BALANCING WATER FOR FOOD AND ENVIRONMENT: HYDROLOGICAL DETERMINANTS ACROSS SCALES IN THE THUKELA RIVER BASIN

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In fulfillment of the Doctor of Philosophy, Faculty of Engineering, University of KwaZulu-Natal

As the candidate's Supervisors we agree to the submission of this thesis

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(Co-supervisor)

June, 2008

PREFACE

DECLARATION

I, ***VICTOR M.KONGO***, declare that:

(i) The research reported in this thesis, except where otherwise indicated, is my original work.

(ii) This thesis has not been submitted for any degree or examination at any other university.

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

(iv) This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

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(v) Where I have reproduced a publication of which I am an author, co-author or editor, I have indicated in detail which part of the publication was actually written by myself alone and have fully referenced such publications.

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

Signed: 

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DEDICATION

This thesis is dedicated to the souls of my beloved parents, the late Edward Kongo and *Mama* Philomena Kongo, for all the sacrifice they made for the future and wellbeing of their children and whom they would have wished to witness the accomplishment of this mission!

ABSTRACT

In this study, geophysical measurements (Electrical Resistivity Tomography-ERT) and remote sensing techniques were applied in the Thukela river basin at various scales to complement the classical hydrometeorological networks. Detailed process hydrological studies were carried out at the Potshini catchment in the Thukela river basin to provide an in-depth understanding of the influence of different land use management practices, notably the impact of conservation tillage practices, on runoff generation and soil moisture retention characteristics at field scale. The general trend that was observed in the field studies is that conservation tillage systems influenced the partitioning of rainfall, by significantly reducing surface runoff over agricultural lands under conservation tillage practices, with a reduction ranging from 46 to 67%. The field soil-water balance studies also indicated that more soil moisture was retained in plots under conservation tillage practices compared to plots under conventional tillage and hence the wider adoption of such a practice could influence the partitioning of rainfall across scales.

The field based study was integrated into catchment process studies where a classical hydrometrical network was complemented with geophysical measurements (ERT) along catchment transects to determine the interaction of the surface and sub-surface water and the relative contribution of the subsurface water to catchment response. The study revealed that the shallow ground water contributes significantly, close to 75%, of the stream flows in the Potshini catchment, especially during the dry seasons, with the response of the shallow ground water being a function of both the rainfall intensity and daily total amount.

The potential of integrating the catchment process studies with the larger river basin scale was explored through the evaporative term of the water balance by applying the Surface Energy Balance Algorithm for Land (SEBAL), a remote sensing methodology, to estimate total evaporation (*ET*) from the Moderate Imaging Spectroradiometer (MODIS) satellite images. This was validated with ground measurements from a Large Aperture Scintilometer (LAS) installed in the Potshini catchment. Good comparison was established between the remotely sensed estimates and LAS measurements with a deviation range of between -14 to 26% on discrete days, where the deviation was defined as the departure of the remotely sensed estimates of *ET* from the respective LAS measurements. The results from this study compare well with results from similar studies in other countries with different climatic conditions. Subsequently, the evaporative water use of various land uses in the upper Thukela river basin was assessed using MODIS images. Commercial forestry was identified to be the

land use with a consistent and relatively high evaporative water use in the study area. High evaporation rates over water bodies were observed during the wet summer season when both the natural and man made water bodies were at full capacity. Nevertheless, it is recognized that the inherent low resolution of the MODIS images could have impacted on the SEBAL results.

Finally, a conceptual framework, drawing the strengths of classical hydrometeorological networks, geophysical measurements, isotope tracers and remote sensing is suggested with the potential of enhancing our understanding and conceptualization of hydrological determinants across scales. The relevance of the framework to water resources management is highlighted through its application to the Potshini catchment and the Thukela river basin using results and findings from this study.

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1.0 Introduction

Understanding, appreciating and nurturing of the intricate coexistence of human and eco-hydrological systems in river basins is fundamental in Integrated Water Resource Management (IWRM), as enshrined in the 1998 South African National Water Act. However, such an understanding needs to be based on detailed information regarding the dominant hydrological processes across scales and their inter-linkages for sustainable water resources management, with sustainability being achieved when consumptive uses do not threaten the short and long-term status of water bodies as sources of water for natural uses. Sustainability also needs consideration in the context of upstream and downstream users of a water resource, especially in water scarce environments such as the arid and semi-arid regions of sub-Saharan Africa. Hence there is a necessity for a holistic approach, primed with scientific information, in addressing both the social and biophysical challenges in water resources management.

The Smallholder water Systems Innovations (SSI) research programme (Rockström et al., 2004) implemented in South Africa and Tanzania (Thukela and Pangani river basins respectively), is a recent research initiative in the sub-Saharan region which aims to holistically address the above challenges. This is detailed in the programme's objectives (SSI, 2004) and further elaborated in the respective six main research projects within the programme, of which this study forms part. Figure 1.1 shows the layout and interactions of the various projects in the SSI research programme with Projects 2 and 4 having a mirror implementation in the Pangani and Thukela River Basins respectively, i.e Project 2a & 4a in Pangani and Projects 2b & 4b in Thukela. Projects 2 and 4 are the main drivers of hydrological research studies in the SSI programme, more specifically, in process hydrology at field scale (Project 2) and at catchment and river basin scale (Project 4), with the research study reported herein forming Project 4b of the SSI research programme. The programme aims at assessing the extent to which water management in rain-fed smallholder farming can reach in securing human livelihoods in semiarid/sub-tropical savannahs while analyzing the upstream and downstream implications of upgrading rain-fed agriculture through the adoption of water use innovations (e.g., rainwater harvesting). This forms the main scientific challenge in the SSI programme, i.e., the advance of knowledge on how to balance water for food and nature, with particular focus on upgrading smallholder rain-fed agriculture in water-stressed catchments and river basins at large (Rockström et al., 2004). Such a challenge should be managed within the context of IWRM, by applying management and scientific tools including those of hydrological and related sciences, especially in the understanding of the interaction of various hydrological determinants across scales as highlighted in this study.

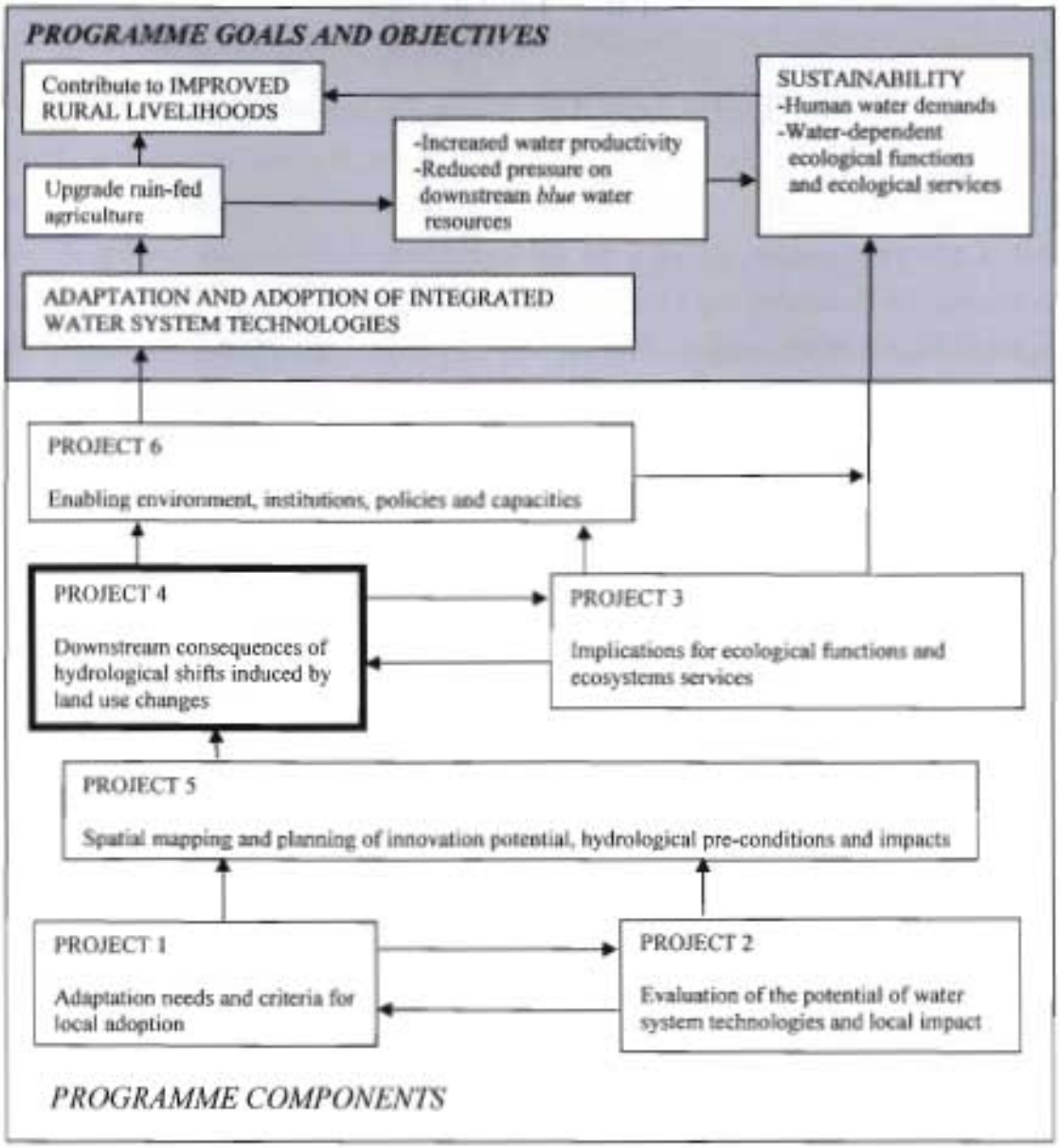

Figure 1.1 Layout of the SSI research projects (adapted from SSI, 2004)

Hydrological processes occur at a wide range of scales both in space and time (Blöschl and Sivapalan 1995) and their variability across scales has been exacerbated by anthropogenic activities which have led to impacts on hydro-climatological regimes at larger scales and far away from the epicentre, with these impacts being transmitted through the land surface-atmospheric feedbacks (Sivapalan et al., 2003). There is a link between disruption of ecosystems, environmental degradation and unsustainable water resources management, with the latter being as a result of uninformed or unwise management decisions especially relating to impending or prevailing human activities. Generally, wise decisions in

daily life are plausible through the support of past experience or knowledge and which is ultimately derived from data. There is little doubt that data is the lifeline of all scientific and analytical endeavours, an opinion also shared by Silberstein (2006) when he stated that "science is founded on observations". Thus, as the hydrological community strives to contribute to successful IWRM, it has no option than to fully engage in seeking a better understanding of the hydrological determinants across scales through observations and analysis. This calls for increased monitoring campaigns of hydro-climatological processes, devising better and innovative monitoring frameworks and approaches across scales, and developing advanced analytical tools capable for analysing the resulting massive data sets from such monitoring campaigns as highlighted in the scientific objectives of the International Association of Hydrological Scientists (IAHS) led Predictions in Ungauged Basins (PUB) initiative (Sivapalan et al., 2003) and advanced in this study.

1.1 Hypothesis and general objective of the study

The general hypothesis of this study was that good understanding and characterization of dominant hydrological processes at different spatial scales in the Thukela river basin can enhance the development of better water resources management strategies, within the context of Integrated Water Resources Management, at these scales. The general objective of the study was to identify and understand the interaction of dominant hydrological determinants at different spatial and temporal scales and their relative importance in water resources management in the Thukela river basin.

To achieve the above objective, process hydrological studies were carried out in the upper Thukela river basin, commencing with the establishment of a research catchment in the Potshini community in Bergville District in the KwaZulu-Natal Province, South Africa (cf. Figure 3.1 and 3.2). Details on the process and methodological approach applied in establishing the Potshini research catchment, including the rationale for choosing it are discussed in detail in Chapter 2 of this thesis. The instrumentation process started in the year 2004 and has progressed since then, with additional monitoring structures and instruments being constructed and installed in the catchment respectively. It is useful to note that the Bergville District, specifically the Potshini catchment, was one of the areas that were targeted during reconnaissance surveys that were carried out between January and February 2004 in search for a suitable catchment for implementation of the SSI research programme (Rockström et al., 2004). The Potshini catchment provided research opportunities for the SSI programme through the then Agricultural Research Council's (ARC) - Bergville Landcare project (Smith et al., 2004). The Landcare project was initiated in the Potshini community in 2002, two years

before the launch of the SSI research programme and hence provided an entry point for the SSI programme to the Potshini catchment through its pivotal role in the adaptation of conservation agricultural practices (water use innovations) to the smallholder farmers in the catchment. Water use innovations by smallholder farmers formed the core of the SSI research, thus the ARC project and the SSI research programme endevours were complementary and provided the rationale for choosing the Potshini catchment.

1.2 Contribution of the thesis to knowledge base

This thesis is a culmination of a four year study, spanning January 2004 to December 2007. Intensive and extensive field work formed a major part of the study reported herein especially at the initial stages in;

i) setting a platform for implementing this research study, and the SSI research programme at large, by initiating links and developing good working relationships with relevant stakeholders, especially the Potshini community, and

ii) establishing a research catchment in the Potshini community. For the purposes of this document, the field data collection and monitoring campaign ended in June 2007, although the SSI hydrological monitoring programme in the Potshini research catchment is ongoing.

The contribution of this study to the scientific knowledge base is on three fronts. The first is the establishment of a research catchment in the midst of a local community using a participatory learning approach. The Potshini research catchment has the potential to significantly improve hydrological process understanding and to play a role with regard to national policy development on water resources management particularly with regard to small scale farmer's requirements. The Potshini research catchment provides an opportunity for future and further research given the fact that the monitoring network comprises several permanent structures which other researchers may use in their studies in the future. The monitoring network at the Potshini catchment is unique in that it was established through a participatory approach, with the local community and other stakeholders playing key roles at different levels of participation as elaborated in Chapter 2. It is noteworthy that some of the catchment monitoring tasks were voluntarily undertaken by the local community after a participatory learning process which focused on the potential importance of catchment monitoring to the community livelihoods. It is acknowledged that there are other research catchments that have been established in rural community areas in the southern African region, e.g the Romwe catchment in Zimbabwe (Moriarty, 2000), but none have adopted the participatory catchment monitoring approach

that was applied in the Potshini catchment, as detailed in Chapter 2 of this thesis. The Potshini catchment monitoring network endeavours to close the water balance in the catchment, as expounded in subsequent chapters, through the monitoring of almost all the components of the hydrological cycle and characterizing the dominant hydrological processes and is uniquely established in a typical rural developmental setting.

Notably, this research study has demonstrated the successful application of geophyical measurements and classical hydrometric monitoring in determining the surface and subsurface water interactions at catchment scale, and the application of remote sensing and scintillation techniques in quantifying the spatial variation of total evaporation (*ET*) at various spatial and temporal scales in the Thukela river basin in South Africa. The interaction of surface and subsurface flows is a major field of current hydrological research, and this study makes an important contribution to this topic particularly in catchments with semi-arid environment. The application of scintillation and remote sensing techniques to estimate *ET* at various scales have not bee applied in the Thukela river basin before, and the cross validation of scintillation-remote sensing results is unique in South Africa. This is the second major contribution made by this research.

The third front is the development and application of a conceptual framework for characterizing dominant hydrological processes at occurrence scales through the integration of geophysical measurements, tracer isotopes and remote sensing in the Thukela river basin. There are several studies from other regions that have applied geophysical measurements and/or tracer isotopes to complement hydrometric measurements e.g. Wenninger et al., (2004) and Uhlenbrook et al., (2005), but none have integrated remote sensing, scintillation studies, geophysical measurements, isotope tracer studies and classical hydrometric measurements in a conceptual framework in the manner performed in this research study. The framework provides a contribution to the process hydrology endeavour of addressing scale issues and provides an opportunity for related research activities to contribute their findings to strengthen the framework.

1.3 Outline of the thesis

This thesis is comprised of eight integrated chapters, starting with the introduction of the thesis in Chapter 1 and ending with conclusions and recommendations for future research in Chapter 8, with cited reference being listed in Chapter 9. Together, these Chapters form a coherent document, with the

main Chapters and core of this research study being Chapters 2 to 7. Chapters 2, 4, 5, 6 and 7 have been structured in such a way that they require minimum editorial effort before submission for review in appropriate hydrological science journals, as per guidelines approved by the University of KwaZulu-Natal. Each of the main Chapters address a specific issue on the understanding of hydrological determinants across scales in the Thukela river basin, with subsequent Chapter(s) being based and or building on the philosophical and analytical framework of previous Chapter(s) thus forming a coherent document. Initial results from this study were published in a hydrological science journal, of which the published article, together with its appendix forms Chapter 3. Specific objectives and relevant literature for each Chapter is discussed and reviewed within the respective Chapter. A brief summary of each of the Chapters is as highlighted below.

In Chapter 2, the establishment of a research catchment in the upper Thukela river basin, i.e the Potshini research catchment, in the midst of the Potshini community is described. This Chapter provides a detailed explanation of the procedures followed in setting up a platform upon which most of the field observations in this study are made. As such, it provides a detailed description of the various hydrometric structures and equipment in the Potshini catchment which were used in this study. In this chapter, the author drew on the expertise and experience of the academic and support staff of the School of Bioresources Engineering and Environmental Hydrology (BEEH) at the University of KwaZulu-Natal in establishing the catchment monitoring network in the Potshini catchment. In particular, the author often consulted and sought advice from the Co-supervisor of this thesis who is credited with establishing hydrological research catchments in the Southern Africa region. Nevertheless, all the design of the monitoring network, the field work and data collection reported in this thesis, including engaging the local community and other stakeholders in participatory catchment monitoring was undertaken and managed by the author with manual labour being sourced from the local community. The design, construction and instrumentation of the flow gauging structures, i.e H-flume and Pressure transducer under a road culvert, was done by the author with guidance from the co-supervisor. Installation of eleven runoff plots out of the seventeen in the catchment (including the accompanying tipping buckets and sediment samplers), Piezometers, manual rain gauges, weather station in the midst of the community, the Large Aperture Scintillometer and insertion of the Time Domain Reflectometry (TDR) access tubes (for soil moisture profiling) in the eleven runoff plots, was done by the author of this thesis. The deep bore holes in the catchment were installed by the Provincial Department of Water Affairs and Forestry in KwaZulu-Natal, but the process was facilitated by the author. These boreholes were installed after a geophysical survey mapping exercise i.e Electrical Resistivity Tomography (ERT), by the author to determine the appropriate sites for installing the

boreholes. Thus, the initiative to establish and the sustained effort to maintain the catchment monitoring network in the midst of the Potshini community are accredited to the author of this thesis. The structural design and writing of this Chapter was done by the author with editorial assistance from the supervisors.

The investigation on the influence of conservation tillage practices on hydrological regime in the Potshini catchment is highlighted in Chapter 3. Conservation tillage practices, like rainwater harvesting systems, are classified as "water system innovations" (Rockström, 2000; Rockström et al., 2004) due to their ability to influence the partitioning of rainfall on the surface and have the potential to change hydrological responses at both field and catchment scale. Thus, the influence of conservation tillage system was investigated against conventional tillage system at field scale. It was found that conservation tillage system significantly reduces surface runoff and encourages retention of soil moisture. The appendix to this Chapter highlights and incorporates the examiners comments for this Chapter and hence is a revised and reformatted version of the published article in Chapter 3. In this Chapter, the author monitored and collected all the field data and carried out the comparative analysis reported herein. The structural design and writing of this Chapter was done by the author in consultation and with editorial assistance from the main supervisor.

Chapter 4 is focused on the interaction of surface and subsurface water in the Potshini catchment, including the contribution of shallow ground water to the integral stream flows observed at the outlet of the catchment. This is an important Chapter given its role in setting the stage for understanding the system dynamics of the catchment from which the link between hydrological determinants and anthropogenic activities could be established. Field work and data collection reported in this Chapter was carried out by the author, including weekly downloading of data from the weather station, the numerous data loggers recording data in the field (e.g H-flume, shallow groundwater wells etc.), obtaining field samples for saturated hydraulic conductivity, carrying out in-situ hydraulic conductivity tests, and carrying out geophysical measurements along nine transects in the catchment (cf. Figure 4.4). The scientific analysis and interpretation reported in this Chapter was done by the author in consultation with the supervisors, especially the Co-supervisor of this thesis who has done similar research work in other parts of South Africa. Otherwise the structural design and writing of this Chapter was done by the author.

In Chapter 5, the process of deriving total evaporation (*ET*) from satellite images using the Surface Energy Balance Algorithm for Land (SEBAL), a remote sensing technique, and the validation of the

SEBAL estimates of *ET* against field measurements from a Large Aperture Scintillometer (LAS) is discussed. The thrust of this Chapter is the fact that total evaporation is the main hydrological flux in the sub-Saharan region and hence the need to quantify and manage its occurrence across scales. The SEBAL estimates of total evaporation retrieved from the Moderate resolution Imaging Spectro-radiometer (MODIS) images compared well with field measurements along a 1.03 km transect from a Large Aperture Scintillometer installed in the Potshini catchment. The author of this thesis attended a one-week special training session in mid 2005, conducted by a remote sensing and SEBAL specialist from the International WaterManagement Institute-Colombo, on the application and interpretation of SEBAL results. All the field work, application of the SEBAL methodology and the analysis reported in this Chapter was done by the author with supervisory assistance from the supervisors.

The methodology described in Chapter 5 is applied through the computation of evaporative water use of various land uses in the upper Thukela river basin from MODIS satellite images, as detailed in Chapter 6. This builds on research by the main supervisor of this thesis on land use change and links to other research ongoing in the School of Bioresources Engineering and Environmental Hydrology. Forestry, water bodies and wetlands were found to have the highest evaporative water use and indigenous forests had the least water use within the forest land use classification. In this Chapter, the author carried the analytical procedures, analysis of results and writing up of the Chapter, with supervisory assistance from the supervisors

A conceptual framework for integrating other related science disciplines into hydrological science is suggested and discussed in Chapter 7. The potential for integrating geophysical measurements, isotope tracers and remote sensing into mainstream hydrological science are detailed and possible future challenges are noted. This is a synthesis Chapter and integrates the scientific evidence and knowledge from the main Chapters into a framework for addressing scale issues in hydrology. This Chapter is a brainchild of the author, who outlined its structure, content and subsequently produced the manuscript in consultation with the supervisors, who also assisted in editing the document.

Chapter 8 provides a synopsis, conclusions and recommendations for future research and is accredited to the author of this thesis.

2.0 Establishment of a catchment monitoring network through a participatory approach in a rural community in South Africa

Summary

The establishment of a catchment monitoring network is a process, from the inception of the idea to its implementation, the latter being the construction of relevant gauging structures and installation of the various instruments. It is useful that the local communities and other stakeholders are involved and participate in such a process, as was realised during the establishment of the hydrological monitoring network in the Potshini catchment in the Bergville district in the KwaZulu-Natal Province in South Africa. This Chapter illustrates the participatory application of various methods and techniques for establishing a hydrological monitoring network, in a small rural inhabited catchment, to monitor hydrological processes at both field and catchment scale for research purposes in water resources management. This Chapter concludes that the participation of the local community and other stakeholders in catchment monitoring and instilling a sense of ownership and management of natural resources to the local communities needs to be encouraged at all times. Success stories in water resources management by local communities can be realized if such a process is integrated with other development plans in the catchment at all forums with due recognition of the social dynamics of the communities living in the catchment.

2.1 Introduction

Sound decision making for water resources and environmental management has to be based on good knowledge and factual information regarding the dominant hydrological processes, together with bio-physical characteristics of a catchment and in combination with socio-economic aspects. Such information can only be obtained through establishing networks that are capable of monitoring such hydrological processes at different temporal and spatial scales. The establishment of a catchment monitoring network involves a process, from inception of the idea to the actual construction of the various structures and installation of the necessary equipment and instruments while engaging relevant stakeholders. Such a process is normally driven by a motive to meet certain research objectives (e.g Wigmosta and Burges, 1997; Gilvear and Bradley, 2000; Hodgson et al., 2002; Ireson et al., 2006), but with consideration of the cost implications with regard to construction and acquisition of the various instruments and their maintenance. However, research catchments are typically established in areas where people do not live. In fact, people are usually excluded from such catchments as they add uncontrollable variables to the experiment as well as the risk of theft and vandalism. This Chapter

describes the establishment and installation of various instruments and structures for a detailed catchment monitoring network that took place in the midst of a rural community, the Potshini community, in the upper Thukela river basin in South Africa. This provides a good case study for considering the many issues and challenges (social, scientific and engineering) that need to be addressed in the process of establishing the monitoring network in a populated rural catchment in a developing region.

There are few case studies in the available literature on the establishment of detailed catchment monitoring networks through a participatory approach involving the local community and other stakeholders. Moriarty (2000) reported the establishment of the Romwe catchment in Zimbabwe through the involvement of the local community, but the participatory approach that was applied in due process was not highlighted. A survey study by Loreta et al., (2006) indicated the desire by local communities and other stakeholders to be involved in water quality monitoring and surveillance in the Mzingwane catchment in Zimbabwe, even though they were not aware of the existence of such a monitoring programme in their locality. However, the participatory approach in catchment monitoring has long term benefits including the opportunity for the relevant stakeholders, notably the local community, to gain insight into the hydrological regime of their locality. This in turn provides a better basis for decision making for farming activities and understanding the impact of anthropogenic activities on water resources in the catchment. Thus, a participatory approach requires a constant effort to initiate a learning process, through which the local community is able to appreciate and recognize the importance of catchment monitoring, not withstanding the willingness of the community to participate in the monitoring exercise.

The Potshini catchment, a small headwater catchment on the foothills of the Drakensberg mountains in South Africa, is inhabited by the Potshini rural community and whose main economic activity is smallholder farming and livestock keeping. As highlighted above, the inclusion of people in research catchments has many challenges. Nevertheless, one can not carry out convincing studies on the interaction between water resources and food security of any rural community without considering the livelihoods of the rural community and the dominant hydrological processes. It is on this understanding that the Potshini catchment monitoring network was established with various objectives as discussed below.

2.2 Objectives for establishing the Potshini catchment monitoring network

The Potshini catchment monitoring network was established to fulfill a threefold mission in line with the overall objective of the Smallholder System Innovations in Integrated Watershed Management (SSI) research programme (Rockström et al., 2004) of addressing the challenges of increasing food production, improving rural livelihoods while safeguarding critical ecosystem functions and services. The threefold mission encompassed:

- Monitoring the hydro-climatological processes of the Potshini catchment in order to gain an in-depth understanding of the hydrological regime of the catchment and investigate the hydrological and ecosystem impacts of adoption and adaptation of water use innovations (rainwater harvesting) in the Potshini catchment;
- Establishing a capacity to assess, monitor, and manage water and environmental resources in the Potshini community in collaboration with various stakeholders through training on the basic methodologies of catchment monitoring;
- Providing an opportunity for future and further research through the establishment of a catchment monitoring network with a potential for upscaling and integrating into other larger networks in the country. This is due to the fact that the network comprises several permanent structures which other researchers may use in their studies in future after the accomplishment of the SSI research programme.

The SSI research programme is focused on investigating the potential of small-scale water system innovations (e.g rainwater harvesting, conservation tillage etc) for upgrading rainfed farming in semi-arid agro-ecosystems, including aspects such as the need for local adaptations of these techniques, adoption of them among smallholder farmers and possible trade-off between water for agriculture and water for surrounding ecosystems. However, it must be noted that SSI is a scientific programme and as such is dedicated to the delivery of innovative and high quality research, albeit in a developmental setting. The instrumentation which forms the Potshini hydrological monitoring network ranges in sophistication from simple manual rainguages, to state of the art instruments such as a Large Aperture Scintillometer and Electrical Resistivity Tomography instruments.

The process of establishing the Potshini catchment monitoring network was initiated in early 2004 under the SSI research programme at the School of Bioresources Engineering and Environmental Hydrology of the University of KwaZulu-Natal, South Africa. The process integrated two approaches (i) a participatory approach where the local community and other stakeholders were involved and

participated (ii) a scientific approach which entailed the application of scientific and engineering principles in designing, construction and installation of various structures and instruments. It should be noted that the two approaches were not treated separately but rather formed an integrated continuous learning process where the relevant stakeholders and researchers made an effort to interact and to learn from each other. The main stakeholders for the SSI programme in the Potshini catchment, at various degrees of participation, included the following (i) smallholder farmers actively participating in various experimental and monitoring activities (ii) members of the local community in the Potshini catchment in observation and construction (iii) smallholder farmers neighbouring the Potshini catchment in attending field days and learning sessions (iv) neighbouring large scale commercial farmers in participating and supporting the catchment monitoring initiative (v) the traditional and local leadership in assembling and motivating the community (vi) the Provincial Department of Agriculture and Environment in supporting teaching, providing material inputs, organizing field days and encouraging the community to become involved (vii) the Agricultural Research Council-Institute of Climate Soil and Water in contributing expertise from past research in Potshini (viii) the Local Authority-the *Okhahlamba* Municipality in encouraging the community to become involved and providing material inputs and (ix) the KwaZulu-Natal Provincial Department of Water Affairs and Forestry in providing monitoring and domestic boreholes.

The Potshini catchment monitoring network comprise gauging structures and instrumentation, mostly automated, for measuring and monitoring stream flows, overland flow from experimental runoff plots, sediment load, shallow and deep ground water tables, subsurface resistivity using Electrical Resistivty Tomography (Loke, 2003), isotopic composition (Deuterium and Oxygen-18) in both surface and subsurface water, volumetric soil moisture content, soil hydraulic parameters, crop transpiration rates and meteorological parameters. The application of scintillation techniques (Large Aperture Scintillometer) in estimating total evaporation in the Potshini catchment forms an intermediate observation and a calibration scale for remote sensed estimates of total evaporation from satellite images in the catchment and the Thukela river basin at large, using the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998a; Bastiaanssen et al., 1998b; Bastiaanssen, 2000). Initial results on hydrological studies based on data obtained from the Potshini catchment monitoring network for part of the 2004/05 hydrological year are reported in Chapter 3.

2.3 Overview of a logical hydrological measurement sequence

Although hydrological processes vary continuously in time and space, they are often described and derived from point measurements. The resulting data form a time series, which are typically subjected

to further processing, including statistical analysis and or hydrological modelling. Chow et al., (1988) highlighted a sequence of logical steps (Figure 2.1) which are commonly followed for hydrological measurements and monitoring, beginning with the instrumentation of a physical device that senses or reacts to the physical phenomenon and ending with the delivery of data to the user.

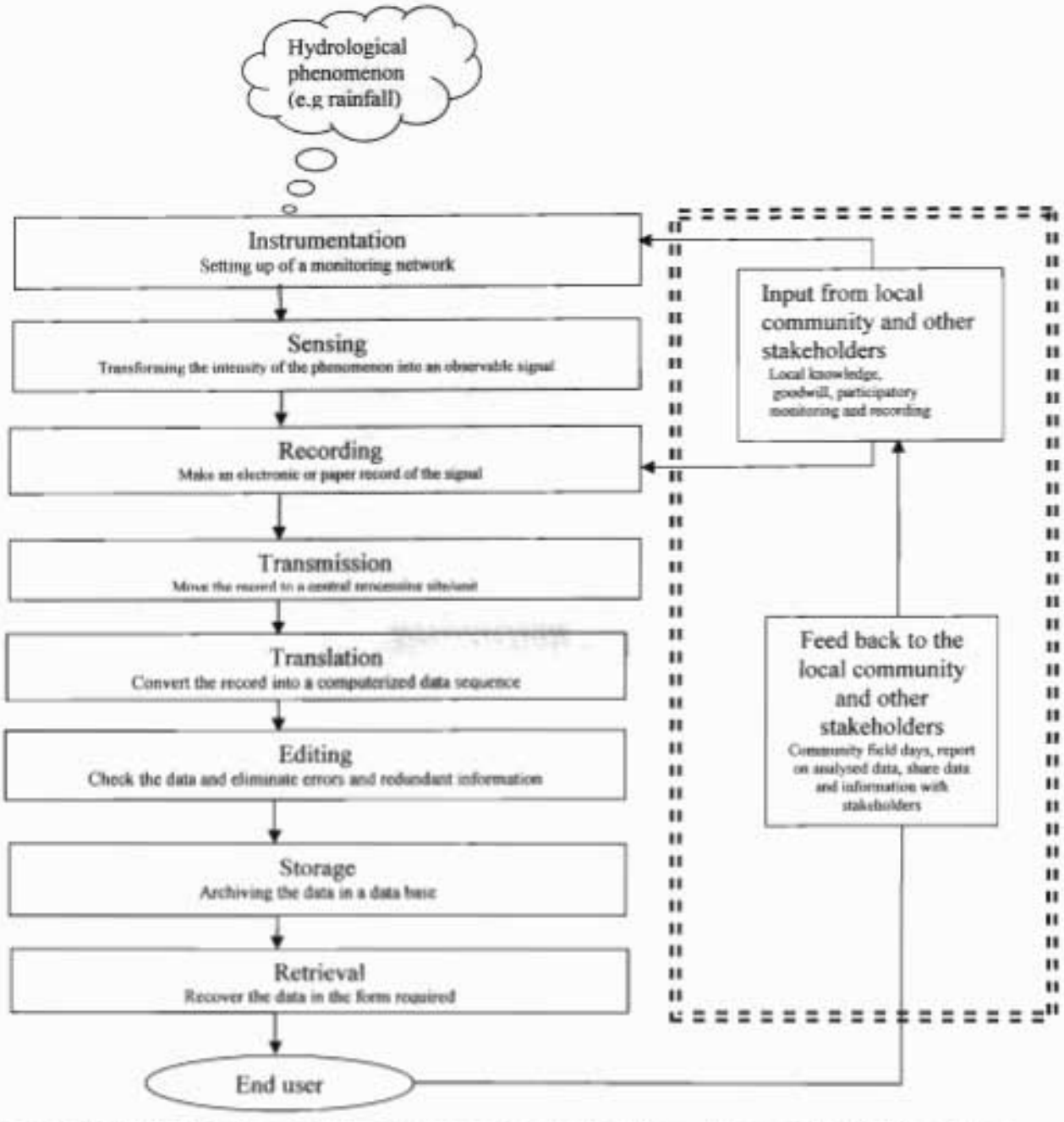

Figure 2.1 Hydrological measurement sequence (adapted from Chow et al., 1988) with an additional participatory component indicating the role of the local community and other stakeholders in establishing the Potshini catchment monitoring network. The feed back loop indicates sharing the analysed data with the respective stakeholders

Such a sequence was adapted during the establishment of the Potshini catchment monitoring network with an additional participatory component where the input from the local community and other stakeholders was sought and incorporated as indicated in Figure 2.1. In the absence of the participatory component, the sequence describes a scenario which is biased to understanding the hydrological processes in a catchment but void of the social dimension of how the local community understand and respond to the hydrological processes being monitored. The social dimension comprises several elements, including the understanding of the knowledge base of the rural community with regard to rainfall patterns, stream flows, temperatures etc, as well as the willingness of the community to learn about and quantify the various hydrological processes taking place in their midst and the importance of understanding such processes. An example of application of the local knowledge base in this study is highlighted in Section 2.5.3 of this Chapter. Such an approach perpetuates a sense of ownership and imparts management skills of natural resources to the local community and hence ensures the security of the various installations comprising the catchment monitoring network. The social dimension can be complicated if several stakeholders with diverse interests are involved in the establishment of a catchment monitoring network. Nevertheless, such diversity can be a source of inspiration and strength if a common understanding is sought at the initial stages. However this must be based on good working relationships and trust as was experienced during the establishment of the Potshini catchment monitoring network. Although the steps indicated in Figure 2.1 may appear to be obvious, even simple, they need to be followed and documented for the purpose of sharing the experience and knowledge as highlighted in this Chapter.

2.4 Study area

The Potshini catchment (E 29.3679^0 S 28.8145^0) is located in the foothills of the Drakensberg mountains at an average altitude 1310m and is predominantly a smallholder farming area and a sub-catchment of the Quaternary Catchment[1] number V13D (Emmaus catchment) in the Thukela River basin in South Africa. The Thukela river basin is comprised of 86 Quaternary Catchments with a total area of 29,036km^2, with the Quaternary Catchment V13D having an area of 285 km^2. Figures 2.2, 2.3 and 2.4 show an overview of the Thukela river basin and the Potshini catchment. The Potshini catchment comprises 2-nested catchments, with an area of 1.2km^2 (gauged by an H-Flume) and 10km^2 (gauged by a pressure transducer) respectively.

[1] Quaternary Catchments (QC) in South Africa are the smallest delimitations of a river basin upon which policies and decision with regard to water resources management are based upon. The QC were defined and established by the National Department of Water Affairs and Forestry

The mean annual precipitation at Potshini is estimated to be 700mm.a^{-1} and the estimated mean annual potential evaporation is between 1600 to 2000mm.a^{-1} (Smith et al., 2004). The rains occurs during the summer season (September to April), with heavy rains being characterized by thunderstorms and occasional hailstorms. The maximum and minimum temperatures recorded in the catchment since 2004 are 34 and -4°C respectively. Frost is common during the dry winter season (May to August) and has often destroyed vegetative materials in the catchment, including vegetables in homestead gardens in the catchment.

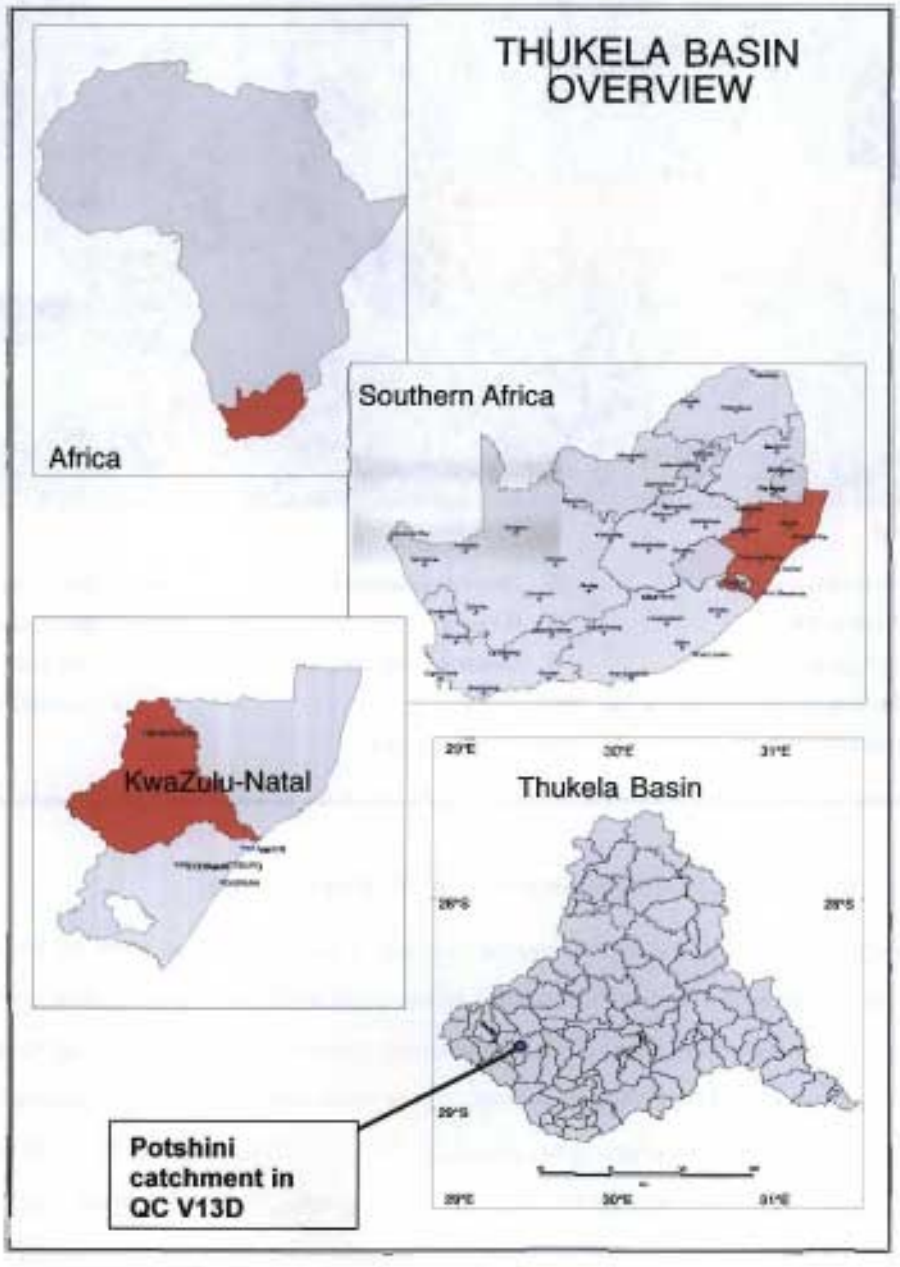

Figure 2.2 An overview of the Thukela river basin (After SSI, 2004)

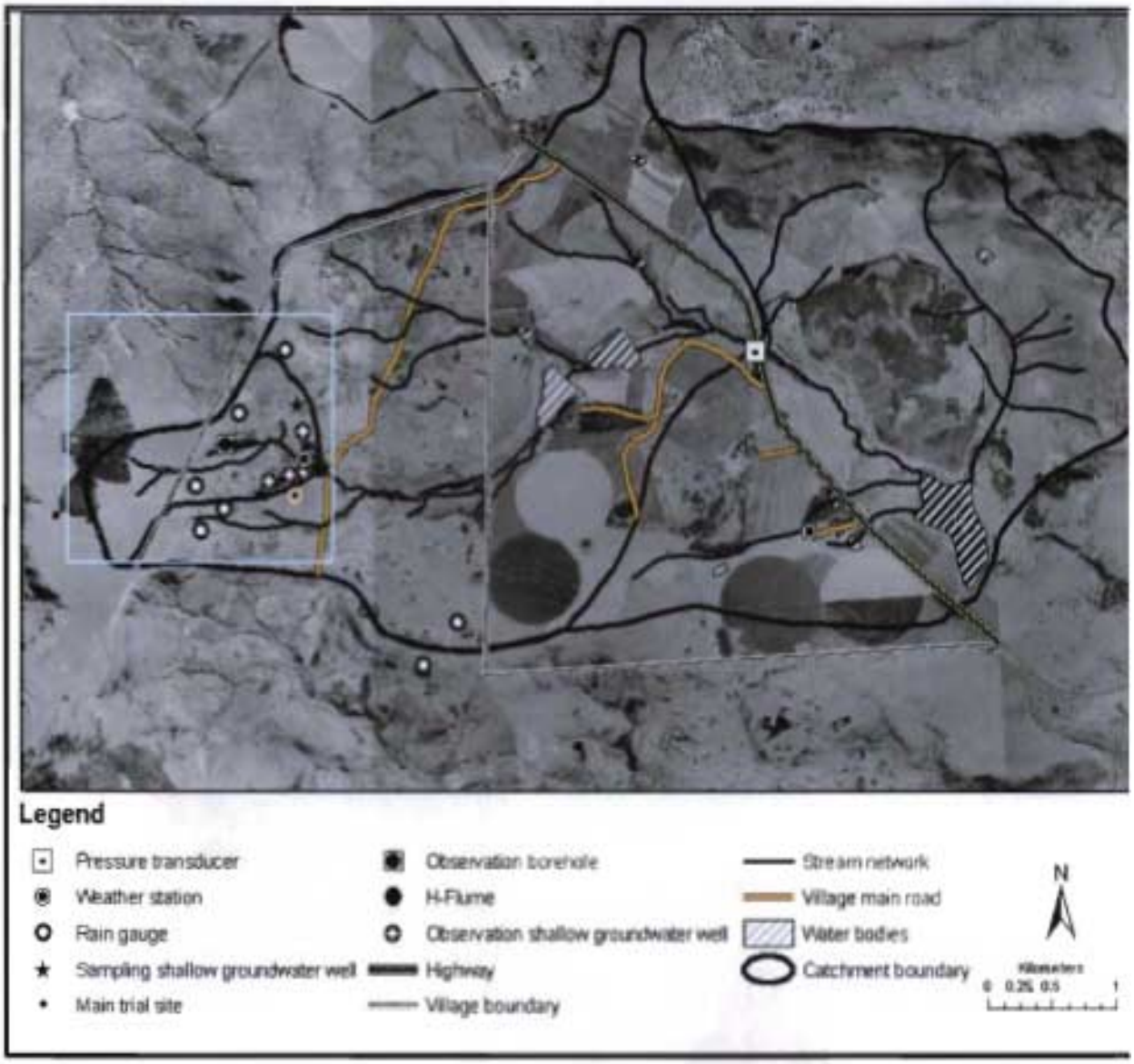

Figure 2.3 An overview of the two nested catchments in Potshini

Due to local topography and high summer rainfall, a good drainage network has developed in the Potshini catchment with most of the streams being perennial and providing water for domestic use to the upper part of the catchment, while replenishing reservoirs for commercial farmers downstream. The main land uses in the catchment include the predominant smallholder farming (crop production) during summer, which constitutes approximately 60% of the total land in the catchment, and grazing. The smallholder farms are individually owned while grazing areas and boreholes that were installed by the local authorities are considered common property. The main sources of water for domestic use in the community are bore holes, springs and the Potshini stream.

