburn, CA, Byrne, JM and Rasmussen, J. 2011. Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada. *Climatic Change* 105(3-4)**:**555-576.

Fowler, HJ, Blenkinsop, S and Tebaldi, C. 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. *International Journal of Climatology* 27(12)**:**1547-1578.

Ghile, YB. 2004. An adaptation of the SCS-ACRU hydrograph generating technique for application in Eritrea,. Unpublished MSc, School of Bioresources Engineering and Environmental Hydrology, University of Natal, South Africa.

Graham, LP, Andersson, L, Horan, M, Kunz, R, Lumsden, T, Schulze, R, Warburton, M, Wilk, J and Yang, W. 2011. Using multiple climate projections for assessing hydrological response to climate change in the Thukela River Basin, South Africa. *Physics and Chemistry of the Earth* 36(14-15)**:**727-735.

Groppelli, B, Bocchiola, D and Rosso, R. 2011. Spatial downscaling of precipitation from GCMs for climate change projections using random cascades: A case study in Italy. Water Resources Research 47.

Hillman, B, Douglas, EM and Terkla, D. 2012. An analysis of the allocation of Yakima River water in terms of sustainability and economic efficiency. *Journal of Environmental Management* 103(2012)**:**102-112.

Homa, ES, Brown, C, McGarigal, K, Compton, BW and Jackson, SD. 2013. Estimating hydrologic alteration from basin characteristics in Massachusetts. *Journal of Hydrology* 503(2013)**:**196-208.

Hulme, M, Doherty, R, Ngara, T, New, M and Lister, D. 2001. African climate change: 1900-2100. *Climate Research* 17(2)**:**145-168.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *In:* Solomon, S, Qin, D, Manning, M, Chen, Z, Marquis, M, Averyt, KB, Tignor, M and Miller, HL (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2013. Summary for Policymakers. *In:* Stocker, TF, Qin, D, Plattner, G-K, Tignor, M, Allen, SK, Boschung, J, Nauels, A, Xia, Y, Bex , V and Midgley, PM (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA.

Jalloh, A, Faye, MD, Roy-Macauley, H, Sérémé, P, Zougmoré, R, Thomas, TS and Nelson, GC. 2013. Overview. *In:* Jalloh, A, Nelson, G. C., Thomas,T. S., Zougmoré,R. And Roy-Macauley, H. (ed.) *West African Agriculture and Climate Change: A Comprehensive Analysis.* International Food Policy Research Institute(IFPRI), Washington, DC, USA.

Jewitt, GPW, Garratt, JA, Calder, IR and Fuller, L. 2004. Water resources planning and modelling tools for the assessment of land use change in the Luvuvhu Catchment, South Africa. *Physics and Chemistry of the Earth* 29(2004)**:**1233–1241.

Johnson, F and Sharma, A. 2009. Measurement of GCM Skill in Predicting Variables Relevant for Hydroclimatological Assessments. *Journal of Climate* 22(16)**:**4373-4382.

Kienzle, SW, Nemeth, MW, Byrne, JM and MacDonald, RJ. 2012. Simulating the hydrological impacts of climate change in the upper North Saskatchewan River basin, Alberta, Canada. *Journal of Hydrology* 412–413(2012)**:**76-89.

Kim, J, Waliser, DE, Mattmann, CA, Goodale, CE, Hart, AF, Zimdars, PA, Crichton, DJ, Jones, C, Nikulin, G, Hewitson, B, Jack, C, Lennard, C and Favre, A. 2013. Evaluation of the CORDEX-Africa multi-RCM hindcast: systematic model errors. *Climate Dynamics*.

Kunstmann, H, Schneider, K, Forkel, R and Koche., R. 2004. Impact analysis of climate change on an Alpine catchment using high resolution dynamic downscaling of ECHMAM4 time slices. *Hydrology and Earth System Sciences* 8(6)**:**1030 - 1044.

L'Hote, Y, Mahe, G, Some, B and Triboulet, JP. 2002. Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 47(4)**:**563-572.

Leblanc, MJ, Favreau, G, Massuel, S, Tweed, SO, Loireau, M and Cappelaere, B. 2008. Land clearance and hydrological change in the Sahel: SW Niger. *Global and Planetary Change* 61(3-4)**:**135-150.

Legesse, D, Abiye, TA, Vallet-Coulomb, C and Abate, H. 2010. Stream flow sensitivity to climate and land cover changes: Meki River, Ethiopia. *Hydrology and Earth System Science* 14(2010)**:** 2277-2287.

Li, Z, Liu, W, Zhang, X and Zheng, F. 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology* 377(2009)**:**35-42.

Liu, X, Coulibaly, P and Evora, N. 2008. Comparison of data-driven methods for downscaling ensemble weather forecasts. *Hydrology and Earth System Sciences* 12(2)**:**615-624.