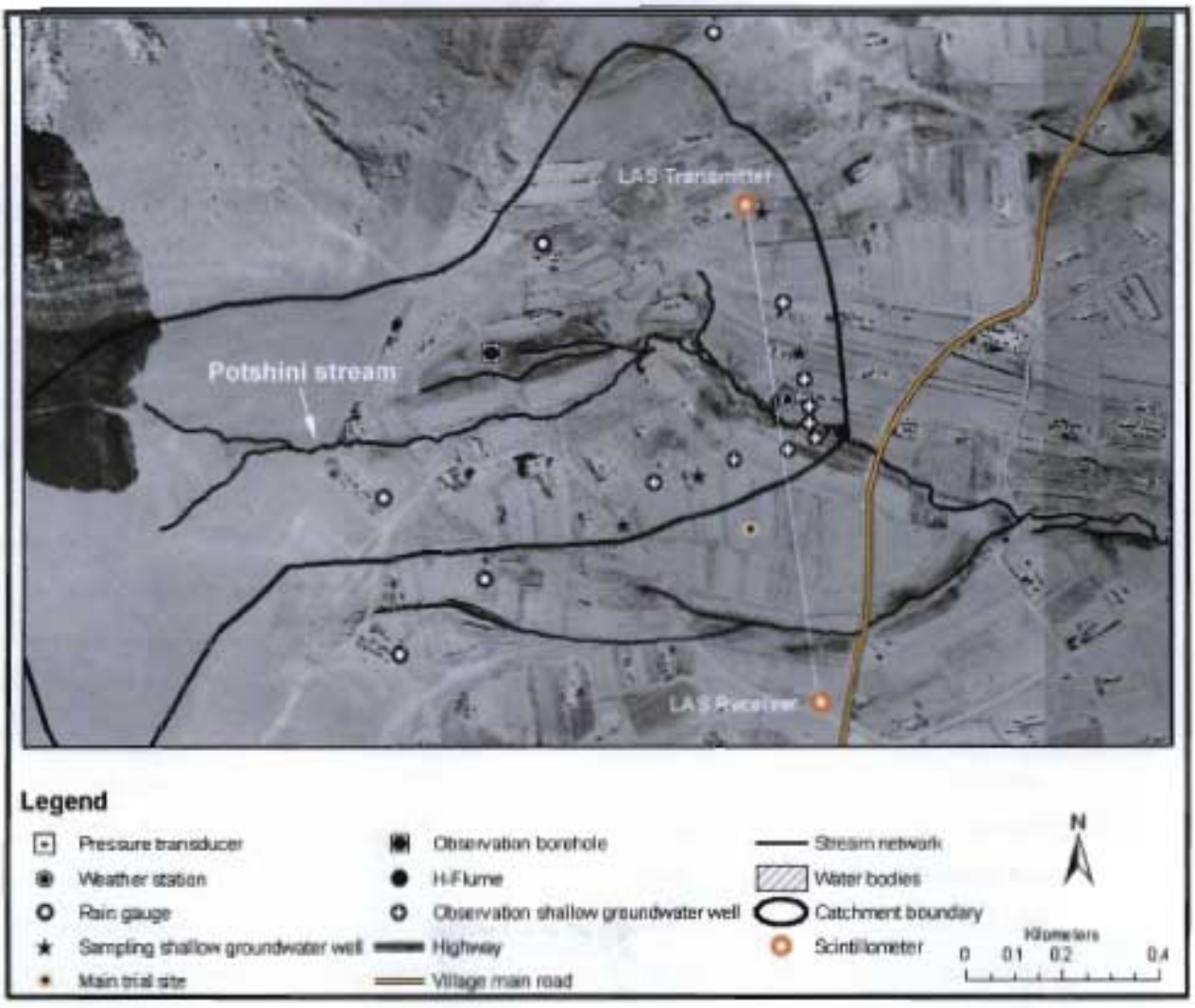

Figure 2.4 The 1.2km^2 Potshini catchment

The geological formations underlying the region around Potshini catchment is sandstone and mudstone of the Tarkastad Formation, Beaufort Group and by shale and sandstone of the Estcourt Formation (Turner, 2000). The Tarkastad Formation is described as comprising fine to medium grained yellow and grey sandstone and maroon (red) to green and blue mudstone. The Estcourt Formation is described as comprising dark-grey shale, siltstone and fine and medium to coarse sandstone. According to Turner (2000), the major soil patterns that are evident and associated with the sandstone and mudstone of the Tarkastad Formation are the red and yellow-brown apedal and the plinthic soil patterns.

2.5 Methodology

2.5.1 The participatory process

The research approach applied in establishing the Potshini catchment monitoring network involved Participatory Research (Bhatt et al., 2006), a process where the smallholder farmers and other stakeholders were involved from the initial preparatory stages to the actual construction and instrumentation of the various structures and instruments. Local input was sought regarding the siting of structures and instruments and permission to develop a monitoring network was sought from the local farmer's forum, individual farmers as well as from the traditional and local leaders of the area. A communication process and dialogue was initiated between the researchers and the relevant stakeholders in the catchment. This involved holding meetings with the local leaders (e.g traditional leaders, Local Government officials, relevant Government Department officials etc.) and the local community. Local artisans and masons were purposely involved in construction of various structures and installation of some of the instruments as part of a wider learning platform and technology transfer to enable them appreciate the operational mechanisms of the network. The local community continued to be a key stakeholder in the SSI research programme and an ongoing effort is made towards creating and maintaining a cordial relationship with the community based on respect, trust and friendship. The culture and practices (e.g abstaining from any field activities that involve digging or excavation of the soil during burials) of the Potshini community were respected at all times both during and after the establishment of the Potshini catchment monitoring network. The approach prooved to be effective in perpetuating a conducive environment for interacting with the local community and hence the goodwill of the community to safe guard any installations in the area. Several smallholder farmers in the Potshini community volunteered to participate in various research activities including managing experimental trials on their farms. The voluntary monitoring of daily rainfall and soil moisture in the catchment by some of the smallholder farmers in the Potshini catchment was beneficial to them especially in determining the appropriate time for planting their single summer maize crop.

2.5.2 Communication and feedback platforms for learning and sustainable adoption

A participatory learning process must involve a feedback mechanism where continuous updating and response are integrated in the learning process. Such feedback mechanisms should accommodate as much as possible, the opinions and ideas from the various stakeholders. In the Potshini catchment, feedback forums were promoted and encouraged for all stakeholders, at the various levels of participation, where the respective stakeholders were continuously updated on the main research

findings, progress on data collection and upcoming research activities within a year. It is during such feedback sessions that the respective stakeholders obtained an in-depth understanding of the ongoing research activities, and appreciation of their contribution to the SSI research programme and to understand the vagaries of hydrological processes in their catchment.

A monthly Farmers Forum, established as a communication and management platform for farmers in the Emmaus ward (the administrative ward in which Potshini falls) in the Bergville District under the then Agricultural Research Council's (ARC) Landcare Project, proved to be a useful platform for the researchers, for dialogue with farmers and for other stakeholders in the area. This forum provided an entry point for the SSI team and through it, the researchers were able to outline the objectives of the SSI programme in the area, its implementation and most importantly the usefulness of voluntary participation of farmers in the research programme. The researchers managed to effectively use the farmer-to-farmer learning structures previously put in place by the then ARC Landcare project (Smith et al., 2004) for establishing contact with individual smallholder farmers who were willing to participate in the SSI research programme, especially in the catchment monitoring exercise. It is through such forums that a good working relationship between the Department of Agriculture (both Provincial and District offices) and the research team were established. Since then, the SSI Programme continued to benefit and enjoyed the support of the Bergville District and KwaZulu-Natal Provincial Agricultural offices and the SSI researchers attended or were represented at relevant Department of Agriculture functions, which provided a forum for all stakeholders and development projects working in the Bergville District on food security, home economics, community resources and the agricultural sector. The SSI research team participated in all field days organized by the Department of Agriculture in Potshini and other nearby wards in the Bergville District and likewise, the Department of Agriculture actively participated and to some extent facilitated some of the field days organized by the SSI research programme in Potshini.

2.5.3 Siting of stream flow gauging structures

The establishment of the Potshini catchment monitoring network involved the initial stage of reconnaissance surveys to gain a general understanding of the catchment before detailed and specific site surveys were performed as per requirements of each structure or instrument. The siting of the streamflow gauging sites and design of the gauging structures in the Potshini catchment involved the application of the local knowledge, scientific and engineering techniques. In particular, the local knowledge on the historical peak flows and flood prone areas was vital during the design and construction of one of the stream flow measuring structures, i.e an H-Flume, where community

members, especially the elders, were involved in some of the reconnaissance surveys in the catchment with regard to siting of the H-flume. The elders were asked on how often the stream in the Potshini catchment overtopped its banks and whether the sites that had been identified as ideal for constructing the H-flume were safe from flooding and inundation. According to the elders, the site where the H-flume was eventually constructed was prone to inundation at most after every three years and they even marked the inundation extent for the last flooding event at this section as indicated in the schematic diagram, Figure 2.5, which was developed after a survey exercise before the construction of the H-flume. This information was useful in the design of the H-flume especially the orientation of the instrumentation house as discussed in Section 2.5.5 of this Chapter.

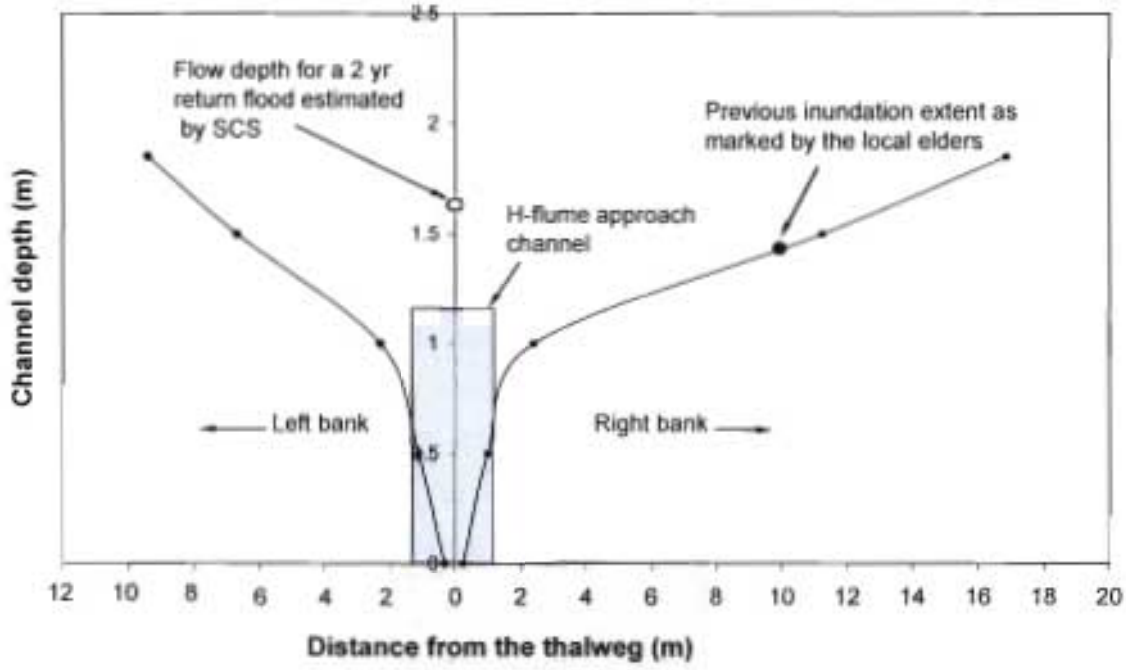

Figure 2.5 Schematic diagram of the cross section at the H-flume gauging site

Even though the stream-section on which the H-flume was constructed was prone to inundation (based on local knowledge), it was preferred due to the structural stability of its narrow banks, presence of underlying rocky material for stability of the approach channel, and most importantly enough bed slope for quick discharge, which is an important parameter in construction of H-flumes (Ackers et al., 1978). It is interesting to note that the information obtained from the local community with regard to historical peak flows, e.g stream flow depth during historical peak flows, was in close agreement with results obtained from a modeling exercise using the Soil Conservation Services (SCS) methodology

(Schulze et al., (1992) in determining peak floods from the Potshini catchment as can be seen in Figure 2.5.

2.5.4 Estimation of peak discharge using the SCS methodology

Most of the hydraulic structures in streams and rivers (e.g bridges, culverts, weirs, flumes etc) need to be designed based on the extreme flow events, which can be obtained through a flow frequency analysis or hydrological modeling. The Soil Conservation Services (SCS) methodology, modified for South Africa conditions, for estimating peak floods in small catchments (Schulze et al., 1992), was applied to estimate the peak discharge for selected return periods in the Potshini catchment to determine the design flow for an H-flume. The South African version of the SCS methodology has been packaged into a computer program at the School of Bioresources Engineering and Environmental Hydrology and was used in determining the peak discharge in the Potshini catchment. In the modified SCS method, the peak discharge for an increment of time *(ΔD)* is defined as:

$$\Delta q_p = \frac{0.2083 * A * \Delta Q}{\Delta D / 2 + L} \tag{2.1}$$

Where Δq_p is the peak discharge of incremental unit hydrograph ($m^3.s^{-1}$), A is the catchment area (km^2), ΔQ is the incremental stormflow depth (mm), ΔD is unit duration time (h) used with distribution of daily rainfall to account for rainfall intensity variations and L is the catchment lag (hrs).

The general hydrological and physical conditions in Potshini catchment neccessitate the use of the SCS lag equation for estimating catchment response time. Dry spells occur during winter (May to September) and most parts of the catchment have limited vegetation and mulch cover due to overgrazing and hence the area could be categorized as semi-arid, which suits the application of the lag equation. The SCS lag equation is given as (Schulze et al., 1992):

$$L = \frac{l^{0.8}(S^{`} + 25.4)^{0.7}}{7069 * y^{0.5}} \tag{2.2}$$

$$y = \frac{M * N * 10^{-4}}{A} \tag{2.3}$$

$$S^{`} = \frac{25400}{CN - II} - 254 \tag{2.4}$$

Where L is the catchment lag time (h), l the hydraulic length of catchment along the main channel (m), A is the catchment area (km^2), y is the average catchment slope (%), M is the total length of all contour lines (m) within the catchment, N is contour intervals (m), A is the catchment area (km^2) and *CN-II* is the curve number of type II. Basically, a curve number is an index relating a catchment's stormflow response to a rainfall event and is a function of catchment characteristics including hydrological soil properties, land cover, and the catchment antecedent soil moisture conditions (Schulze et al., 1992). The South African soils have been classified into hydrological groupings, with each group having unique hydrological properties that are used in the derivation of the curve number in the SCS package. Thus, the curve number for the Potshini catchment was determined using the procedure outlined in Schulze et al., (1992). Table 2.1 indicates the physical and hydrological parameters for the Potshini catchment used as inputs to the SCS model. The catchment area, number of contours, total length of contours and the hydraulic length of the catchment was determined from a 1:50000 topographical map covering the catchment while the Mean Annual Precipitation (MAP) was obtained from the nearby Bergville weather station.

Table 2.1 Physical and hydrological characteristics of the Potshini catchment

Area (km^2)	No. of contours	Total length of contours (km)	Contour interval (m)	Hydraulic length (m)	Slope (%)	MAP (mm)
1.2	7	5.75	20	1400	10.46	675

Based on previously mapped rainfall intensity distribution types in South Africa, the location of the catchment coincided with storm intensity distribution type 4 (Schulze et al., 1992). With a coefficient of initial abstraction being 0.1, the catchment lag time was estimated to be 0.58 hours (37 minutes). A summary of the SCS model results is presented in Table 2.2

Table 2. 2 Summary of SCS model results

Return period (yrs)	**2**	**5**	**10**	**20**
Design daily rainfall depth (mm)	59	81	98	117
Computed curve number	74.5	74.5	74.5	74.5
Runoff depth (mm)	18.4	32.8	45.2	60.0
Runoff volume (x1000 m^3)	20.27	36.09	49.75	66.05
Peak discharge ($m^3.s^{-1}$)	6.4	11.6	16.2	21.6

2.5.5 Design of the H-flume

The most common hydraulic structures that are used for measuring stream flows are weirs and flumes (Ackers et al., 1978). If not well designed, weirs may end up being sediment traps leading to change of the channel geometry (width and depth), which is the main reason why weirs need to be re-calibrated with time. This is not the case for H-flumes. The geometry and design of an H-flume allows for free flow of the stream discharge, save for the constriction at the front end, and hence enabling the implementation of a sediment load monitoring scheme as is the case with the Potshini H-flume. In designing the Potshini H-flume, a 2-year return peak flood was considered i.e 6.4 $m^3.s^{-1}$, although the actual design flow for the H-flume was 3.42 $m^3.s^{-1}$. The main reasons for adopting a lesser design flow was the fact that the available stage-discharge relationship for H-flumes, developed by SCS, is only valid for a maximum discharge of 3.42 $m^3.s^{-1}$, and it was necessary to use an H-flume rather than a weir in the catchment to facilitate accurate monitoring of the sediment load from the catchment. This is rather difficult to achieve using a weir. Also, low flows were considered important to capture accurately, so a size smaller than that required for the 1:2 year event was accepted. This is also supported by the fact that large H-flumes are not sensitive to lows flows of which were considered important in this study and other research projects that were being implemented in the catchment under the SSI research programme. Since this was the largest H-flume calibration available, it was accepted in lieu of complex calibration of an off-spec flume. The design of the Potshini H-flume was based on the criteria outlined by Ackers et al., (1978). The fundamental concern and priority during the design and construction of the Potshini H-flume was maintaining structural stability during and after excessive loading events i.e peaks floods. The SCS modeling results were used as one of the bases for determining the design flood for the H-flume. Necessary precautionary features and safety factors were incorporated in the design and construction of the instrumentation house and the approach channel to allow the safe passage of a 2-year return period flood of 6.4 $m^3.s^{-1}$ without affecting structural stability. Some of the precautionary features included constructing the instrumentation house on a higher ground away from the stream bank to avoid damage to the flow-recording instruments in the house by unpredictable seasonal floods, reinforcing the walls of the approach channel with starter bars drilled into the bedrock, anchoring the foundation against sliding and stabilizing the slopes of the stream banks both on the upstream and downstream of the 11.5m long approach channel for a distance of 4m with reinforced rip-rap. It is useful to note that the orientation of the H-flume's instrumentation house was influenced by the local knowledge from the elders of the Potshini community on inundation extent at the site where the H-flume was constructed as illustrated in Figure 2.5. Apart from being constructed 6m away from the stream, the instrumentation house was

designed with an elevated floor foundation, 0.4 m above the ground surface, thus further taking precautionary measures against any unexpected inundation due to floods.

2.5.6 Streamflow measurements and monitoring of water quality parameters

Streamflow in the Potshini catchment is monitored at two sites coinciding with two nested subcatchments of 1.2 and 10km^2 respectively, as indicated in Figure 2.3 & 2.4. The smaller subcatchment, 1.2km^2, is gauged by the H-Flume, while the larger catchment is gauged by monitoring water level fluctuations using a pressure transducer installed at a road culvert. The monitoring of the flow rates at the Potshini H-flume is governed by a set of 3 rating equations, each describing a unique stage-discharge relationship for a given range of flow depths. Monitoring of level of discharge in the Potshini H-flume is via a tube, connecting the open channel discharge to a stilling well. In the Potshini H-flume, the approach channel is connected to a stilling well, 5.6 meters away, by a 50mm pipe at the floor level of the approach channel and sloping slightly in the direction of the stilling well. With this set-up, the water level in the approach channel and the stilling well will always be the same and hence makes it possible to monitor the water levels in the approach channel by recording the water levels in the stilling well through the use of a float and a data logger mechanism as illustrated in Figure 2.6. The float in the stilling well follows the rise and fall of the water level in the approach channel and such movements are translated into rotational movements, and subsequently depth of flow, through a pulley system on a shaft encoder, which is linked to a data logger. Figure 2.7 shows the Potshini H-flume in operation.

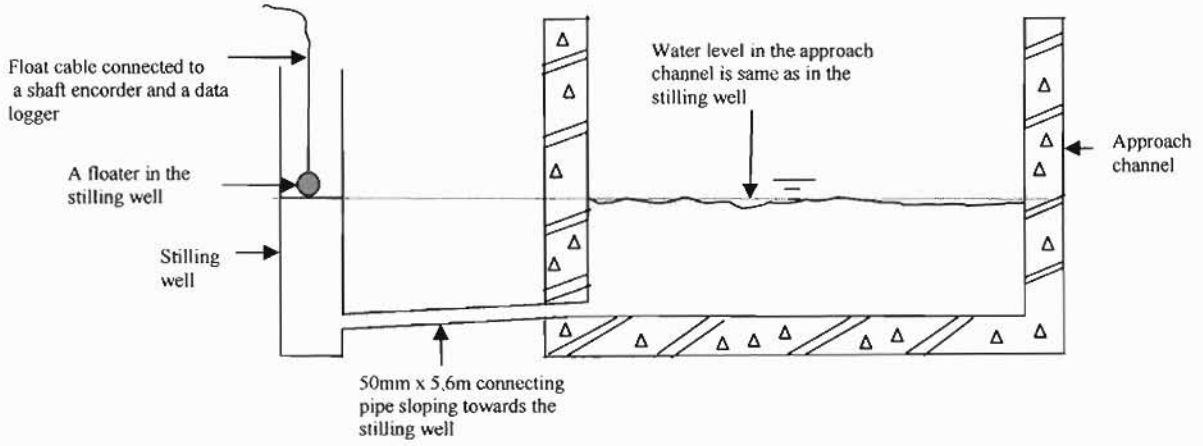

Figure 2.6 A schematic diagram indicating the mechanism for monitoring the approach channel flow depth using a stilling well and float at the Potshini H-Flume. The length and width of the approach channel are 11.5m and 2.7m respectively

Figure 2.7 The operational H-Flume in the Potshini catchment

2.5.7 Monitoring of sediment load and isotopic composition of stream flow

It is always a challenge to obtain a representative water sample in streams at the desired time, for analytical work on water quality. This is compounded by the fact that stream flows emanating from head water catchments of relatively small area in semi arid areas are highly variable, with rapid overland flows and interflows. A good sampling scheme should take into consideration such variations of flow by taking frequent samples during changing flow.

Water quality, e.g sediment load, and isotopic composition, e.g. Oxygen-18 and Deuterium (^{18}O and ^{2}H) of stream flow will show less variation at constant flow and hence less frequent sampling is required. The Potshini H-flume was equipped with an ISCO sampler, with a capacity of 24 sampling bottles of 500ml. The sampler was controlled by a Mike Cotton System (MCS) data logger which recorded the water levels in the stream as described above. The sampling-trigger parameters in the MCS data logger were varied accordingly, depending on the season, to achieve an appropriate sampling scheme in which a sample was only taken if the depth of flow changed by 10mm. During the dry season, and for low and high constant flows, the sampling scheme was set to trigger a sampling event after 7 and 3 m^3 of discharge respectively was recorded to have passed the sampling point. For

the wet summer season, the sample volumes were 15 and 5 m^3 respectively. The Potshini community is actively involved in the catchment monitoring and one person from the community was specifically trained on the operational aspects of the H-flume including the ISCO sampler and always checked the number of samples taken after a rainfall event and subsequently notified the researcher if the number of bottles filled were more than 14. The researcher would then visit the catchment (1h45min drive from campus) and replace the bottles. Most often the researcher was based in the field during the summer seasons and would handle any issues with regard to instrumentation and or sampling accordingly. However, the sampling scheme was revised once in a while, depending on the prevailing flow conditions, to enable objective sampling on both the rising and recession parts of the hydrograph. It is useful to note that the Potshini catchment has a flushy response and hence the need to capture as many samples as possible on the rising limb of the hydrograph. The samples were then analyzed for suspended solids and the isotopic composition of ^{18}O and ^{2}H.

2.5.8 Monitoring of stream flow depth using a pressure transducer

The choice of using any of the stream flow gauging structures depends on a number of factors, one being the geometry of the stream channel at the gauging site. For example, in wide channel sections where the construction of a flume or a weir may not be feasible (e.g due to cost constraints), a cheaper option is to use a pressure transducer to monitor the water levels in the stream accurately and subsequently develop a rating curve for that section after carrying out a detailed survey of the cross-section at the site, applying open channel flow theory and/or conducting flow velocity transects at different discharges. It must be noted that the cross-section must be stable, i.e. not changing with time, for the integrity of the developed rating curve to hold. In the Potshini catchment monitoring network, a pressure transducer together with a HOBO data logger were installed under a culvert bridge approximately 4km downstream from the Potshini H-flume. Sediment load was not monitored at this site due to the existence of small farm-dams on the upstream which were established by the local commercial farmers (Figure 2.3 & 2.4), which in turn trap the sediment load in the stream Thus, the flows at this site were controlled and mostly low flows were observed at this site. The pressure transducer was calibrated by subjecting it to pressure from a gradually increasing column of water, from 0 to 1000mm while recording the output voltage signal from the transducer. A similar exercise was done for a decreasing water column. The calibration equation for the pressure transducer is as indicated in Equation 2.5

$$H = 13.531 + 0.454 * V \tag{2.5}$$

where H is the stream flow depth (mm) and V is voltage output from the pressure transducer (mV). Velocity transect surveys, at different discharges, were carried out across the culvert bridge using a propeller current meter. The concrete culvert bridge had a regular rectangular shape and hence made it easier to apply the Manning's open channel flow equation and subsequent development of the rating curve. As mentioned above, the flows at this section were controlled by the upstream farm-dams and most often the flows recorded at this section were low flows and fairly constant except after big rainfall events that led to spilling of the upstream dams. It is noteworthy that most of the big rainfall events in the catchment occurred at night and hence it was not possible to carry out discharge measurements for the corresponding high flows. The initial discharge measurements were done on discrete days between the year 2005 and 2006. More discharge measurements were done in early 2007 and were incorporated in the computation of the rating curve, with the discharge ranging from 0.01 to 0.27 $m^3.s^{-1}$. A total of 46 measurements were done between 2005 and 2007. Figure 2.8 shows the discharge measurement results and the fitted rating curve at the culvert bridge and which was applied to both high and low flows.

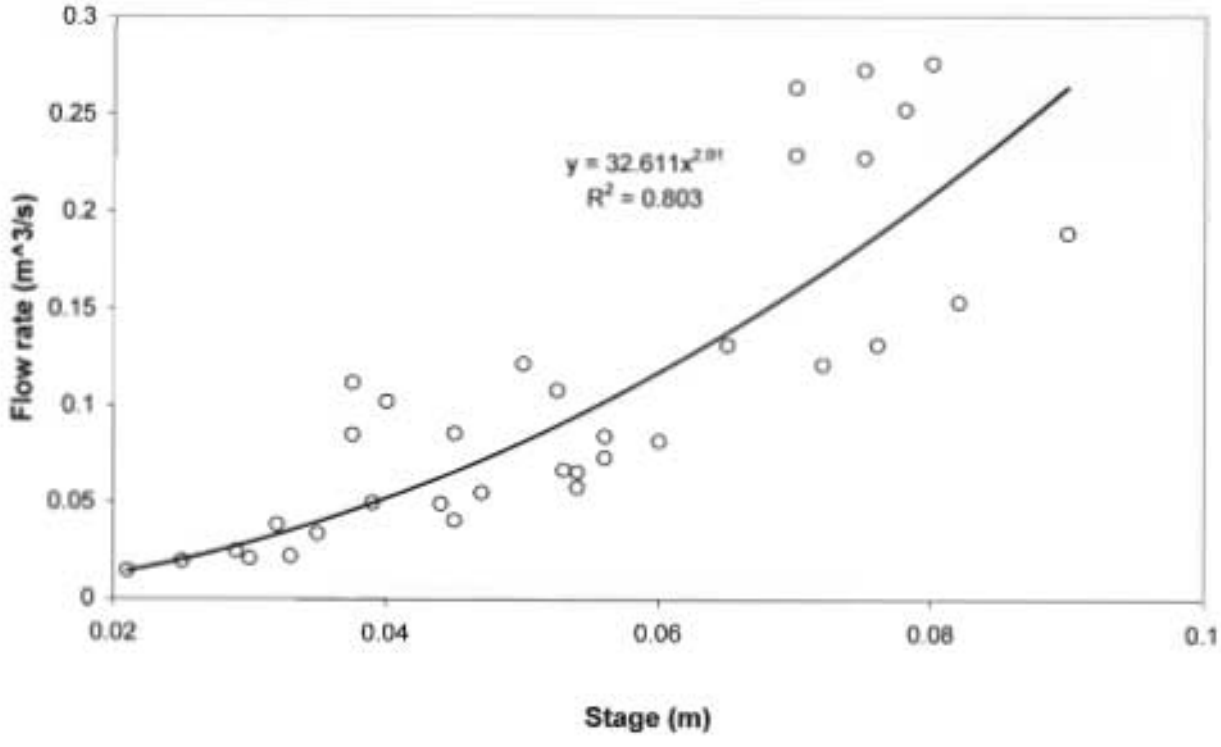

Figure 2.8 Established rating curve at the culvert bridge

Equation 2.6 shows the established rating curve at the culvert bridge.

$$Q = 32.611 * H^{2.01} \tag{2.6}$$

where Q is flow rate in $m^3.s^{-1}$ and H is the stream flow depth (m)

2.5.9 Climatic parameters

Rainfall is clearly the main parameter that drives the hydrological cycle in a catchment, hence the need to observe its occurrence accurately, both spatially and temporally. Manual raingauges, if well managed, can provide relatively accurate daily rainfall data in a catchment and their affordability, availability and the ease of installation and operation makes them attractive, especially to smallholder farmers. After a reconnaissance survey in the catchment, 8 potential sites (homesteads) were identified in the Potshini community for installing manual raingauges and their location is as shown in Figure 2.3 and 2.4. The family members in these homesteads were then approached, beginning with the head of the homestead, to seek permission and the goodwill from the members of the homestead to permit the installation of the manual raingauges and most importantly take daily rainfall readings. A rainfall data recording booklet, translated into the local language-the *IsiZulu*, was given to the identified households and training to record and keep the daily rainfall records was provided. The smallholder farmers recorded rainfall twice a day, i.e. at 09h00 and 17h00, from which the total daily rainfall was computed as the sum of the morning and evening readings. Various individuals and households in Potshini participated by monitoring manual raingauges on a daily basis of which the data was collected on a weekly basis, during the rainfall season, and incorporated in a database for the Potshini catchment. The voluntary participation of the local community in data collection promotes the philosophy of participatory catchment monitoring to the Potshini community as envisioned in the SSI research programme.

Rainfall data from the manual raingauges were augmented by climatic records from two automatic weather stations installed in the Potshini catchment. Each weather station was positioned near a stream flow gauging station (H-flume and the pressure transducer) at a distance of 4 km apart, in the two nested subcatchments. One of the weather stations was installed in 2005 in the midst of the local community (community weather station) and upstream of an existing telemetric weather station which was operational since 2002 on a nearby commercial farm and managed by the Agricultural Research Council (ARC) of South Africa. The parameters that were measured in the two weather stations include rainfall, air temperature, soil temperature, relative humidity, solar radiation, wind-speed and

wind direction. A rainfall *collector* was attached to the automatic raingauge in the community weather station to collect rainwater for analysis of isotopic composition of ^{18}O and ^{2}H. The *collector* comprised six-400ml bottles which filled sequentially during a rainfall event and is designed to prevent evaporation of the collected samples. The community members assisted in taking and labeling of the rainwater samples after a rainfall event and emptied the bottles to allow fresh rainwater samples to fill the bottles during a subsequent rainfall event. Since their installation, each of the two weather stations was maintained by the owner of the commercial farm and the local community respectively. Some of the community members participated in the fencing of the community weather station and maintained tidiness within and on its surroundings. Fencing of the weather station was meant to safeguard the instrumentation against the cattle which graze freely, especially during the winter season. Otherwise the security of the weather station is entrusted to the local community, through the traditional leadership of the community and the goodwill generated by the participatory engagement of the Potshini community and other stakeholders at the initial stages. Recording of climatic data in the two weather stations was done at a time step of 15minutes and 1 hour respectively, and the data has since been accessible to all researchers in the ARC, the SSI programme and any other interested stakeholder.

2.5.10 Runoff plots

A standard runoff plot, as described by the Soil Conservation Services, measures 22.13m long with an appropriate width of greater than 2m on a slope of 9%. Such runoff plots are used in estimating the soil erodibilty factor in the Universal Soil Loss Equation-USLE (Wischmeier and Smith, 1978). One of the research themes in the SSI research programme was aimed at investigating the hydrological processes at field scale (<1 hectare) and hence runoff plots were used for this purpose as controlled micro-catchments. Seventeen runoff plots, under different treatments, i.e, agricultural management practices, were installed in three different smallholder farms (sites *MDU, HA & MA*) and one researcher managed site (*MT*) as indicated in Figure 2.8, on similar slopes, in an effort to carry out water balance studies at the field scale (smallholder farms) and to investigate the influence and impact of different tillage and other innovative agricultural practices i.e water use innovations, on surface runoff generating characteristics and soil moisture in the catchment. Figure 2.9 shows the location of the experimental sites and Table 2.3 shows the number of experimental plots at each site and the description of the treatments on each plot.

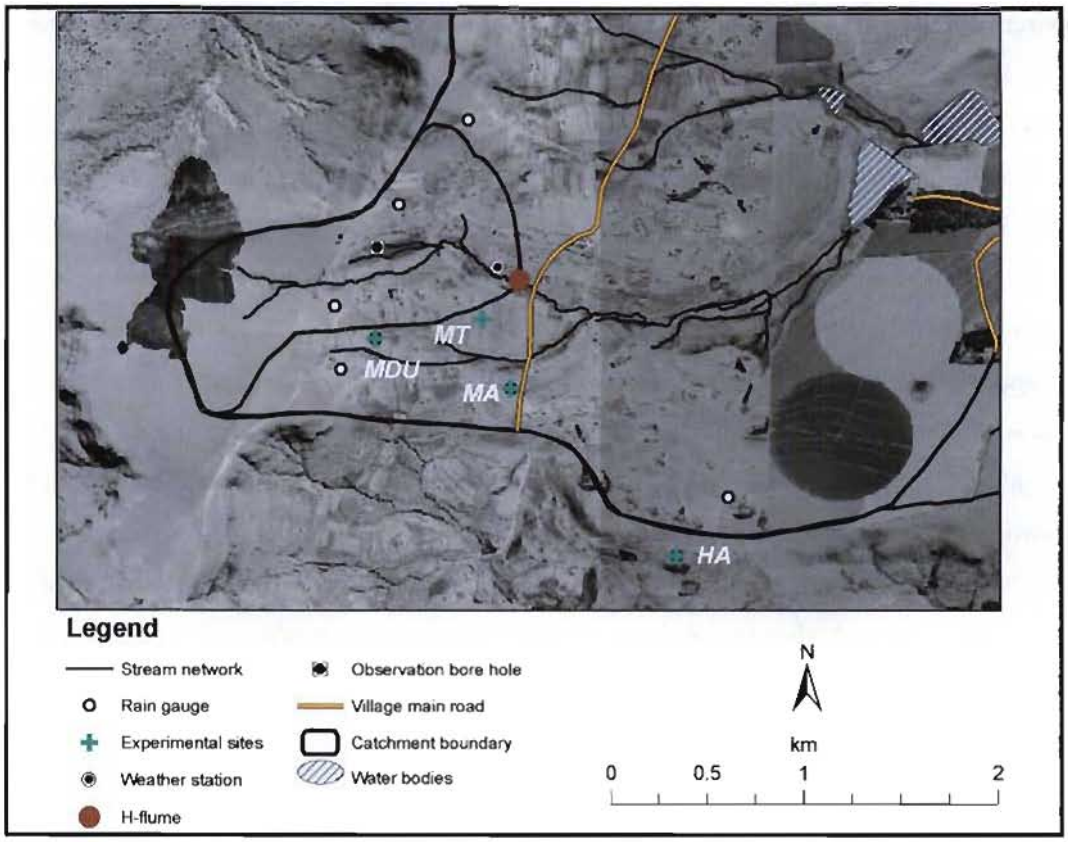

Figure 2.9 Location of the the field experimental sites in the Potshini catchment

The experimental design entailed installing a runoff plot in each conservation and conventional tillage treatments (cf. Table 2.3) in the four sites (three smallholder farms and one researcher managed site- cf. Figure 2.9) and monitoring the surface runoff, volumetric soil moisture content, soil hydraulic characteristics, crop transpiration rates, crop phenological properties and biomass production. Some of the results obtained from this experimental set-up are highlighted in Kongo and Jewitt (2006), i.e Chapter 3 and in Kosgei et al., (2007). There were 17 runoff plots in the catchment, each with an access tube and a tipping bucket for measuring surface runoff (runoff plots). However, site *MT* had 5 runoff plots though the treatments were replicated on another set of plots where only soil moisture was monitored. The 17 runoff plots mentioned and discussed in this thesis, and summarized in Table 2.3, are those on which measurements of soil moisture and surface runoff were carried out. It is useful to note that site *MDU* was established later during the 2005/6 rainfall season and does not form part of the main discussion and or analysis in this thesis. Since late 2005, the four sites *MDU, MA, MT* and *HA* formed the focus of another PhD research, i.e Project 2 in the SSI programme (cf. Figure 1.1), which covered field process studies including evaluation of the potential of water use innovations in improving crop production at field scale.

Table 2.3 Field experimental trial sites in the Potshini catchment

Site ID	Number of plots	Tillage practice (Treatment)	No. of replicates
MT (researcher managed)	5	- Maize + conventional tillage + grazing - Maize + No till + winter intercrop + mulching + fertilizer - Pure maize + No till + grazing + fertilizer - Maize + No till + summer intercrop + grazing + fertilizer - Maize + No till + summer intercrop + mulching + fertilizer	None
MA (farmer managed)	6	- Maize + conventional tillage + grazing - Maize + conventional tillage + grazing + supplemental irrigation - Pure maize + No till + grazing - Pure maize + No till + grazing + fertilizer - Pure maize + No till + grazing + fertilizer + supplemental irrigation - Pure maize + No till + grazing + supplemental irrigation	None
MDU (farmer managed)	4	- Maize + conventional tillage + grazing - Pure maize + No till + grazing + fertilizer (R) - Pure maize + No till + grazing + No fertilizer	1
HA (farmer managed)	2	- Maize + conventional tillage + grazing - Pure maize + No till + grazing + fertilizer	None

The 17 runoff plots were designed while taking into account the rainfall intensities in the area. A runoff coefficient of 0.2 was used to compute the maximum discharge from the runoff plots at the maximum rainfall intensity of the area recorded in the past 3 years, of which was obtained from the nearby ARC weather station. This maximum discharge was then used to estimate the size of the tipping buckets and subsequent calibration of the tipping volumes. Modified USLE runoff plots were installed with dimensions of 10m long and 2.45m wide. It is noteworthy that approach and focus in this study were aimed at investigating hydrological determinats within a runoff plot (a controlled micro catchment) and comparing such results from other runoff plots under different treatments but on

similar slopes of less than 9 percent and hence the use of modified USLE runoff plots. Above all, it was rather difficult to obtain a smallholder farm with all the attributes of a standard USLE runoff plot, especially the 9% slope.

Strips of 0.245m wide galvanized sheet metal were used to demarcate the area of each runoff plot. A fundamental parameter that had to be determined before the installation of the runoff plots was the general slope of individual smallholder farms. This was done through a leveling survey exercise. A contour map for each field where the runoff plots were to be installed, was created and general slopes estimated. These slopes where found to range from 2 to 4%. Four sites were identified for the installation of the 17 runoff plots, three of them being managed by smallholder farmers in the catchment, i.e site *MA, HA, MDU* in Figure 2.9. The fourth site, *MT,* was a controlled researcher managed site where experimental set up and trials, with some of the treatments being similar to the farmer managed trials, were carried out in an effort to compare and validate the results from the farmer managed trials. Figure 2.10 shows a set of runoff plots at the controlled researcher managed site in the catchment while Figure 2.11 shows runoff plots in a smallholder farmer's field (farmer managed trial).

2.5.11 Tipping buckets

The flow rate of overland flow from each runoff plot was measured by use of a tipping bucket (Figure 2.11), which was calibrated to hold 2 litres in each bucket. The knowledge of the rainfall intensities in the catchment was useful in estimating the size of the tipping buckets and subsequent calibration of the tipping volumes. The number of tips was recorded using a HOBO event data logger, secured in a housing (Figure 2.12), and linked to a proxy switch which was triggered at each tip. A manual counter was used as a backup data recording device. A small button-magnet was attached to one side of the tipping bucket, while a stationary proxy switch was fixed to the frame supporting the tipping buckets. As the buckets swing on their axis (oiled bearings), the proxy switch detects the changing magnetic field due to the movement of the magnet on the side of the swinging bucket. The proxy switch then sends a logging signal to the data logger when the button magnet and the proxy switch are in the same axis, i.e when the magnetic field is strongest. This set up eliminates "double counting" when using manual counters as a result of the rebounding action of the buckets.

Figure 2.10 A set of runoff plots in the controlled research site

Figure 2.11 A set of runoff plots under different treatments in a farmer managed trial

Figure 2.12 A flow *splitter* attached to a tipping bucket, showing the five outlet pipes, only one of which drains to the sample tank

2.5.12 Overland flow samplers in runoff plots for water quality analysis

Five runoff plots at the researcher managed experimental site were fitted with semi-automated sediment samplers with the objective of determining the sediment loads from the different agricultural practices under investigation. The sediment samplers consisted of flow splitting containers (flow *splitters*) and a sample storage tank. The flow *splitters*, Figure 2.12, captured the discharge from one side of a tipping bucket (half of the total flow from a runoff plot) during each runoff event. Each *splitter* was fitted with five outlet pipes, as indicated in Figure 2.12, of which only one pipe drained by gravity into a sample holding tank, while the remaining four outlet pipes discharged to waste in a drainage channel. Thus one tenth of the total flow from the runoff plot was captured in the sampling tank. After each runoff event, and after vigorous stirring, 500ml discharge samples were manually taken from the sample tank and labeled by members of the local community for sediment load analysis and composition of stable isotopes of water. The sample tanks are emptied by the members of the community after the sampling exercise to allow fresh discharge to drain into the tanks in subsequent runoff events. The design of the sample collection system involved surveying the terrain of the area near the drainage channel so as to determine the excavation depths and computing the required capacity of the sample tanks. A simple approach was used to determine the tank volumes by assuming

a runoff coefficient of 0.2 and using the maximum daily rainfall event recorded in a nearby manual rain gauge during the prior 3 years, which was 76 mm, and allowing for a 10% freeboard volume.