Lutz, AF, ter Maat, HW, Biemans, H, Shrestha, AB, Wester, P and Immerzeel, WW. 2016. Selecting representative climate models for climate change impact studies: an advanced envelope-based selection approach. *International Journal of Climatology n/a-n/*

Mackay, NG, Chandler, RE, Onof, C and Wheater, HS. 2001. Disaggregation of spatial rainfall fields for hydrological modelling. *Hydrology and Earth System Sciences* 5(2)**:**165-173.

Mango, LM, Melesse, AM, McClain, ME, Gann, D and Setegn, SG. 2011. Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: results of a modeling study to support better resource management. Hydrology and Earth System Science 15(2011):2245-2258.

Maurer, EP and Hidalgo, HG. 2008. Utility of daily vs. monthly large-scale climate data: an intercomparison of two statistical downscaling methods. *Hydrology and Earth System Sciences* 12(2)**:**551-563.

Mendlik, T and Gobiet, A. 2016. Selecting climate simulations for impact studies based on multivariate patterns of climate change. *Climatic Change* 135381-393.

Moradkhani, H, Baird, RG and Wherry, SA. 2010. Assessment of climate change impact on floodplain and hydrologic ecotones. *Journal of Hydrology* 395(3-4)**:**264-278.

Moss, RH, Edmonds, JA, Hibbard, KA, Manning, MR, Rose, SK, van Vuuren, DP, Carter, TR, Emori, S, Kainuma, M, Kram, T, Meehl, GA, Mitchell, JFB, Nakicenovic, N, Riahi, K, Smith, SJ, Stouffer, RJ, Thomson, AM, Weyant, JP and Wilbanks, TJ. 2010. The next generation of scenarios for climate change research and assessment. *Nature* 463(7282)**:**747-756.

Park, JY, Park, MJ, Joh, HK, Shin, HJ, Kwon, HJ, Srinivasan, R and Kim, SJ. 2011. Assessment of MIROC3.2 HIRES climate and CLUE-S land use change impacts on watershed hydrology using SWAT. *Transactions of the Asabe* 54(5)**:**1713-1724.

Quintana Segui, P, Ribes, A, Martin, E, Habets, F and Boe, J. 2010. Comparison of three downscaling methods in simulating the impact of climate change on the hydrology of Mediterranean basins. *Journal of Hydrology* 383(1-2)**:**111-124.

Richter, BD, Baumgartner, JV, Powell, J and Braun, DP. 1996. A method for assessing hydrologic alteration within ecosystems *Conservation Biology* 10(4)**:**1163-1174.

Ruelland, D, Ardoin-Bardin, S, Collet, L and Roucou, P. 2012. Simulating future trends in hydrological regime of a large Sudano-Sahelian catchment under climate change. *Journal of Hydrology* 424-425(2012)**:**207-216.

Schmidt, J, Kienze, SW and Srinivasan, MS. 2009. Estimating increased evapotranspiration losses caused by irrigated agriculture as part of the water balance of the Orari catchment, Canterbury, New Zealand. *Journal of Hydrology (Wellington North)* 48(2)**:**73-94.

Schulze, RE. 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System,* Water Research Commission,Pretoria, South Africa.

Schulze, RE. 2000. Modelling hydrological responses to land use and climate change: A southern African perspective. *Ambio* 29(1)**:**12-22.

Sharma, D, Das Gupta, A and Babel, MS. 2007. Spatial disaggregation of bias-corrected GCM precipitation for improved hydrologic simulation: Ping River Basin, Thailand. *Hydrology and Earth System Sciences* 11(4)**:**1373-1390.

Sood, A, Muthuwatta, L and McCartney, M. 2013. A SWAT evaluation of the effect of climate change on the hydrology of the Volta River basin. *Water International* 38(3)**:**297-311.

Teng, J, Chiew, FHS, Timbal, B, Wang, Y, Vaze, J and Wang, B. 2012. Assessment of an analogue downscaling method for modelling climate change impacts on runoff. *Journal of Hydrology* 472(2012)**:**111-125.

The Nature Conservancy. 2009. Indicators of Hydrologic Alteration Version 7.1, User's Manual.

Thompson, JR, Green, AJ, Kingston, DG and Gosling, SN. 2013. Assessment of uncertainty in river flow projections for the Mekong River using multiple GCMs and hydrological models. *Journal of Hydrology* 486(0)**:**1-30.

Wang, G and Eltahir, EAB. 2000. Role of vegetation dynamics in enhancing the low-frequency variability of the Sahel rainfall. *Water Resources Research* 36(4)**:**1013-1021.

Warburton, ML, Schulze, RE and Jewitt, GPW. 2010. Confirmation of ACRU model results for applications in land use and climate change studies. *Hydrology and Earth System Sciences* 14(2010)**:**2399-2414.

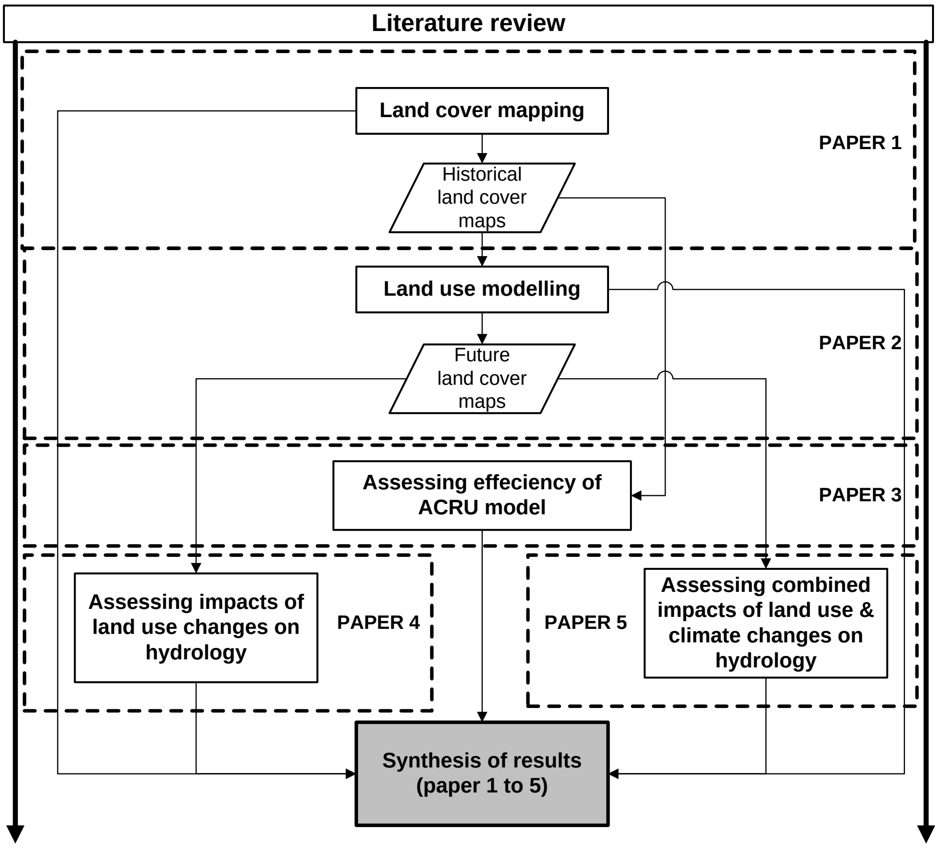
Warburton, ML, Schulze, RE and Jewitt, GPW. 2012. Hydrological impacts of land use change in three diverse South African catchments. *Journal of Hydrology* 414-415(2012)**:**118-135.

Xue, Y. 1997. Biosphere feedback on regional climate in tropical North Africa. *Quarterly Journal of the Royal Meteorological Society* 123(542)**:**1483-1515.

Yidana, SM, Ophori, D and Banoeng-Yakubo, B. 2007. Irrigation water resource management for sustainable agriculture - The Ankobra basin, Ghana. *Journal of Irrigation and Drainage Engineering-Asce* 133(6):609-615.

Preface to chapter 8

This chapter synthesizes the conclusions of the entire study in relation to the objectives and states the key knowledge contributed by the study. The chapter also states the limitations of the study and presents recommendations for future studies.



CHAPTER 8 : CONCLUSIONS

The research undertaken in this PhD thesis is presented and discussed in the respective chapters, with the main objective of seeking understanding of the long-term impacts of climate change and land cover changes on hydrology in a lowland rainforest catchment of West Africa, using case studies. Overall, the research sought to determine whether there have been significant land use changes and to identify the driving forces, as well as to determine whether relationships between the driving forces and land uses are significant enough to simulate potential future land use and to simulate future land use under different scenarios. The research also sought to understand how land uses and climate change impacts streamflows and river ecology. The responses to these questions based on the research presented in the respective chapters, are discussed, starting with issues on land use mapping and modelling and ending with issues relating to hydrological modelling to assess impacts of land use and climate changes.

8.1 Key Conclusions

Firstly, lack of land use/land cover (LULC) data is a key challenge to the assessment and understanding of Global change impacts. Mapping LULC is the first stage in understanding the land use change dynamics and it provides data for projecting potential future land use changes, as well as assessing the potential impacts. Multi-temporal land use mapping, which was undertaken in this study (Chapter 3), has highlighted the importance of regular satellite image acquisition to enable accurate inventory of vegetation dynamics, as well as assessment of land degradation. The drivers of LULC identified in this study were mainly population growth and changing economic structures, which led to the conversion of a large proportion of natural forests to shrubs/farms, settlements and mining areas. The main uncertainty with the land use/land cover mapping was the coarse spatial and spectral resolution of the applied satellite images, which limited the detectable land use classes to only six. Since the rainforest region of West Africa has persistent cloud cover, using optical images for mapping land use/land cover is challenging. However, as demonstrated in this study combination of images from different satellite sensors (ALOS AVNIR-2 and Landsat) ensured that four images spanning twenty-six years was obtained and application of sound image processing and post-processing techniques ensured that relevant data was generated. It is recommended that future studies acquire high spatial and temporal resolution images at regular time intervals to enable accurate determination of land use dynamics. With high spatial and spectral resolution images, more vegetation classes than those obtained in this study may be detected and mapped and spectral discrimination between land use classes will improve, which could enhance accuracy of any impact assessments.