2.5.13 Soil moisture profiling

Ongoing monitoring of the volumetric soil moisture in the Potshini catchment was implemented using a Time Domain Reflectometry (TDR) method (TRIME-FM, 2003). This involved inserting a TRIME-T3 probe into 42mm access tubes, inserted into the soil profile to convenient depths, and taking volumetric soil moisture content readings at different depths. Several methods have been suggested on how to insert these access tubes into the soil and one of them is by pre-boring holes with appropriate soil augers, of relatively small diameter, and inserting the access tubes into the augered holes. This method was followed in the Potshini catchment. Twenty two access tubes of different depths ranging from 1.2m to 1.5m were inserted in the field experimental sites at the Potshini catchment, and specifically in all the experimental plots under different land management practices (cf. Table 2.3 and Figure 2.9), notably conservation and conventional agricultural practices. It is noteworthy that the 1.2 and 1.5m depths were the depths to which the bored holes for inserting the tubes could be augered to with a relatively small diameter soil auger. A weekly monitoring exercise for volumetric soil moisture content in the Potshini catchment was then established since 2005 where readings were taken at 30cm intervals in all access tubes. The weekly soil moisture data on these experimental plots was complemented with data from Watermark sensors, where a nest of three sensors were installed in all the 17 runoff plots in the catchment at depths of 30, 60 and 90cm and linked to a HOBO data logger with a logging time step of 15 minutes. The Watermark sensors (Allen et al., 2000; Hanson and May, 2006) provide a continuous and indirect measurement of soil matric potential and a calibration exercise, which entailed subjecting the sensors to known soil moisture conditions, preceeded their installations in the field. These sensors are manufactured by the Spectrum Technologies, Inc., USA., and the initial installation of the sensors in the runoff plots was in the year 2006.

2.5.14 Monitoring of shallow ground water

Subsurface flows constitute an important component in developing a water balance for a catchment. In particular, accumulated hillslope seepage forms a shallow ground water table which contributes significantly to the total stream flow. It is therefore important to establish its occurrence, direction of flow and possible flow rates. The shallow ground water in the Potshini catchment is monitored via 12 shallow ground water wells, which were installed through the collaboration and participation of the local community. Since the intensively monitored upper subcatchment (Figure 2.3 & 2.4) is

predominantly an agricultural area for smallholder farmers, permission was sought from the local leaders and individual farmers to allow the augering of the 100mm diameter holes in some of the farms. The holes were drilled, on transects, after a reconnaissance survey, and the wells were strategically installed on sites where they could not interfere with the farming activities since most of the farming operations in the area make use of animal and or tractor drawn implements. Two transects, one on each side of the catchment, were identified and running along the general slope of the catchment. 100mm holes were augered to depths reaching the bedrock or confining layer, but not deeper than 3.5m. 63mm diameter plastic pipes of appropriate lengths were inserted into the augered holes so that at least 0.4m length of the pipe protruded above the ground surface. The pipes have thin horizontal slots machined through the pipe over their bottom 0.6m so that the shallow ground water level could be recorded in the well. To avoid clogging of the slotted perforations by the fines and clay at the bottom of the wells, a clean (washed) sand screen was packed around the outer annulus of the plastic pipes, covering the perforations to a height of 0.8m from the bottom of the wells. For each well, the rest of the well's depth was filled with the previously augered soil material save for the top 0.3 m, where cement mortar was cast around the 63 mm plastic pipe before a 0.4 m concrete slab was cast at the top to a level slightly above the ground surface. Such cement mortar and concrete works prevent preferential flows down the external wall of the pipe when the soils are saturated during wet seasons. Pressure transducers were then installed in 8 of the shallow ground water wells, after a calibration exercise, and linked to HOBO data loggers which recorded the fluctuation of the water table at a time step of 30 minutes. The data loggers and their respective power batteries were secured in metallic safe boxes embedded in concrete to safeguard the data loggers from unfavorable weather conditions. The other 4 shallow ground water wells were used to sample the shallow ground water for composition of stable isotopes of water. Table 2.4 summarises the observation shallow ground water installation data. The layout of the 12 shallow ground water wells in the Potshini catchment is as shown in Figure 2.4.

2.5.15 Monitoring of deep ground water

Through funding from the Department of Water Affairs and Forestry (DWAF), and in collaboration with the local community to identify the optimal sites, two deep ground water observation well sites were identified and subsequently sunk in the Potshini catchment. One of the wells (100m deep) was to supply water to the local community for domestic use while the other (120m deep) was dedicated to research purposes under the ongoing SSI research programme. It should be noted that DWAF is one of the main stakeholders of the SSI research programme and is supportive of the SSI research themes especially on hydrological studies and institutional development on water resources management.

Table 2.4 Summary of the shallow ground water wells and their installation characteristics

Well ID	Position from the stream	Column of water during installation (m)	Total depth of the shallow ground water well (m)	Altitude (masl)	Soil textural class
PRB1	1st, right bank	2.12	3.22	1308	Sandy loam
PRB2	2nd, right bank	1.98	3.32	1309	Clay loam
PRB3	3rd, right bank	1.24	2.84	1316	Loam
*PRB5**	4th, right bank	0.52	3.38	1318	Loam
PRB4	5th, right bank	0.63	3.38	1324	Loam
*PRB6**	6th, right bank	0.1	3.2	1334	Sandy loam
PLB1	1st, left bank	2.06	3.32	1308	Sandy loam
PLB2	2nd, left bank	1.86	3.46	1313	Loam sand
PLB3	3rd, left bank	2.1	3.41	1315	Loam
*PLB5**	4th, left bank	1.35	3.21	1323	Sandy loam
PLB4	5th, left bank	2.08	3.38	1328	Sandy loam
*PLB6**	6th, left bank	0.64	3.32	1335	Sandy loam

*PLB5**: Wells not automated and are mainly used for sampling shallow groundwater for isotopic composition of Oxygen-18 and Deuterium

It is noteworthy that there exist five domestic water supply wells (greater than 50m deep) in the Potshini community, previously sunk by the local authorities, and these complemented and expanded the spatial coverage of monitoring deep ground water in the catchment including monitoring for the stable isotopes of subsurface water. The monitoring of the deep ground water was to contribute towards closing of the gap in defining the various components of the hydrological cycle in the catchment. The continued support and collaboration with the Department of Water Affairs and Forestry facilitated a sustainable monitoring programme of the deep ground water in the Potshini catchment, as part of an ongoing DWAF initiative to monitor ground water in the larger Thukela river basin (Mkidze, 2006). DWAF was to continue monitoring the deep ground water in the Potshini catchment after the end of the ongoing SSI research programme. Figure 2.13 shows the borehole log information for the 120m deep ground water observation well in the Potshini catchment.

Figure 2.13 Borehole log information including the lithology, grain size and colour for a 120 m deep observation ground water well in the Potshini catchment

2.5.16 Electrical Resistivity Tomography (ERT) survey

The geophysical Electrical Resistivity Tomography (ERT) techniques are non-destructive techniques that provide a pseudo-section of apparent or effective resistivity of the subsurface. These pseudo-sections are then inverted to provide an interpretation of the actual resistivity distribution in a 2D section of the subsurface. More literature on the description, theory and practical application of ERT is highlighted in Loke (2003). The 2-D Electrical Resitivity Tomography (ERT) surveys in the Potshini catchment were carried out with the objective of characterizing the occurence of subsurface water. The method is useful both as a means of rapid site reconnaissance that can provide information on the subsurface structures and facilitates the extrapolation of observed data, e.g observed ground water levels, between observation points. This can only be done where sufficient site correlations have been established between the observed data being extrapolated and the information derived from the geophysical survey. The ERT methodology, as applied in the Potshini catchment, is aimed at augmenting and up-scaling the monitoring of the point-shallow ground water in the Potshini catchment using shallow ground water wells to a relatively larger spatial extents and depths. Six transects in the catchment were identified for the ERT survey; 2 of which coincided with the shallow ground water well transects on the right and left bank of the stream as indicated in Figure 2.14. Resistivity surveys were carried out in collaboration with the local community where permission was

sought from the local leaders and individual owners of the parcels of land where the survey transects were to pass through. The resistivity meter that was available for this research study was the ABEM Terrameter© system with four cables of 100m long.

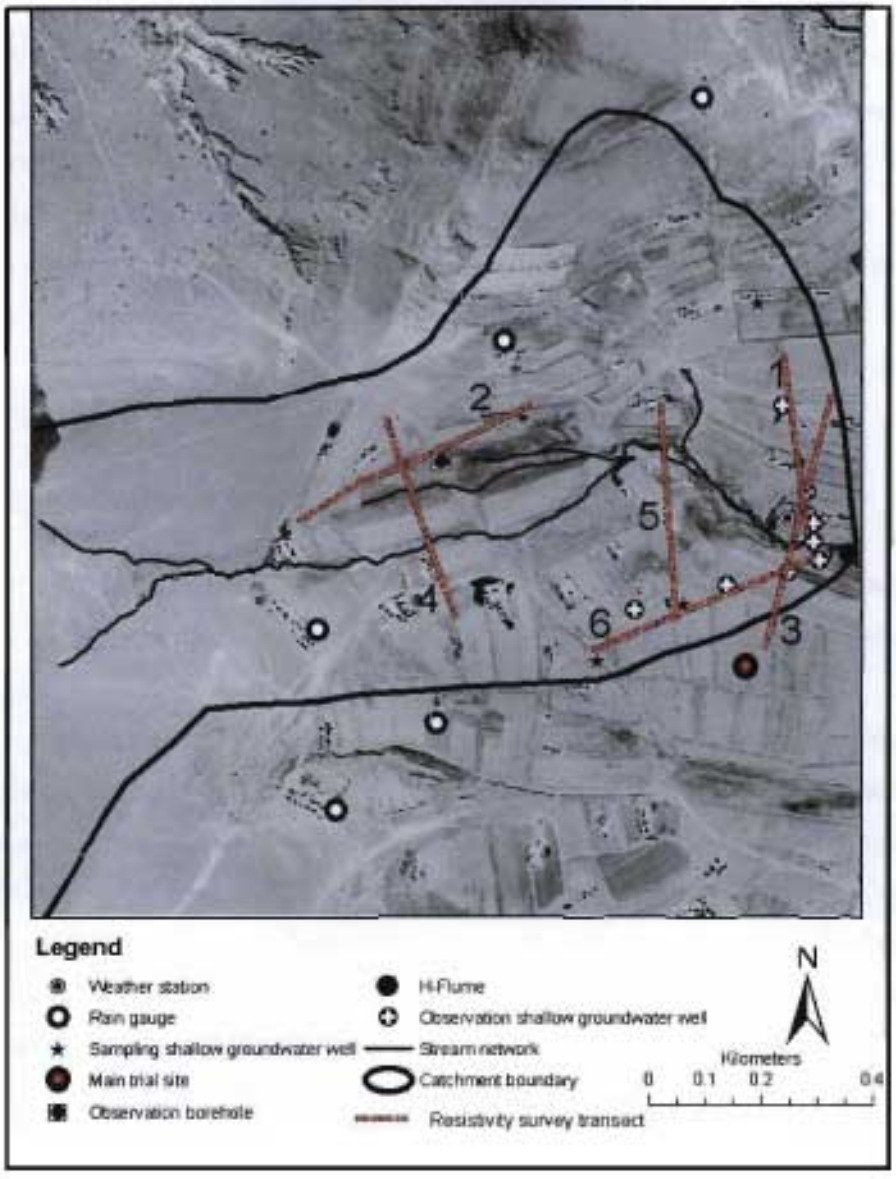

Figure 2.14 Location of resistivity survey transects in the Potshini catchment

Most of the smallholder farmers were eager to have the ERT survey transects passing through their farms so that they could get to know the sub-surface profiling of their farms, especially the occurrence of ground water. In an effort to characterize the hydrological processes in the catchment over seasons,

the resistivity survey was scheduled to be carried out during the wet and dry season of each year. During the initial ERT surveys, an electrode spacing of 1 and 5m was used for mapping shallow (<10m) and deep (up to 60m) subsurface resistivites respectively. Each transect was 400m long and a total of 81 electrodes were used. The Wenner Log protocol, which is sensitive to vertical changes in the subsurface resistivity (Loke, 2003) was used in the survey exercise. The resistivity survey was also aimed at identifying potential sites for sinking 2 deep observation ground water wells in the catchment in collaboration with the Department of Water Affairs and Forestry as described in Section 2.5.15 of this thesis. The resistivity sections were computed using the RES2DINV software, applying the 2-D inverse numerical modelling technique and optimized using standard Gauss-Newton methods. Relative elevation data for each electrode on each transect was included in the modelling exercise to account for the effect of topography on the occurrence of geological features (resistivities) along the respective transects.

2.5.17 Monitoring of total evaporation using a Large Aperture Scintillometer

According to Rockström (1999), in semi-arid tropical agricultural areas, direct Evaporation *(E)* from the surface generally accounts for 30–50% while transpiration *(T)* accounts for only 15–30% of total rainfall. Total evaporation *(ET)* is highly variable over time and space and any effort towards enhancing the ability to confidently quantify it at large spatial scales is recognized as an important contribution in water resources management. As highlighted in Chapter 5 and 6 of this thesis, the challenge in determining the spatial and temporal variation of *ET* over large areas is compounded by the many factors that influence its occurrence and prevalence and hence make it the most difficult parameter to determine in hydrology. The conventional approaches for quantifying *ET* have been based on localized point measurements which do not allow for flux estimation over large geographical areas. These approaches include direct measurements (evaporation pan, Lysimeters etc.), climatic stations (Penman-Monteith etc.) and hydrological models (water balance).

The Large Aperture Scintillometer (LAS) is an instrument that measures the turbulent intensity of the refractive index fluctuations of air from the intensity fluctuations of a received signal (Kohsiek and Herben, 1983; Andreas, 1989; Hill, 1992; Cain et al., 2001). This signal is transmitted by a light source placed at a set distance apart (typically less than 10 km). Figure 2.15 shows the receiver station of the Large Aperture Scintillometer at the Potshini catchment. At the receiver the spatial turbulent intensity is measured as a refractive index structure parameter C_n^2 ($m^{-2/3}$) which can be related to the structure function parameter of temperature C^2_T ($K^2.m^{-2/3}$). The latter can be converted to sensible heat

flux using the Monin-Obukhov Similarity Theory (MOST) as described by de Bruin et al., (1993), with additional data on temperature, pressure and humidity. With known net radiation (obtained from net radiometers in weather stations) and soil heat flux (obtained from field soil heat flux measurements), the latent heat flux can be computed as a residual in the energy balance equation as indicated in Equation 2.7.

$$\lambda E_f = R_n - H - G \tag{2.7}$$

where λE_f is the latent heat flux ($W.m^{-2}$), R_n is the net radiation ($W.m^{-2}$), H is the sensible heat flux ($W.m^{-2}$) and G is the soil heat flux ($W.m^{-2}$). The total evaporation can then be computed from the latent heat flux.

Figure 2.15 The receiver of the Large Aperture Scintillometer in one of the homesteads in the Potshini catchment

The measurement of total evaporation in the Potshini catchment using scintillation techniques (Meijninger, 2003) started in April 2006 and continued until early 2007, though the exercise was occasionally interrupted after the LAS was damaged by lightning strike, especially during the wet summer season, and it took a while to get the instrument repaired due to technical and logistical

problems. The frequency of measurement with the LAS was every minute and the instrument was left in the field throughout the measurement period. The installation and siting of the LAS was done in collaboration with the local community in the Potshini catchment. Both the transmitter and the receiver were stationed at homesteads in the community, and the owners volunteered to maintain and guard the respective instrumentation. Nevertheless, it is useful to note that the whole community was involved during the initial stages of installing the LAS through community meetings which were mobilised by the local leadership. As was the case with other installations in the catchment, the goodwill of the community was sought with regard to the safety and security of this state of the art instrument.

2.5.18 Remote sensing

There are many applications of remote sensing in water resources management including hydrogeologic mapping, landuse change studies, estimation of total evaporation, mapping and monitoring of wetlands etc. The main application of remote sensing, as reported in this thesis, is the estimation of total evaporation in the Potshini catchment and the Thukela river basin using energy balance methods. The Surface Energy Balance Algorithm for Land (SEBAL), (Bastiaanssen et al., 1998a; Bastiaanssen et al., 1998b; Bastiaanssen, 2000) was applied and validated in the Potshini catchment and Thukela river basin using scintillation techniques as described in detail in Chapter 5. As highlighted in Chapter 3, i.e Kongo and Jewitt (2006), SEBAL was initially applied in the Potshini catchment and beyond using Landsat-TM data and subsequent analysis was to be carried out using the freely available satellite data indicated in Table 2.5. SEBAL is an energy partitioning algorithm comprised of twenty-five computational sub-models that calculate *ET* and other energy exchanges at the earth's surface. The algorithm computes most essential hydro-meteorological parameters from a satellite image and requires limited ground based meteorological data (Farah and Bastiaanssen, 2001). Only incoming solar radiation, air temperature and wind speed data are required. SEBAL estimates *ET* as the residual of an energy balance (similar approach as in the scintillation technique) applied to the land surface for each pixel of the satellite image. The application of the scintillation techniques in estimating total evaporation in the catchment forms an intermediate observation and calibration scale for the SEBAL estimates in the catchment and beyond. One of the intermediate outputs of SEBAL is the sensible heat flux, estimated on each pixel of a satellite image. Given the fact that Scintillometers measure sensible heat flux along transects, then, it is possible to compare the SEBAL pixel estimates of sensible heat flux with the scintillometer measurements for pixels overlaying the transect length on condition the transect is within a pixel of a satellite image as highlighted in Chapter 5. Table 2.5 indicates some of the potential satellite data available for the SEBAL analysis in the ongoing study.

Table 2.5 Satellite data for SEBAL analysis in the Potshini catchment

Imager	Temporal resolution	Spatial resolution (m)	Archive data	Availability
Landsat -TM	8 or 16 days	30	Since 1982	Classified
MODIS	Daily	250, 500, 1000	Since 1999	Free
ASTER	15 days	15	Since 1999	Classified
NOAA(AVHRR)	Daily	1000	Since 1980	Free

2.6 Conclusions

Catchment monitoring is fundamental to understanding the occurrence and interaction of various dominant hydrological processes in a catchment. Using this understanding, researchers formulate catchment responses which aid in water resources management. This Chapter has highlighted and underscored the importance of applying Participatory Research techniques in hydrological research studies where other stakeholders are involved. The feedback process where various stakeholders were updated on the research activities including visual interpretation of the data collected from the catchment monitoring network proved to be a useful tool in instilling a sense of ownership to the local community while the other stakeholders appreciated their contribution and participation in the SSI research programme thus enhancing sustainability of the catchment monitoring initiative in the community.

The experience drawn from establishing the catchment monitoring network in Potshini, a rural community in Bergville District in South Africa, has proved that there are more opportunities and gains (both material and ideas) to benefit from involving other stakeholders. In particular, the establishment of the goodwill of the local community in Potshini has avoided problems of vandalism or theft that have plagued several research catchments in South Africa and other parts of the world. The level and stage of participation of each stakeholder differs but ultimately contributes to the success of such a process. The Potshini catchment monitoring network has several permanent structures and instrumentation which will benefit other researchers for a long period of time. The structures and instruments have been installed in individual farms belonging to willing smallholder farmers in the Potshini community. A number of the farmers volunteered to monitor some of the

hydrological processes and take readings accordingly. The traditional leadership in Potshini agreed to host and support the SSI research programme and the local leaders (elected) facilitated, to a great extent the linking of the SSI researchers to the local municipality officials while the extension personnel from the Department of Agriculture in Bergville District and the ARC-Landcare project in Bergville played a key role in linking the SSI research programme with other similar projects and stakeholders in the Bergville district and beyond.

Furthermore, it has been shown that the participation of a local community in a hydrological monitoring programme need not compromise the quality of the scientific endeavour nor the level of sophistication of the instrumentation used. The participatory process of establishing the Potshini catchment monitoring network has emerged as a positive impact to the local community and other stakeholders with regard to appreciating the research findings and above all, the ability to sustain the goodwill of the local community in safeguarding the instruments and structures comprising the network.

3.0 Catchment hydrology in response to agricultural water use innovations: a case study of the Potshini catchment-S. Africa

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Preliminary investigation of catchment hydrology in response to agricultural water use innovations: A case study of the Potshini catchment – South Africa

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Abstract

Water use system innovations encompass various techniques for storing and conserving water resources in different mediums for domestic and livestock use including agricultural production. Although, several authors have indicated that rainwater harvesting techniques, especially for upgrading smallholder farming systems, are not new but have been practiced since ancient civilizations, the impacts of such water use innovations on eco-hydrological systems are rarely assessed, especially from a cascading spatial and temporal perspective. The need to quantify the supposedly potential and related hydrological impacts of water use innovations on a catchment and river basin at large, led to the on-going research study aimed at investigating the biophysical consequences at different spatial and temporal scales in the Thukela river basin, of increased productivity in smallholder rainfed agriculture enabled through adoption at larger spatial scale of integrated land use management and water use system innovations. In this paper we discuss and outline the approach used in setting up the research study in one of the catchments in the Thukela river basin, the Potshini catchment, in the KwaZulu-Natal Province of South Africa in an effort to seek answers to the question: "What is the impact of adapting water use innovations in a predominantly agricultural area on catchment ecology and hydrology?" The approach incorporates a catchment monitoring network, hydrological modelling and application of a remote sensing technique, the Surface Energy Balance Algorithm for Land (SEBAL), for spatially estimating the total evaporation in the region covering the Potshini catchment and beyond. Preliminary results indicate that water use innovations in the Potshini catchment have influenced the partitioning of rainfall, by significantly reducing surface runoff over agricultural lands under conservation tillage practices, with a reduction of above 100%, while encouraging infiltration and deeper percolation into the soil. It is envisaged that, on accomplishment, the study will contribute to formulation of sustainable adaptation of water use innovations and up-scaling strategies to enhance food production and hydro-ecological balance in semi-arid savannahs of Africa, at which stage hydrological modelling will form an important part of the study.

Keywords: Water use innovations; Smallholder farming; Rainfed agriculture; Remote sensing; SEBAL

1. Introduction

The hydrological response of a catchment, as used in this context, can generally be defined as the reaction of a catchment to rainfall. Every catchment has a specific response to rainfall and which is related to hydro-climatological and physical characteristics, such as soil parameters, slope, climate, etc. Some of the catchment characteristics can be obtained through measurements at specified spatial and temporal scales depending on their frequency and nature of occurrence, and the required resolution of data for meaningful analytical work when addressing questions related to catchment response. There are several factors that may influence a catchment response and can broadly be identified with change in land use/cover and climatic

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change (Costa et al., 2003). The influence or impact of climate change to catchment hydrology may not be depicted within a short term, as emerging trends of catchment response as a result of climate change may indicate randomness rather than systematic pattern as compared to land use change. It is important to note that causes of climate change are often not localized as compared to land use change, and thus making it easier to monitor and investigate impacts of land use changes on the hydrological regime of a catchment, and possibly impacts of the same to the downstream ecosystems as envisioned in the ongoing research study.

Such an investigation and analysis can be achieved through establishing a catchment monitoring network, a task that was accomplished at the Potshini sub-catchment in the foothills of the Drakensberg Mountains under the ongoing research programme, the Smallholder Water System Innovations (SSI) at the University of KwaZulu-Natal (Rockström et al., 2004) The SSI research programme has the general objective of assessing the extent to which water management in rainfed smallholder farming can assist in securing human livelihoods in semi-arid tropical savannahs in sub-Saharan Africa, together with trying to analyse the downstream hydrological implications of upgrading rainfed agriculture through adoption and adaptation of water use innovations, e.g. rainwater harvesting. Fig. 1 provides an overview of the Thukela river basin and the Potshini catchment. The Potshini catchment monitoring network facilitates the monitoring of the main hydrological processes in a predominantly agricultural catchment whilst recognizing the existing heterogeneity within the catchment.

Heterogeneity exists at any scale under consideration and it is a great challenge to hydrologists and water resource managers to uniquely define and quantify various hydrological processes in a catchment and establish the link between such processes and scales, both spatial and temporal. Such a challenge is further convoluted by the existence of a link between variability of hydrological processes and heterogeneity of the catchment (Jewitt and Gorgens, 2000). This paper highlights the design and implementation of the field data collection programme, the importance of involving the local community in the process and preliminary research findings from the Potshini catchment, and in specific, a comparison of overland flow and volumetric soil moisture content from runoff plots installed in the catchment under different land management practices.

1.1. The study area

The Potshini catchment is predominantly a smallholder farming area and a sub-catchment of the South Africa Quaternary Catchment (QC) number V13D (Emmaus catchment) in the Thukela river basin in the foothills of the Drakensberg Mountains. The Potshini catchment is located in the Bergville District in the KwaZulu-Natal Province of South Africa. Fig. 1 shows the location of Thukela river basin together with the stream network at the Potshini sub-catchment.

The Thukela river basin has an area of 29,036 km^2, while the area of QC V13D and Potshini sub-catchment are 280 and 1.2 km^2 respectively. Potshini is at an altitude of about 1250 m above sea level, and with the mean annual precipitation estimated to be 700 mm/yr and mean annual potential evaporation between 1600 and 2000 mm/yr (Guy and Smith, 1995; BEEH, 2003). The mean annual temperature ranges between 16 and 18 °C. Frost is severe to very severe during winter (May to August) and hail is sporadically severe in summer (September to April). Fig. 2 shows

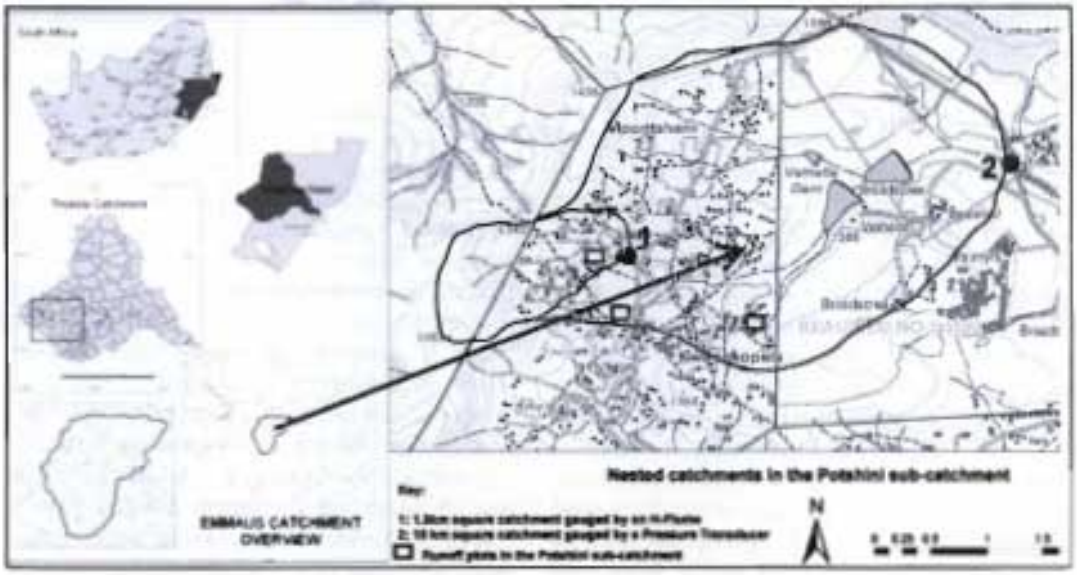

Fig. 1. An overview of the Thukela river basin and the Potshini sub-catchment.

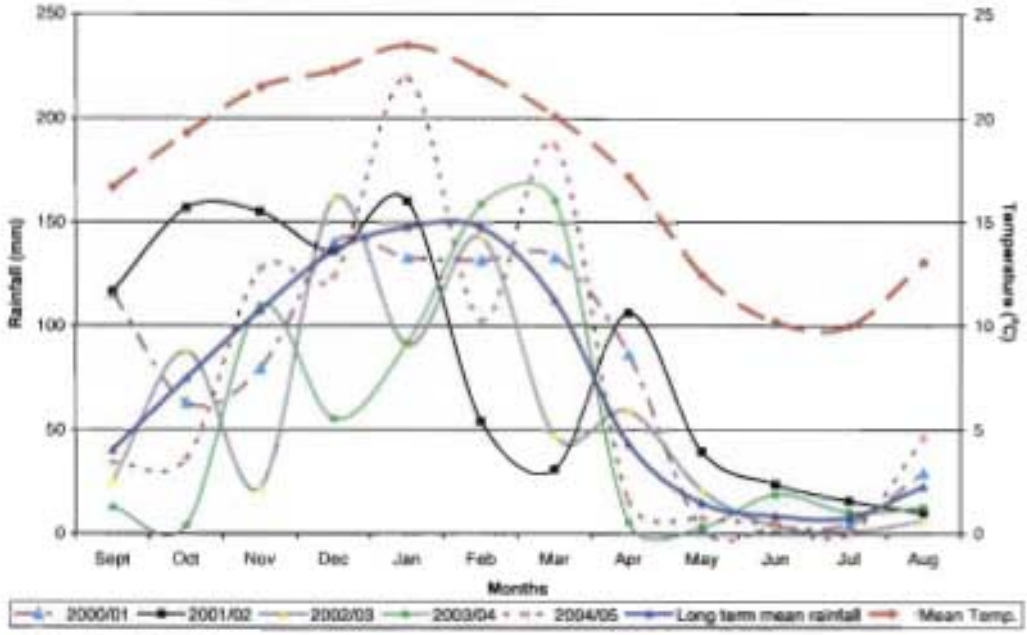

Fig. 2. Monthly variation of rainfall and temperature from a weather station in the Potshini catchment from 2000 to 2005. The long term mean monthly rainfall and temperature was derived from a 28 year climatic data record from a nearby weather station in Bergville.

monthly variation of rainfall and temperature in the Potshini catchment.

Due to the hilly terrain, a good drainage network has developed in the Potshini sub-catchment with most of the streams being perennial and providing water for domestic use to the upper part of the catchment, and replenishing reservoirs for commercial farmers downstream. Extreme low flows occur in winter. The main river, which drains the Quaternary Catchment V13D, is the Lindequespruit, a tributary of the Little Thukela which later joins the Thukela river. The Potshini catchment has a relatively high water table ranging from 1.5 to 2.4 m below the surface (Kongo et al., 2005), with two perched aquifers on the upper and middle parts of the catchment. The soils in the Potshini catchment are generally acidic with varying depths from 1.8 m to over 3 m on the lower parts of the catchment. Smith et al. (2001) cited Turner (2000) as having described the geological formation underlying the region around the Potshini catchment to have sandstone and mudstone of the Tarkastad Formation, Beaufort Group and by shale and sandstone of the Estcourt Formation, Beaufort Group. The Tarkastad Formation is described as comprising fine to medium grained yellow and grey sandstone and maroon (red) to green and blue mudstone. The Estcourt Formation is described as comprising dark grey shale (often carbonaceous), siltstone and fine and medium to coarse sandstone. According to Turner (2000), the major soil patterns that are evident and associated with the sandstone and mudstone of the Tarkastad Formation are the red and yellow–brown apedal and the plinthic soil patterns. The dystrophic sandy loam and sandy clay loam soils are dominant in the Tarkastad Formation, of which the red clay soils (Hutton Soil Form) forms an integral part of this soil pattern and probably derived from dolerite, and hence associated with the sandier soils developed from the sandstones and mudstones of the Tarkastad Formation. The plinthic soil pattern predominantly comprises mesotrophic Avalon soils. Pinedene, Clovelly and Oakleaf soils are also present, with a proportion of dystrophic soils. Seven major soil patterns are evident in the soils derived from the dark grey shale, siltstone and sandstone of the Estcourt Formation. Two of these soil patterns comprise soils with major agricultural importance in terms of dry-land crop production. The first is red and yellow apedal soil pattern with Hutton, Griffon and Clovelly soils dominant. Katspruit, Mispah and Glenrosa soils are subdominant. In the plinthic soil pattern, Avalon, Glencoe, Longlands, Wasbank and Westleigh soils are present together with Mispah, Glenrosa, Cartref soils and rock land.

The main land use types in the Potshini catchment include the smallholder farming (crop production) during summer, which constitutes approximately 80% of the total land in the catchment, and grazing. It is useful to note, during winter, all the domestic animals (cattle and goats) are freed to graze on the smallholder farming land due to depleted pastures on the secured grazing lands on the upper slopes of the catchment. Due to the need to intensify agricultural production in the area for food security, various agricultural management practices have been adapted in the Potshini sub-catchment through the South African National Landcare programme in the Bergville District, notably conservation agriculture (a water use innovation). There is a great potential for adoption of such practices in

the area due to the successful results obtained so far where smallholder farmers have managed to increase their crop production per unit area by appreciable margins (Smith et al., 2004). The farmer-to-farmer participatory learning process, a participatory action research approach introduced in the area by the Agricultural Research Council (ARC), the implementing agency of the National Landcare programme in the Bergville District has been highly successful in achieving the uptake of new techniques, notably conservation tillage practices, by the local farmers. The challenge is to quantify the impact of such novel water management strategies on the eco-hydrological system of the catchment with regard to their up-scaling to larger areas and wider adoption. This is the challenge which the ongoing research study is trying to address.

1.2. Water use innovations

According to Pandey et al. (2003), water use innovations are not new, but have persistently been developed and adopted by mankind as an adaptation to climate variability since ancient civilizations. These innovations are either locally inspired or adapted from other regions. In the past few decades, efficient communication networks have greatly influenced and enabled technology transfer and hence adaptations of water use innovations in various regions of Africa. Water use innovations encompass various methods and strategies for mitigating drought in an effort to sustain livelihood. These innovations are typically water harvesting techniques for concentrating, storing and collecting surface runoff in different mediums, for domestic or agricultural uses. Runoff can be collected from roofs or ground surfaces (rainwater harvesting) as well as from seasonal streams (flood water harvesting). The various methods for harvesting runoff can be distinguished after the following (Rockström et al., 1999; Rockström, 2000):

- Source of the surface water (external or within-field catchments from sheet, rill, gully or stream flow).
- The method of managing the water (maximising infiltration in the soil, storing water in tanks/dams, inundating crop fields with storm floods).
- The use of water (livestock, households, crop production and erosion management).

According to Rockström (2000), water harvesting practices generally contribute to an increase in the recharge of water to the root zone and finally to the water table and operate at different scales (household, field, catchment and basin). Such practices have the potential to affect water availability and management for downstream water users and natural ecosystems due to reduced catchment water yields. Rockström (2000) cited SSSA (1987) as having defined conservation tillage as any tillage sequence with the objective of minimizing the loss of soil and water, and having an operational threshold of leaving at least 30% mulch or crop residue cover on the surface throughout the year. Conservation tillage aims at reversing a persistent trend in farming systems of reduced infiltration due to compaction and crust formation, and reduced water holding capacity due to oxidation of organic materials (due to excessive turning of the soil). From this perspective, conservation tillage qualifies as a form of water harvesting (and hence a water use innovation), where runoff is impended and soil water is stored in the crop root zone (Rockström et al., 1999). Conservation tillage covers a range of non-inversion practices from zero-tillage to reduced tillage which aim to maximize soil infiltration and productivity, by minimizing water losses (evaporation and surface runoff) while conserving energy and labour. GHARP (2002) indicated the successes of conservation tillage in harnessing rainwater and improving yields (more than 50%) particularly in Machakos and Laikipia districts of Kenya.

1.3. Measurement of components of the hydrological cycle

In order to achieve an in-depth understanding of the hydrological regime and the likely hydrological impacts of Water Use Innovations in the Potshini sub-catchment, it was imperative to establish a catchment monitoring network in the Potshini catchment. This comprises gauging structures and instruments, most of them automated, for measuring stream flows, sediment load, runoff generated from runoff plots, shallow ground water table, volumetric soil moisture content, soil moisture wetting front, soil infiltration rates, crop transpiration rates, and meteorological parameters. The establishment of the Potshini monitoring network was achieved through a participatory process where the local community was involved and engaged as a key stakeholder in the research study. Such a participatory process has the unique advantage of capacitating the local communities to assess, monitor and manage water and environmental resources in the catchment in a sustainable way. This is not withstanding the setting of a precedent in enabling a conducive environment for further and future research in the catchment through establishing cordial relationship with the local leaders and the community at large. It is important to note that all the instruments and structures installed in the Potshini catchment have been maintained and safeguarded through the goodwill of the local community. The description of the main components of the Potshini catchment monitoring network is described below.

1.4. Climatic parameters

An automatic weather station was installed in the Potshini sub-catchment (in the midst of the local community) upstream of an existing telemetric weather station which has been operational since 2002 on a nearby commercial farm. Each weather station is positioned near a stream flow gauging structure and at a distance of 5 km apart, in two nested catchments of 1.2 and 10 km^2 respectively as indicated in Fig. 1. Eight manual rain gauges were installed in the 1.2 km^2 catchment to capture the spatial variation

of the rainfall over the entire Potshini sub-catchment. Such an effort was necessary due to the fact that rainfall is one of the main parameters that drives the hydrological cycle and because of its variability over small spatial scales there is a need to accurately estimate its occurrence, both spatially and temporal. Manual rain gauges, if well managed, can provide relatively accurate daily rainfall data in a catchment and their affordability, availability and the ease to install and take readings makes them attractive especially to smallholder farmers. The fact that an individual has to take readings from a manual rain gauge on a daily basis promotes the philosophy of participatory catchment monitoring to the Potshini community where eight smallholder farmers are voluntarily recording daily rainfall from manual rain gauges installed in their farms/homesteads. Each manual rain gauge was accompanied by a rainfall data recording booklet which was translated into the local language, the *IsiZulu*. The recording of rainfall is being done twice a day, i.e at 9 h and 17 h, from which the daily average rainfall can be computed as the average of the morning and evening readings. The daily rainfall data collected provide an invaluable supplement to the data gathered from the two automatic weather stations.

1.5. Stream flow measurements

Stream flow at the Potshini sub-catchment is monitored at two locations by use of an H-flume and a Pressure transducer coinciding with the nested catchments of 1.2 and 10 km^2 respectively. The H-flume was constructed by the SSI project team and the downstream pressure transducer makes use of a regular section of a river associated with a road culvert. Voltage signal measurements of the pressure transducer are logged after every 5 min in a data logger and the acquisition of the stream flow data involves the translation of the output voltage signal of the pressure transducer into stream flow depths using a rating curve for that section. The H-flume has a discharge capacity of 3.34 m^3/s and governed by a set of three rating equations, each describing a unique stage-discharge relationship for a given range of flow depth (Ackers et al., 1978) corresponding to high, low and intermediate flows. The design of the H-flume is described in detail in Kongo et al. (2005). The H-flume is also equipped with an ISCO sampler for water quality analysis with a capacity of 24 sampling bottles and which is controlled by an MCS data logger. The sampling scheme has been programmed to take into account the variation of flow by taking frequent samples during a changing flow. This is due to the fact that water quality (e.g. sediment load) will show less variation at constant flow and hence less frequent sampling is required at constant flow.

1.6. Runoff plots

A standard runoff plot, as described by the Soil Conservation Services (SCS), measures 22.13 m long with an appropriate width of greater than 2 m on a slope of 9%. Such a runoff plot is used in estimating the soil erodibilty factor in the Universal Soil Loss Equation-USLE (Wischmeier and Smith, 1978). However, the 9% slope is rarely achieved especially in agricultural fields, as was the case in this study. The approach and focus in this study was on investigating hydrological processes within a runoff plot (a controlled micro catchment) and trying to compare such results from other runoff plots under different treatments but on similar slopes. This approach was adopted in the design of 11 runoff plots which were installed in the Potshini sub-catchment, in an effort to investigate the influence and impact of conservation agriculture practices, i.e. water use innovations, on surface runoff generating characteristics and soil hydraulic properties in the predominantly agricultural catchment. Fig. 3 shows a set of runoff plots on an experimental station in the Potshini sub-catchment, while Fig. 4 is a tipping bucket with a data logger attached to it for automatic recording of surface runoff intensities from

Fig. 3. A set of five runoff plots on an experimental station in Potshini.

Fig. 4. A tipping bucket with a data logger.

a runoff plot. The 11 runoff plots were designed while taking into account the rainfall intensities in the area. The dimensions of the runoff plots were 10 m long and 2.45 m wide and strips of 0.245 m wide galvanized sheet metal was used to demarcate the area under each runoff plot.

The knowledge of the rainfall intensity was useful in an effort to estimate the size of the self recording tipping buckets, which are used to measure the intensities of surface runoff, and subsequent calibration of the tipping volumes.

1.7. Soil moisture profiling

Ongoing monitoring of the volumetric soil moisture in the Potshini catchment has been implemented by use of the Time Domain Reflectometry (TDR) method. The concept of TDR involves measuring the capacitance of the soil within a radius of 150 mm and converting it into volumetric soil moisture content at any depth. This is facilitated by use of access tubes which are inserted into the soil profile to convenient depths. Several methods have been suggested on how to insert these access tubes into the soil and one of them is by pre-boring holes with appropriate soil augers, of relatively small diameter, and inserting the access tubes into the augered holes as was done in the Potshini catchment. A total of 16 access tubes of different depths ranging from 1.2 m to 1.5 m have been inserted in various sites in the 1.2 km^2 Potshini sub-catchment. All the access tubes have been inserted within runoff plots under different land management practices, notably conservation and conventional agricultural practices. A weekly regime for monitoring volumetric soil moisture content in the Potshini catchment has been established, where readings have continued to be taken at different depths of 30 cm interval in each access tube. Some of the volumetric soil moisture data from six runoff plots under different tillage practices in the Potshini catchment is analyzed and presented in this paper.

1.8. Shallow observation ground water wells

Through the collaboration and participation of the Potshini community, 12 shallow observation groundwater wells were installed in the Potshini sub-catchment. Since the catchment is predominantly an agricultural area for smallholder farmers, permission was sought from the local leaders and individual farmers to allow for the augering of the 100 mm holes in some of the farms on transects. The wells were strategically installed at sites where they could not interfere with the farming activities, considering the fact that most of the farming operations in the area make use of animal and/or tractor drawn implements. Two transects, one on each side of the sub-catchment, were identified and running more or less perpendicular to the general slope of the sub-catchment. The relatively shallow soils on one of the transects restricted the augering of the two wells to a depth of 2.4 m while the rest were to a depth of 3 m. The basic approach was to auger the wells as deep as possible to depths reaching the bedrock. Special 63 mm diameter plastic pipes of appropriate lengths were inserted into the augered wells such that at least 0.4 m length of the pipe was above the ground surface. These pipes have minute perforations at the bottom to a length of 0.6 m. It is through such perforations that the shallow groundwater seeps into the pipe upon which the monitoring of fluctuation of the shallow groundwater table is effected by the use of a pressure transducer and a data logger. The logging interval for all wells has been set to 30 min. To avoid clogging of the minute perforation by the fine clay soil at the bottom of the wells, a clean (washed) sand screen was packed around the plastic pipes covering the perforations to a height of 0.8 m from the bottom of the wells. For each well, the rest of the well's depth was filled with the previously augered soil material save for the top 0.3 m, where a cement mortar was cast around the 63 mm plastic pipe before a 0.4 m × 0.4 m concrete slab was cast at the top to a level slightly above the ground surface. Such cement and concrete works are to prevent any preferential flows from either side around the pipe when the soils are saturated during wet seasons.