Secondly, modelling historical and future land use is important in providing data to gain a deeper understanding of the land use change process, as well as for effective land use planning and natural resources management. It appears that the plethora of economic, environmental, health, social and health problems facing West African countries is largely the result poor land use planning, as the causes of these problems are linked to land use decisions at the local scale. Settlement expansion as urban sprawl, for example, does not only lead to potential pollution of surface and ground water through nonpoint source pollution and increases in carbon emissions with removal of vegetation and burning of fossil fuels (Randolph, 2012), it also makes it challenging to provide social services and amenities to citizens as the urban area increases at a rate faster than the planning and execution of development by government authorities. Hence, adoption of consistent evaluation and simulation techniques will provide planners in West Africa with the requisite information to assess different development scenarios, which account for important variables such as population growth and changes in per capita incomes, far into the future, and so control land use changes and plan development sustainably. The methodology adopted in this study i.e. the combination of logistic regression, Markov chain and the Dyna-CLUE models was consistent and considered reasonable, as it ensured that multiple land use classes were simulated spatially, based on appropriate biophysical and socio-economic drivers. The adopted methodology also ensured that simultaneous removal and regeneration of vegetation at different parts of a catchment, which occurs in reality was accounted for.

Although as the period of simulation exceeds ten years, the credibility of land use projections starts to reduce with time (Robinson *et al.*, 1994). The long-term (60 years) projections of land use, which were made in this study (Chapter 4) are necessary because they lead to understanding of any feedbacks beyond the historically observed land use change process. Long-term simulations of land use also produce long-term data, consistent with GCM climate projection time scales, which are required for assessment of Global Change impacts far into the future. Furthermore, regardless of the deficiencies, projections of land use using consistent techniques as demonstrated in Chapter 4, is superior to ad hoc predictions using expert judgement or the use of assumed land use scenarios. This study (Chapter4) has emphasised the importance of adequate information on drivers of land use changes to successful simulation, as the lack of adequate data in the Bonsa catchment resulted in only a moderately successful simulation. However, the use of multiple land use scenarios (BAU, EG and EGR) as demonstrated in this study, is a way to quantify the uncertainties associated with relying on a single scenario, thereby enhancing the applicability of simulation results.

With regards to assessment of Global Change impacts i.e land use and climate change impacts on hydrology, as well as the consequent potential river ecological alterations, this study has presented and discussed the results in Chapters 6 and 7. Preceding these chapters, Chapter 5 presented hydrological modelling, which was considered satisfactory. As demonstrated in Chapter 5, data scarcity and uncertainty of the available data were the major challenges in streamflow simulations. The uncertain climate data was due to data gaps and presence of rainfall outliers. There was also a lack of input data for vegetation and soil parameters. The uncertainties and lack of data, limited the choice of a hydrological model to one that is flexible enough to allow incorporation of landscape reading to perform physically meaningful sensitivity analysis to select model variables. Since hydrological models represent approximations of real world hydrological processes (Rosbjerg and Madsen, 2005), the use of any model to generate streamflows is also bound to have some uncertainties. Uncertainty in hydrological models result from the randomness of hydrological processes, uncertainty of the input data and model parameters, as well as errors in model structure (Rosbjerg and Madsen, 2005; Pechlivanidis *et al.*, 2011). Data processing techniques such as the conversion of point rainfall to areal rainfall using spline interpolation and driver station technique (Chapter 5) and appropriate image processing and ground truthing (Chapter 3), are used to reduce the uncertainty in the input data such as climate and land use, respectively. The uncertainty in the parameter space can however be reduced using sensitivity analysis (Blasone *et al.*, 2008). As demonstrated in this study (Chapter 5), a sensitivity analysis was used to reduce the uncertainty associated with using the ACRU hydrological model for the Bonsa catchment, as it enabled selection of model parameters, which led to satisfactory modelling. The ACRU model was selected as it relies on relatively few but physically meaningful parameters that can be derived from catchment variables. Apart from using physically meaningful sensitivity analysis to minimize the uncertainties with using the ACRU model, the study success was also based on the fact the ACRU hydrological model has been verified in a wide range of catchments, which have different land uses and climates, thereby making it an appropriate tool for assessing Global Change impacts on hydrology

Application of physical conceptual hydrological models such as ACRU to assess impacts of changes in data scarce regions is common, as data driven techniques of impact assessments are not viable due to lack of long-term field data. As demonstrated in this study (Chapters 6 and 7), land use has a more dominant control than climate change on streamflow changes within seasons, under a dry climate, but climate will have a dominant control on streamflow changes, when the climate becomes wetter. Deforestation generally leads to increased flows, while reforestation leads to reduced flows. However, as demonstrated in this study (Chapter 3) and others, deforestation is a more widespread phenomena in West Africa currently. In the future deforestation may also be a significant problem as the identified drivers of land use changes such as population growth and changing economic structures may intensify and due to already degraded landscape, vegetation rehabilitation may have little to no impact on rates of deforestation as shown in this study (Chapter 4). Impacts of land use and climate changes are scale dependent as highlighted in Chapter 6 and 7. This study has therefore shown through semi-distributed hydrological modelling, that modelling at the subcatchment scale is more appropriate than at the catchment scale, to understanding hydrology of rainforest catchments.

Lastly, although the findings of impacts studies are useful for water resources management, the limitations with regards to land use and climate change impact assessments include the uncertainty with conceptualization of hydrological processes by hydrological models, land use and climate input data. Uncertainties with the climate data and climate change scenarios are, however, greater than those with hydrological models. This study identified and removed rainfall outliers to improve accuracy of the observed climate records and applied spatial interpolation and driver station techniques to make the rainfall more spatially representative. Uncertainties with GCM climate data arise because prediction of future climates are based on prescribed emission scenarios, which depend on global development pathways, which is also uncertain. The uncertainties of GCM scenarios are also as a result of the coarse spatial resolution of GCMs, as they aggregate local scale biophysical variables. Downscaling of multiple GCM scenarios was used in this study to obtain local scale data representative of a future climate. Since individual GCM scenarios are highly uncertain, the use of multiple downscaled GCM scenarios quantifies the climate change uncertainty as it provides a set of alternative future climates, which can be used in models to evaluate water resources management plans. This study makes a significant contribution to understanding how climate change impacts streamflows in West Africa. It extends beyond existing studies in that five downscaled scenarios from the latest GCMs have been applied. Previous studies have largely relied on single GCM scenarios. Using the wettest and driest scenarios, the 25th and 75th percentile GCM scenarios as well as multi-model median of nine GCMs ensured that the full range of climate change scenario uncertainties were incorporated into the impact assessments. Uncertainties with land use input data presents another source of limitation to Global Change impact assessment on hydrology. However, since the historical land use was mapped with satisfactory accuracy (Chapter 3) and the future land use was simulated based a validated land use model (Chapter 4), the results of this study makes a significant contribution to understanding impacts of land use changes in the rainforest of West Africa, as there has never been any such study in that part of West Africa.

The results of this study mean that the use of reforestation strategies alone are not enough for effective catchment management. It is suggested that an adaptive management approach should be adopted aided by the results of this study. For example vegetation rehabilitation can be targeted in shrub land areas and runoff reduction measures (e.g. rain water harvesting, pervious pavement, bioretention basins and rain gardens and constructed wetlands) can be implemented in settlement and mining areas. Intensive rather than extensive farming can also be promoted. Urban expansion which also contributes to the removal of the pervious land cover and increases in streamflows downstream can be controlled by restricting the spatial extent of urban areas, by promoting for example, high density and high rise smart urban development (Randolph, 2012). Since streamflows are more variable at the subcatchment than at the catchment scale, evaluation of land use planning objectives with respect to water resources and environment should be based on streamflows and ecological surveys at both the subcatchment and catchment scales. To this end, installation of additional streamflow and climate stations and an intensive research and monitoring programmes should be carried out. These measures enumerated above have the potential to protect the local communities from potential floods, reduce water scarcity and pollution under changing land use and climate, as well as promote sustainable development by taking advantage of the positive impacts of Global Changes and minimizing or mitigating the negative impacts.

Based on the discussion of the achieved objectives of this research, the key contributions of this PhD thesis to knowledge are presented below.

8.2 Contributions to Knowledge

The research conducted in the Bonsa catchment contributes significantly to knowledge because to the best of my knowledge studies that have analysed scenario-based combined land use and climate change impacts on river flow and the potential ecological consequences are rare in general and in West Africa, none have been done. Also, in the regional context, this study is the first in the rainforest catchments of West Africa, which have analysed long-term impacts of combined land use and climate change on both hydrology and river ecology, using the most recent and ensemble GCM climate model data. The study provides information that can be used to support management of the Bonsa catchment and also for further studies across the region. At the end of the study the following specific contributions to knowledge on Global Change impacts on a lowland rainforest catchment in West Africa have been made.

- Improved knowledge on the current, as well as the historical rate of deforestation of the Bonsa catchment and the potential drivers of land use changes, which can be used in planning economic development and adapting to effects of land degradation has been generated.
- Improved understanding of the relationships between land use change, biophysical and socio-economic drivers in the Bonsa catchment of Ghana, which can be analysed jointly with the relationships between the drivers of land use changes in dissimilar catchments (e.g. savannah or Sahel) in West Africa, to determine the connectivity between the drivers at the regional scale to arrive at a region model, to explain land use changes in the region has been produced.
- Potential future land use data, which is vital in assessing the potential future impacts of land use changes on hydrology and water resources has been generated.
- In the context of data scarcity, a first stage calibration of the ACRU model for hydrological modelling in the Bonsa catchment, a representative lowland rainforest catchment of West Africa, has been carried out through physically meaningful sensitivity analysis.
- Improved knowledge and understanding of separate and joint impacts of land use and climate changes on hydrology in the Bonsa catchment of Ghana, which provides the opportunity to plan data collection, monitoring and management of lowland rainforest catchments effectively. The following specific information has been derived from the study:

i. The study has shown that peak, low and median streamflows of the Bonsa catchment have increased significantly in the current (2011) land use scenario, compared to the baseline (1991) and the future simulations indicate the potential for further increases, where the BAU land use scenario may result in the highest and the EGR the lowest.
ii. The 309 km^2 (343%) increase in area of shrubs/farms between 1991 and 2011 was mainly responsible for the substantial streamflow increase between the baseline (1991) and the current (2011) hydrological regime, suggesting that the shrubs/farms areas should be the main focus if the catchment is to be managed effectively.
iii. The spatial variability of the land use change impacts on hydrology were higher at the subcatchment scale than at the catchment scale. The spatial variability may also increase in the future, with the BAU producing the highest variability.
iv. When the climate change impacts on hydrology were assessed separately, their magnitudes generally reduced and were less than impacts of land use changes. The spatial variability was also less for the climate change impacts, compared to land use change impacts. However, the joint climate change and land use change impacts on hydrology, were higher than the separate climate change impacts. The impacts of the combined scenarios, were higher than separate land use impacts under a wet climate, but lower than separate land use change impacts under a dry climate. The combined impacts were also an addition of the separate impacts. Consequently, land use changes in Bonsa catchment may exert a more dominant control on streamflow changes than climate changes under a dry climate.
v. Spatial variability of streamflow changes under combined future land use scenarios and climate changes was higher and complex in comparison to those of the current land use and the historical, as well as the separate climate change or separate land use change impacts.
vi. The study has established that the seasonal pattern of streamflows in the Bonsa catchment may change when either separate climate change impacts or combined climate and land use change impacts are assessed.

The length of the dry season may increase, while the wet season length may reduce as it may start one month later than present.

vii. The potential for the stress on river ecology due to increased magnitudes and duration of high flows relative to the baseline streamflows for current (2011) land use, has been created. For the separate and joint impacts of potential future land use and climate changes, the stress on the river ecology is also predicted to increase, where the separate climate changes may lead to stress related to low flows, while the separate impacts of land use, as well as the combined impacts of land use and climate changes, may lead to stress on the river ecology related to increased high streamflows. However, the separate impacts of land use changes generated the highest potential river ecological alterations, where the BAU scenario produced the highest and the EGR produced the lowest.

viii. The problems with data scarcity and the uncertainties of available data can be quantified using land use mapping aided by ground truthing, spatially distributed land use modelling for multiple scenarios and streamflow sensitivity analysis using physically-based conceptual semi-distributed model requiring less data. Observed climate data can also be pre-processed to remove outliers and spatially interpolated to improve temporal and spatial representativeness, while multiple downscaled GCM climate scenarios can used to account for the full range of climate change uncertainties.

8.3 Future Studies

It is recommended that future studies should use high spatial and spectral resolution optical satellite images, acquired at regular time intervals to monitor land use dynamics in Bonsa and other catchments in the lowland rainforest region of West Africa. Radar images should be used for periods when cloud cover prevents the use of optical images, to ensure continues monitoring. Future studies should also investigate the connectivity of the relationships between driving factors of land use changes in the different ecological zones of West Africa, in order to establish relationships that can be used to explain and model land use changes at the regional scale, based on similar reasoning as the syndromes approach of Petschel-Held (Petschel-Held *et al.*, 1999; Steffen *et al.*, 2004), but for land use. The suggested studies will benefit from results of the land use modelling in this and previous studies and can provide seamless potential future regional land use maps required to assess impacts of potential future land use changes on hydrology and other ecosystem goods and services at the regional scale.

The uncertainties with hydrological modelling are due to inaccurate data, poor understanding of hydrological processes and model structural errors. In order to reduce the uncertainties due to poor understanding and inaccurate data inputs, it is recommended that field campaigns be conducted to measure the water-use of the different vegetation types in the rainforest catchments of West Africa, as well as conduct detailed soil surveys to determine the hydrological soil properties in the region. In terms of model verification/calibration, it is suggested that future studies investigate the value of using multisite streamflow gauges to validate hydrological modelling; this thus means more streamflow gauges are required not only at the outlets, but also in the interior of catchments. The installation of streamflow gauges in the interior part of catchments will also enable the accurate determination of the spatial variability of water resources and the consequent river ecological alterations, as well as monitor restoration effectively. Future studies should also determine quantitatively, the uncertainties due to the use of GCM climate scenarios and modelled land uses on Global Change impacts on streamflows in the rainforest region of West Africa, as these were not done in this study, but can provide additional information to improve catchment management under changing conditions.

8.4 References

Blasone, R-S, Madsen, H and Rosbjerg, D. 2008. Uncertainty assessment of integrated distributed hydrological models using GLUE with Markov chain Monte Carlo sampling. *Journal of Hydrology* 353(1–2)**:**18-32.