1.9. Spatial computation of "Green Water Flows"

Increased levels of water resource management require increased accuracy in the quantification of various components of the hydrologic cycle especially the "Green" water flows (Falkenmark, 1995; Savenije, 1999) i.e. the gross return flow of water to the atmosphere-total evaporation (E_t) in the form of water vapour, which includes a productive part as Transpiration (T) and a non-productive part as direct Evaporation (E) from the soil, lakes, and from the part of Precipitation (R) intercepted by canopy surfaces. According to Rockström (1999), in semi-arid tropical agriculture, direct Evaporation (E) generally accounts for 30–50% while transpiration (T) account for only 15–30% of total rainfall received. Total evaporation (E_t) is highly variable over time and space and any effort towards enhancing the ability to confidently quantify it at large spatial scales is recognized as a key issue in water resources management. The challenge in determining the spatial and temporal variation of E_t over large areas is compounded by the many factors that influence its occurrence and prevalence and hence make it the most difficult parameter to determine in hydrology. The conventional approaches for quantifying E_t has been based on localized point measurements which do not allow the flux estimation over large geographical areas. These approaches include direct measurements (evaporation pan, Lysimeters etc.), climatic stations (eddy correlations, Penman, Bowen ratio etc) and hydrological models (water balance).

Remote sensing data provided by satellites are a means of obtaining consistent and frequent observation of spectral reflectance and emmitance of radiation of the land surface on micro and macro scale from which E_t can be retrieved (Bastiaanssen et al., 1998). The main disadvantage of remote sensing approaches for estimating E_t is the

limitation of accessing quality and timely data due to the influence of weather (cloud free images are required) and time overpass of satellite sensors, (Tasumi et al., 2003). One of the remote sensing approaches applied in this case study is the Surface Energy Balance Algorithm for Land (SEBAL), (Bastiaanssen et al., 1998a,b;Bastiaanssen, 2000). SEBAL is an energy partitioning algorithm comprised of 25 computational sub-models that calculate E_t and other energy exchanges at the earth's surface. The algorithm computes most essential hydro-meteorological parameters and requires limited ground based meteorological data (Farah and Bastiaanssen, 2001). Only incoming solar radiation, air temperature and wind speed data is required. SEBAL estimates E_t as the residual of an energy balance applied to the land surface for each pixel of the satellite image i.e.

$$\lambda E_t = R_n - H - G \quad (1)$$

where λE_t is the latent heat flux (W m^{-2}), R_n is the net radiation (W m^{-2}), H is the sensible heat flux (W m^{-2}) and G is the soil heat flux (W m^{-2}). The Large Aperture Scintillometer (LAS) is an instrument that measures the turbulent intensity of the refractive index fluctuations of air from the intensity fluctuations of a received signal (Cain et al., 2001). This signal is transmitted by a light source placed at a given distance apart (typically less than 10 km). At the receiver the spatial turbulent intensity is measured as a refractive index structure parameter $C_n^2(m^{-2/3})$ which can be related to the structure function parameter of temperature $C_T^2(K^2 \cdot m^{-2/3})$. Additional data on temperature, pressure and humidity are necessary to compute the structure function parameter of temperature which can then be converted to sensible heat flux (Kite and Droogers, 2000). With the knowledge of the net radiation and soil heat flux, the latent heat flux and subsequently Total Evaporation can be computed as indicated in Eq. (1). An important feature of the scintillation technique is that, although the measurement is along a path of a light beam, this is actually an estimate of sensible heat flux over an area because of the wide fetch (Meijninger and Bruin, 2000). The method therefore forms an intermediate scale between field (point measurement) and the large area remote sensing estimates with no instrument calibration requirement. It is important to note that one of the intermediate outputs of the SEBAL algorithm is the sensible heat flux for each pixel of the satellite image and this gives an opportunity to calibrate the satellite image using measured sensible heat flux data obtainable from a LAS.

In this case study, a subset of cloud free 7-band satellite Landsat-ETM image (path 160, row 080) with a spatial resolution of 30 m was used in estimating the E_t using SEBAL in this case study. The subset of the image, Fig. 5 covered part of the Thukela river basin and the whole of the Potshini catchment.

The acquisition date for this image was on 2nd March, 2001 and was freely downloaded from the Global Land Cover Facility (GLCF)-Earth Science Data Interface web-

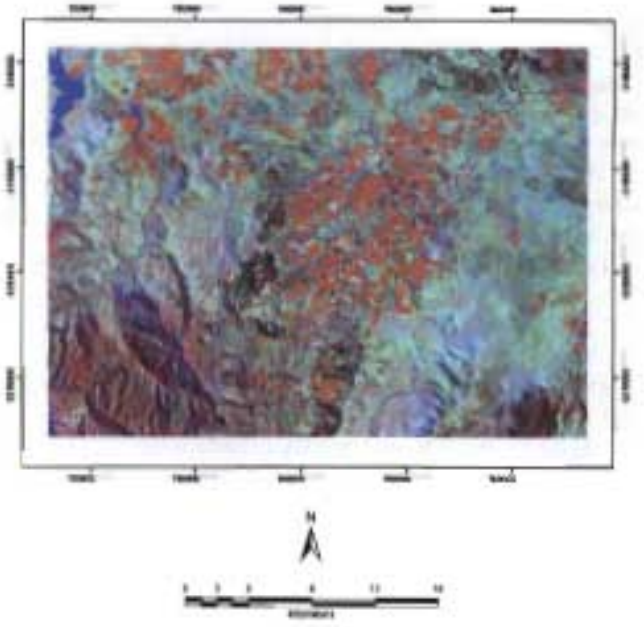

Fig. 5. A subset of a Landsat7-ETM satellite image (path 160, row 080) used for estimation of E_t using SEBAL algorithm.

site. The fundamental idea in this satellite image processing exercise was to initiate a process – the spatial estimation of E_t using remote sensing techniques in the Potshini catchment and Thukela river basin at large. It is an aim of this study to apply the SEBAL algorithm in real time situations and using the freely available NOAA/AVHRR and MODIS images (with spatial resolution of 1.1 km and 500 m respectively) which has the advantage of almost daily scene coverage, with the NOAA/AVHRR images being used on a larger river basin scale. In this case study, the 25 sub-models of the SEBAL algorithm were regrouped into 20 computational steps and which can broadly be classified into five general steps as described in Bastiaanssen et al. (1998a), Bastiaanssen et al. (1998b), Bastiaanssen (2000) and Mohamed et al. (2004).

2. Results and discussion

Preliminary analysis of some of the data obtained from the Potshini catchment monitoring network and SEBAL results is presented here.

2.1. Runoff plots and soil moisture

Preliminary experimental results obtained from the three pairs of runoff plots (3 sites) installed in the Potshini catchment are presented. Each runoff plot in a pair was installed under conventional and conservation tillage practice respectively. Volumetric soil moisture content, measured using TDR at different depths in the soil profile and at 30 cm interval, and cumulative surface runoff data from three pairs of runoff plots over a period of 17 weeks

starting from 21st April to 18th August 2005 is as shown in Figs. 6a and 6b,7a and 7b and 8. The span of data collection covered both wet season (April) and dry season (May to August). It was useful to carry out such an experiment through the two seasons in order to investigate the potential of such water use innovations (conservation tillage practices) in retaining extra water in form of soil moisture in the catchment especially during the dry season. A comparison can be made between Figs. 6a and 6b at *MA*, Figs. 7a and 7b at site *HA* and Fig. 8 at site *TS*.

The two experimental sites were smallholder farms in the Potshini catchment and which is predominantly an agricultural area. The main observation from Figs. 6a and 6b is that, conservation tillage practices significantly reduce surface runoff volumes as compared to conventional tillage practices. It was observed that the total runoff generated from the runoff plot under conservation tillage at site *MA*was 0.672 m^3 compared to 1.5616 m^3 from a runoff plot under conventional tillage practice. This translates to a reduction of over 100% of surface runoff by practicing conservation tillage practices. A similar reduction of cumulative surface runoff was also observed at site *HA*, where the cumulative runoff from the runoff plot under conservation tillage was found to be 0.718 m^3 while that under

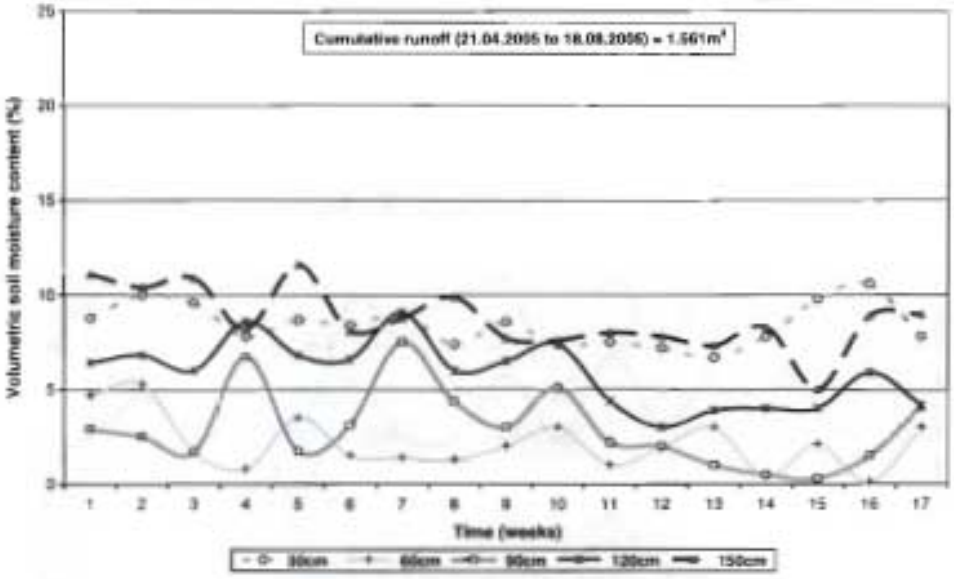

Fig. 6a. Weekly volumetric soil moisture (%) measurements under conventional tillage practice and cumulative surface runoff at site *MA*.

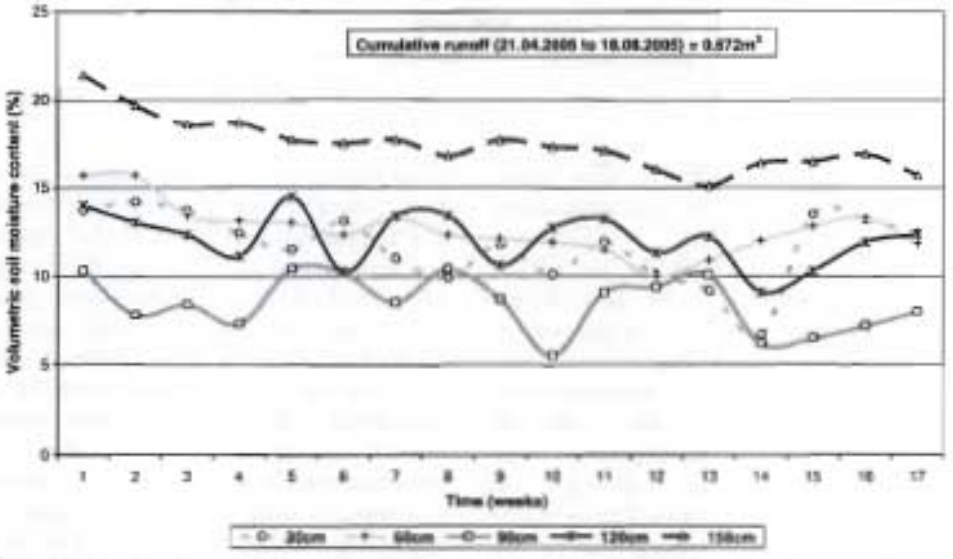

Fig. 6b. Weekly volumetric soil moisture (%) measurements under conservation tillage practice and cumulative surface runoff at site *MA*.

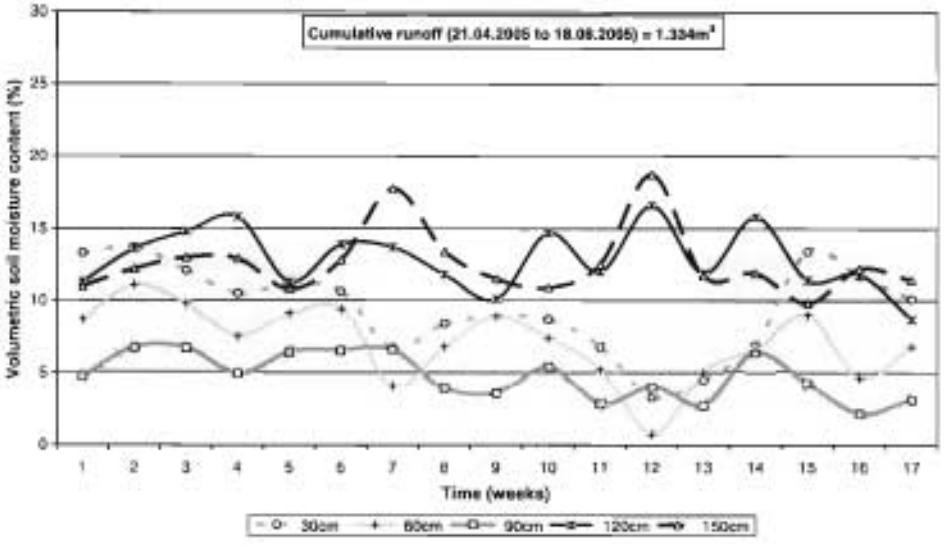

Fig. 7a. Weekly volumetric soil moisture (%) measurements under conventional tillage practice and cumulative surface runoff at site *HA*.

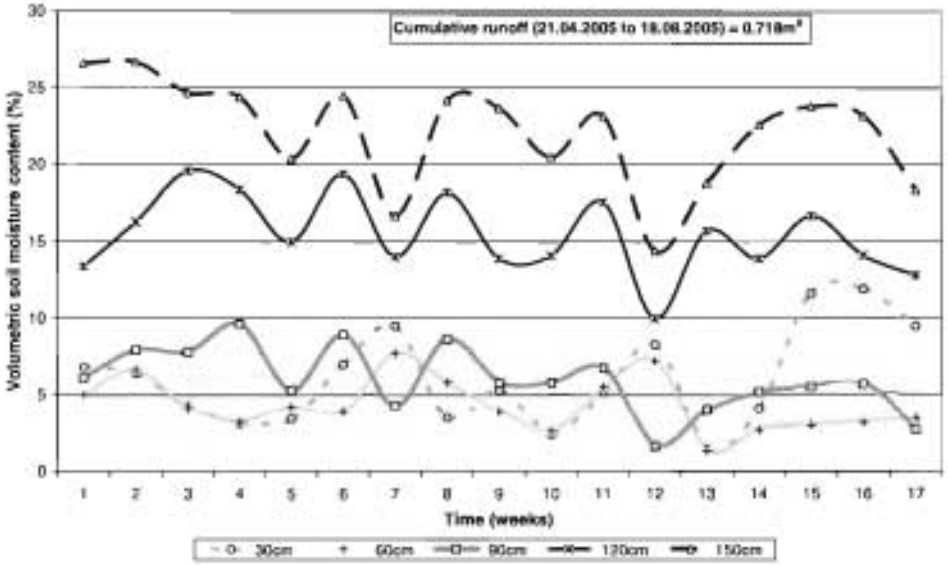

Fig. 7b. Weekly volumetric soil moisture (%) measurements under conservation tillage practice and cumulative surface runoff at site *HA*.

conventional tillage practice was 1.334 m^3, and hence translating to a reduction of close to 100% on cumulative surface runoff under conservation tillage.

Even though there is a difference in the percentage reduction of cumulative surface runoff from the two sites *MA* and *HA*, the general understanding one can derive from such analysis is that conservation tillage practices significantly reduces surface runoff compared to conventional tillage practices. The difference in percentage reduction could be attributed to the local heterogeneities of soils and the physical characteristics (e.g. slope) at the respective sites. The ability of conservation tillage practices to significantly reduce surface runoff is further supported by the influence of such practices in retaining more soil moisture compared to conventional tillage practices as indicated in Figs. 6a and 6b, together with Figs. 7a and 7b. Fig. 8 shows a graphical representation of the variation of volumetric soil moisture content for the third pair of runoff plots, one runoff plot under conservation and the other under conventional tillage practices respectively at another smallholder farm (site *TS*) in the Potshini sub-catchment.

Cumulative surface runoff from the runoff plot under conventional tillage over the entire observation period at site *TS* amounted to 1.238 m^3 while 0.45 m^3 was recorded from the runoff plot under conservation tillage practice and hence translating to a percentage reduction of over 200%. Such results more or less conforms to observations made at site *MA* and *HA*. From Fig. 8, even though the

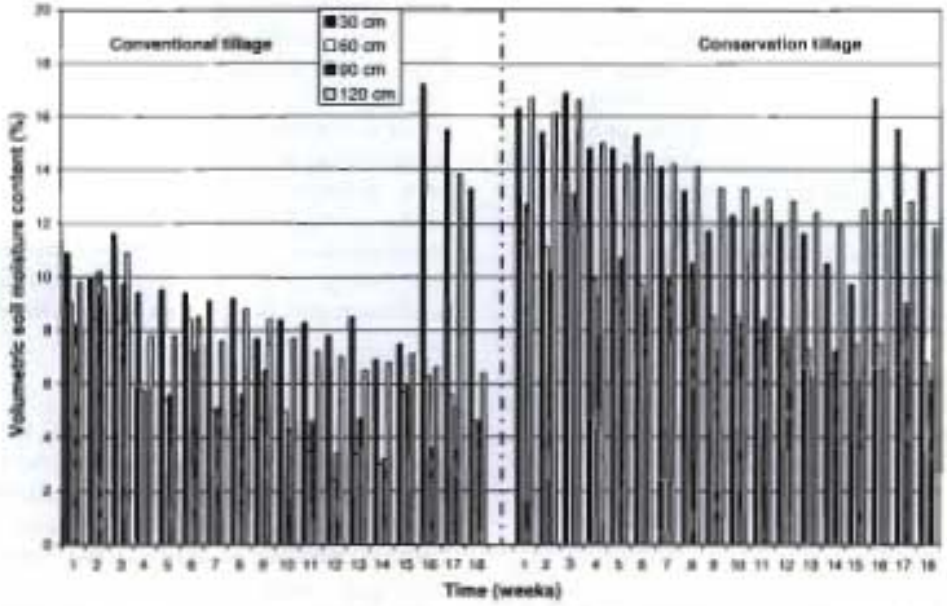

Fig. 8. Comparison of volumetric soil moisture content under conventional and conservation tillage practices at site *TS* over an observation period of 18 weeks starting from 21.04.2005 to 25.08.2005.

volumetric soil moisture content in the two runoff plots was on recession; as expected during drought spells, the conservation tillage practices influenced the retention of more volumetric soil moisture compared to conventional tillage practices. It can be seen that, at the beginning of the recession of soil moisture in the catchment in general, the volumetric soil moisture content at the top soil (top 30 cm) in runoff plots under conservation and conventional tillage practices was around 16% and 11% respectively. Such a significant difference is maintained across the soil profile and throughout the observation period till the last three weeks of measurements (week 16–17) in August, when early rains were recorded in the catchment, as indicated in Fig. 9, and the volumetric soil moisture content under the two tillage practices was observed to be more or less the same. Fig. 9 shows weekly rainfall and total evaporation over the Potshini catchment during the period considered in this study (21st April to 25th August 2005). A similar pattern is depicted in Figs. 6a and 6b together with Figs. 7a and 7b. Of great interest is the availability of relatively higher

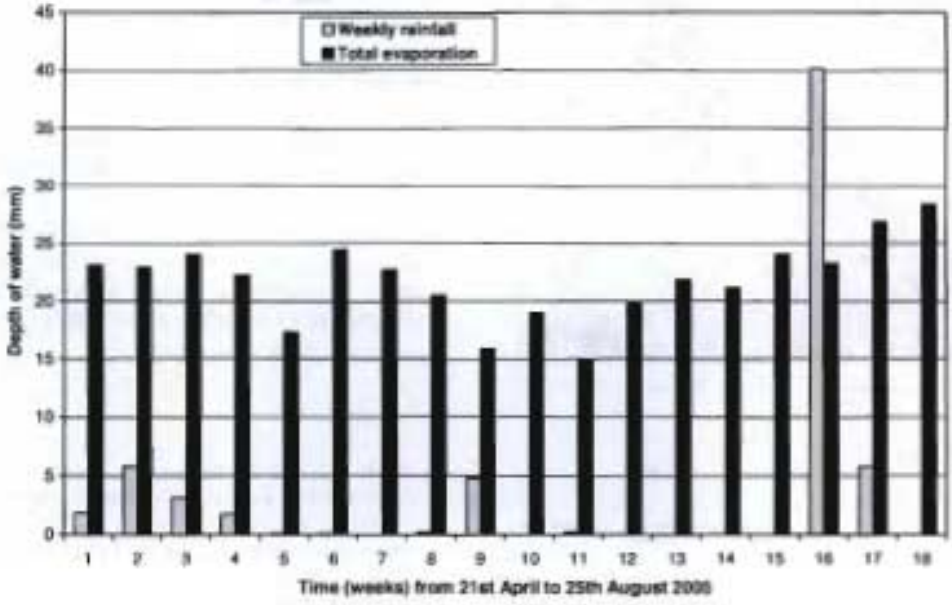

Fig. 9. Weekly rainfall and total evaporation at the Potshini catchment (21.04.2005 to 25.08.2005).

volumetric soil moisture content at greater soil depths (>120 cm) in smallholder farms under conservation tillage practices as compared to conventional tillage practices. Such a phenomenon could lead to the recharging of the shallow ground water in such areas and the catchment at large if such tillage practices are widely adopted (up-scaled) in the catchment. The recharging of shallow groundwater could lead to increased interflows and sub-surface flows and which has an influence to the variation of stream flows.

However, the opposite could occur if the additional soil moisture is fully utilized by the plants. An effort has been made to get an in-depth understanding of the influence of conservation tillage practices on shallow ground water in the Potshini catchment with the installation of 12 self recording shallow groundwater wells (Piezometers) in the catchment under the ongoing study.

2.2. SEBAL results

On application of the SEBAL algorithm, a map was generated for the day's spatial variation of E_t, Fig. 10, over the entire subset image for 2nd March 2001.

Relatively high E_t rates are observed to have taken place in areas under active growing crops as seen from Figs. 5 and 10. It was also observed that the same areas had relatively high NDVI values indicating high vigor of vegetation/crop growth. A comparison was done for this day between SEBAL estimates for E_t and from a weather station in Bergville, on the same pixel. It was found out that SEBAL over estimated E_t by 1.3 mm/day, with the weather station reading being 7.2 mm/day for a point in the same pixel. Further investigation and verification of SEBAL outputs form an important part of the next two years of investigation. The application of SEBAL in computing E_t in the ongoing study will be of great significance especially when trying to understand the spatial variation of such hydrological processes in the Potshini catchment and Thukela river basin at large and as a key input to the agro-hydrological modeling system. Such an approach will lead to a greater understanding of the impacts of upscaling of water use innovations on the eco-hydrological system in the Potshini catchment and the Thukela river basin at large.

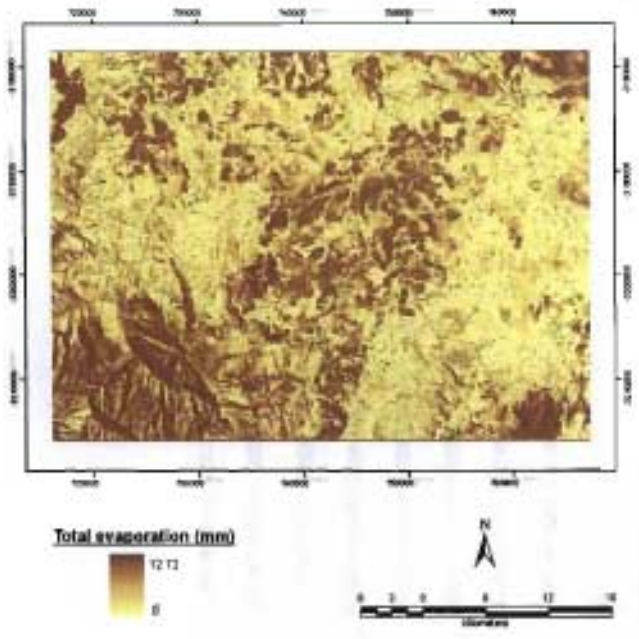

Fig. 10. Spatial variation of computed E_t in the Potshini sub-catchment and surrounding areas for 2nd March 2001 computed using the SEBAL algorithm.

3. Conclusion

A catchment monitoring network has been established at the Potshini sub-catchment and the SEBAL algorithm was used to derive E_t from a Landsat7-ETM satellite image. Preliminary results on the impact of innovative agricultural practices on the field soil–water balance indicate that such practices (conservation tillage) can significantly reduce surface runoff and increase soil moisture content and hence influence the partitioning of rainfall over the catchment. These preliminary results sets the platform for further investigation on the possible impacts to the eco-hydrological system of the catchment if such water use innovations are adopted by many smallholder farmers in the catchment (up-scaling) and the Thukela River basin at large. Such an investigation can be accomplished through a hydrological modeling exercise as will be done in the ongoing research study. Despite the difference observed between estimates of E_t from weather station data and SEBAL, there is potential for using SEBAL in the Potshini sub-catchment and Thukela river basin (large spatial scales) especially in quantifying actual water use by crops/vegetation (e.g. forestry in line with the 1998 National Water Act) in an effort to manage the river basin's water resources in a sustainable way.

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3.1 Appendix

Summary

Climatic and hydrologic parameters in smallholder farms under different landuse management practices in the Potshini catchment were monitored and analyzed in an effort to seek answers to on the question: "What is the impact of adapting water use innovations (rainwater harvesting) in a predominantly agricultural area on catchment ecology and hydrology?". Three sites in the catchment, two farmer-managed experimental plots and a researcher controlled plot under different tillage systems, were monitored for volumetric soil moisture content and surface runoff generating characteristics over a period of seventeen weeks. The general trend that was observed is that conservation tillage systems, a water use innovation, in the Potshini catchment have influenced the partitioning of rainfall, by significantly reducing surface runoff over agricultural lands under conservation tillage practices, with a reduction ranging from 46 to 67%. More soil moisture was retained in plots under conservation tillage practices compared to plots under conventional tillage.

3.1.1 Introduction

The hydrological response of a catchment, as used in this context, can generally be defined as the reaction of a catchment to rainfall. Every catchment has a specific response to rainfall and which is related to hydro-climatological and physical characteristics, such as soil parameters, slope, climate etc. Some of the catchment characteristics can be obtained through measurements at specified spatial and temporal scales depending on their frequency and nature of occurrence and required resolution of data for meaningful analytical work when addressing questions related to catchment response. There are several factors that may influence a catchment response and can broadly be identified with change in land use/cover and climatic change (Costa et al., 2003). The influence or impact of climate change to catchment hydrology may not be depicted within a short term, as emerging trends of catchment response as a result of climate change may indicate randomness rather than systematic pattern as compared to land use change. It is important to note that causes of climate change are often not localized as compared to landuse change and thus making it easier to monitor and investigate impacts of landuse changes on the hydrological regime of a catchment and possibly impacts of the same to the downstream ecosystems.

This can be achieved through establishing a catchment monitoring network, a task that was accomplished at the Potshini catchment in the foothills of the Drakensberg Mountains under the research programme, the Smallholder Water System Innovations (SSI) at the University of KwaZulu-Natal (Rockström et al., 2004) The SSI research programme has the general objective of assessing the extent to which water management in rainfed smallholder farming can assist in securing human livelihoods in semi-arid tropical Savannahs in sub-Saharan Africa, together with trying to analyse the downstream hydrological implications of upgrading rainfed agriculture through adoption and adaptation of water use innovations e.g rainwater harvesting. Figure 3.1 provides an overview of the Potshini catchment. The Potshini catchment monitoring network facilitates the monitoring of the main hydrological processes in the predominantly agricultural catchment whilst recognizing the existing heterogeneity in such a catchment.

Water use system innovations encompass various techniques for storing and conserving water resources in different mediums for domestic and livestock use including agricultural production. Although, several authors including Pandey et al., (2003) have indicated that rainwater harvesting techniques, especially for upgrading smallholder farming systems, are not new but have been practiced since ancient civilizations, the impacts of such water use innovations on eco-hydrological systems are rarely assessed, especially from a cascading spatial and temporal perspective. The need to quantify the supposedly potential and related hydrological impacts of water use innovations on a catchment and river basin at large led to this study, within the SSI research programme, aimed at investigating the biophysical impacts of adopting such water use innovations at a catchment scale. It is recognized that heterogeneity exists at any scale under consideration and it is a great challenge to hydrologists and water resource managers to uniquely define and quantify various hydrological processes in a catchment and establish the link between such processes and scales, both spatial and temporal. Such a challenge is further convoluted by the existence of a link between variability of hydrological processes and heterogeneity of the catchment (Jewitt and Görgens, 2000). This Chapter discusses the comparative results on basic hydrological parameters obtained from three sites in the Potshini catchment, i.e runoff generating characteristics and volumetric soil moisture content, from runoff plots installed in the catchment under different land management practices.

3.1.2 The study area

The Potshini catchment is predominantly a smallholder farming area and a sub-catchment of the Quaternary Catchment (QC) number V13D in the Thukela river basin in the foothills of the Drakensberg Mountains. Figure 3.1 shows the location of the three experimental sites in the Potshini

catchment, i.e *MT, MA, HA*, that were used in this study and which forms the main focus of this Chapter.

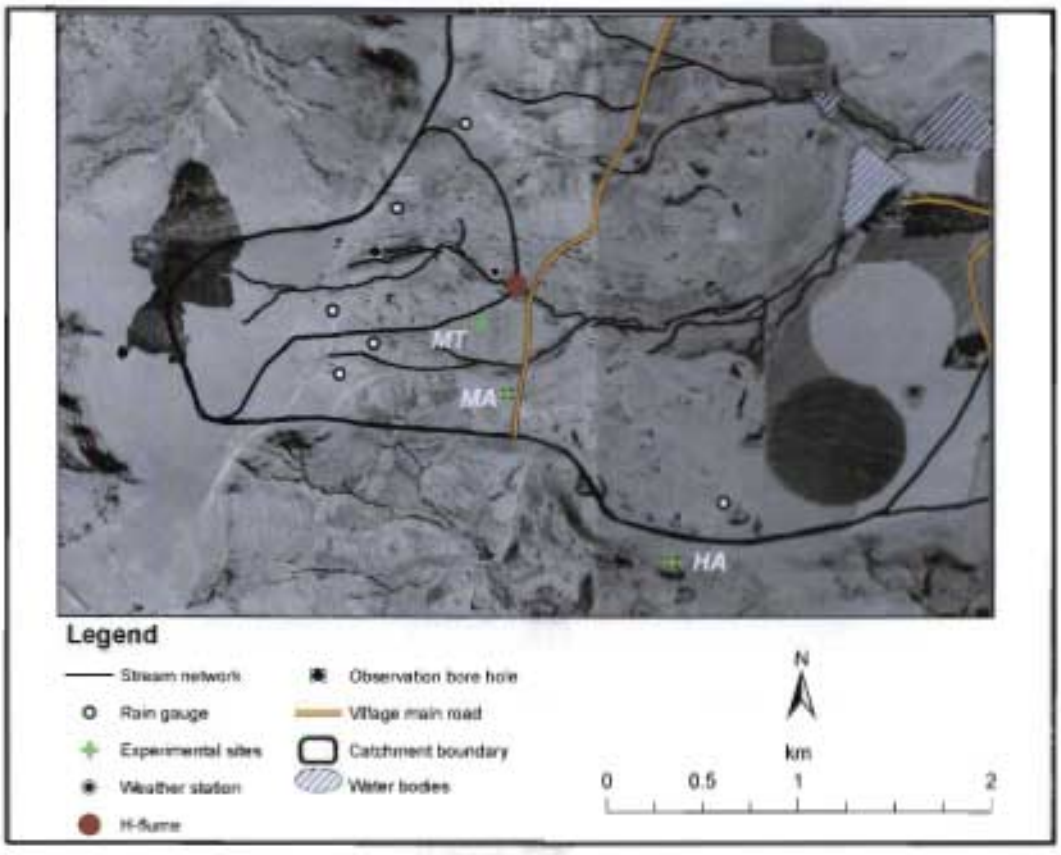

Figure 3.1 Experimental sites in the Potshini catchment

The Potshini catchment is located in the Bergville District in the KwaZulu-Natal Province in S.Africa. The Thukela river basin has an area of 29,036 km^2, while the area of QC V13D and Potshini catchment are 280 and 1.2 km^2 respectively. The altitude range in the Potshini catchment is between 1300 and 1340 meters above sea level and the mean annual precipitation at Potshini is estimated to be 700 $mm.a^{-1}$ with an estimated mean annual potential evaporation between 1600 to 2000 $mm.a^{-1}$ (Guy and Smith, 1995; BEEH, 2003). The mean annual temperature ranges between 16 and 18 °C, with the minimum and maximum temperatures recorded between 2001 and 2007 being -4 and 34°C respectively. Frost is severe to very severe in winter (May to August) and hail is sporadically severe in summer (September to April). Poor grazing management on the upper hill slopes of the Potshini catchment has resulted into severe erosion as evident by small gullies that have developed from cattle tracks. The lower parts of the catchment have undulating gentle slopes on which the local community carries out their smallholder farming activities. Land cover in the catchment changes with seasons,

with maize crop and tall veld-grass dominating during wet summer season, while bare soils, dilapidated pastures and crop residues dominating during the dry season.

Figure 3.2 shows monthly variation of rainfall and temperature in the Potshini catchment. The long-term mean monthly rainfall and temperature was derived from a 28-year climatic data record from a weather station in Bergville located at an elevation of 1310 meters above sea level, and which is 8km away from the Potshini catchment. Due to the hilly terrain, a good drainage network has developed in the Potshini catchment with most of the streams being perennial and providing water for domestic use to the upper part of the catchment, while replenishing reservoirs for commercial farmers downstream. Extreme low flows occur in winter. The main river, which drains the Quaternary Catchment V13D, is the Lindequespruit, a tributary of the Little Thukela which later joins the Thukela river.

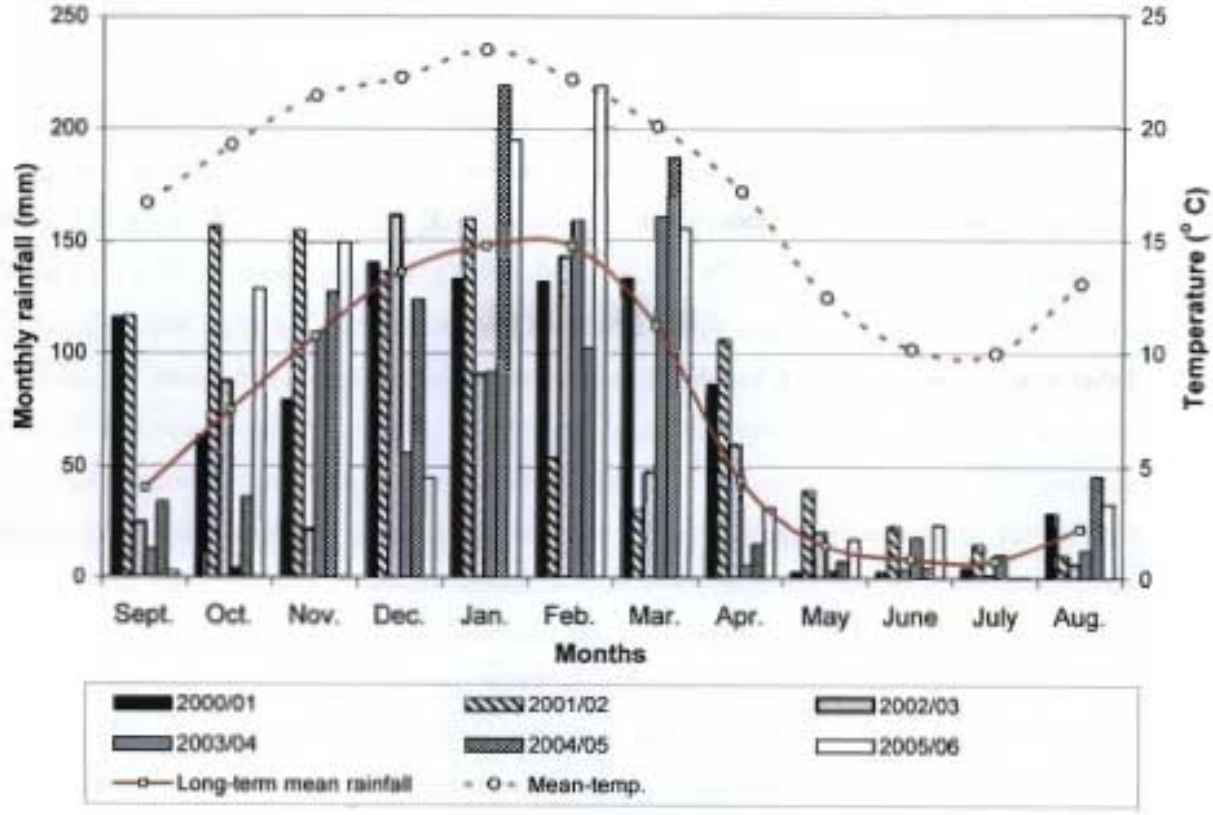

Figure 3.2 An overview of the monthly variation of rainfall and temperature in the Potshini catchment. The long term mean monthly rainfall and temperature was derived from a 28-year climatic data record from a nearby weather station in Bergville

3.1.3 Soils

The Potshini catchment has a relatively high water table ranging from 1.5 to 2.4m below the surface (cf. Chapter 4) and the the soils are generally acidic with varying depths from 1.2m to over 3m on the lower parts of the catchment. Smith et al., (2001) cited Turner (2000) as have described the geological formation underlying the region around the Potshini catchment to have sandstone and mudstone of the Tarkastad Formation, Beaufort Group and by shale and sandstone of the Estcourt Formation, Beaufort Group. The Tarkastad Formation is described as comprising fine to medium grained yellow and grey sandstone and maroon (red) to green and blue mudstone. The Estcourt Formation is described as comprising dark-grey shale (often carbonaceous), siltstone and fine and medium to coarse sandstone. According to Turner (2000), the major soil patterns that are evident and associated with the sandstone and mudstone of the Tarkastad Formation are the red and yellow-brown apedal and the plinthic soil patterns.

3.1.4 Land uses and economic activities

The main landuse types in the Potshini catchment include the predominantly smallholder farming (crop production) during summer, which constitutes over 60% of the total land in the catchment, and grazing of the domestic animals (cattle, goats, horses). The number of cattle in the Potshini community is estimated to be 378 (Smith et al., 2004). The population of the 1.2 km^2 Potshini catchment is estimated to be less than 1000, with smallholder farming being primarily done on the lower slopes of the catchment, and the main crop being maize, legumes and pulses. It is useful to note that, during winter, all the domestic animals are freed to graze on the smallholder farms due to depleted pastures on the secured grazing lands on the upper slopes of the catchment. Due to the need to intensify agricultural production in the area for food security, various agricultural management practices have been adapted in the Potshini catchment which is located in the Emmaus ward in Bergville district, through the then South African National Landcare programme in the Bergville district, and notably conservation agriculture (a water use innovation). There is a great potential for adoption of such practices in the area due to the successful results obtained so far where smallholder farmers have managed to increase their crop production per unit area by appreciable margins as shown in Figure 3.3 as reported in Smith et al., (2004).

The farmer-to-farmer participatory learning process, a participatory action research approach introduced in the area by the Agricultural Research Council (ARC), the implementing agency of the then National Landcare programme in the Bergville district has been highly successful in achieving the uptake of new techniques, notably conservation tillage practices, by the local farmers. The

challenge is to quantify the impact of such novel water management strategies to the eco-hydrological system in the catchment with regard to their up-scaling to larger areas and wider adoption. This is the challenge in which this study, and the SSI programme in general, is trying to address.

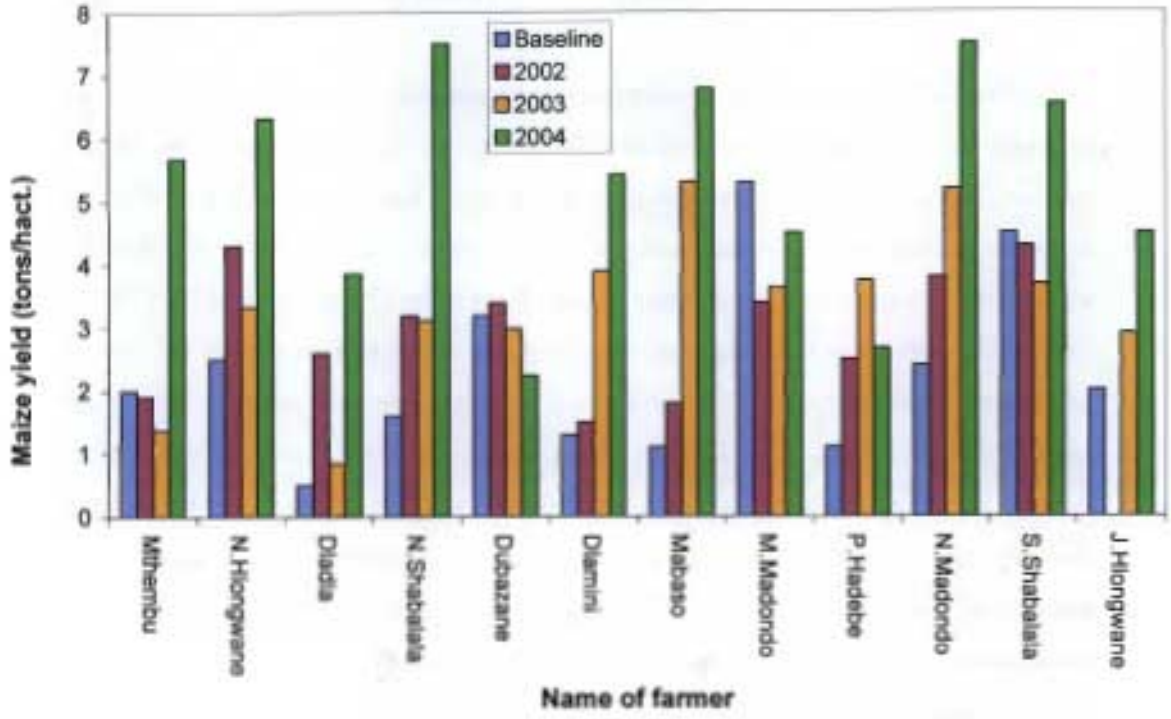

Figure 3.3 Average maize yields on farmer-managed trials in Emmaus ward, including Potshini – 2001 to 2004 (Adapted from Smith et al., 2004)

3.1.5 Water use innovations

According to Pandey et al., (2003), water use innovations are not new, but have persistently been developed and adopted by mankind as an adaptation to climate variability since ancient civilizations. These innovations are either locally inspired or adapted from other regions. In the past few decades, efficient communication networks have greatly influenced and enabled technology transfer and hence adaptations of water use innovations in various regions of Africa. Water use innovations encompass various methods and strategies for mitigating drought in an effort to sustain livelihood (Rockström et al., 2004). These innovations are typically water harvesting techniques for concentrating, storing and collecting surface runoff water in different mediums, for domestic or agricultural uses. Runoff can be collected from roofs or ground surfaces (rainwater harvesting) as well as from seasonal streams (flood water harvesting). The various methods for harvesting runoff can be distinguished after the following (Rockström et al., 1999; Rockström, 2000):

- Source of the surface water (external or within-field catchments from sheet, rill, gully or stream flow),
- The method of managing the water (maximising infiltration in the soil, storing water in tanks/dams, inundating crop fields with storm floods),
- The use of water (livestock, households, crop production and erosion management).

According to Rockström (2000), water harvesting practices generally contribute to an increase in the recharge of water to the root zone and finally to the water table and operate at different scales (household, field, catchment and basin). Such practices have the potential to affect water availability and management for downstream water users and natural ecosystems due to reduced catchment water yields due to increased total evaporation rates. Rockström (2000) cited SSSA (1987) as have defined conservation tillage as any tillage sequence with the objective to minimize the loss of soil and water, and having a operational threshold of leaving at least 30 percent mulch or crop residue cover on the surface throughout the year. Conservation tillage aims at reversing a persistent trend in farming systems of reduced infiltration due to compaction and crust formation and reduced water holding capacity due to oxidation of organic materials (due to excessive turning of the soil). From this perspective, conservation tillage qualifies as a form of water harvesting (and hence a water use innovation), where runoff is impended and soil water is stored in the crop root zone (Rockström et al., 1999). Conservation tillage covers a range of non-inversion practices from zero-tillage to reduced tillage which aim to maximize soil infiltration and productivity, by minimizing water losses (evaporation and surface runoff) while conserving energy and labour. GHARP (2002) indicated the successes of conservation tillage in harnessing rainwater and improving yields (more than 50%) particularly in Machakos and Laikipia districts of Kenya. Other studies from different regions, including Lafond et al., (2006); Bescansa et al., (2006); De Vita et al., (2007), have reported similar results.

3.1.6 Field measurements

- **Climatic parameters**

Climatic parameters were monitored by an automatic weather station installed in the midst of the Potshini local community, and who also assisted in manually recording rainfall in the catchment. The manual rain gauges including installation of other instrumention in the Potshini catchment started in 2004 as detailed in Chapter 2. Figure 3.1 shows the location of the raingauges in the Potshini catchment.

- **Runoff plots**

A total of six runoff plots measuring 10m by 2.45m were installed in three sites in the catchment, two on each site and under different tillage systems. On each site, (*MT, HA & MA* in Figure 3.2) one runoff plot was installed in a field under conservation tillage (minimum tillage) while the other under conventional tillage. It is useful to note that the treatment that was investigated and compared at each site, thus forming the main discussion of this Chapter, was conventional versus conservation tillage practice under maize crop and grazing (cf. Table 2.3 in Chapter 2). Thus, in this experiment, maize crop and grazing was maintained in all runoff plots with the tillage system being the only variable. A tipping bucket was used to measure the surface runoff intensities from each site and the data was recorded in a HOBO data logger. The knowledge of the rainfall intensities in the catchment was useful in estimating the size of the self recording tipping buckets and subsequent calibration of the tipping volumes. A manual counter was used as a back up system in case of failure of the data logging system. Figure 3.4 shows a set of runoff plots on the researcher managed experimental site, *MT*, while Figure 3.5 is a tipping bucket with a data logger attached to it for automatic recording of surface runoff intensities from a runoff plot.

Figure 3.4 A set of 5 runoff plots on an experimental station in Potshini

Figure 3.5 A tipping bucket with a data logger

- **Soil moisture profiling**

Volumetric soil moisture content was monitored every week along the soil profile on each runoff plot using a TRIME-TDR probe (TRIME-FM, 2003) at an interval depth of 30cm. One access tube was inserted in the middle of the respective runoff plots to depths ranging from 1.2 to 1.5m and were used to guide the TDR probe to convenient depths.

3.1.7 Results and discussion

Experimental results obtained from the 3 pairs of runoff plots installed in three sites i.e (*MA, HA, MT* as shown in Figure 3.2) in the Potshini catchment are presented. Volumetric soil moisture content and cumulative surface runoff data from 3 the pairs of runoff plots over a period of 17 weeks, starting from 21st April to 18th August 2005, is as shown in Figure 3.6 & 3.7; 3.8 & 3.9 and 3.10 & 3.11. The span of data collection covered part of the wet season (April) and dry season (May to August). It was unfortunate that soil moisture data was only available beginning from 21st April, after the TDR-TRIME probe broke down in the early part of the rain season, i.e in October, and it took long to get it repaired. Nevertheless, it was useful to carry out such an experiment through the two seasons in order to investigate the potential of such water use innovations (conservation tillage practices) in retaining extra water in form of soil moisture in the catchment especially during the dry season. For each tillage

system, i.e conservation and conventional systems, only summer maize crop was grown on each plot and the data obtained from these plots is presented here.

A comparison can be made between Figure 3.6 & 3.7 for site *MA*, Figures 3.8 & 3.9 for site *HA* and 3.10 & 3.11 for *MT*.

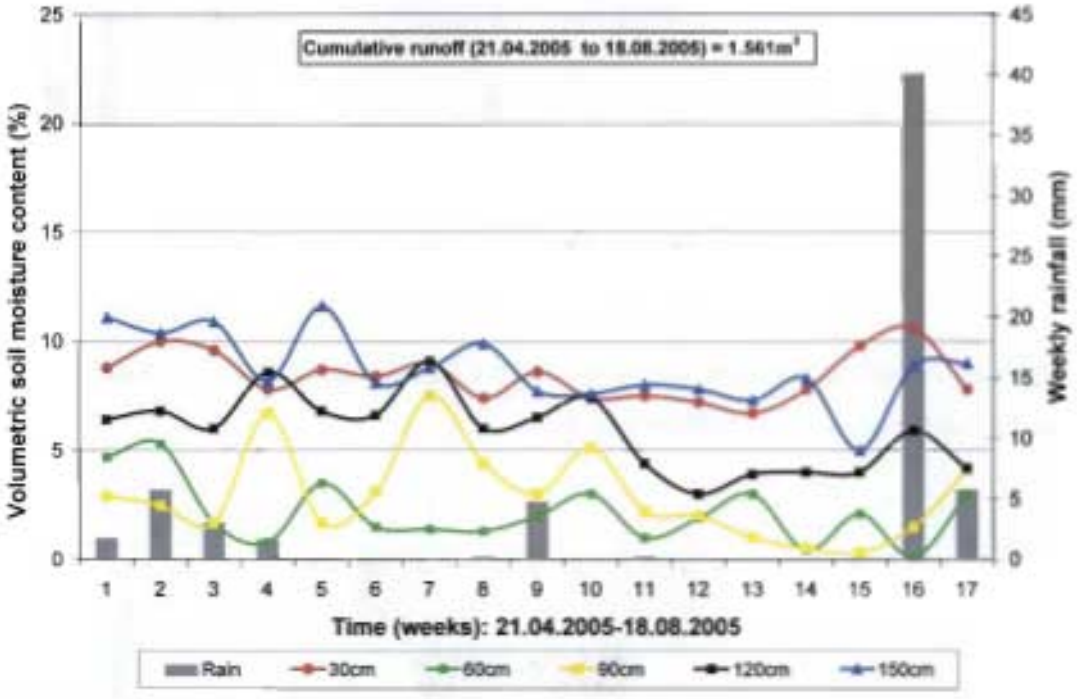

Figure 3.6 Weekly volumetric soil moisture (%) measurements and cumulative surface runoff at site *MA* under conventional tillage practice

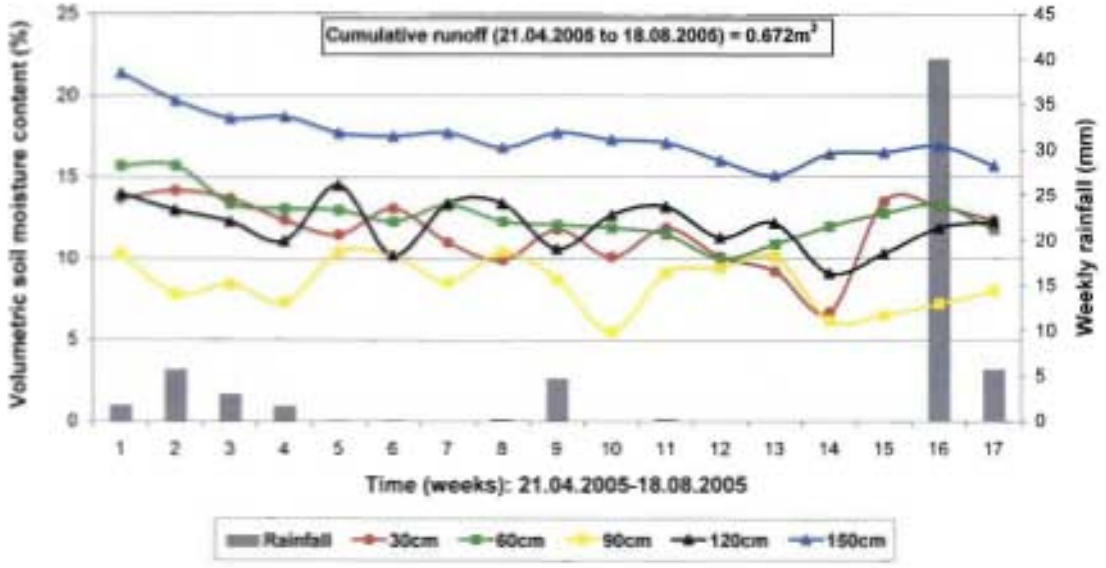

Figure 3.7 Weekly volumetric soil moisture (%) measurements and cumulative surface runoff at site *MA* under conservation tillage practice

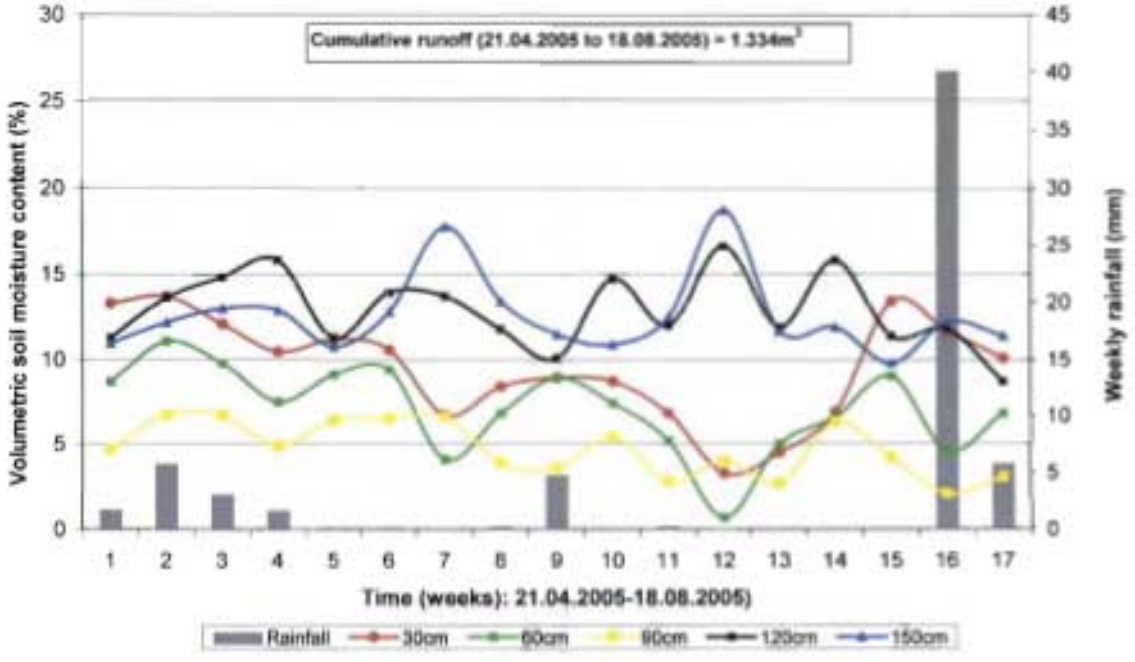

Figure 3.8 Weekly volumetric soil moisture (%) measurements and cumulative surface runoff at site *HA* under conventional tillage practice

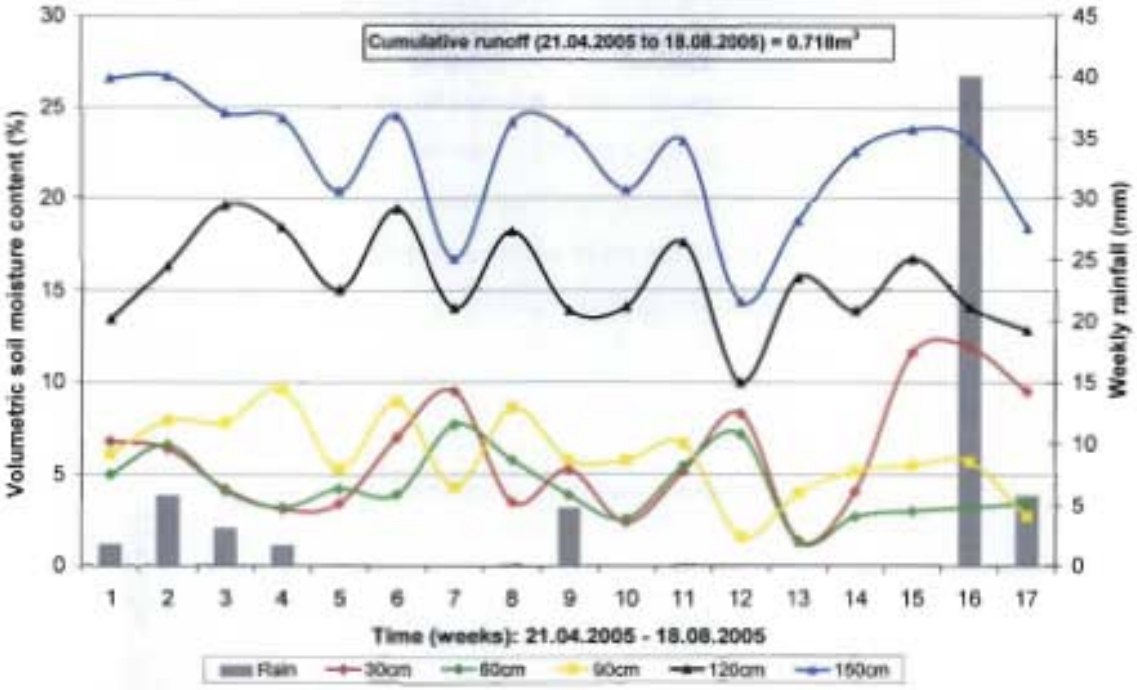

Figure 3.9 Weekly volumetric soil moisture (%) measurements and cumulative surface runoff at site *HA* under conservation tillage practice

The two experimental sites, *MA & HA*, were smallholder farms in the Potshini catchment and which is predominantly an agricultural area. The main observation from Figures 3.6 and 3.7 is that, conservation tillage practices significantly reduce surface runoff volumes as compared to conventional tillage practices. Also, the volumetric soil moisture content at different depths in all the sites most often responded and varied with weekly rainfall amounts as can be seen from Figures 3.6 to 3.11. It was observed that the total runoff generated from the runoff plot under conservation tillage at site *MA* was 0.672 m^3 compared to 1.5616 m^3 from a runoff plot under conventional tillage practice. This translates to a reduction of 57% of surface runoff by practicing conservation tillage practices. A reduction of cumulative surface runoff was also observed at site *HA*, where the cumulative runoff from the runoff plot under conservation tillage was found to be 0.718 m^3 while that under conventional tillage practice was 1.334 m^3, and hence translating to a reduction of 46% on cumulative surface runoff under conservation tillage.

Even though there is a difference in the percentage reduction of cumulative surface runoff from the two sites *MA* and *HA*, the general understanding one can derive from such analysis is that conservation tillage practices significantly reduces surface runoff compared to conventional tillage practices. The difference in percentage reduction could be attributed to the local heterogeneities of soils and the

physical characteristics (e.g slope) at the respective sites. The ability of conservation tillage practices to significantly reduce surface runoff is further supported by the influence of such practices in retaining more soil moisture compared to conventional tillage practices as indicated in Figure 3.6 & 3.7 for site *MA*, together with Figure 3.8 & 3.9 for site *HA*. Figures 3.10 and 3.11 shows a graphical representation of the variation of volumetric soil moisture content for the third pair of runoff plots, one runoff plot under conservation and the other under conventional tillage practices respectively at the research managed site, *MT*, in the Potshini sub-catchment.

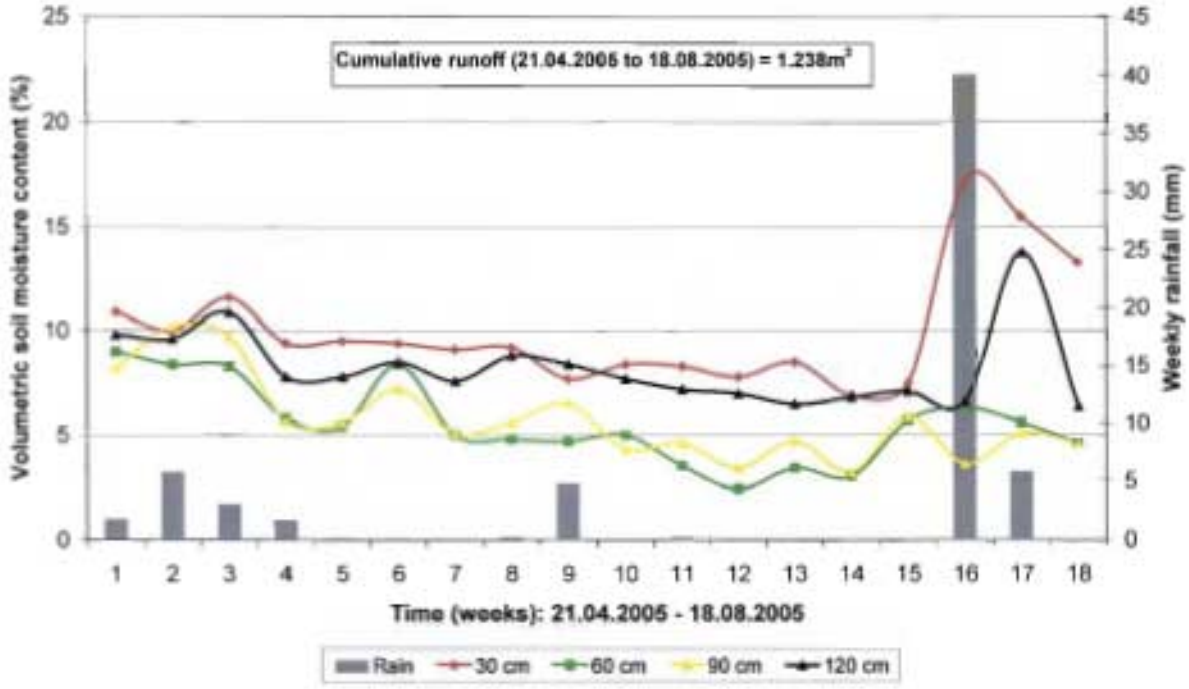

Figure 3.10 Weekly volumetric soil moisture (%) measurements and cumulative surface runoff at site *MT* under conventional tillage practice

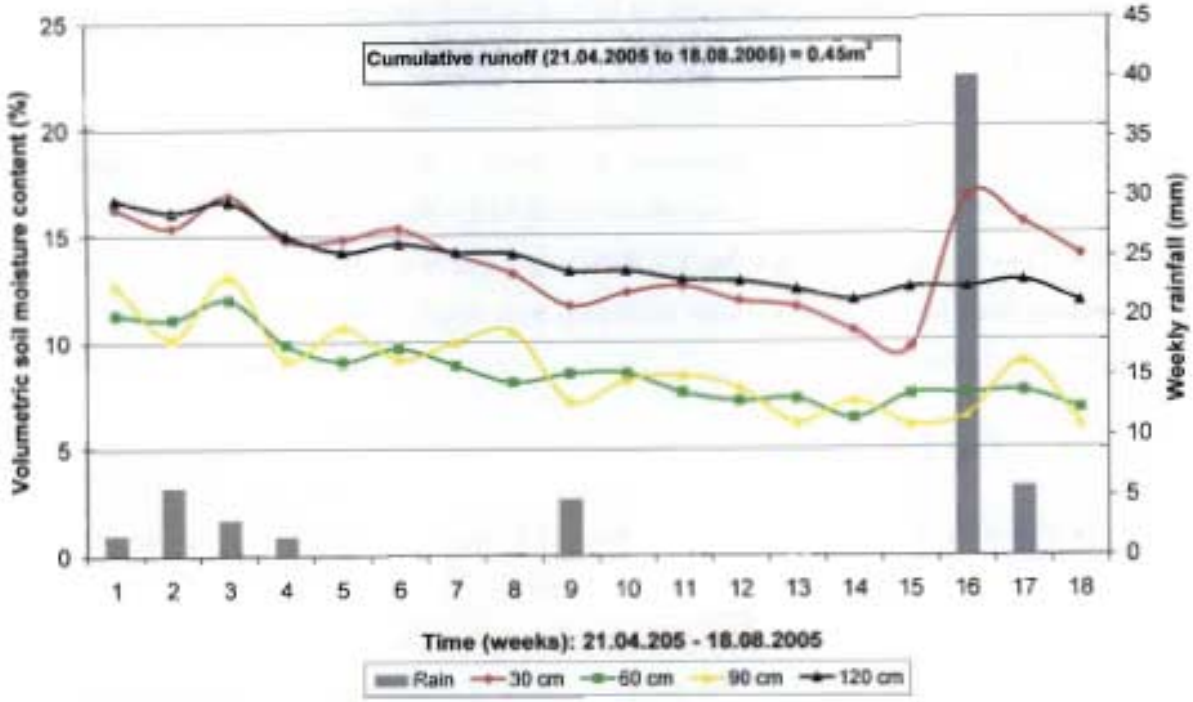

Figure 3.11 Weekly volumetric soil moisture (%) measurements and cumulative surface runoff at site *MT* under conservation tillage practice

Cumulative surface runoff from the runoff plot under conventional tillage over the entire observation period at site *MT* amounted to 1.238 m^3 while 0.45 m^3 was recorded from the runoff plot under conservation tillage practice and hence translating to a percentage reduction of close to 64%. Such results more or less conforms to observations made at site *MA* and *HA* as previously discussed. From Figures 3.10 and 3.11, even though the volumetric soil moisture content in the two runoff plots was on recession, as expected during drought spells, the conservation tillage practices influenced the retention of more volumetric soil moisture compared to conventional tillage practices. It can be seen that, at the beginning of the recession of soil moisture in the catchment in general, the volumetric soil moisture content at the top soil (top 30 cm) in runoff plots under conservation and conventional tillage practices was around 16% and 11% respectively. Such a significant difference trend is maintained across the soil profile and throughout the observation period till the last three weeks of measurements (week 16-17) in August, when early rains were recorded in the catchment, as indicated in Figures 3.6 to 3.11 and the volumetric soil moisture content under the two tillage practices was observed to be more or less the same. A similar pattern is depicted in Figure 3.6 & 3.7 at site *MA*, together with Figure 3.8 & 3.9 at site *HA*. Of great interest is the availability of relatively higher volumetric soil moisture content at greater soil depths (>120 cm) in smallholder farms under conservation tillage practices as compared to conventional tillage practices. Such a phenomenon could lead to the recharging of the shallow ground

water in such areas and the catchment at large if such tillage practices are widely adopted (up-scaled) in the catchment. The recharging of shallow ground water could lead to increased interflows and sub-surface flows and subsequently influence the variation of stream flows in the catchment. However, the opposite could occur if the additional soil moisture is fully utilized by the plants. Nevertheless, there is a possibility of the shallow ground water interacting with the soil moisture in the root zone through a capillary rise given the fact that the shallow ground water in the catchment is relatively shallow, ranging from 1.8 to 2.4m. This is an interesting hydrological interaction worthy investigating in future studies in the catchment.

3.1.8 Conclusions

The general trend observations with regard to the impact of innovative agricultural practices on the field soil-water balance indicate that such practices (conservation tillage) can significantly reduce surface runoff and increase the retention of soil moisture content and hence influence the partitioning of rainfall over the catchment. Nevertheless, there is a need to establish if there is any interaction between the shallow ground water and the soil moisture at deep depths in the soil profile given the fact that the shallow ground water in the catchment was found to fluctuate between 1.8 to 2.4m below the surface. These results sets the platform for further investigation on the possible impacts to the eco-hydrological system of the catchment if such water use innovations are adopted by many smallholder farmers in the catchment (up-scaling) and the Thukela River basin at large. Such an investigation can be complemented with a hydrological modeling exercise.

4.0 Surface and sub-surface water interactions in the Potshini catchment-S.Africa

Summary

Stream flows, weather parameters and fluctuation of shallow ground water table were monitored in the 1.2km^2 Potshini catchment over a period of two years. The fluctuation of the shallow ground water table was monitored by the use of shallow ground water observation wells (piezometers) along two transects, with each transect having four wells and running along the general slope of the catchment. These observations were complemented by geophysical measurement (Electrical Resistivity Tomography-ERT) surveys along several transects in the catchment, including the wells transects, at wet and dry times of the year.

The field observations indicate that the first response of the shallow ground water to rainfall decreases from 5 days to less than 1 day, the latter being during mid rain reason when the soils are saturated. The analysis further indicates that there is a correlation between the rainfall intensities and the fluctuation of the shallow ground water table in the catchment, with subsiding ground water levels mimicking the recession part of the stream flow in the Potshini catchment. The importance of shallow ground water to sustain the base flows, through the dry winter season, in the catchment was demonstrated, with shallow ground water contributing around 75% of the stream flow during the dry season. Thus, the surface water and shallow ground water systems in the Potshini catchment are closely linked and hence any land use changes in the catchment that may influence the occurrence of shallow ground water will have a direct effect on the stream flows, of which may be quantified through further hydrological analysis including hydrological modelling. The ERT investigation and results facilitated the characterization of the subsurface and identification of hydrological variables in the subsurface, especially preferential flow paths and connection between the subsurface water and the stream flows in the catchment, which are otherwise difficult to establish using classical hydrometric measurements. Thus, the ERT mapping gave a pictorial view and understanding on the interaction of surface and sub-surface water in the Potshini catchment.

4.1 Introduction

The main components of stream flow include overland flow, interflow and the base flow. The contribution of overland flow to the integrated stream flow is only significant during rainfall events,

often leading to peak flows, while interflow and base flow are the main components that sustain stream flows during the recession part of a hydrograph especially in smaller semi-arid catchments, such as the Potshini catchment (Figure 4.1) in the Bergville district in South Africa. Interflow, the preferential lateral flow through the soil matrix, contributes significantly to stream flow after a rainfall event while the base flow (contribution of ground water) dominates the stream flows thereafter. Several authors including Montgomery et al., (1997); McGlynn et al., (2002) and Wenninger et al., (2004) have highlighted the imperative need of the knowledge on the processes, pathways and interaction of the surface and sub-surface water in a catchment, especially in the conceptual and physical understanding of the hydrological processes with regard to evaluating the vulnerability of surface and ground water systems in a catchment. A catchment water balance strives to account for the various components of the hydrological cycle and studies of interactions between surface water and ground water often target interactions that occur on different timescales (Judson et al., 2006). For example, hillslope process hydrologists are interested in the relatively fast exchanges that occur, such as hillslope subsurface stormflow and bank storage of river channel water. These processes greatly influence the magnitude and timing of effective rainfall from the catchments and routing of stream flows through the channel network. The occurrence of shallow ground water in any catchment is generally influenced by two main factors i.e anthropogenic activities and the biophysical characteristics of the catchment. Wolski and Savinije (2006) cited Winter (1999), Woessner (2000) and Saphocleous (2002) to have indicated that the nature of the interaction between surface and ground water, i.e, direction and magnitude of the water flux, is a result of complex interplay of climate, morphology, soils, geology, vegetation and hydrology of a system. Several authors including Uhlenbrook et al., (2002), Judson et al., (2006) and Randall et al., (2006) have indicated that shallow ground water contributes significantly to the total stream flow volumes and hence the necessity to establish its direction and magnitude of flow. McCarthy (2006) further highlighted that ground water and surface water cannot be considered in isolation, as they form components of a highly integrated system. Several methods for quantifying the recharge and discharge fluxes of shallow ground water have been tested and applied in various regions including the use of isotope tracers, measurement of hydraulic heads in piezometers combined with hydraulic conductivities (e.g Wenninger et al., 2004), use of modeling tools etc.

This Chapter focuses on the hydrological interactions within a small headwater catchment in the upper Thukela river basin, in Bergville district of KwaZulu-Natal province in South Africa (cf. Figure 4.1). Nevertheless, it is rather difficult to determine such interactions under different environments without field investigations. To achieve the objective of this study, two approaches of field investigations were conducted, i.e classical hydrometric studies using piezometric shallow ground water levels along two

transects in the catchment and geophysical measurements to explore subsurface soil properties. A slug test was also conducted on six out of the 12 piezometers in the catchment (cf. Figure 4.1) in an effort to determine the in-situ saturated soil hydraulic conductivity (K_{sat}) along the two transects and to complement the K_{sat} results obtained from laboratory analysis of soil samples obtained in the catchment.

The Potshini sub-catchment (cf. Figure 4.1) is characterized by a relatively high water table (cf. Table 4.1), with patches of small marshy areas on the upper slopes of the catchment which contribute significantly to stream flow volumes, especially during the dry season (May to September). One of the subsurface geophysical methods, Electrical Resistivity Tomography (ERT), was applied in surveying and mapping subsurface conditions over a wide area of interest (along hillslope transects) in the Potshini catchment in an attempt to improve the characterization of the hydrological processes in the subsurface. The subsurface resistivity is mainly related to various geological and hydrological parameters i.e lithology, (rock and grain sizes, porosity, mineralogy etc), the fluid content (solutes) and the degree of water saturation (Uhlenbrook et al., 2005; Samouëlian et al., 2005). More detailed information on the theories and practical application of geophysical methods can be obtained from Telford et al., (1976) and Loke (2003). Nevertheless, resistivity measurements are particularly useful when they are integrated into other site measurements where they can be interpreted along with other available information for the site e.g. piezometric heads as in the case of ground water investigations. The resistivity survey is a typical method for measuring the bulk resistivity of soil or rock volumes occurring between the measuring electrodes. This technique utilizes artificial electric currents that are introduced into the ground through electrodes or a long line of contacts and at the same time determining the apparent resistivity of the subsurface volume by measuring the potentials at other electrodes in the vicinity of the current flow, thus providing information on the form of subsurface heterogeneities and their electrical properties (Kearey et al., 2002). Uhlenbrook et al., (2005) highlighted the limitations of the 1-D method (vertical sounding) where the electrode array is measured by sequentially increasing the distance between the current electrodes to obtain vertical resistivity information at increasing depths. This method does not take into account the lateral changes in subsurface resistivity which are caused by the heterogeneities that exist on a hillslope and hence the 2-D method was used in this study. The 1-D resistivity sounding surveys usually involve about 10 to 20 readings, while 2-D imaging surveys involve about 100 to 1000 measurements; combining surface profiling and vertical sounding. In comparison, 3-D surveys usually involve several thousand measurements (Griffiths and Barker, 1993 and Loke, 2003) and are expensive to carry out and is still a research domain for geophysists but not practically applicable for environmental and or hydrological investigations.

The objective of this study was to understand the main hydrological variables and determine the interaction of the surface and sub-surface water in the 1.2 km^2 Potshini catchment as a contribution to the characterization of similar hydrological systems especially in semi arid environments. In this Chapter, the complementary role of the ERT surveys on the point-piezometric ground water measurements is explored in quantifying the relative contribution of subsurface water to the stream flows in the Potshini catchment and their integral interpretation led to the development of a conceptual model for the Potshini catchment. In order to appreciate and have an overview of the surface-subsurface water interaction, it is imperative to examine the main bio-physical parameters driving the hydrological system in the Potshini catchment.

4.2 Study site

The Potshini catchment (E 29.3679^0 S 28.8145^0) is a small headwater catchment on the upper Thukela river basin, Figure 4.1, in the KwaZulu-Natal province of South Africa. The Department of Water Affairs of South Africa has subdivided the Thukela river basin into 86 management units (Quaternary Catchments), which add up to a total area of 29,036 km^2. The Potshini catchment, with an area of 1.2 km^2, falls within the Quaternary Catchment number V13D which has an area of 280 km^2. The mean annual precipitation at Potshini is estimated to be 700 mm per annum (Smith et al., 2004) and the estimated mean annual potential evaporation is between 1600 to 2000 mm per annum (Guy and Smith, 1995).

The altitude of the catchment ranges from 1300, on the lower parts of the catchment, to 1340m on the divide. The maximum and minimum temperatures recorded in one of the two weather stations in the catchment (cf. Figure 4.2) between April 2004 and April 2007 is 34 and -4°C respectively. Frost is severe to very severe in winter (May to August) and hail is sporadically severe in summer (September to April), i.e during the rainy season. Figure 4.2 indicates and overview of the daily variation of rainfall, reference evapotranspiration and temperature while Figure 4.3 shows an overview of the monthly variation of rainfall and temperature in the Potshini catchment. May to August are the coldest months in the catchment with the least rainfall, as illustrated in Figure 4.2 and 4.3, and it is during these months that the contribution of the subsurface water to the stream flows in the catchment is more significant. A perennial stream drains the Potshini catchment which provides water for domestic use in the upper parts of the catchment while replenishing reservoirs for commercial farmers downstream. The main river which drains the Quaternary Catchment V13D is the Lindequespruit, a tributary of the Little Thukela which later joins the Thukela river.

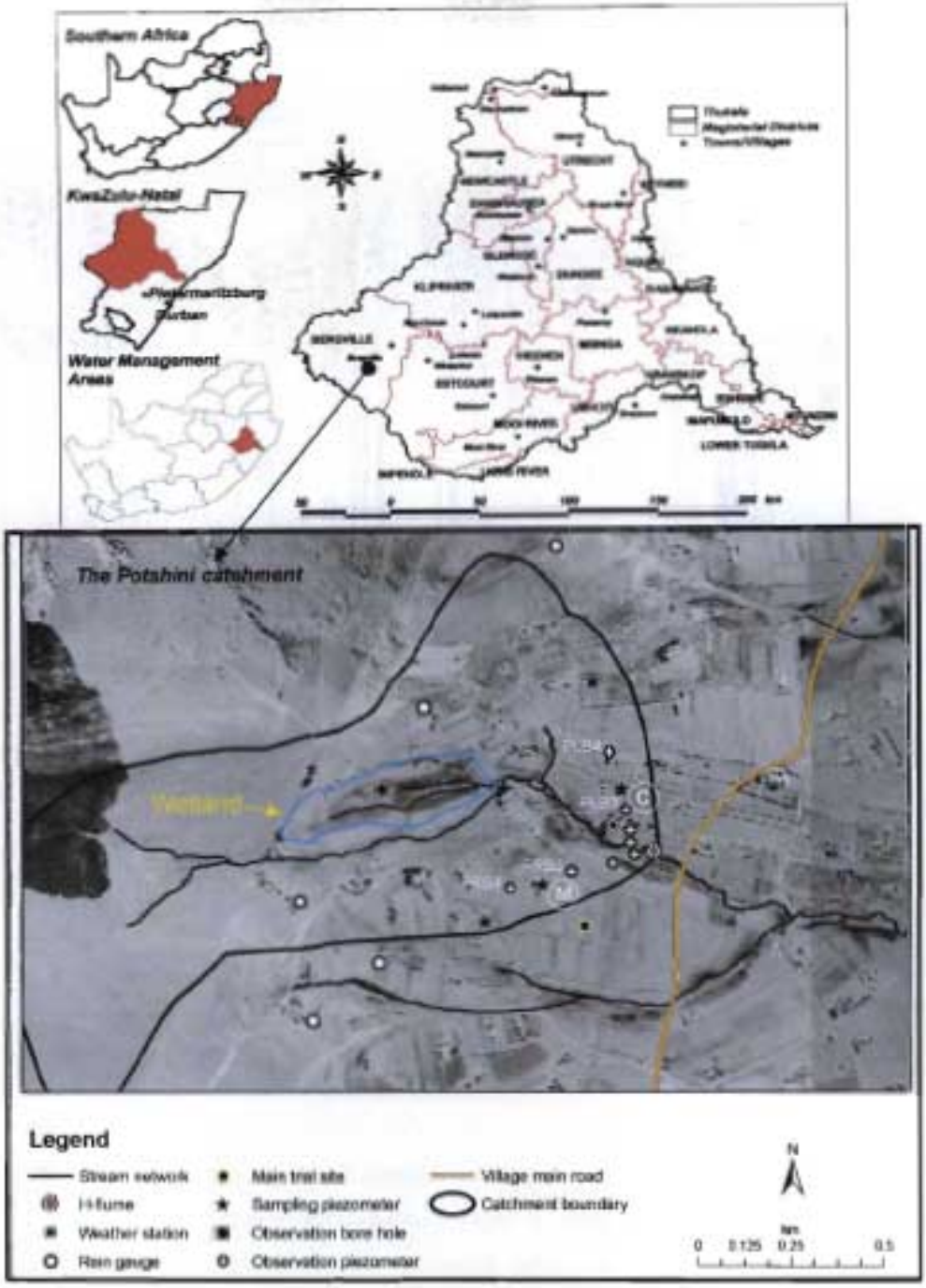

Figure 4.1 An overview of the Thukela river basin and the Potshini catchment

The Potshini catchment has a relatively high water table ranging from 0.8 to 2.4m below the surface during the dry season as shown in Figure 4.8. During the wet season, the water table has been observed to rise close to the ground surface as highlighted in the results section of this Chapter. The

rising water table in the catchment led to the collapse of several houses in late February 2006 when the catchment received heavy rainfall of high intensities.

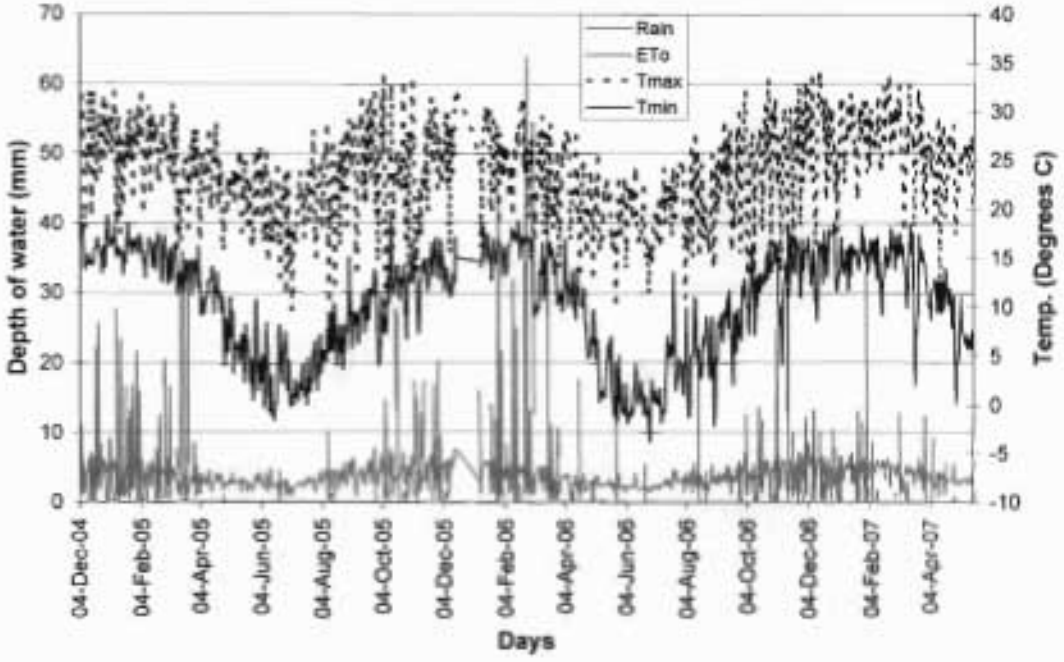

Figure 4.2 An overview of the variation of daily rainfall, reference evapotranspiration and temperature in the Potshini catchment between December 2004 and May 2007. The data was recorded from one of the weather stations in the Potshini catchment

4.2.1 Soils and geology

The soils in the Potshini catchment are generally acidic with depths varying from 1.2m to over 3m on the lower parts of the catchment. The soil texture varies with the proximity to the stream, with sandy loam soils being dominant near the stream, while loam and clay loam soils on the higher periphery of the catchment. Table 4.1 indicates the soil textural class around each of the 8 observation piezometers (cf. Figure 4.1 and 4.4) installed on the two transects of the catchment. There is a remarkable spatial variation of soil bulk densities in the catchment, with values ranging from 1417 to 916.4 $Kg.m^{-3}$, and hence the heterogeneity in other soil hydraulic parameters including infiltration rates and hydraulic conductivity. Smith et al., (2004) cited Turner (2000) in describing the dominant geological formations underlying the region around the Potshini catchment as being sandstone and mudstone of the Tarkastad Formation and by shale and sandstone of the Estcourt Formation (based on the South African soil classification system).

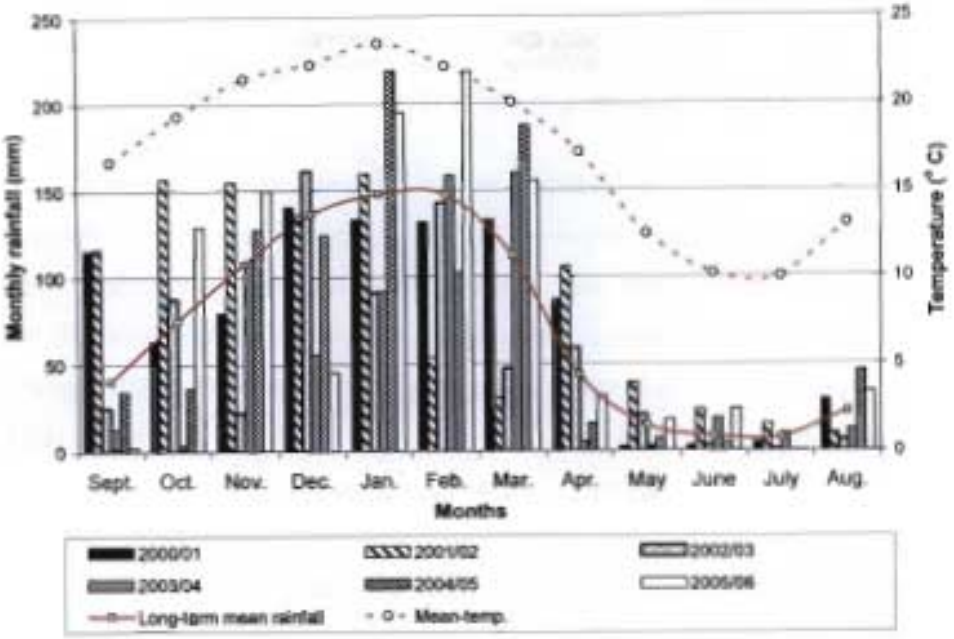

Figure 4.3 Monthly variation of rainfall in the Potshini catchment as recorded at one of the weather stations in the Potshini catchment. The long term mean monthly rainfall and mean temperature was derived from a 28-year climatic data record from Bergville weather station located 8 km away from the Potshini catchment)

4.2.2 Land uses

The main landuse types in the Potshini catchment include the predominant smallholder farming (crop production) during summer, which constitutes approximately 60% of the total land in the catchment, and grazing. The smallholder farms are individually owned while grazing areas and boreholes that were installed by the local authorities are considered common property. The main crop that is grown during the rain season (October to April) is maize, beans and pulses while the main natural vegetation in the catchment is veld grass which is used for thatching houses in the community. The main sources of water for domestic use in the community are bore holes, springs and the Potshini stream. The community grazing management entails allowing the domestic animals (cattle, goats and horses) to graze freely on the smallholder farming land during the dry winter season (May to September), as a consequence of depleted pastures on the secured grazing lands on the upper slopes of the catchment during the wet summer season. Such a practice has contributed to the increasing soil erosion in the catchment especially at the onset of rain season when the vegetation cover is poor and soils are bare and loose due to the grazing of livestock.