Jackson, B, Nicholson, SE and Klotter, D. 2009. Mesoscale Convective Systems over Western Equatorial Africa and Their Relationship to Large-Scale Circulation. *Monthly Weather Review* 137(4)**:**1272-1294.

Pechlivanidis, IG, Jackson, BM, Mcintyre, NR and Wheater, HS. 2011. Catchment scale hydrological modelling: a review of model types, calibration approaches and uncertainty analysis methods in the context of recent developments in technology and Applications. *Global NEST Journal* 13(3)**:**193-214.

Petschel-Held, G, Block, A, Cassel-Gintz, M, Kropp, J, Lüdeke, MKB, Moldenhauer, O, Reusswig, F and Schellnhuber, HJ. 1999. Syndromes of Global Change: a qualitative modelling approach to assist global environmental management. *Environmental Modeling & Assessment* 4(4)**:**295-314.

Randolph, J. 2012. *Environmental Land Use Planning and Management,* Island Press,Washington, USA.

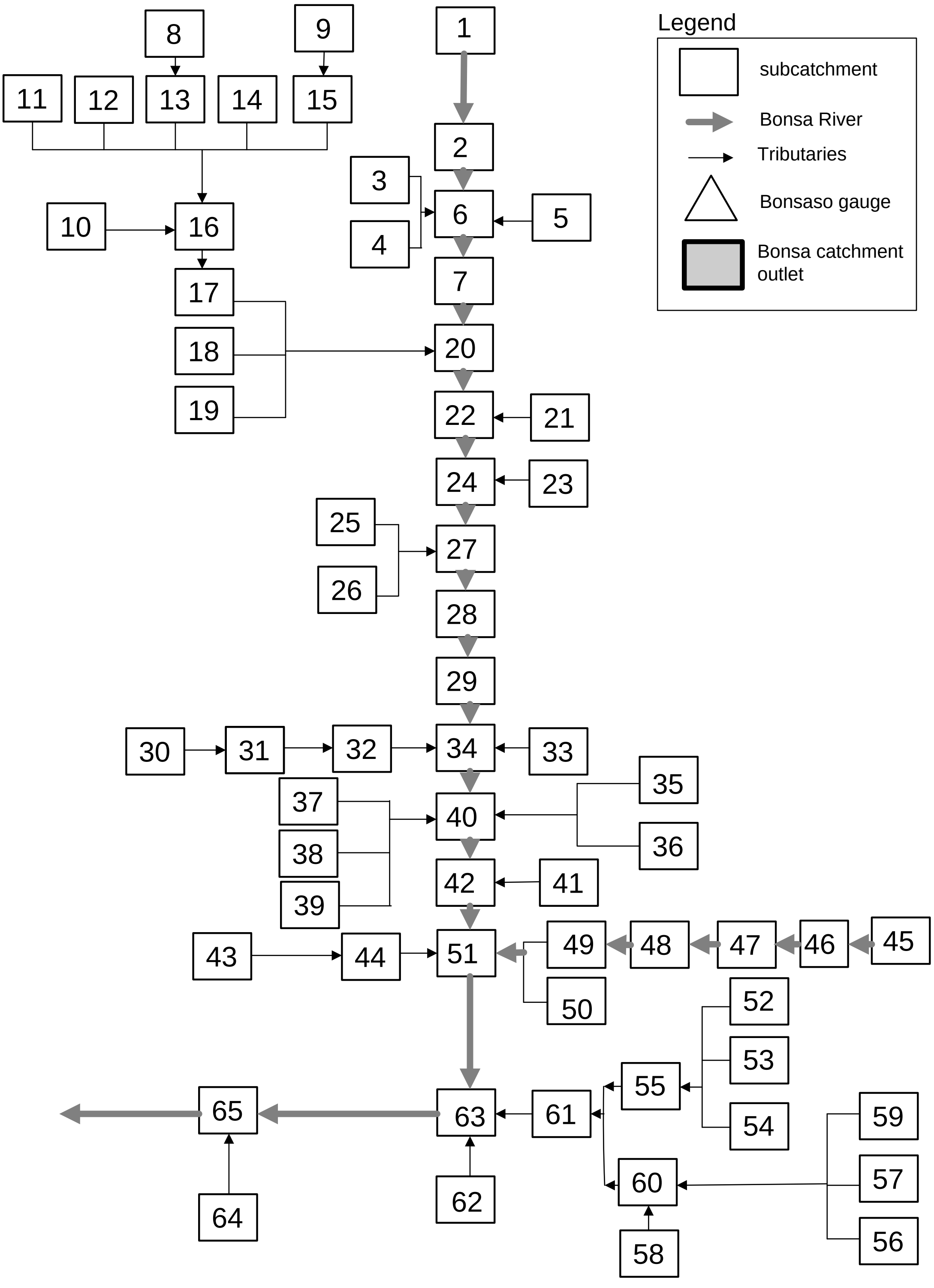
Robinson, J, Brush, S, Douglas, I, Gradel, TE, Graetz, D, Hodge, W, Liverman, D, Melillo, J, Moss, R, Naumov, A, Njiru, G, Penner, J, Rogers, P, Ruttan, J and Sturdevant, J. 1994. Land-Use and Land-Cover Projections: Report of Working Group C. *In:* Meyer, WB and Turner Ii, BL (eds.) *Changes in Land Use and Land Cover: A Global Perspective.* Cambridge University Press, Cambridge, United Kingdom.