4.3 Material and methods

4.3.1 Monitoring of shallow ground water

A detailed account on the establishment of the Potshini research catchment monitoring network is documented in Chapter 2 of this thesis. Through the collaboration and participation of the Potshini community, 8 observation and four sampling piezometers were installed in the 1.2km^2 Potshini catchment (cf. Figure 4.1) after a reconnaissance survey. Two transects, one on each side of the catchment, were identified and running along the general slope of the catchment as indicated in Figure 4.1. 100mm diameter holes were augered by hand to depths reaching the bedrock but never deeper than 3.5m. Slotted 63mm diameter plastic tubes of appropriate lengths were inserted into the augered holes such that at least 0.4m length of the pipe was above the ground surface. The tubes had thin horizontal slots machined through the pipe over the bottom 0.6m, through which subsurface water could seep into the tube. To avoid clogging of the perforations by fine clay soil at the bottom of the wells, a clean (washed) sand screen was packed around the plastic tubes covering the perforations to a height of 0.8m from the bottom of the wells. Pressure transducer and HOBO data logger systems were installed in the 8 observation piezometers to record the fluctuation of the water table at a time step of 30 minutes. The data loggers and their respective power batteries were secured in metallic safe boxes embedded in concrete to safeguard the data loggers from unfavorable weather conditions and vandalism. Table 4.1 indicates the respective depth of each observation piezometer, the observed column of water in the piezometers during installation of the data loggers and their relative position with respect to the Potshini stream.

The soil textural class information indicated in Table 4.1 was obtained after a study by de Winnaar et al., (2007), from which the spatial variation of the dominant soil textural classes in the Potshini catchment was mapped. Thus, Table 4.1 indicates the dominant soil textural class in the vicinity of each of the 8 observation piezometers in the Potshini catchment.

4.3.2 Saturated hydraulic conductivity (K_{sat})

Undisturbed soil samples were obtained on both the left and right side of the catchmet on two sites (Site *C* and *M* in Figure 4.1) that represented the dominant land use in the catchment, i.e smallholder farming. These two sites were close to the third piezometer from the stream on each transect, with site *M* being close to *PRB3* and *C* close to *PLB3* respectively (see Figure 4.1). The textural class of the soils around *PRB3* and *PLB3*, as highlighted in de Winnaar et al, (2007), is indicated in Table 4.1. On each site, core rings were used to obtain the soil samples at depths of 0, 300, 600, 900 and 1200mm,

from which the saturated hydraulic conductivity (K_{sat}) was measured in a laboratory by means of a permeameter (Klute, 1986) with the pore water pressure determined at the base and the top of the sample, by applying Darcy's Law across the soil samples (Lorentz et al., 2001) and using three settings of constant head tank, i.e 900, 1200 and 1500mm from which three determinations of gradient and outflow rates were made.

Table 4.1 Details of the piezometers installation in the Potshini catchment

Piezometer ID	Position from the stream	Initial depth of water column in the Piezometer (m)	Total depth of the Piezometer (m)	Altitude (masl)	Soil textural class
PRB1	1st, right bank	2.12	3.22	1308	Sandy loam
PRB2	2nd, right bank	1.98	3.32	1309	Clay loam
PRB3	3rd, right bank	1.24	2.84	1316	Loam
PRB4	4th, right bank	0.63	3.38	1324	Loam
PLB1	1st, left bank	2.06	3.32	1308	Sandy loam
PLB2	2nd, left bank	1.86	3.46	1313	Loam sand
PLB3	3rd, left bank	2.1	3.41	1315	Sandy loam
PLB4	4th, left bank	2.08	3.38	1328	Sandy loam

The laboratory analysis was done at the Process Hydrology Laboratories at the School of Bioresources Engineering and Environmental Hydrology in the University of KwaZulu-Natal. The average saturated hydraulic conductivity for each sample and associated standard deviations were then computed. The laboratory K_{sat} results were complemented with in-situ measurements of K_{sat} obtained from a slug test (Klute, 1986) on six piezometers on the left and right bank of the catchment, i.e *PRB1, PRB2, PRB3, PLB1, PLB2* and *PLB3* as indicated in Figure 4.1 (the piezometers in Figure 4.1 are numberd decreasing towards the stream). Water was pumped out of the piezometers and the rate of rise of ground water was recorded. The pumping exercise, using a Treadle pump, involved pumping all the water in the piezometers and the exercise was repeated at least thrice in each piezometer, depending on the recovery rate. The average in-situ K_{sat} was then computed using the methodology outlined in Klute (1986), i.e:

$$K = \frac{\pi r^2}{C(t_{i+1} - t_i)} * ln \frac{y_i}{y_{i+1}} \quad (4.1)$$

where K is the saturated hydraulic conductivity (mm.h^{-1}), r is the radius of the piezometer (cavity) (mm), y_i and y_{i+1} is the difference between the depth of ground water and the depth of the water in the pipe (mm) at time t_i and t_{i+1} (hrs) respectively and C is a geometrical shape factor (mm) for the piezometer pipe obtained from a table as illustrated in Klute (1986).

As highlighted in (Klute, 1986), unlike laboratory methods, there is no simple methodology for determining in-situ K_{sat} due to the fact that flow of water into the piezometer is three-dimensional and the flow properties could be different in each direction and the piezometer cavity might extend through strata with different hydraulic characteristics.

4.3.3 Stream flow monitoring

As described in Chapter 2, the stream flow at the 1.2 km^2 Potshini catchment was monitored by use of an H-flume that was constructed in 2004 with the assistance and participation of the local community. The H-flume is governed by a set of 3 rating equations, each describing a unique stage-discharge relationship for a given range of flow depth (Ackers et al., 1978) corresponding to high, low and intermediate flows and controlled by a Mike Cotton System (MCS) data logger. It is noteworthy that the flow recording scheme at the H-flume was governed by the flow regime, with the MCS data logger logging more frequently during high flows and hence made it possible to record the maximum and minimum flows in a day.

The H-flume was also equipped with an ISCO sampler to allow for automated sampling of the stream discharge, for water quality and isotopic analysis. The automatic sampler had the capacity of 24 sampling bottles of 500ml each. The sampling scheme was controlled by an MCS data logger and programmed to take into account of the variation of flow by taking frequent samples during a changing flow. This is due to the fact that water quality (e.g sediment load) shows less variations at constant flow and hence frequent sampling is only required for changing flow.

4.3.4 Meteorological parameters

Two automatic weather stations were operational in the Potshini catchment since 2002 and 2004, respectively. In addition, eight manual rain gauges were installed in the 1.2 km^2 catchment to capture the spatial variation of the rainfall over the catchment. The manual recording of rainfall was done

twice a day, i.e at 09h00 and 17h00, from which the daily rainfall was computed as the sum of the morning and evening readings.

4.3.5 2-D electrical resistivity imaging survey

The geophysical electrical resistivity techniques are non-destructive techniques that provide pseudo-section of the subsurface in terms of changes in resistivity. In this study, the 2-D Electrical Resitivity Tomography surveys were carried out with the objective of characterization of the structure and to identify hydrological processes in the subsurface. The geophysical methods are useful both as a means of rapid site reconnaissance that can provide information on the subsurface structures and also in extrapolation of observed data to previously uninvestigated areas where sufficient site correlations have been established between the subsurface structure being extrapolated and the information derived from the geophysical survey. In this study, 6 hill-slope transects (Number 1 to 6 in Figure 4.4) were surveyed during the dry winter season (August 2006), with a maximum electrode spacing of 5 meters, with two of the transects coinciding with the hillslope piezometer transects on the right and left bank of the stream. Figure 4.4 shows the layout of the resistivity survey transects in the Potshini catchment. The resistivity survey was repeated on three out of the six transects during the wet summer season, March 2007. The inability to repeat the resistivity survey on all the six transects in March 2007 was due to the presence of actively growing summer crops on some of the transects, which traversed across the smallholder farms in the catchment. These crops could otherwise be damaged during the survey exercise. Three "new" transects were surveyed in March 2007 (Number 7, 8 & 9 in Figure 4.4) at an electrode spacing of 1 meter in an effort to characterize in detail the structure and identify the hydrological processes across the stream cross-section. Two of these "new" transects ran across the stream channel while the other one was parallel to the right bank, 50 meters from the stream. The other transects were surveyed with an electrode spacing of 5m. The resistivity survey was carried out using the ABEM Terrameter system (comprising 4 cables with a total of 81 outlets), with the transects having an electrode spacing of 5m spanning to 400m long.

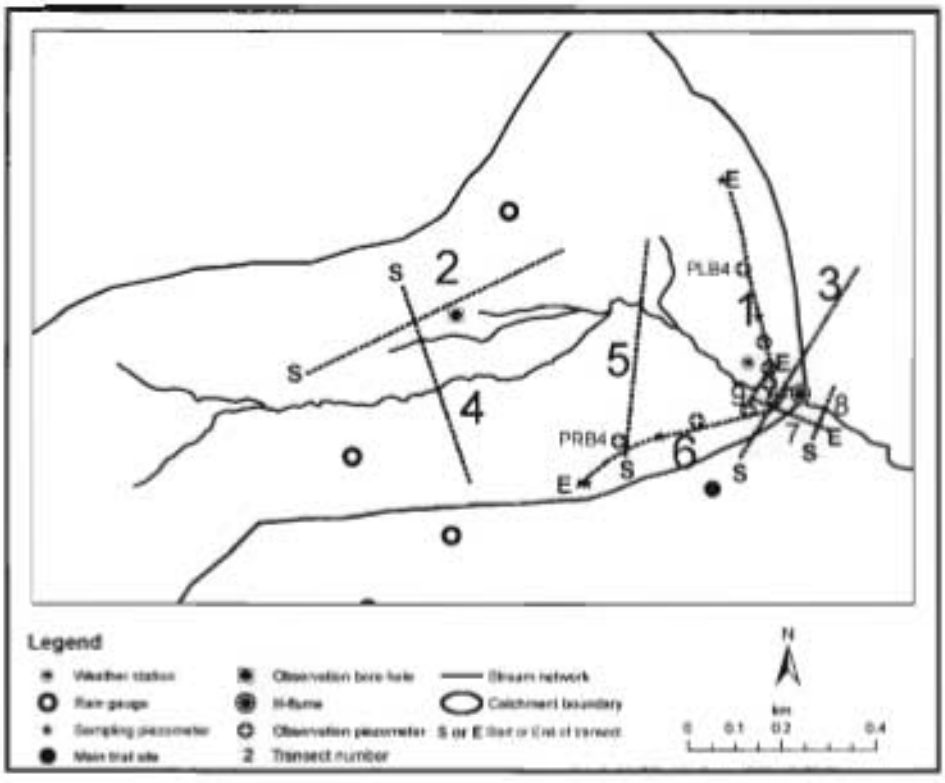

Figure 4.4 Resistivity survey transects in the Potshini catchment. Right bank ground water observation hole PRB4 and left bank observation hole PLB4 are shown. The other observation wells are numbered, decreasing towards the stream.

A roll-along procedure (installing quarter of the electrodes at the end of the transect as soon as the first quarter of the electrodes are free) was used along the transects with an electrode spacing of 1m to enable carry out measurements on transects spanning more than 100m. The Wenner Log protocol, which is sensitive to vertical changes in the subsurface resistivity (Loke, 2003) was used to provide deeper subsurface measurements. It is worth noting that the resistivity survey was also aimed at identifying potential sites for installing 2 deep observation ground water wells in the catchment. The apparent resistivities were computed using the RES2DINV software and applying the 2-D inverse numerical modelling technique and optimized using a standard Gauss-Newton method, where an exact solution of the apparent resistivity's least squares equation was determined. This is applicable where the number of data points are less than 2000 as was the case in this study, otherwise the time taken to solve the least squares equation can be long and hence increases the time for the inversion process. Relative elevation data for each electrode on each transect was included in the modelling exercise to account for the effect of topography on the occurrence of geological features (resistivities) along the respective transects.

4.4 Results and discussion

4.4.1 Rainfall, stream flow and ground water levels

The data recorded from the piezometers was useful in the interpretation of the storage and movement of subsurface water on the respective transects along the hillslope of the catchment. It is noteworthy that the data logging scheme at the H-flume was designed based on the characteristics of the flow regime, e.g. more data points were to be recorded during a varying flow, while the rainfall events and the fluctuation of the water table were recorded at an hourly time step. In this study, the fluctuation of the water table as observed from four piezometers on the South-westerly transect (right bank in Figure 4.1) is presented. It was not possible to record concurrently the fluctuation of the ground water in all piezometers due to occasional failure of the respective data logging systems. Figure 4.5 shows the variation of maximum daily discharge and rainfall while Figure 4.6 shows the variation of maximum daily discharge and the cumulative rainfall between 23rd October 2004 and 7th April 2007 thus covering three rainfall seasons. In this analysis, a rainfall season was defined to start on 1st September and end on 30th June of the following year. From Figure 4.6 it can be noted that the 2005/6 season had the highest cumulative rainfall of 864mm which was received in 139 days compared to 2004/05 and 2006/7 which received 677 (113 days) and 445mm (115 days) respectively.

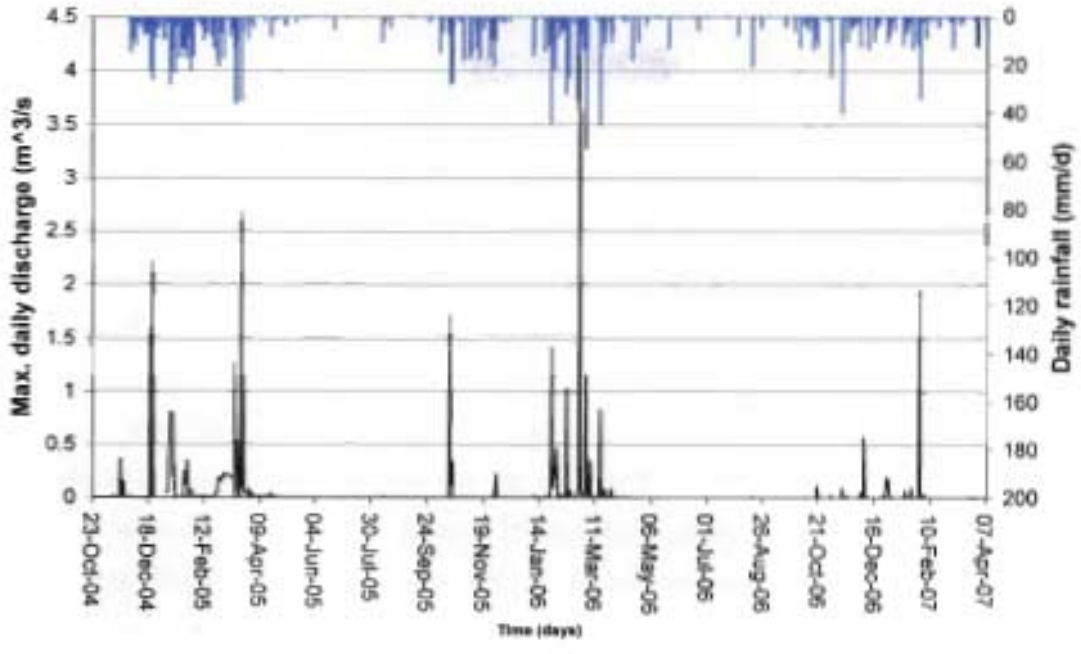

Figure 4.5 Maximum daily flows and rainfall

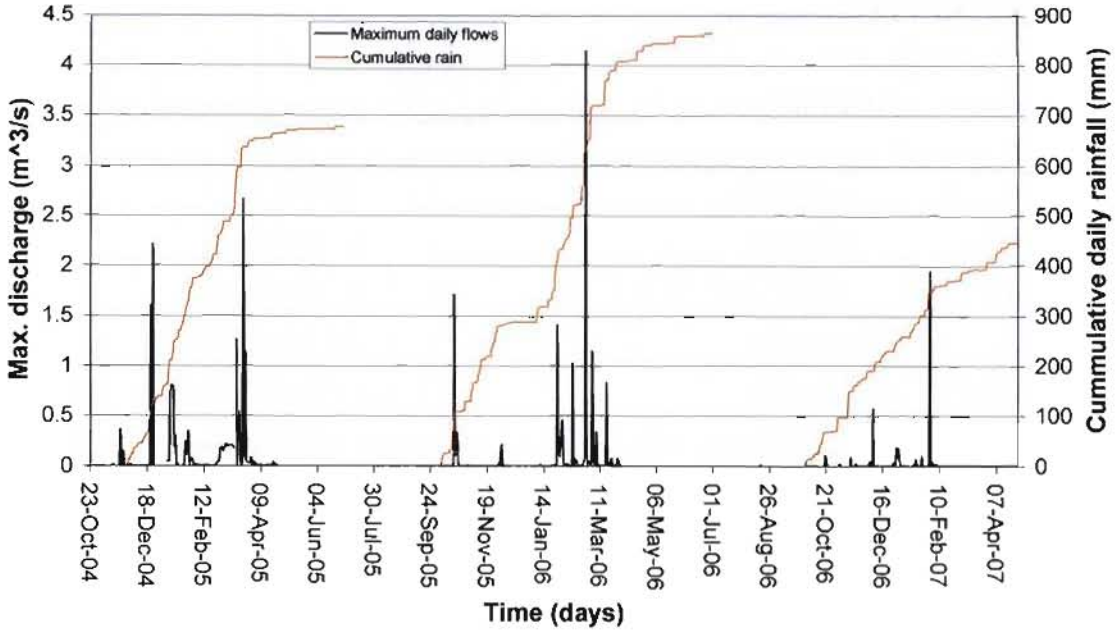

Figure 4.6 Cumulative daily rainfall and daily maximum discharge

It is interesting to note that the 2006/07 period had more days of rainfall compared to 2004/05 although the later had relatively higher cumulative rainfall. This could be attributed to the variation of intensities of the daily rainfall events over these periods as indicated in Figure 4.5, where 2004/05 received more than 10 rainfall events of greater than 20 $mm.d^{-1}$ compared to only 3 events over the 2006/07.

A plot of the cumulative rainfall for each season, Figure 4.6, depicted the variation of the intensities of the daily rainfall events, with the cumulative curve for the season 2006/07 having the gentlest slope, a possible indication of lower daily intensities, and hence the lowest total rainfall over the three rain seasons. The highest daily rainfall over the three seasons was observed on 23rd February 2006, where 67mm were recorded on this day. This event generated the highest stream discharge estimated at 4.12 $m^3.s^{-1}$ as indicated in Figure 4.5. It is noteworthy that even though this discharge is above the rated flume capacity of 3.42 $m^3.s^{-1}$, all the flow was accommodated in the approach channel and hence provided an opportunity to cautiously extend the H-flume's rating curve, otherwise this could not be applicable if the approach channel was inundated or overtopped its walls. The highest peak flow for 2004/05 and 2006/07 was found to be 2.26 and 1.9 $m^3.s^{-1}$ respectively with all peak flows coinciding with the highest daily rainfall events. The 2005/06 season experienced the longest intra-seasonal dry spell of 28 days as indicated in Figure 4.5 and 4.6. This occurred between 10th December 2005 and January 7th 2006, depicted by a flat peak on the cumulative curve of daily rainfall, and this resulted into great losses to majority of the smallholder farmers in the community after their newly germinated

crop seeds withered and scorched under the hot and dry weather conditions. The first rainfall event of intensity greater than 5mm.h^{-1} in the 2005/06 season was recorded on 16/10/05. A summary of similar events prior to 19/11/05, when monitoring of ground water commenced in the Potshini catchment, is as indicated in Table 4.2.

Table 4.2 Rainfall events prior to installation of piezometers in the Potshini catchment in 2005

Date (day/month)	16/10	17/10	18/10	29/10	04/11	06/11	12/11	14/11
Max. intensity (mm.h^{-1})	13.2	7.5	20.7	5.5	8.6	5.6	5.2	12.6
Daily rainfall (mm.d^{-1})	27	13.5	27.1	17.7	17.4	14.9	6.1	17.4

From Table 4.2, it can be observed that most of the rainfall intensities greater than 5mm/h in the catchment resulted in relatively high amounts of daily rainfall on the respective days as further confirmed by the cumulative daily rainfall curve in Figure 4.6, where a relatively steep slope is observed until 10/12/05 when the 28-day intra-seasonal dry spell started. The highest rainfall intensity and daily amount recorded before 19/10/05 was 20.7mm.h^{-1} and 27.1mm.h^{-1} respectively, on 18/10/05 as indicated in Table 4.2. This event produced a maximum daily discharge of 1.7 $m^3.s^{-1}$ as indicated in Figure 4.6, even though most of the events indicated in Table 4.2 did not result in significant increase in stream flows. This could be attributed to the fact that these events came after a prolonged dry season (May-September) in the catchment and hence the soil was dry enough to accommodate more soil water in its porous media. Figures 4.7, 4.8, 4.9 and 4.10 show the variation of rainfall intensities, fluctuation of ground water table and stream flows in the Potshini catchment, with the observation that the variation of stream flow and fluctuation of ground water levels was influenced by both the hourly rainfall intensities and amount of daily rainfall in the catchment. It is unfortunate that there were no records from the piezometers before 19/11/05 on record the fluctuation of the ground water tables in response to the initial rainfall intensities and amounts, but one can have a rough idea of such fluxes by analyzing the trend on the cumulative daily rainfall curve, Figure 4.6, over that period. The steep slope of the cumulative daily rainfall curve over this period, signifies substantial and frequent daily rainfall events, and the high intensity rainfall of 18/10/05 may have caused the water table to rise significantly as is supported by the fact that the recession of the water table (recorded as from 19/11/05) seems to have started from a relatively high level as can be seen in Figure 4.8. It is possible to argue that, if the event of 18/10/05 was not of relatively high intensity (20.7mm.h^{-1}), then the water table could not have risen due to the high absorption and retention effect of the soil matrix under dry conditions. Such conditions have the tendency of initially rendering most of the water in the soil matrix to be restricted

to the micro-pores and not easily drained to the water table under gravitational forces. The dominant soils in the Potshini catchment are sandy clay loam soils (Turner, 2000), with relatively high retention capacities. With high intensities of 21mm.h^{-1} the storage capacity of the soil micro-pores could have been surpassed and hence the soil water sequentially filled the macro-pores in the soil matrix and subsequently drained rapidly to the water table. Such an argument could further explain the insignificant influence of the second rainfall event, on 24/11/05 of 17mm.h^{-1}, to the water table (Figure 4.7 and 4.8). On this day, the water table was observed to be on recession until 02/01/06 when it started to rise again, after a period of 40 days.

The 30-minute ground water levels were averaged to hourly time steps in an effort to plot them against the hourly rainfall intensities, from 30th December 2005 to 30th March 2006, as shown in Figure 4.10. This is the period when the catchment received the highest rainfall intensities and quantities for the last three years as indicated in Figure 4.5 and 4.6. From Figure 4.10, it can be observed that rainfall intensities of greater than 7mm.h^{-1} caused the ground water levels to rise significantly though at different lag times through the season, with the ground water levels responding slower to rainfall intensities at the beginning of the rain season and faster from the middle of the season onwards. The rainfall intensity of 17mm.h^{-1} that was received on 02/01/06 led to the rising of ground water table, from 415mm below surface and reaching the peak level of 269mm on 05/01/06 (3 days after the event) at *PRB1*, while the ground water levels at *PRB2* rose from 980mm to a peak of 614mm below surface between 02/01/06 and 13/01/06, i.e 11 days after the event. The positions of piezometers indicated in Figure 4.4 are numbered decreasing towards the stream, with *PRB1* closer to the stream. It is useful to note that the initial response (rise) of ground water to rainfall at *PRB1* was noted on the same day the 17 mm.h^{-1} event was recorded, i.e on 02/01/06, while at *PRB2* was on 03/01/06. *PRB1* is closer to the stream and the water levels before the event were much higher and closer to the surface than at *PRB2* (Figure 4.8), and hence the relatively faster response at *PRB1* could be attributed to the wetting front reaching the water table much earlier at *PRB1* than at *PRB2*.

The piezometer on the highest elevation and last on transect, *PRB4,* responded on 05/01/06 to this event (Figure 4.8) while PRB3 on 03/01/06. It is interesting to note from Figure 4.8 and 4.10 that the piezometer on the lowest elevation *(PRB1)* registered a rather a high and stable water table compared to the other piezometers. Such a high and stable water table could be attributed to lateral sub-surface inflows from higher elevations while discharging to the stream flow at the same time. The Potshini stream channel is in a steep and moderately deep gully, and it is common to see soil water (sub-surface water) discharging into the stream from the sides of the gully over the rainfall season and even beyond into the first months of the dry spell.

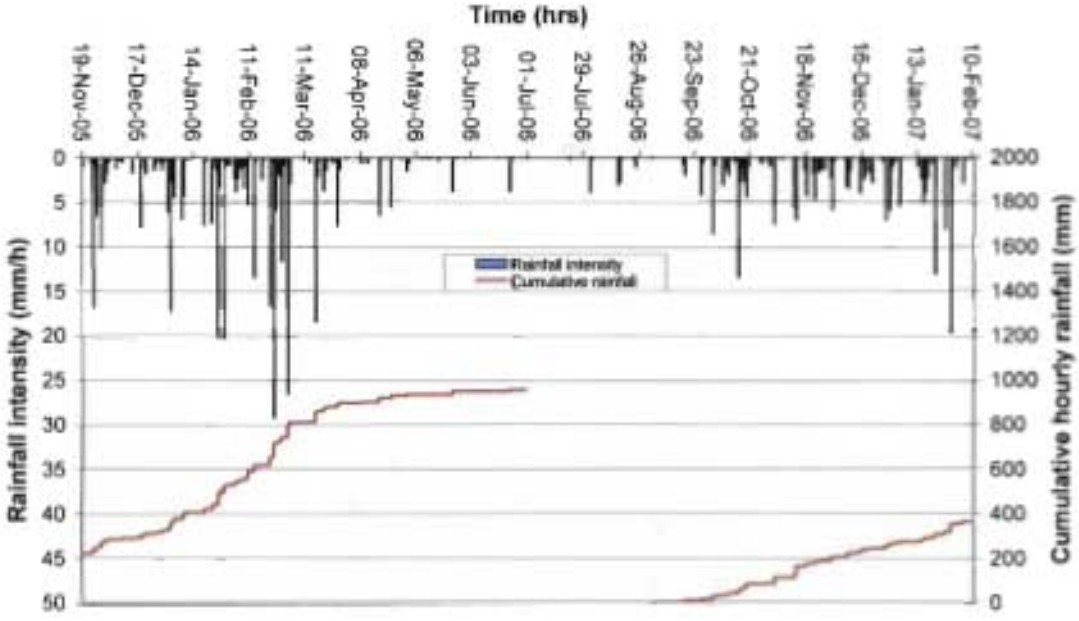

Figure 4.7 Variation of hourly rainfall in the Potshini catchment

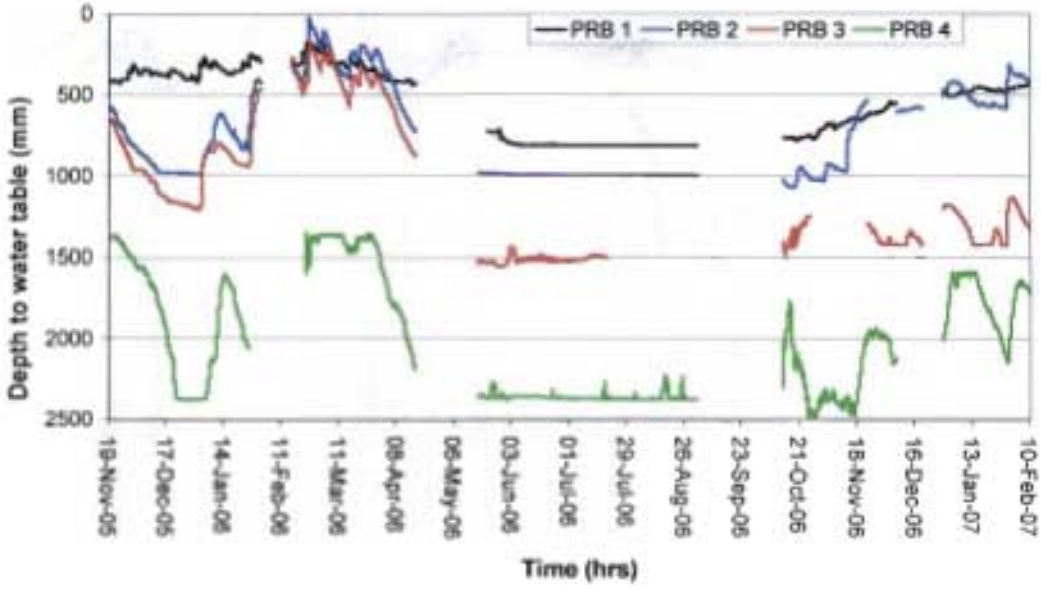

Figure 4.8 Fluctuation of ground water table in the Potshini catchment

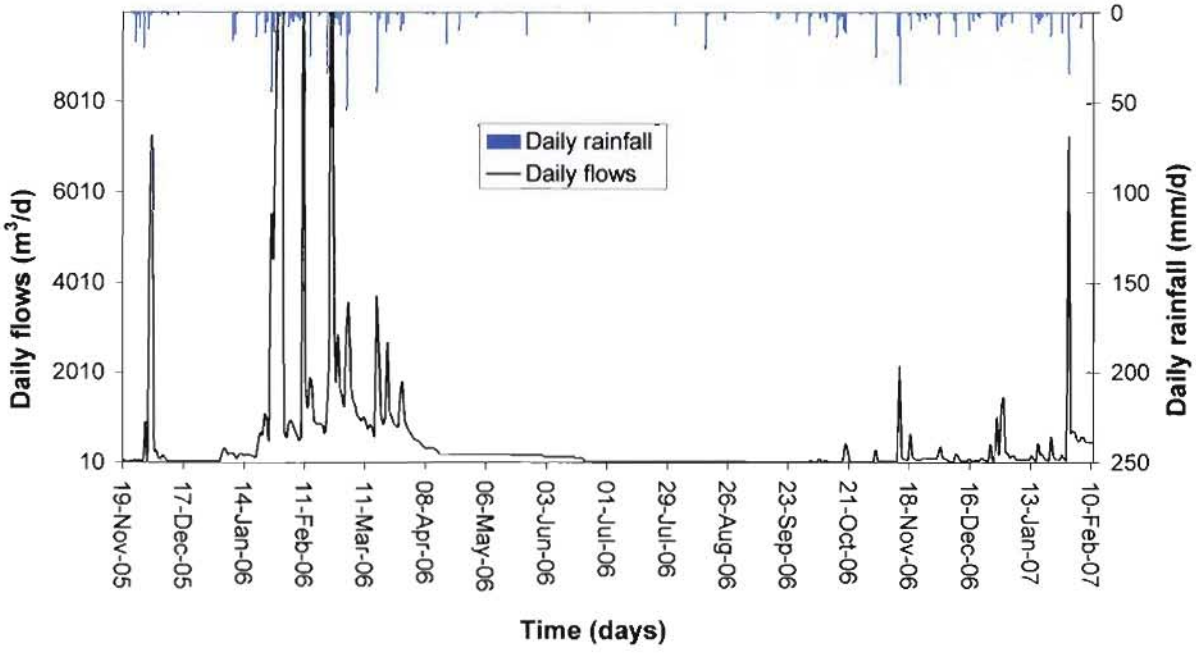

Figure 4.9 Variation of daily flows and rainfall in the Potshini catchment

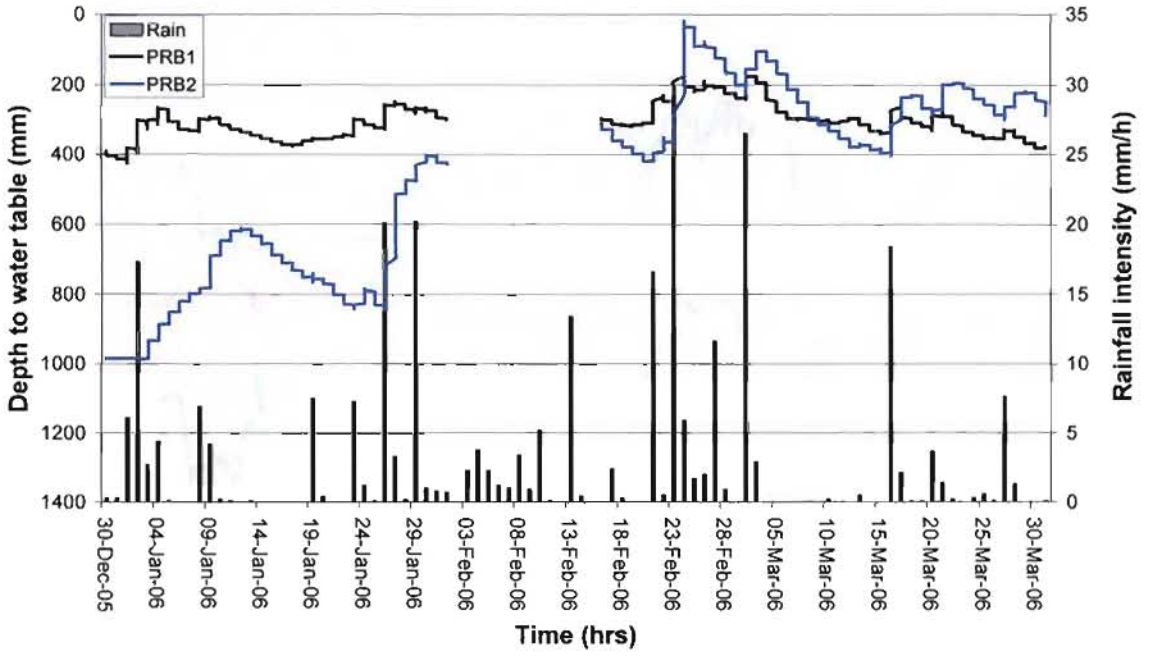

Figure 4.10 Hourly rainfall and ground water levels for the period between December 2005 and March 2006

Such a recharge and discharge phenomenon of sub-surface flows on the lower parts of the catchment could lead to the stable water table and on higher levels relative to the upper slopes of the transect.

The 7mm.h^{-1} event on 08/01/06 caused a significant rise of water table at *PRB1* and *PRB2* respectively, with *PRB2* rising from 767 to 690 mm with a lag on 1 day, while *PRB2* levels rose from 332mm below surface to 298mm with a lag of only 5 hours. The 7.5mm.h^{-1} event on 19/01/06 caused only a small increase of ground water levels, 7 and 16mm at *PRB1* and *PRB2*, respectively. This could be attributed to the 10-day dry spell between the last rainfall event of 4.5mm.h^{-1} on 09/01/06 and the 7.5mm.h^{-1} event, of which the relatively less antecedent soil moisture could have played a significant role in such a phenomenon. The 20.1 and 20.2mm.h^{-1} rainfall events of 26/01/06 and 29/01/06 lead to more recharge of ground water in the catchment, with water levels in *PRB2* increasing much faster from 830 to 405mm below surface on 30/01/06 and nearly reaching the water levels at *PRB1* (273mm), and hence a difference of only 132mm. It is useful to note that the fluctuation trend exhibited by *PRB2* was more or less the same for the other two piezometers, *PRB3* and *PRB4* as shown in Figure 4.8, though the ground water levels in *PRB3* were generally much higher than in *PRB4*, the later being the furthest piezometer on the hillslope transect.

A high intensity rainfall event of 29mm.h^{-1} occurred on 23/02/06, (Figure 4.10), which generated a lot of overland flows and subsequently stream flows, causing damage to a road culvert along the village main road (cf. Figure 4.1) and the only access into the catchment. The total rainfall that was received on this day was 67mm (i.e Figure 4.9) with an estimated corresponding stream discharge of 4.12 m^3.s^{-1}. It was observed that the catchment lag time for this rainfall event was 37 minutes, and which conforms to previous design flood computation results for the Potshini catchment as highlighted in Chapter 2 of this thesis, where it was found that the catchment lag time for a 4.2 m^3.s^{-1} flood was 34 minutes with a coefficient of initial abstraction of 0.1. The water table in all piezometers was observed to have risen significantly after this event, with *PRB2* recording the highest levels ever recorded, reaching close to the ground surface. During the same period several housing structures in the catchment collapsed due to rising water table and the maize crop in some of the smallholder farmer's fields performed poorly due to stagnant water as a result of high water table. Thus, the overland flow generated on 23/02/06 could have been generated as a consequence of rainfall intensities exceeding soil infiltration capacity or as a consequence of saturation. From Figure 4.7 and 4.10, it can be observed that, after the 23/02/06 event, the water table and stream flows rose and were maintained at relatively high levels, with an additional recharge from two events of 26 and 18mm.h^{-1} on 02/03/06 and 16/03/06, respectively. The significant recharge of shallow ground water by the big rainfall events, Figure 4.7 and 4.8, was responsible for the high ground water levels and stream flows till end

of March 2006 when significant recession of ground water levels was observed, with *PRB4* recording the first recession on 27/03/07 while *PRB2* and *PRB3* on 30/03/06, though at a difference 5 hours, with *PRB3* receding first. The influence of elevation could have played a significant role in the differential recession of ground water along the hill-slope transect. The recession of stream flows, after the end of the high intensity rainfall events, was noted to start on 28/03/06 with the stream discharge decreasing from 1780 $m^3.d^{-1}$ and reaching 185 $m^3.d^{-1}$ on 16/04/06, with the later flows maintaining until 31/05/06 when they dropped to 147 $m^3.d^{-1}$ on 02/06/06 and further to 109 $m^3.d^{-1}$ on 16/06/06 and finally to 32 $m^3.d^{-1}$ on 23/06/06. There seemed to be a pattern in the recession of both the ground water levels and stream flows, with high base flows being observed when the ground water levels receded from relatively high levels and vise versa. Of interest are the 32 $m^3.d^{-1}$ flows that were observed to be relatively stable and sustained throughout the dry season, a significant contribution of sub-surface flows, where the ground water levels in all piezometers were stable and very low, e.g 1570 and 2182mm below surface for *PRB3* and *PRB4*, respectively.

The onset of the 2006/07 rainfall season in September 2006 was marked with relatively low rainfall intensities and daily amounts compared to the 2005/06 season as shown in Figure 4.7 and 4.9. There was a remarkable difference in the cumulative rainfall for the two seasons at any given time, e.g, the cumulative rainfall at the end of the month of November in 2005 and 2006 was 272 and 189mm respectively, with the 2005/06 cumulative rainfall curve having a steeper gradient than the 2006/07 curve. It is generally acknowledged that the steeper the cumulative rainfall curve gradient the higher the rainfall intensities depending on the time scale under consideration. The highest rainfall intensity observed over the 2006/07 season was on 30/01/07 where 19mm.h^{-1}, were recorded and a daily total rainfall of 34mm.d^{-1}, of which generated the highest discharge events over the season, with a maximum daily flow of 1.9 $m^3.s^{-1}$ and total daily flow of 7,246 $m^3.d^{-1}$. These maximum flow rates for the 2006/07 season are quite low compared to the previous season of 2005/06, where the maximum daily flow was estimated to be 4.12 $m^3.s^{-1}$, by extrapolating the H-flumes rating curve, and a total daily flow of 20,501 $m^3.d^{-1}$ after the catchment received 29mm.h^{-1} rainfall intensity and a daily total of 67mm.d^{-1} on 23/02/06. From Figure 4.9, one can distinctively use the 1000 $m^3.d^{-1}$ flow rate mark to categorize the contribution of various flow components in the catchment in the two seasons, with the maximum base flows in the 2005/06 season approaching the 1000 $m^3.d^{-1}$ mark, the later being the average peak storm flows for the 2006/07 season. Ground water levels in the catchment during the 2006/07 rainfall season were observed to respond to the rainfall hourly intensities and daily amounts even though the ground water levels were generally lower compared to the 2005/06 season as shown in Figures 4.7, 4.8 and 4.9. It is interesting to note that ground water levels in *PRB3* during the 2005/06 rain season, especially during the months of February and March, were close to water levels

at *PRB2*. This was not the case during 2006/07 rain season, where ground water levels at *PRB3* were much lower than those recorded at *PRB2*, with the later often rising to higher levels, close to the surface, than *PRB1*. Again, it was observed that water levels at *PRBI* did not fluctuate much as compared to other piezometers along the transect and hence the influence of elevation with regard to the movement and accumulation of ground water to lower parts of hill-slopes and the recharge-discharge phenomenon of ground water near the stream could be the main reason for such stable ground water levels. Generally, it can be concluded that the relatively low ground water levels observed in the catchment during the 2006/07 rain season was as a result of the rather low rainfall amounts and intensities that were received in the catchment.

In summary, the results presented in this section highlights the importance of rainfall intensity and total daily amount with regard to generation of stream flows and response of shallow ground water in the Potshini catchment. The response of the shallow ground water to rainfall at the beginning of the wet season was slower (e.g 2-3 days), compared to the mid of the rain season when the shallow ground water responded to rainfall events within hours.

4.4.2 Saturated hydraulic conductivity

Results of the saturated hydraulic conductivity from undisturbed soil samples obtained from two sites in the catchment, site *C* and *M* (cf. Figure 4.1), and associated bulk densities are presented in Figure 4.11 and 4.12. Conductivities at site *C* ranged from 10.13 to 120.43mm.h^{-1} with the 300-600mm depth being the highest. Material at this depth is also the least dense, which accounts for the high conductivity. It is unfortunate that the spatial variation of the bulk density at this depth was not investigated to determine whether this is a feature of the soil form at this depth or otherwise. Conductivities at site *M* are somewhat lower, ranging from 0.17 to 9.20mm.h^{-1}. However, the bulk densities are similar to those at site *C*, and hence the difference in K_{sat} values could be attributed to heterogeneity in soil texture at the two sites, with the dominant soil texture around site *M* and *C* being loam and sandy-loam respectively (de Winnaar and Jewitt, 2007). The two sites had low conductivities at deeper depths of 1200mm and relatively high bulk densities, of which could be attributed to minimal human activities at such depths, e.g, tillage, and the possibility of clay soils.

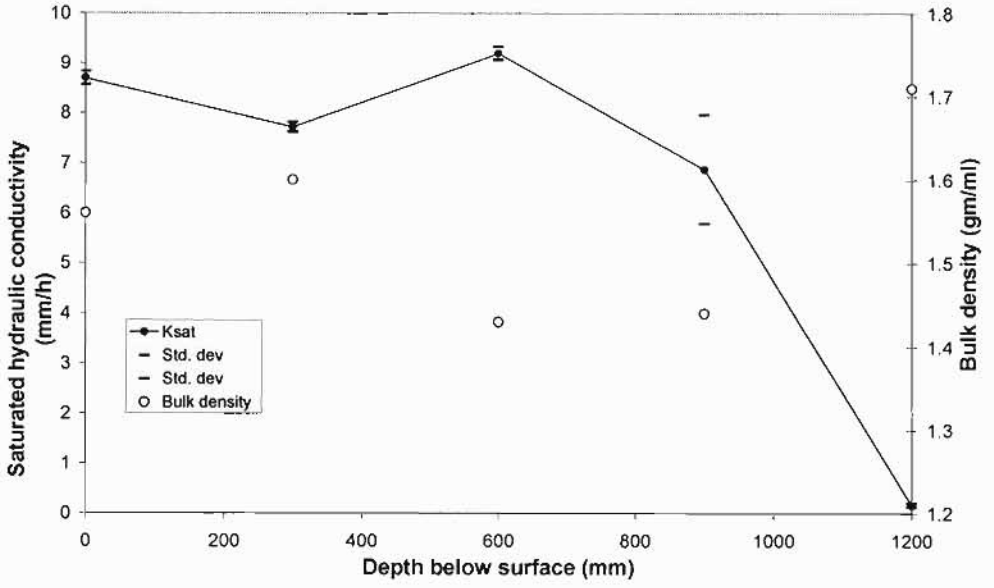

Figure 4.11 Hydraulic conductivity at site *M*

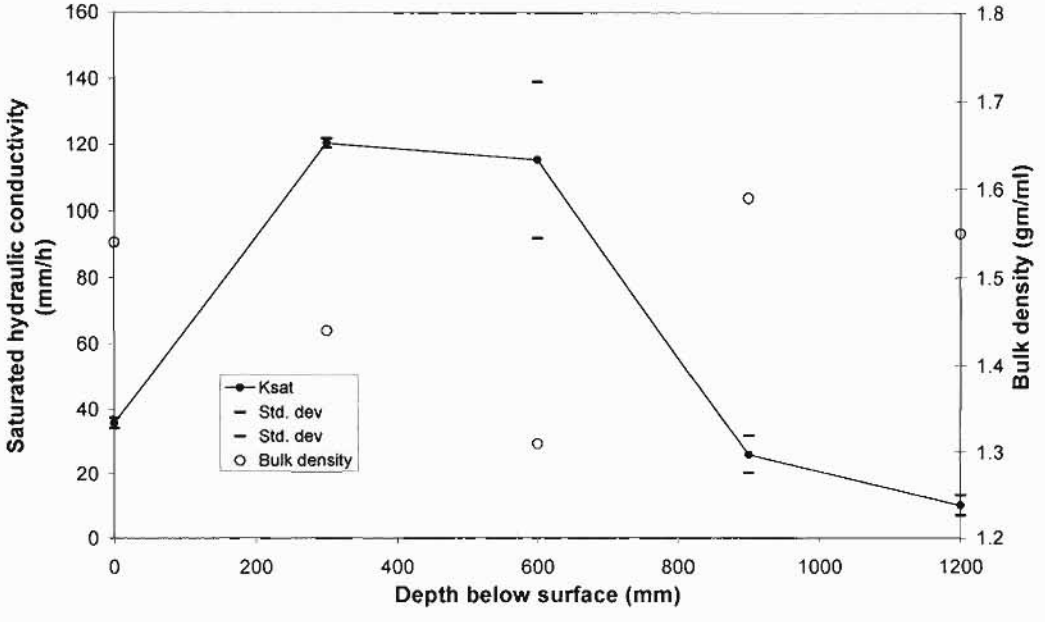

Figure 4.12 Hydraulic conductivity at site *C*

4.4.3 In-situ hydraulic conductivities

A slug test conducted on 6 piezometers in the catchment further revealed more variation of hydraulic conductivities in the catchment as indicated in Table 4.3. The general attributes of the six

piezometers, including their respective elevation above sea level, are given in Table 4.1 in the methodology section. The slug test was conducted on 01/05/07, at the end of the 2006/07 rain season.

Table 4.3 In-situ hydraulic conductivity results from slug test

Piezommeter ID	Right bank			Left bank		
	PRB1	PRB2	PRB3	PLB1	PLB2	PLB3
Average conductivity ($mm.h^{-1}$)	0.14	0.72	0.56	1.77	2.58	1.44
Depth of the piezometer (mm) below the surface	3220	3320	2840	3320	3460	3410
Initial depth of column of water (mm) in the piezometer during slug test	1450	605	60	900	330	400

It is useful to note that, the piezometer *PRB3* and *PLB3* are located close to the sites *M* and *C* respectively, Figure 4.1, where soil samples were taken for the laboratory measurement of saturated hydraulic conductivity. An interesting observation was the difference in hydraulic conductivity measurements on the left and right bank, with conductivities measured on the left bank ranging from 1.44 to 2.58 $mm.h^{-1}$ while the right bank 0.14 to 0.72$mm.h^{-1}$. Such a difference could be attributed to spatial heterogeneity in soil profile textural class in the catchment. The low conductivities on the right bank could be the reason for the high columns of water in the piezometers on the right bank, measured during the slug test, and notably *PRB1* and *PRB2*. There was a general conformity of the slug test results to the conductivities measured from soil samples, in that, both methodologies produced higher estimates of conductivities on the left bank, though the depth of measurement was different for each methodology. Nevertheless, the difference in the results obtained from the two methods may be as a consequence of laboratory method measuring only the vertical conductivity in a soil sample, while slug test measures both the horizontal and vertical conductivity (Wolski and Savenije, 2006), thus lower conductivity values are anticipated from slug tests. Naturally, hydraulic conductivities obtained from in-situ tests provide better estimates and are more representative and preferred than laboratory results. Nonetheless, the slug test carried out in the Potshini catchment provided estimates of conductivities at deeper depths (i.e below 3m) and it was inevitable to obtain the stratified hydraulic conductivity estimates for the soil material above the 3m for use in the computation of the relative contribution of subsurface flows to the stream flows as dicussed in Section 4.4.5. Thus, the laboratory

method in this study was used to complement the in-situ measurements for the upper subsurface layers above 3m.

The highest conductivities on the left and right bank were recorded at *PLB2* and *PRB2*, respectively. These two piezometers are located second from the stream along the respective hill-slope transects and hence the quick response of ground water levels at *PRB2* (Figure 4.8), rising to highest levels after an event, could be attributed to the localized high conductivities. Generally, the saturated hydraulic conductivity results from both the slug test and laboratory measurements gave an insight of the spatial heterogeneity of such a soil hydraulic parameter in the catchment, which is a function of soil characteristics and an important parameter in hydrological studies with regard to moisture retention characteristics and dynamics of the sub-surface water.

4.4.4 Electrical resistivity measurements

It is noteworthy that the Electrical Resistivity Tomography (ERT) method is useful both as a means of rapid site reconnaissance that can provide information on the subsurface structures and facilitates the extrapolation of observed data, e.g observed ground water levels, between observation points. This can only be done where sufficient site correlations have been established between the observed data being extrapolated and the information derived from the geophysical survey. As highlighted in Loke (2003), low resistivities are associated with materials of relatively high conductance e.g water, clay, salts etc. In this study, the piezometric readings along hill-slope transects were used to relate the resistivity measurements with the occurrence of subsurface water in the Potshini catchment.

The electrode spacing of 5m along the 400m transects was chosen in the resistivity survey exercise to allow deep penetration of the measurements while the 1m spacing for detailed characterization of the sub-surface processes, especially across the stream cross-section. The large spatial heterogeneity of the subsurface resistivity in the catchment, both in dry and wet seasons of the year is well depicted in Figures 4.13 to 4.23. The position and orientation of the respective transects is as indicated in Figure 4.4.

It is apparent that there is a connection between the Potshini stream and the underlying saturated sub-surface in transect No's. 3 and 4 (Figures 4.18, 4.19 and 4.20), where low resistivity material was observed to be dominant surrounding and in the vicinity of the stream both in wet (summer) and dry (winter) season of the year. Low resistivities, less than 300Ωm, along the surveyed transects in the

catchment were interpreted as saturated conditions based on values suggested by Griffiths (1993) and Loke (2003), and also from correlation of the resisitivity values and the piezometric readings along hill-slopes in the Potshini catchment. As highlighted in the methodology section, it was not possible to repeat the ERT survey exercise in the wet summer season on all transects previously surveyed during dry winter season, due to the crops in the farmers fields. Only transects 1, 2 and 4 were repeated (Figures 4.13 & 4.14; 4.16 & 4.17 and 4.19 & 4.20 respectively).

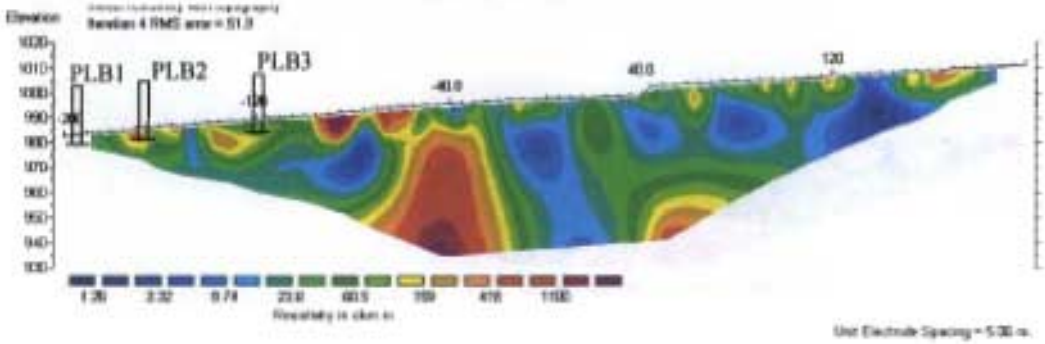

Figure 4.13 Resistivity survey along transect No. 1 during the dry season

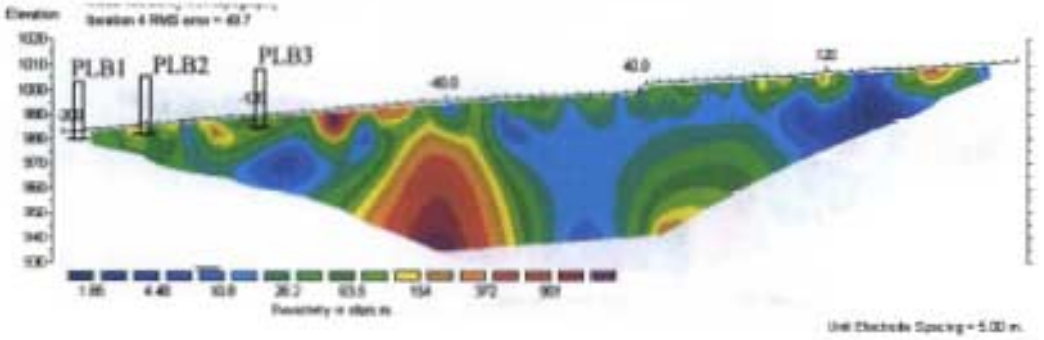

Figure 4.14 Resistivity survey along transect No. 1 during the wet season

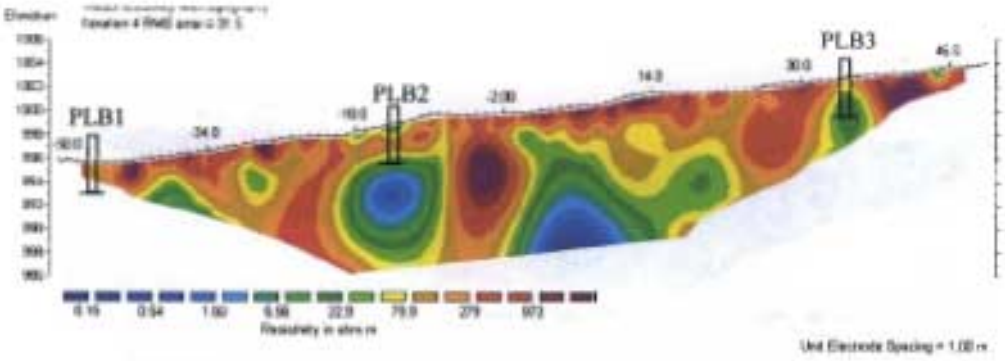

Figure 4.15 Resistivity survey along transect No. 1 during the wet season (1 m spacing)

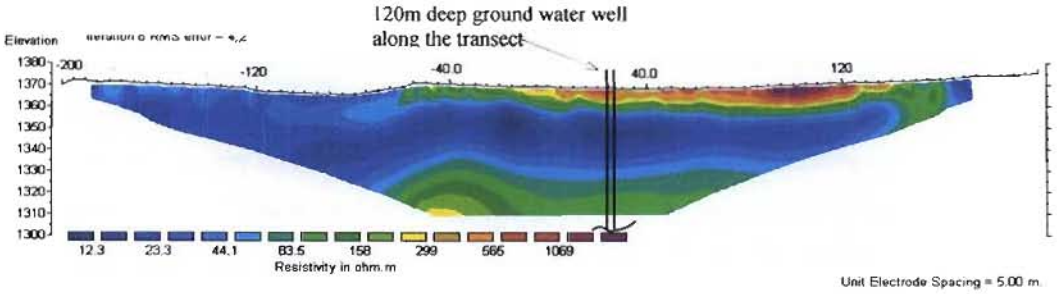

Figure 4.16 Resistivity survey along transect No. 2 during dry season

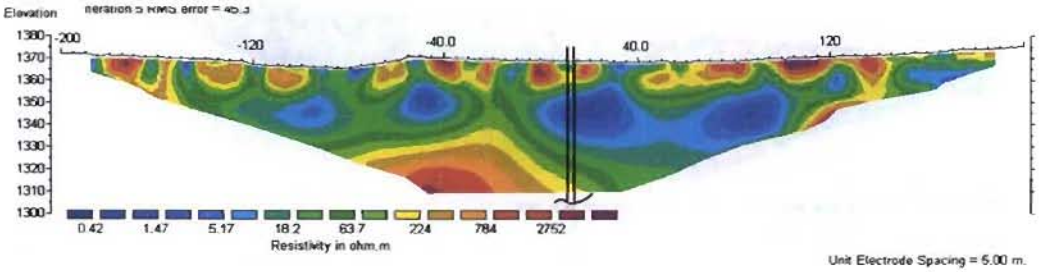

Figure 4.17 Resistivity survey along transect No. 2 during wet season

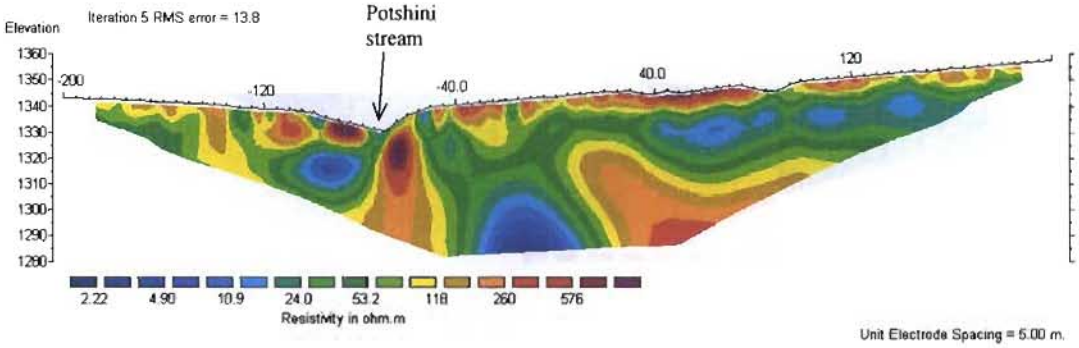

Figure 4.18 Resistivity survey along transect 3 during dry season

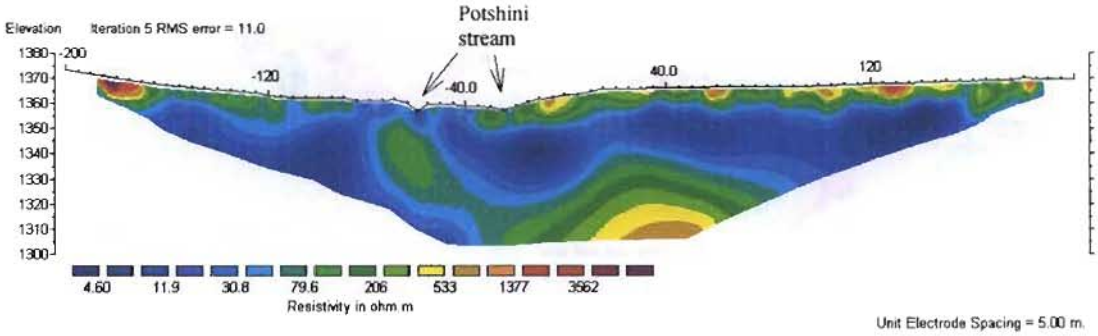

Figure 4.19 Resistivity survey along transect No. 4 during dry season

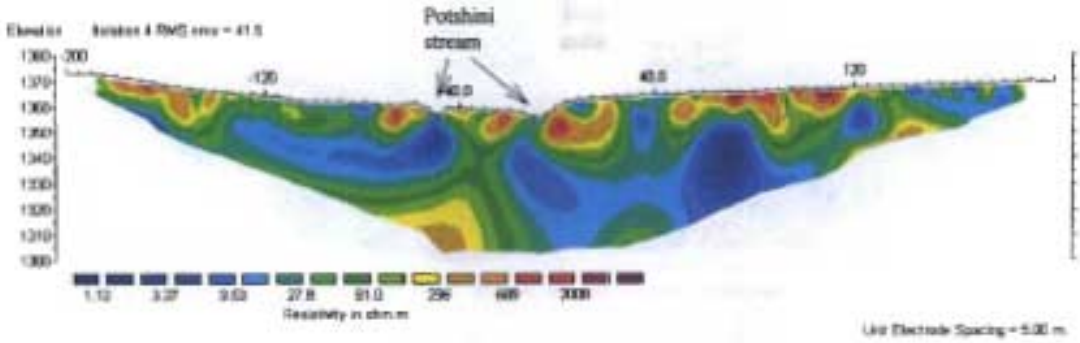

Figure 4.20 Resistivity survey along transect No. 4 during wet season

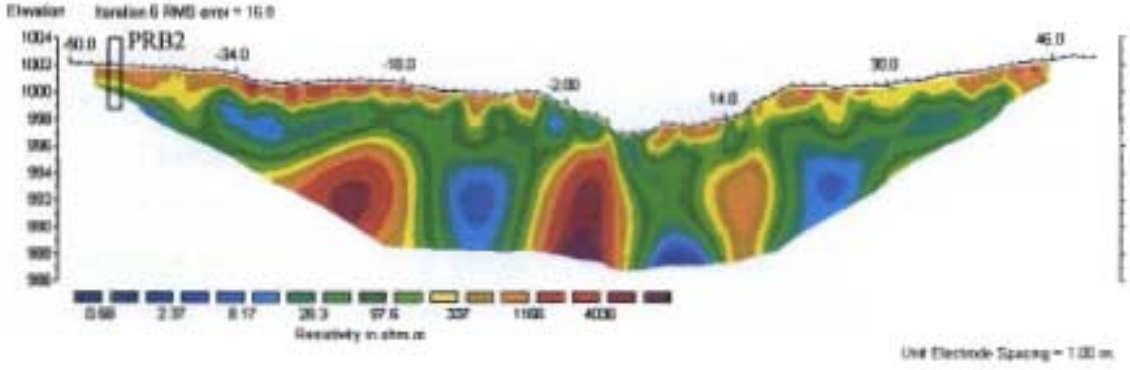

Figure 4.21 Resistivity survey across the stream cross-section transect No. 9

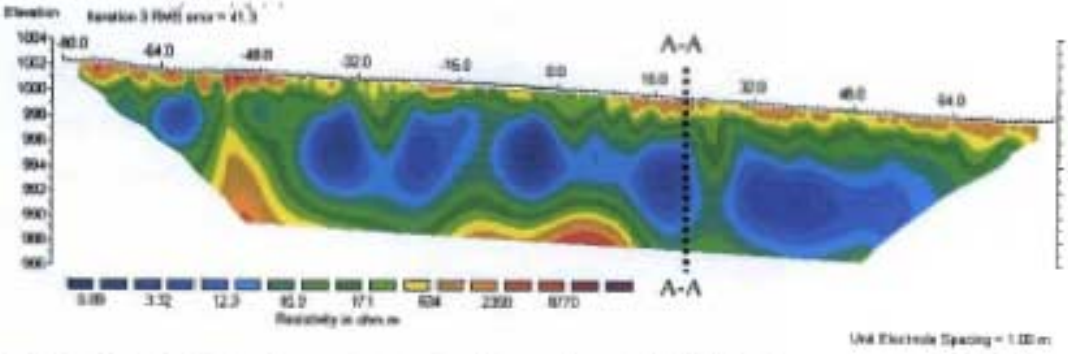

Figure 4.22 Resistivity survey along a transet parallel to the stream transect No. 7

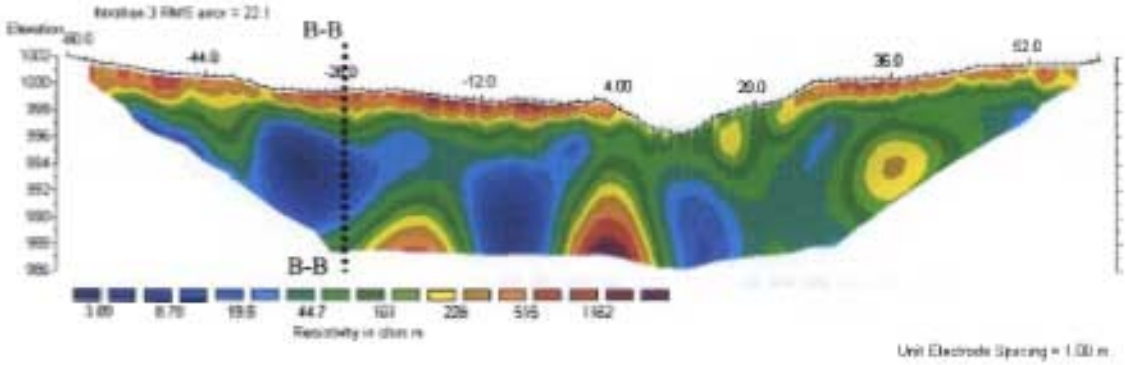

Figure 4.23 Resistivity survey across the stream cross-section transect No 8

An emphasis was given to the characterization of the subsurface resistivity against piezometric readings along transect 1 as shown in 4.15. It is useful to note that previous resistivity measurements were carried out with an electrode spacing of 5m, with the advantage of deeper measurements and longer transects though at the expense of lateral resolution as can be seen in Figures 4.13, 4.14 and 4.15. Figure 4.15 shows resistivity measurements along a section of transect 1 and which was surveyed during the wet season with an electrode spacing of 1 m. This section had 3 out of the 4 observation piezometers on transect 1 and the resistivity measurements were interpreted against the respective piezometric readings. The average depth of measurement along the transects surveyed with an electrode spacing of 5 and 1 m was 50 and 10 m respectively. It is rather difficult to characterize the subsurface material in the vicinity of the piezometers on Figure 4.13 and 4.14, as compared to Figure 4.15 due to spacing of electrodes. The piezometer *PLB1* is located on the brink of the flood plain and it was unfortunate that, due to the configuration of the measurement protocol and data processing, no resistivity measurements were depicted at deeper depths of the piezometer as was desired. Nevertheless, from Figures 4.13 and 4.14, there is no remarkable difference in the resistivity measurements around piezometers *PLB2* and *PLB3* during the dry and wet season. A comparison can be made between Figure 4.14 and 4.15, both of which are measurements done during the wet season but at different electrode spacing. A clear characterization of the subsurface can be made from the survey measurements carried out with an electrode spacing of 1 m, with the 5 m electrode spacing generating relatively higher resistivity measurements along the transect. Such a phenomenon could be attributed to the spatial heterogeneity of the subsurface material, of which the 5 m spacing measurement could not resolve and hence the lumping of the subsurface characteristics in the modeling exercise. The position and depth of the three piezometers along transect 1 is as shown in Figure 4.13 to 4.15. It is interesting to note the variation of the subsurface resistivity below *PLB2* on both the 5 and 1 m electrode spaced transect surveys, with very low resistivities being observed with the 1 m spacing. Intermittent piezometric readings along transect 1 have indicated that ground water

levels at *PLB2* are always higher than *PLB3* especially after a rainfall event. The revelation of the low resistivity measurements in the vicinity of *PLB2* and the relatively high in-situ saturated hydraulic conductivity of 2.58 mm/h (cf. Table 4.3), led to the conclusion that the subsurface formation below the piezometer was dominated by localized saturated material sandwiched between two formations with higher resistivities (unsaturated material), on both the upper and lower slope, which would probably have low conductivities as well. It is useful to note that the terrain just above *PLB2* is undulating, and which may have a significant influence on the subsurface formations.

The general observation from Figures 4.13 to 4.20 is that there was a decrease in the subsurface resistivity in all transects over the wet season compared to the dry season. Table 4.4 is a summary of the maximum and minimum resistivities, as indicated on the scale bar of Figures 4.13 to 4.20, for the respective transects surveyed during wet and dry seasons. Transects 2 and 4 had the highest maximum resistivities during wet than in dry season even though low resistivities dominated in all transects surveyed during the wet season.

Table 4.4 Resistivity values in wet and dry seasons

Transect No	**Winter season (dry) resistivities**		**Summer season (wet) resistivities**	
	Min. (Ω m)	Max. (Ω m)	Min. (Ω m)	Max. (Ω m)
1	1.26	>1100	1.85	>901
2	12.3	>1069	0.42	>2752
3	2.22	>576	No measurement in summer	
4	4.6	>3562	1.12	>2008

Nevertheless, it would be interesting to quantity the change in subsurface resistivity as a result of a known rainfall event (change in soil moisture) of which could be related to the fluctuation of ground water levels along hill-slopes.

A resistivity survey on a 150 m long transect, 50 m parallel to the Potshini stream (Figure 4.22), revealed a continous band of low resistivity sub-surface material, along the transect with numerous "pockets" of very low resistivities which were interpreted as either preferential flow paths for subsurface flows towards the stream or clay. The electrode spacing on this transect was 1 m. The resistivity values on this transect ranged from 0.89 to 8770Ωm, though the dominant resistivity values ranged from 0.89 and 171Ωm and which were observed to occur at average depths between 2 and 10 m below the surface. Transect 8 (Figure 4.23) was surveyed perpendicular to both the stream and transect No. 7 (Figure 4.22). The intersection point for the two transects is marked by profile sections

A-A in Figure 4.18 and *B-B* in Figure 4.23 respectively. The two profile sections depicted relatively the same resistivity values.

Figures 4.21 and 4.23 (transect 9 and 8) affirmed the connectivity between the subsurface water and the stream flows. Relatively low resistivity subsurface material, ranging from 50 to 100 Ωm, was observed to dominate and extend from the upper slopes down to the bottom of the stream channel. The low resistivity profiles on the upper slopes of the transect, both on the right and left bank, were observed to be skewed towards the stream and hence a possible indication of the direction of flow of the subsurface water. The stream discharge on the upper part of the catchment flows in an incised channel and it is a common feature to see subsurface flows discharging from the embankments of the channel into the stream during the rain season and even during the early months of the dry winter season. The connection between subsurface water and the stream channel was also revealed in Figures 4.18, 4.19 and 4.20 (transect 3 and 4), where very low resistivity subsurface formation (saturated soil material) underlies the channel bed and extends down to deeper depths. Such connectivity further highlights the interaction between the stream flows and the subsurface discharge, the later being a significant contributor to the stream flows in the catchment especially during the recession part of the hydrograph as discussed in a subsequent section.

Transect 2, i.e Figures 4.16 and 4.17, is located on the upper parts of the catchment along a relatively wet area, which is characterized by high clay content and high water table. This area is mainly used for livestock grazing during winter (dry season) and is abandoned by the local people during the rain season because of marshy conditions. It is from this area that two tributaries of the main Potshini stream, with discharge most of the year, originate (Figure 4.1 and 4.4) and hence an important source of the base flows for the Potshini stream during dry spells. From 4.16, it can be seen that low resistivities are dominant along the transect, from the lower to the upper parts of the slope. Of particular interest is the low resistivity formation that is sandwiched between two relatively high resistivity materials from the middle to the upper part of the transect, which could be interpreted as saturated soil material from which subsurface discharge sustains the stream flows of the small tributaries of the main stream especially during the dry season. A similar pattern of resistivities was observed when the ERT measurements were carried out during the wet season, Figure 4.17, where lower resistivities were observed compared to the dry season measurements. A deep observation ground water well was installed at the upper parts of transect 2 (cf. Figure 4.1) and the well was observed to produce substantial yield at 13m below the surface but reduced after some time during the pump testing of the well. The soil material at the 13m depth was found to have fine grained clay and organic matter. The well was sunk deeper to 120m after the first strike of ground water at 100m failed

to produce substantial yields. Such observations, e.g, water strike at 13m below surface, at the newly installed deep observation well conform to the interpretation of the resistivity values across the vertical profile of Figure 4.16 where very low resistivity values were observed at depths between 10 and 20m below surface. The high organic matter content in the subsurface water at 13m could be as a result of the marshy conditions in the area where the subsurface water is in contact with the ground surface water most of the time and where organic material (plant matter) is plentiful.

The interpretation of the various resistivity measurements against classical piezometric measurements in the Potshini catchment allowed for the determination of resistivity values for saturated zones in the sub-surface, and which were found to be less than 300Ωm, thus conforming to the average value suggested by Griffiths (1993) and Loke (2003). Table 4.5 shows the water levels recorded in the 8 piezometers during the resistivity measurement exercise, for the dry and wet seasons.

Table 4.5 Ground water levels below the surface during the resistivity measurements

Piezometer ID	Ground water levels (mm) during dry season (18/08/06)	Ground water levels (mm) during wet season (21/03/07)
PLB1	914	824
PLB2	1827	1779
PLB3	1964	1643
PLB4	1740	738
PRB1	806	658
PRB2	992	1095
PRB3	1497	1938
PRB4	2376	2491

The corresponding resistivity measurements at the piezometric heads in all piezometers, during the wet and dry season measurements, fell within the saturated zone described by Griffith (1993) and Loke (2003) of less than 300Ωm. From Table 4.5, the ground water levels in *PRB2* and *PRB3* were observed to be relatively lower on 21/03/07 compared to 18/08/06. These two dates fall within the wet and dry seasons respectively, and naturally, the ground water levels in the catchment were expected to be higher and closer to the ground surface during the wet season than in dry season. Nevertheless, as

previously discussed, the rainfall intensities and rainfall amount received in the catchment during the 2005/06 rain season was much higher compared to the 2006/07 rain season. The corresponding resitivity measurements at such depths in all piezometers fell within the defined saturated zone by Loke (2003).

4.4.5 Subsurface water and stream discharge

Darcy's law illustrates how the rate of ground water movement is governed by the hydraulic conductivity of the subsurface material and the hydraulic gradient (Todd, 1995). With these field measurements, i.e hydraulic conductivity and hydraulic gradient, it is possible to estimate the relative contribution of subsurface flows into the integrated stream discharge thus an attempt to improve the classical hydrograph baseflow separation technique as was attempted in the Potshini catchment. Heterogeneity is a natural phenomenon in subsurface formations as depicted in the ERT surveys in the Potshini catchment and further affirmed by the variation of the hydraulic conductivity across soil profiles. In an attempt to estimate the subsurface water fluxes into the stream in the Potshini catchment, some basic assumptions were made as follows:

i) The subsurface material in the catchment is stratified with 3 anisotropic layers (with different hydraulic conductivities) bordering the stream channel as illustrated in Figure 4.24. This assumption is supported by ERT surveys in the catchment (Figures 4.21 to 4.23).

ii) The hydraulic conductivity of each layer is uniform.

iii) One driving hydraulic potential affects all the three layers

iv) The total depth of the three anisotropic layers on each side of the stream channel is the same as the depth of the piezometers close to the stream, i.e *PRB1* and *PLB1*. The justification for this assumption is the fact that piezometers were installed in bored holes augered to depths reaching the bedrock or confining layer.

The K_{sat} values obtained from the soil samples at 300mm depth intervals in the catchment were integrated over depths of 600mm (Figure 4.11 and 4.12) while the in-situ hydraulic conductivities (cf. Table 4.3) were assumed to dominate the bottom layer (below 1200mm) on each side of the channel banks. The thickness of the individual layers, starting from the top (layer No. 1), and their respective hydraulic conductivities are as indicated in Table 4.6.

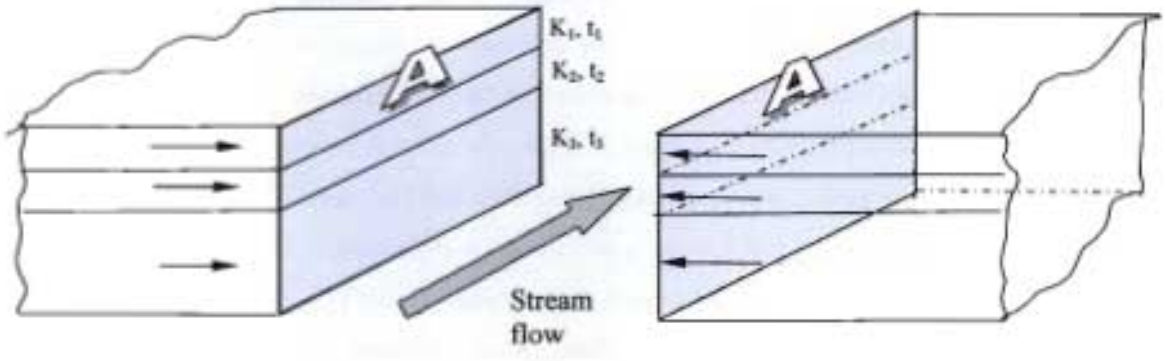

Figure 4.24 Illustration of stratification of subsurface layers

Table 4.6 Hydraulic parameters in the Potshini catchment

	Right bank			Left bank		
Layer No	1	2	3	1	2	3
Thickness, t_n (mm)	600	600	2022	600	600	2120
Average conductivity, K_n (mm.h^{-1})	8.54	3.53	0.14	90.56	18.07	1.77

It is interesting to note that the thickness of the bottom layers (layer's No. 3) on both right and left banks are more or less the same as the depths of the water column that was observed during the initial installation of the piezometers, that was done during the dry summer season in 2005 (cf. Table 4.1). The equivalent horizontal hydraulic conductivity, K_e on each side of the channel banks was computed as weighted average of the respective layer's conductivities by taking into account the thickness of the individual layers in parallel as follows:

$$K_e = \frac{K_1 t_1 + K_2 t_2 + K_3 t_3}{t_1 + t_2 + t_3} \qquad (4.2)$$

where K_i and t_i is the hydraulic conductivity and thickness of the individual layers, respectively. Thus, the effective horizontal hydraulic conductivity for the right and left banks of the stream channel were found to be 2.33 and 20.76mm.h^{-1} respectively.

The hydraulic gradient was computed from the difference in ground water elevation and the horizontal distance between the first and second piezometers closest to the stream, i.e *PRB1 & PRB2* and *PLB1 & PLB2* respectively. Basically, the difference in ground water elevations is a crucial determinant of the ground water movement given the fact that the horizontal distance between any of the piezometers is a constant parameter. Figure 4.25 shows the difference in ground water elevation between *PRB2* and *PRB1* over part of the wet season (November 2005 to April 2006) and the dry seasons (May to August 2006). Relatively high ground water elevation difference is evident between end of January and early April 2006 and coinciding with high stream flows (cf. Figure 4.9) while low differential head dominates during the dry winter season, May to August.

The daily shallow ground water fluxes into the Potshini stream were estimated using the Darcy's equation, i.e

$$Q = KiA \tag{4.3}$$

where Q is the volumetric flow rate ($m^3.d^{-1}$), K the hydraulic conductivity ($m.d^{-1}$), i the hydraulic gradient and A the cross-sectional area of flow (m^2) (Figure 4.24). A similar approach, for computing relative contributon of subsurface flows, was applied in a catchment study that was conducted in Zimbabwe and reported in McCartney (1998). The depth of the cross sectional area of flow was obtained by summing the respective thickness of the three layers on each side of the bank, which was assumed to be equal to the depth of the piezometers close to the stream (*PRB1 & PRB2*), while the length of the stream channel (gully) where ground water fluxes significantly contributes to the stream flows was obtained from 1:10,000 aerial photograph (Figure 4.1). It is useful to note that most of the stream channels around and above the wetland (Figure 4.1) are relatively shallow and are therefore not likely to contribute to subsurface flows hence were not used in this analysis. Field survey and observations during the dry and wet seasons pointed out that the sections of the stream where a deep gully was evident with ground water seeping out into the stream was upstream of the H-flume and below the wetland (Figure 4.1) and which was found to span to 630m. This is the length that was used in the computation of the shallow ground water fluxes into the Potshini stream as shown on a log-plot in Figure 4.26.

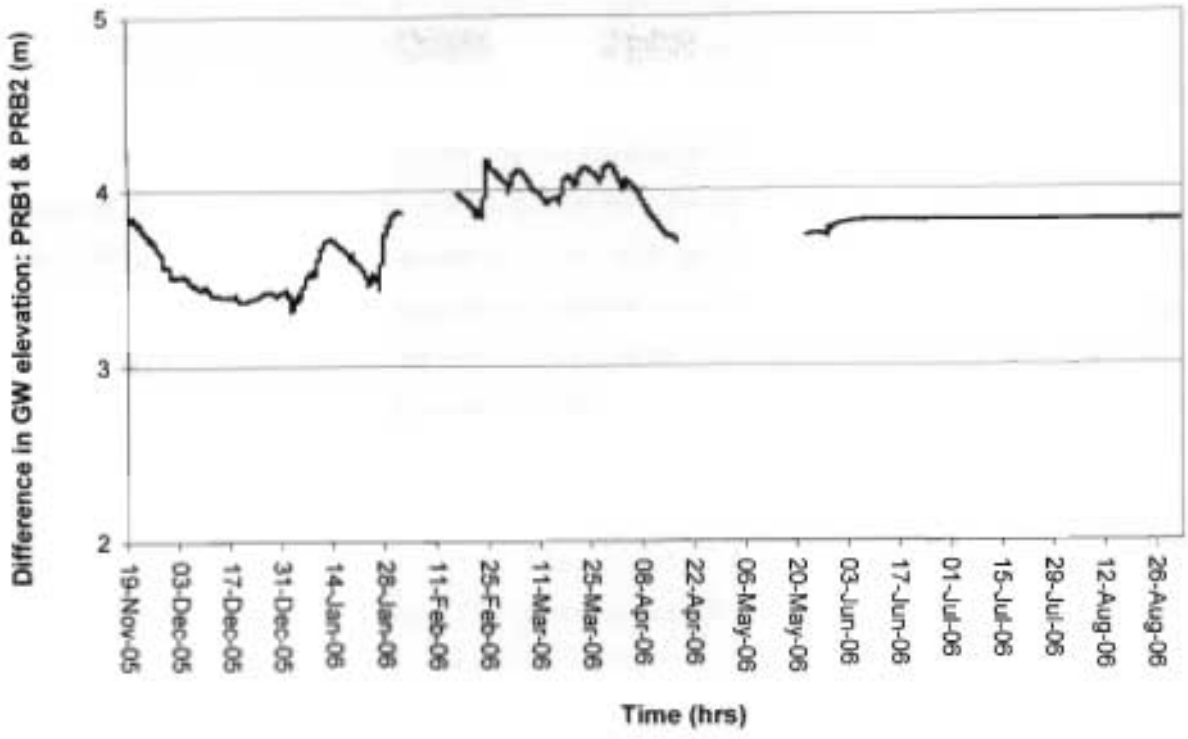

Figure 4.25 Difference in ground water levels

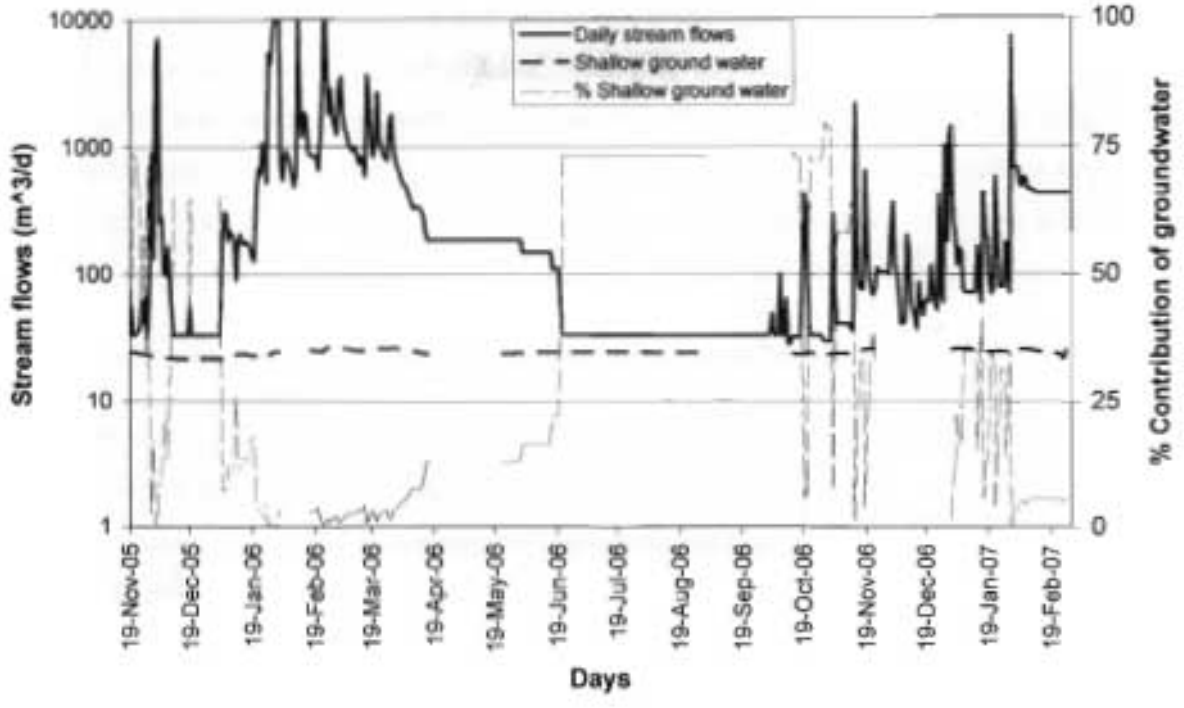

Figure 4.26 Base and stream flows in the Potshini catchment

Generally, the shallow ground water fluxes varied from 19 to 26 $m^3.d^{-1}$, with the lesser flows occurring during the dry winter months while higher fluxes ranging from 24 to 26 $m^3.d^{-1}$ were found to occur between February and April 2006, when the catchment received the highest rainfall intensities and amount over the study period. The average integral stream flows recorded at the H-flume during the dry winter season (May to September 2006) was 32.8 $m^3.d^{-1}$, while the average ground water fluxes contributing to the integral stream flows were estimated to be 23 $m^3.d^{-1}$. The difference could be attributed to the contribution from the wetland on the upper reaches of the catchment which is drained by small tributary channels to the main stream. A plot of the percentage contribution of the ground water in the integral stream flow revealed the importance of the shallow ground water in maintaining the stream flows in the Pothsini catchment over seasons. During the dry winter season, the shallow ground water fluxes were estimated to contribute close to 75% of the stream flows in Potshini, with insignificant contribution of around 0.1% during the rainfall events. These fluxes, especially during rainfall events, seem to be low than expected and this could be attributed to the existence and influence of macro pores and preferential flow paths which are not accounted in the application of the Darcy's law, which is simplistic. The effect of a "pressure wave" in the subsurface flows induced by displacement of "old" water by "new" water could not be captured in the Darcy's law as well, and which could have lead to high amount of subsurface discharge into the stream.