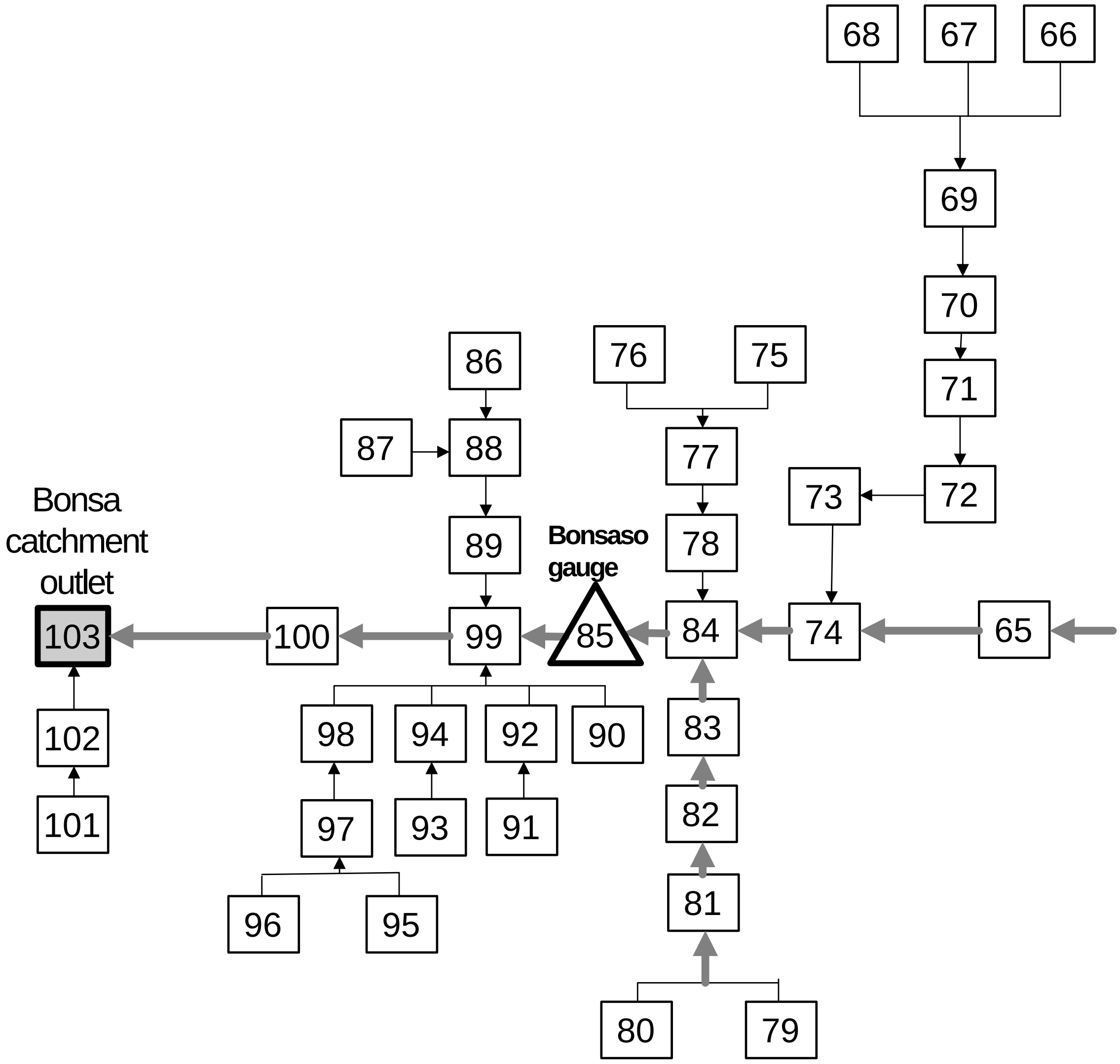
Rosbjerg, D and Madsen, H. 2005. Concepts of hydrologic modeling. *Encyclopedia of hydrological sciences.* John Wiley and Sons, Chichester, England.

Steffen, W, Sanderson, A, Tyson, PD, Jäger, J, Matson, PA, Moore III, B, Oldfield, F, Richardson, K, Schellnhuber, HJ, Turner, BL and Wasson, RJ. 2004. *Global Change and the Earth System: A Planet Under Pressure,* Springer-Verlag Berlin Heidelberg New York, Germany.

APPENDICES

APPENDIX A: Streamflow configuration of Bonsa catchment

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