Thus, tracer studies would have been useful in this case in estimating the relative contribution of the subsurface water especially the "old" and "new" water to the total stream flows as highlighted in other studies e.g Souslby et al., (1998); McCartney et al., (1998); Uhlenbrook and Hoeg (2003), where tracer studies demonstrated and revealed the domination of "old" water in total streamflow. Hence, surface and subsurface water in a catchment cannot be isolated from each other but forms an integrated system that has to be understood within its integral context.

4.4.6 Schematization of the hydrological processes in the Potshini catchment

Based on field observation and investigations, a schematic representation of the hydrological processes in the Potshini catchment is presented in Figure 4.27 describing the contribution of the hillslope to the stream flows and the interaction between the stream flows and the subsurface water. The cross-section in Figure 4.27 was surveyed using a Theodolite at a spacing of 1m and the respective position and altitude of four piezometers (*PRB1, PRB2, PLB1, PLB2*) is as indicated in Figure 4.27.

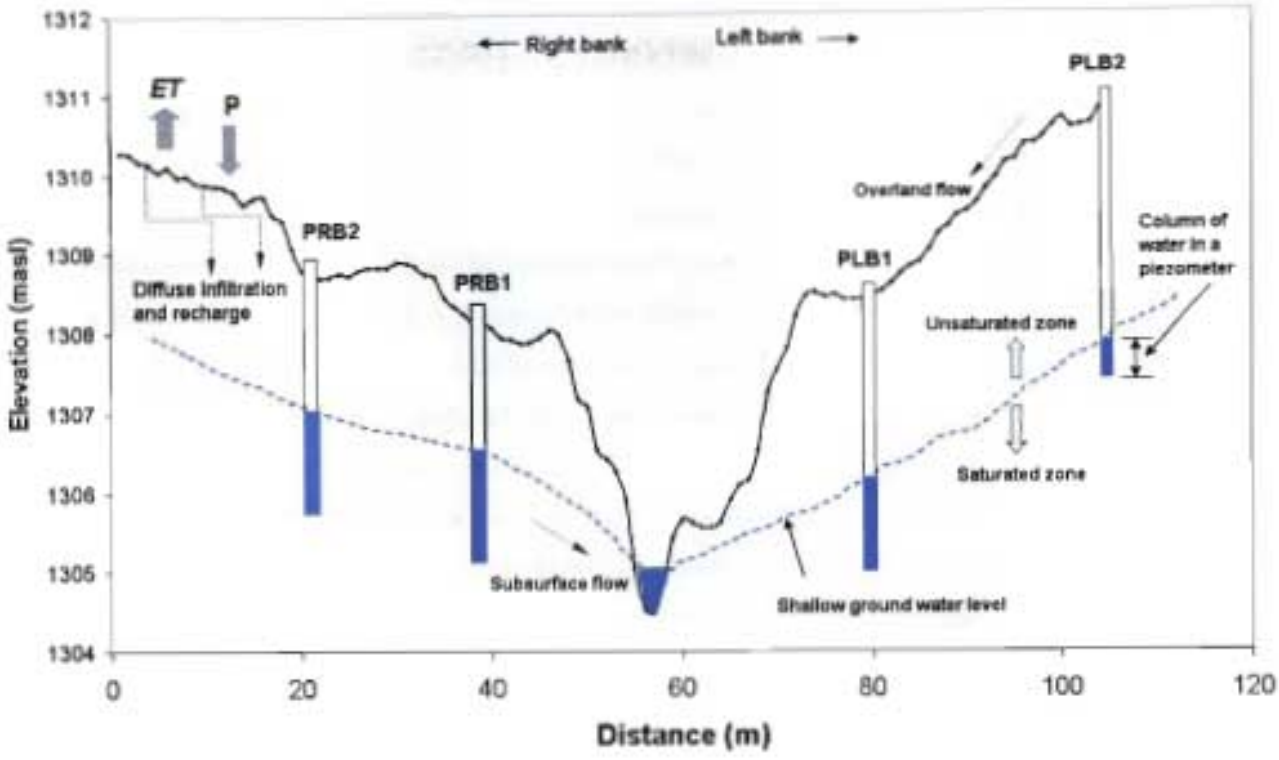

Figure 4.27 A schematic representation of the surface and dominant hydrological processes in the Potshini catchment

The piezometric readings recorded in the four piezometers on 30/04/2007 facilitated the mapping of the shallow ground water level along the cross-section by joining the ground water levels in the piezometers on each side of the stream and extrapolating these levels downstream as shown in Figure 4.27. On average, the depth of shallow ground water along the section on 30/04/2007 was 2m on the upper slopes and less than a meter in the flood plain of the stream. Such a phenomenon is expected along hill-slopes profiles especially where there is an interaction between surface and subsurface water as is the case in the Potshini catchment (cf. Section 4.4.1 and 4.4.5).

With reference to Figure 4.27, and complemented with field observations, it is possible to summarise the interactions of the main hydrological determinants in the Potshini catchment where quick overland flows, indicated in Figure 4.27, generated by high intensity rainfall (P) and amounts (cf. Figure 4.5 and 4.9) are responsible for the rapid rise of hydrographs in the stream with diffuse infiltration and recharge of ground water over the catchment. The hilly terrain in the catchment could have an influence in the generation of quick overland flows especially at the onset of the rain season when most of soil cover material (vegetative material and crop residues) are depleted as a result of overgrazing in the catchment.

Part of the received rainfall is lost to the atmosphere through evapotranspiration (*ET*). The recharge of ground water is mainly through infiltration (diffuse recharge) over the catchment. This hypothesis is supported by the geophysical measurements that were carried out in the catchment along transects spanning from 100 to 400m (cf. Figure 4.4 and Figures 4.13 to 4.23) of which did not reaveal fissures in the catchment. The infiltrated water accumulates between the upper soil material and the subsurface formations with low hydraulic conductivities (assumed impervious). The difference in slope and the build up of hydraulic pressure due to the accumulated water induces a transient ground water flow down the slope, where it accumulates before discharging into the stream through preferential flow paths. This hypothesis is supported by the geophysical measurements along a transect parallel to the stream in the Potshini catchment (cf. Figure 4.4 and 4.22) where "pockets" of low resistivity were observed and which were interpreted as preferential flow paths. Also, the shallow ground water levels at the piezometers close to the stream (e.g *PRB1*) recorded high water levels (piezometric readings) with less fluctuation most of the time.

4.5 Conclusions

This study further highlights the significance of subsurface flows in semi-arid catchments in their contribution to the stream flows discharge. The subsurface flows contribute significantly to the stream flows in the Potshini catchment especially during the dry winter seasons and this case study gives an insight on the partitioning process of rainfall in the Potshini catchment and in particular the response of the catchment with regard to response of shallow ground water to rainfall events and the contribution of shallow ground water to the stream flows. However, the simplicity and assumptions associated with the application of the Darcy's law in this study limited the better estimation of shallow grundwater fluxes into the stream flow especially during rainfall events as shown in Figure 4.26 and hence better estimation or monitoring methods, e.g application of tracer studies are recommended. The analysis of the piezometric heads and rainfall intensities demonstrated the relationship between the fluctuation of ground water table and rainfall intensities. Similar relationships were established for the Potshini catchment based on the observations of daily rainfall events, cumulative rainfall and the fluctuation of ground water table. The resistivity survey along the various transects, during the dry and wet seasons of the year, provided additional information on the spatial variation and characterization of the subsurface formations at the hillslope scale, and which together with piezometric observations along two transects was used to interpret the structure of the subsurface with respect to water content (saturated and unsaturated zones). The subsurface information obtained during the drilling of a deep observation ground water well on one of the transects (Transect No 2 in Figure 4.4) further validated

the results obtained from the resistivity surveys in the catchment. The application and combination of the classical hydrometrical field methods with geophysical techniques in the catchment facilitated a better understanding of the various hill-slope processes in the catchment.

5.0 Application of scintillation and remote sensing techniques to estimate total evaporation in the Thukela River basin-S.Africa

Summary

Total evaporation is the dominant component of the water balance in semi-arid and arid regions and is considered an important component in water resources planning. However, there are many challenges in determining its spatial and temporal variation over a river basin from ground measurement alone. In the past two decades, there has been significant progress in the development of satellite image processing algorithms for computing the amount and spatial distribution of total evaporation, most commonly as a residual of the surface energy balance. One such algorithm is the Surface Energy Balance Algorithm for Land (SEBAL). This approach was applied in the Thukela river basin, South Africa, using the public domain Moderate resolution Imaging Spectroradiometer (MODIS) images which has a pixel resolution of 1km.

In this study, SEBAL estimates of the components of surface energy balance, i.e net radiation, sensible, soil and latent fluxes were compared with field measurements in the Potshini catchment for MODIS pixels overlaying a Large Aperture Scintillometer (LAS) measurement transect of 1.03km. Comparison was also made between SEBAL estimates of total evaporation and Scintillometer measurements in Potshini. The average deviation of SEBAL estimates of net radiation, soil heat flux and sensible heat for the 9 discrete days used in this study was found to be -4.11, 3.10 and 6.44% respectively, with the deviation being a departure from LAS measurements, while the relative deviation of SEBAL estimates of total evaporation for discrete days over the study period ranged between -14 to 26%. Such reasonable comparative results highlights the potential of applying remote sensing techniques, notably SEBAL, as a contribution to monitor the impact of lands use on catchment hydrology by quantifying total evaporation at various spatial and temporal scales from natural and managed landscapes in South Africa. Such a contribution is of great significance with regard to understanding system dynamics in ungauged river basins in Southern Africa and world wide.

5.1 Introduction

Total evaporation (also commonly referred to actual evapotranspiration) (*ET*) is the loss of water from open water bodies, soil and plant surfaces. *ET* is a process governed by the energy and heat exchanges at the land surface, with the upper bound being constrained and controlled by the amount of available

energy and water respectively (Hemukamara et al., 2003). Evaporation of water requires relatively large amount of energy in the form of latent heat (latent heat of vaporization is 2.45×10^6 J.kg^{-1} at 20 ^{0}C). Although *ET* is one of the most important components of the water balance, it is one of the most difficult to measure especially under composite terrains (Wu et al., 2006). Traditionally, total evaporation *(ET)* from agricultural fields has been estimated by multiplying potential evapotranspiration ET_o by a crop coefficient *(Kc)* determined according to the crop type and the crop growth stage as described in Allen et al., (1998) and Allen (2000). However, questions arise as to whether the crops grown compare with the conditions represented by the idealized *Kc* values, especially in water scarce areas. Such certainty is further compounded in heterogeneous land surfaces with various types of vegetation at different stages of growth as well as the dynamic atmospheric parameters that influence the evaporation and transpiration process. Given the complex nature of mixed vegetation and different land use patterns at basin scale, it is extremely difficult to assess the validity and applicability of evaporation and transpiration fluxes extrapolated from point measurement to catchment scale (Hemakumara et al., 2003). One of the chief logistical challenges in obtaining good estimates of spatial variation of the total evaporation using classical hydrometeorological networks in many countries, especially in sub-Saharan Africa, is poor distribution and or less dense monitoring networks, unlike rainfall measurements. This is due to the relative complex nature and skill requirements in evaporation and transpiration measurements (e.g. Class A-Pan, Lysimeters, Bowen ratio, Eddy covariance, chemical tracers, weather stations etc.) compared to rainfall measurement where raingauges are found in many areas and even monitored by individuals and/or institutions, e.g. smallholder and commercial farmers, schools etc.

It is useful to note that most of the water resources management strategies and policies in many countries, including South Africa, are formulated and based at catchment scale and hence there is a need to quantify the spatial variation of the various components of the hydrological cycle at this scale. An example is the Thukela River basin in South Africa, which has an area of 29 036 km^2 and subdivided into 86 Quaternary Catchments[2] which essentially form water resources management units (DWAF, 2000). It is upon this premise that this study was based, i.e. to investigate the potential of applying scintillation and remote sensing techniques to quantify total evaporation at various scales within the Thukela river basin. The 1.2km^2 Potshini catchment in the Bergville District of the KwaZulu-Natal province in South Africa, where ground measurements were carried out, was used as a pilot validation case study, as discussed herein.

[2] Quaternary Catchments (QC) in South Africa are the smallest delimitations of a river basin upon which policies and decision with regard to water resources management are based upon. The QC were defined and established by the National Department of Water Affairs and Forestry

Several authors, including Wu et al., (2006) have highlighted that net radiation and vapour pressure deficit are the principal driving parameters for most models used to estimate total evaporation *(ET)*. Recent effort and research in satellite remote sensing *ET* models have led to the development of algorithms that account for the surface energy balance and subsequently computing total evaporation from the estimated latent heat flux from satellite images. The surface energy balance can be expressed as:

$$R_n = H + LE + G_o \qquad (5.1)$$

where R_n is the net radiation ($W.m^{-2}$), H the sensible heat flux ($W.m^{-2}$), LE the latent heat flux ($W.m^{-2}$) and G_o the soil heat flux ($W.m^{-2}$). The satellite remote sensing algorithms for estimating *ET* are attractive due to their ability to estimate such fluxes over large areas and can provide estimates at very high resolution, depending on the spatial resolution of a satellite image (Kite and Droogers, 2000). Intensive field monitoring is not required although some ground-truth measurements are useful in interpreting a satellite image. Some of the algorithms that have been applied in different climatic and geographical conditions include the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998a&b, Bastiaanssen 2000); The Surface Energy Balance System (SEBS), Su (2002); and the Two-Source Energy balance (T-SEB) (Kustas et al., 2004 and Timmermans et al., 2007) among others. These algorithms provide estimates of surface fluxes derived from infrared and thermal satellite imagery and convey valuable information regarding spatial variations in partitioning the fluxes identified in Equation 5.1, and further provide a means for remotely monitoring vegetation conditions and ecosystem health over the land surface (Moran, 2004). The validation of the remotely sensed estimates of surface fluxes against ground measurements, e.g. the sensible heat flux, complements and adds value to the validity of the spatial estimates of *ET* from any of the aforementioned methods. Such a complementary role was explored and applied in this study where the sensible heat flux was measured in the Potshini catchment, using scintillometry techniques, in an attempt to compare and validate the remotely sensed spatial estimates of such fluxes computed using SEBAL and MODIS satellite images, with a pixel resolution of 1km, in the Potshini catchment and the Thukela river basin at large. In addition, SEBAL *ET* estimates were compared to field measurements obtained from a Large Aperture Scintillometer (LAS) for pixels overlaying a 1.03 km LAS transect.

5.2 The study area

Figure 5.1 shows an overview and location of the Thukela river basin in South Africa and the Potshini catchment in Bergville district in KwaZulu-Natal Province.

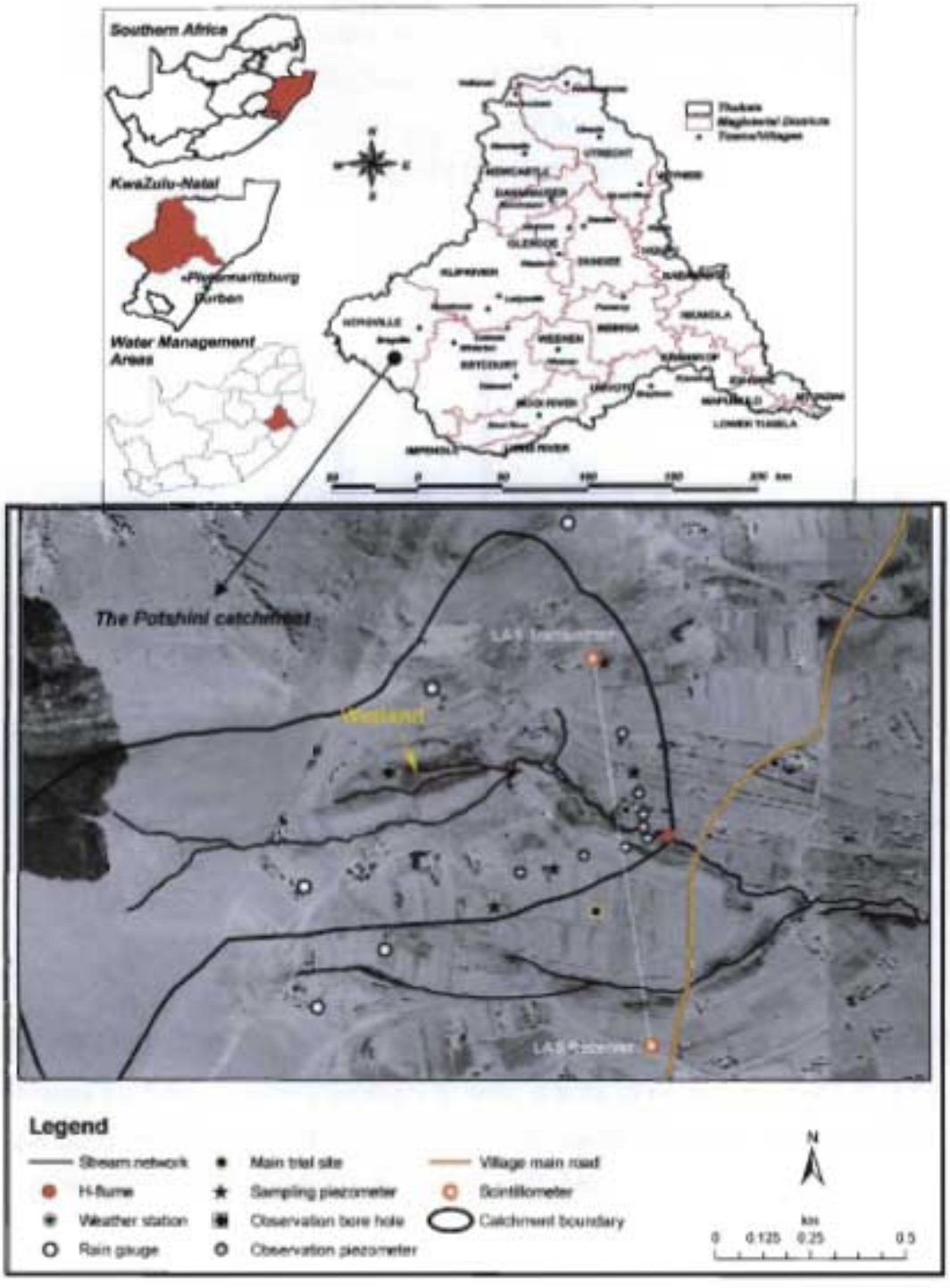

Figure 5.1 An overview of the Thukela river basin and the Potshini catchment

The hydro-climatological parameters of the larger Thukela river basin are highlighted in detail in Schulze (1997). The 1.2 km^2 Potshini catchment (E 29.3679^0 S 28.8145^0) is located in the foothills of the Drakensberg mountains at an average altitude 1310m. The catchment is inhabited by smallholder farmers with an average acreage of less than 1 hectare (as can be seen in the aerial photo in Figure 5.1) on which they grow mainly maize during the wet summer season (September to April). The average annual rainfall is 700mm.a^{-1} with a potential evapotranspiration of 2000mm.a^{-1} (Smith et al., 2004). Figure 5.2 shows monthly variation of rainfall and temperature in the catchment. Most often, the peak rainfall in the catchment occurs between January and March coinciding with the highest mean monthly temperature in the area as indicated in Figure 5.2.

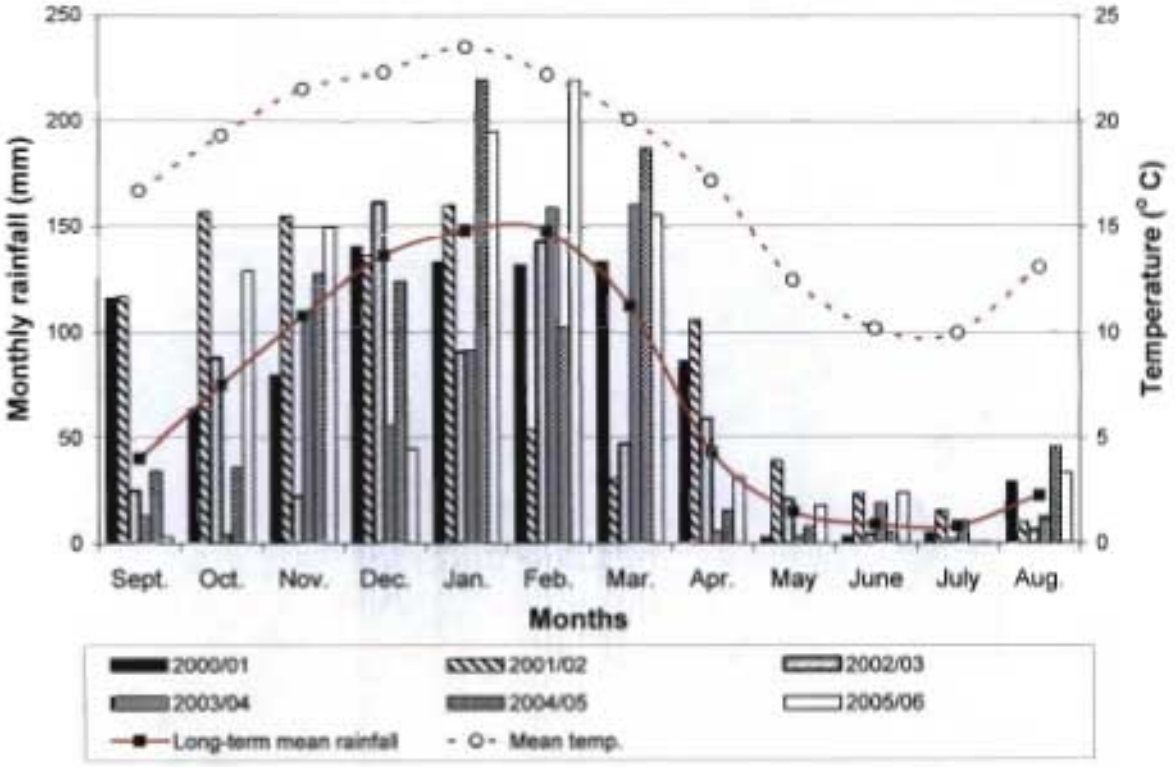

Figure 5.2 Monthly variation of rainfall and temperature in the Potshini catchment

The long term mean monthly rainfall mimics a similar pattern as the long term mean monthly temperature, with the lowest temperatures being observed during the dry winter season (May to August). The years 2001/02 and 2005/06 had the highest rainfall, with most of the months receiving rainfall above the monthly mean value.

5.3 Large Aperture Scintillometer

Scintillation is a general term used to describe changes in the brightness of an object when viewed from the atmosphere (Hemakumara et al., 2003). The Large Aperture Scintillometer (LAS) is an instrument used to measure the turbulent intensity function of the refractive index fluctuations of air between a collimated light source (transmitter) and a detector (receiver) (Meijninger et al., 2000). The typical distance between the receiver and the transmitter is less than 10km depending on the make of the LAS. As electromagnetic radiation emitted by the transmitter in the direction of the receiver propagates through the turbulent atmosphere, it is distorted and scattered by random refraction, absorption and diffraction resulting in intensity fluctuations (Kite et al., 2000; Meijninger, 2003). This is caused by fluctuations in the refractive index of air (n), which are in turn caused by heat, moisture and pressure fluctuations. The intensity fluctuations are analysed at the receiver and expressed as the structure parameter of the refractive index of air C_n^2 ($m^{-2/3}$).

The theoretical description, principles and application of the optical scintillation technique is well documented by many authors ranging from Clifford et al., (1974) to Meijninger, (2003); Asanuma and Lemoto (2007) and Ezzahar et al., (2007) more recently. A brief overview of the measurement principles of LAS is provided in this Chapter. Wesely (1976) showed that, for a LAS operating at near infra-red wavelength, the structure parameter of the refractive index of air C_n^2 is related to the structure parameter of temperature C_T^2 ($K^2.m^{-2/3}$) as follows:

$$C_T^2 = C_n^2\left(\frac{T^2}{\gamma P}\right)^2\left(1+\frac{0.03}{\beta}\right)^{-2} \tag{5.2}$$

where γ is the refractive coefficient of air (7.8×10^{-4} KPa^{-1}), T is the absolute air temperature, P is the atmospheric air pressure and β is the Bowen ratio. Using the Monin-Obukhov Similarity Theory (MOST), de Bruin et al., (1993) showed that

$$\frac{C_T^2(z-d)^{2/3}}{T_*^2} = 4.9\left(1-9\frac{z-d}{L_{mon}}\right)^{-2/3} \tag{5.3}$$

$$L_{mon} = \frac{Tu_*^2}{kgT_*} \tag{5.4}$$

$$u^* = \frac{ku}{ln\left(\frac{z-d}{z_o}\right) - \psi_m\left(\frac{z_o}{L_{mon}}\right)} \tag{5.5}$$

$$H = T_* \rho C_p u_* \tag{5.6}$$

Where z is the measurement height (m), z_o is the roughness length (m), d is the displacement height (m), T_* is a temperature scale factor, ψ_m is the integrated stability function, L_{mon} is the Monin-Obukhov length (m), k is the von Karman constant, u is the wind speed ($m.s^{-1}$), g is the acceleration due to gravity ($m.s^{-2}$), H is the sensible heat flux ($W.m^{-2}$), ρ is the air density ($kg.m^{-3}$), C_p is the air specific heat capacity at constant pressure ($Jkg^{-1}.K^{-1}$) and u^* is the friction velocity ($m.s^{-1}$). The sensible heat flux (Equation 5.6) is then computed iteratively using Equations 5.3 to 5.5. Meijninger (2003) cited Wang et al., (1978) to have shown that the C_n^2 is path-averaged according to a bell-shaped spatial weighting function and hence the scintillations produced near the centre of the measurement path (transect) contribute more to the path-averaged C_n^2 than scintillations produced near the transmitter and receiver. The measurement of the sensible heat flux using scintillation techniques along transects forms an intermediate measurement and a possible calibration scale between the classical point measurements (e.g Class A-pan, Eddy covariance etc) and the spatial estimates from satellite imagery as is highlighted in later sections of this Chapter.

5.4 The Surface Energy Balance Algorithm for Land

The formulation and validation of the Surface Energy Balance Algorithm for Land (SEBAL) is documented in Bastiaanssen et al., (1998a) and Bastiaanssen et al., (1998b), respectively. SEBAL uses satellite images to compute both the instantaneous and 24-hr integrated surface heat flux for each pixel of a remotely sensed satellite image where the latent heat flux, representing the energy required for evapotranspiration, is computed as a residual of the energy balance as expressed in Equation 5.1. The computation process requires spectral radiances in the visible, near infrared and thermal infrared regions of the spectrum to determine the intermediate parameters such as surface albedo, Normalized Difference Vegetation Index and surface temperature and uses both physical and semi-empirical relations with limited field data requirements (wind speed, relative humidity and air temperature (Bastiaanssen 2000). The algorithm has been applied in various geographical locations and using different remotely sensed data sets as highlighted in Timmermans and Meijerink (1999), Kite and Droogers (2000), Farah and Bastiaanssen (2001), Bastianssen and Ali (2003), Bastiaanssen and

Chandrapala (2003), Mohammed et al., (2004), WaterWatch (2006), Akbari et al., (2007), Kimura et al., (2007) among others.

5.5 Material and methodology

5.5.1 Experimental set up

Figure 5.1 shows the location of the LAS transmitter and receiver and other instrumentation in the Potshini catchment. The LAS that was used in this study was a BLS900 manufactured by the Scintec Inc. in Germany (Scintec, 2004). A dual infra-red beam from the two disks of the transmitter, each 0.15m in diameter, was emitted at $125H_z$ throughout the measurement period. It is useful to note that the BLS900 transmitter could operate in four pulse (emission) repetition rates between $1H_z$ and $125H_z$, with the high frequency dual beam emission allowing for cross winds to be accounted for. Such a high frequency emission of infra-red beam from the transmitter results in high power consumption and is only sustained by a constant sustainable power source e.g electrical power supply, and not chargeable batteries. The receiver of the LAS, with an aperture diameter of 0.15m, records the intensities of the received beam signal from which a one-minute average structure parameter of the refractive index (C_n^2) could be computed. The one-minute data was processed to compute 1-hour data statistics which were then integrated to daily values as presented in this Chapter.

The scintillometer path was chosen to pass above composite landscape, i.e mixed vegetation of mainly natural grass and smallholder farms in the Potshini catchment, with a path length of 1.03km at an effective height of 24m. The "effective height" of 24m reported in this study is basically the path height at the center of the path length, which happened to be in a valley (path height from the bottom of the valley). This was measured in the field using a GPS by measuring the relative elevations of the transmitter and receiver stations and at the centre of the path length, which was at the bottom of a valley. It is useful to mention that the setting and siting of the BLS900 Large Aperture Scintillometer is detailed in the field manual (Scintec, 2004). There are three siting scenarios which have been highlighted in the field manual with regard to the path height, i.e:

i) Siting on a flat surface
ii) Slanted path
iii) Siting over a valley

The path length in the Potshini catchment traversed a valley and Scintec Inc. has provided path weighting functions for this siting scenario (Scintec, 2004), such that one uses an average path height with an increased weight at the path centre. Thus, the path height that was used to compute the

sensible heat flux in this study was not 24m as it may appear literally in the text but rather a weighted height along the path length with a maximum of 24m at the centre of the path and hence the variation of shear stress with height in the velocity distribution was indirectly taken into account.

The experiment was carried out between August and September, during the dry winter season. During winter, the land cover in the Potshini catchment is normally characterized by bare soils, grazed grass and crop residues from maize crop and pulses which are harvested in May. Due to the composite nature of the land cover, and considering the fact that the land cover was changing with time due to grazing of animals, it was not possible to ascertain the proportion of path length covered by each land cover over the study period. The main criteria used in the selection of the installation sites for the BLS 900 transmitter and receiver was sufficient elevation for the line of sight (preferably across a valley) and the availability of electrical power at the transmitter. The Scintec Signal Processing Unit (SPU) at the receiver, with an in-built volatile memory for storing data, was powered by two-12volts batteries in parallel which were replaced every week to ensure adequate and continuous power supply. Frequent power outages occur in the Potshini community especially during the rain season, due to frequent thunderstorms, and hence it was not advisable to use mains power supply to run the receiver and the SPU. The LAS measurements were performed over a period of 90 days starting from 5th May to 15th August 2006. It was not possible to carryout measurements over the rain season (October to March) after the transmitter was repeatedly damaged by lightening strikes during the frequent thunderstorms in the Potshini catchment, and repairs were difficult to effect on time.

5.5.2 Computation of the soil heat flux

The approach that was applied for computing soil heat flux in the Potshini catchment is highlighted in Blight (2002). It requires soil parameters including moisture content, temperature and bulk density. The monitoring of the volumetric soil moisture content in the Potshini catchment is well documented in Chapter 2 and 3. Since March 2004, weekly measurements were taken using a Time Domain Reflectometry (TDR) method (TRIME-FM, 2003). This involved inserting a TRIME-T3 probe into 42mm access tubes, inserted into the soil profile to convenient depths, and taking volumetric soil moisture content readings at 30cm interval from the surface. Three out of the twenty access tubes in the catchment were located close to the LAS transect. Three soil thermometers, with a logging interval of 30 minutes, were used to measure the soil temperature at three sites in the Potshini catchment at depths of 0.2 and 0.25m from the surface respectively. The three sites represented the main landuse/landcover in the catchment, i.e smallholder farming and grazing (grassland). These sites were

also located along the LAS transect, from which the average soil heat flux was computed from the depth of soil heated diurnally (0.2m) by the incoming net radiation (Blight, 2002), i.e:

$$G = Z_G(\overline{\Delta T})C_G\rho_G \tag{5.7}$$

where G is the soil heat flux ($kJ.m^{-2}$), Z_G is the depth of soil heated in meters (usually 0.2 to 0.25m), $(\overline{\Delta T})$ is the average measured rise in temperature over depth Z_G, C_G is the specific heat of the soil ($kJ.kg^{-1}{}^{o}C^{-1}$) and ρ_G is the bulk density of the soil ($kg.m^{-3}$). The specific heat capacity of the soil was computed using the method described in Campbell Scientific (1987), i.e:

$$C_G = C_{Gd} + wC_w \tag{5.8}$$

where C_G is the specific soil heat capacity ($kJ.kg^{-1}{}^{o}C^{-1}$), C_{Gd} is the specific heat of the dry soil particles, C_w is specific heat capacity of water ($kJ.kg^{-1}.{}^{o}C^{-1}$), w is gravimetric water content of the soil mass (mass of water/mass of solids). C_{Gd} and C_w has values of 0.85 and $4.19kJ.kg^{-1}.{}^{o}C^{-1}$ respectively. The soil bulk density, measured at three sites in the catchment where soil moisture measurements were undertaken, was found to be 1417, 1439 and $916.4kg.m^{-3}$, and hence the average soil bulk density for the catchment was estimated to be $1257kg.m^{-3}$.

5.5.3 Meteorological data

As highlighted in Chapter 2 and 3, two weather stations, 4 km apart, were equipped with a set of standard meteorological instrumentation to monitor the climatic parameters in the Potshini catchment. Figure 5.1 shows the location of one of the weather stations and other instrumentation to monitor the hydrological parameters in the catchment. This weather station was installed in early 2005 in the midst of the Potshini community and upstream of an existing telemetric weather station which has been operational since 2002 on a nearby commercial farm and managed by the Agricultural Research Council (ARC) of South Africa. The community weather station was located close to the measurement path between the transmitter and the receiver of the LAS and close to one of the flow gauging stations (H-Flume) in the catchment as shown in Figure 5.1. The community weather station had two radiometers that measure the incoming shortwave (facing upwards) and outgoing longwave radiation (facing downwards) and logged into a Mike Cotton System (MCS) data logger. The MCS radiometers were calibrated against a Net radiometer (Kipp and Zonen) with data logged to a Campbell Scientific CR1000 data logger. The calibration exercise took two weeks, from 21st February to 4th March 2007, and the MCS system was calibrated at a time step of two minutes. It is useful to note that the

calibration exercise could not be done earlier than this due to logistical challenges including availability of a Net radiometer. Figure 5.3 shows a scatter plot of calibrated estimates of net radiation from the MCS system and the measured values from the Kipp & Zonen Net radiometer, from which a good fit was obtained.

5.5.4 Satellite data

In this study, the MODIS-AQUA Level 1B images, with a pixel size of 1km x 1km, were freely obtained from the NASA's Level 1 Atmosphere Archive and Distribution System. The images were selected to cover whole or most of the Thukela river basin while taking into account cloud contamination over the area of interest. A total of 38 MODIS AQUA cloud free images were obtained between June 2005 and September 2006. It is useful to note that the SEBAL methodology requires cloud free satellite images and which is a challenge in the southern Africa region especially during the cloudy summer season. The time of capture of nine of these images coincided with field measurement of sensible heat flux using the Large Aperture Scintillometer (LAS), which started in May 2006. This study is based on the comparative analysis of the various surface flux estimates from the nine MODIS images compared to the LAS and other field measurements. Table 5.1 indicates the date and time of acquisition of the nine MODIS.

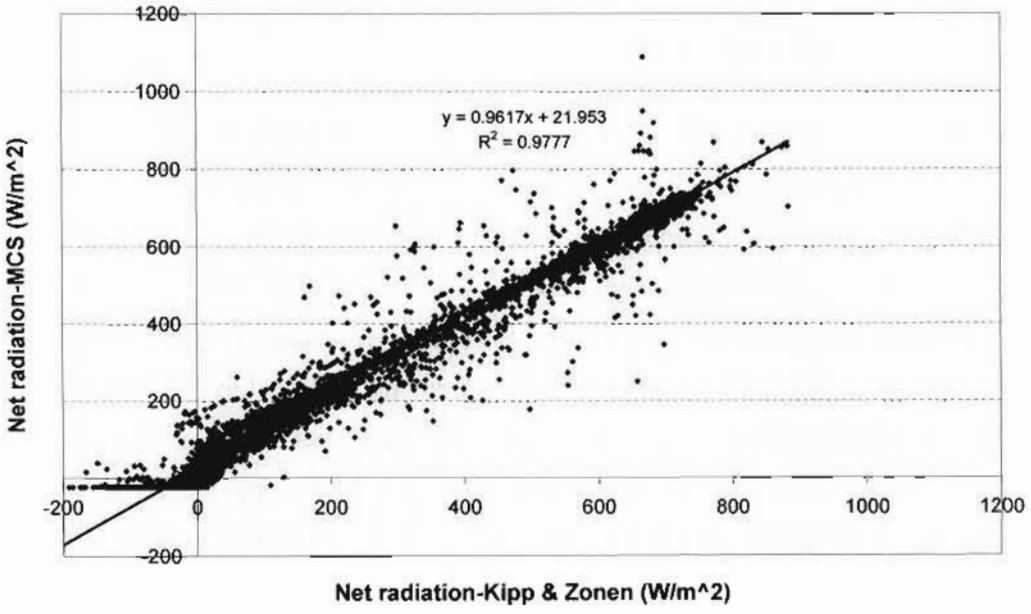

Figure 5.3 Calibration curve for the MCS radiometers (21st February to 4th March 2007)

Table 5.1 Acquisition of the MODIS L1B images in the year 2006

No	Date	Time of capture
1	10th May	12h35
2	27th May	11h40
3	4th June	12h30
4	19th June	11h45
5	21st June	11h35
6	3rd July	12h00
7	10th July	12h05
8	28th July	11h55
9	11th Aug	12h05

SEBAL, like other similar surface energy-based algorithms, requires cloud free satellite images for the computation of the surface energy balance on the earth's surface. From each image, the reflectance of bands 1-7 was computed together with the thermal emission of band 31 and 32. Their respective geo-location attributes were obtained from the accompanying geo-location data files. The general attributes of the sub-set bands that were subsequently used for the SEBAL analysis are as indicated in Table 5.2.

Table 5.2 Band attributes of the nine bands from MODIS AQUA images that were used in SEBAL computation

Band	Spatial resolution (m)	Wavelength (micron)	Band type
1	250	0.645	Reflectance
2	250	0.866	Reflectance
3	500	0.470	Reflectance
4	500	0.555	Reflectance
5	500	1.24	Reflectance
6	500	1.64	Reflectance
7	500	2.13	Reflectance
31	1000	11.03	Emissive
32	1000	12.02	Emissive

5.5.5 Surface albedo

Surface albedo is the ratio of reflected to incident solar radiation at the earth's surface and is a critical variable affecting the earth's climate (Cess, 1978; Dickinson, 1983; Kiehl et al., 1996). In semi arid regions, an increase in albedo leads to a loss of radiative energy absorbed at the surface, and convective overturning is reduced (Liang, 2000). Brest and Goward (1987) and Wu et al., (2006) indicated that the reflectivity of a surface is wavelength dependent, with few natural surfaces being uniform reflectors across portion of the electromagnetic spectrum of interest.

In this study, the broadband surface albedo (α_s) was computed by integrating band reflectances within the short-wave spectrum (band 1-6) as highlighted in Starks et al., (1991), Liang (2000), Tasumi et al., (2000) and Wu et al., (2006) and as described in Equation 5.9.

$$\alpha_s = 0.160\mu_1 + 0.291\mu_2 + 0.243\mu_3 + 0.116\mu_4 + 0.112\mu_5 + 0.08\mu_6 - 0.0015 \qquad (5.9)$$

where μ_i is the reflectance of the respective band.

5.5.6 Normalized Difference Vegetative Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is commonly used to provide information on vegetation density, colour of surface and cultivation practice due to the property of the chlorophyll, which strongly absorbs radiation in the red parts of the electromagnetic spectrum and reflects it in the near-infrared part (Farah and Bastiaanssen, 2001). NDVI was computed using the difference in reflectance in the red and near infra-red region of the spectrum as indicated in Equation 5.10

$$NDVI = \frac{\mu_2 - \mu_1}{\mu_1 + \mu_2} \qquad (5.10)$$

where μ_1 and μ_2 are the spectral reflectance of bands 1 and 2, respectively.

5.5.7 Surface emissivity

The ratio of the thermal energy radiated by the earth's surface to the thermal energy radiated by a black body at the same temperature, i.e, surface emissivity (ε), was computed using the relationship developed by Van de Griend and Owe (1993), i.e:

$$\varepsilon = 1.009 + 0.047 ln(NDVI) \quad (5.11)$$

It should be noted that this method is applicable in the NDVI range of 0.16 to 0.74. This equation is hence not valid for water bodies with negative NDVI values. Therefore, the water bodies were masked and constrained to an emissivity value of 0.999.

5.5.8 Surface temperature

The land surface temperature was computed from the radiant temperature, which was obtained after atmospheric correction of the brightness temperature using the surface emissivity as highlighted in Tasumi et al., (2000). The brightness temperature was derived from the thermal bands (31 and 32) through the inversion of the Plank's function as indicated in Equation 5.12.

$$T_r = \frac{C_2}{r\, ln\left[\frac{C_1}{\pi r^5 B_r} + 1\right]} \quad (5.12)$$

where T_r is the band's brightness temperature (°K), C_1 and C_2 are constants, r is the respective wavelength (μm) and B_r is the radiance value (W.m^{-2} steradian^{-1}). The surface temperature was then computed using the "split window" technique as described in Kerr et al., (1992) and Tasumi et al., (2000).

5.5.9 Instantaneous shortwave radiation

The incoming instantaneous shortwave radiation, $R_{s\downarrow}$ (W.m^{-2}), was computed using the astronomical relationship between the sun and the earth as highlighted in Iqbal (1983), Tasumi et al., (2000) and Farrah & Bastiaanssen (2001), i.e:

$$R_{s\downarrow} = \tau_{sw} G_{sw} \cos\left(\frac{\pi}{180}\theta\right) d_r$$

$$= \left[0.75 + 2 * 10^{-5} DEM\right] * \left[G_{sw} Cos\left(\frac{\pi}{180}\theta\right)\right] * \left[1 + 0.033 Cos\left(\frac{2\pi d}{365}\right)\right] \quad (5.13)$$

where where τ_{sw} is the one-way transmittance, G_{sw} is a solar constant (1367 W.m^{-2}) and d_r is the inverse squared relative earth-sun distance, DEM is estimate of height above sea level (m), d is Julian day and θ is the solar zenith angle (Radian).

5.5.10 Net radiation

This was computed using the methodology described in Bastiaanssen et al., (1998a), Timmermans et al., (2007) and Koloskov et al., (2007), i.e:

$$\begin{aligned} R_n &= (1-\alpha_s)R_{s\downarrow} + R_{l\downarrow} - R_{l\uparrow} - (1-\varepsilon)R_{l\downarrow} \\ &= (1-\alpha_s)R_{s\downarrow} + \varepsilon'\sigma T_{air}^{\ 4} - \varepsilon\sigma T_o^{\ 4} - (1-\varepsilon)\varepsilon'\sigma T_{air}^{\ 4} \end{aligned} \qquad (5.14)$$

where $R_{l\downarrow}$ and $R_{l\uparrow}$ is the incoming and outgoing longwave radiation respectively (W.m^{-2}), ε' is the apparent atmospheric emissivity (air emissivity), ε is the surface emissivity, σ is the Stefan-Boltzmann constant (5.67*10^{-8} W.m^{-2}K^{-4}), T_{air} is the air temperature (K) and T_o is the land surface temperature (K).

5.5.11 Soil heat flux

The soil heat flux was computed using a relationship between the net radiation, surface temperature, surface albedo and NDVI as described in Bastiaanssen et al., (1998a), i.e:

$$G_o = R_n\left(\frac{T_o - 273.15}{\alpha_s}\right)\left(0.0032\alpha_s + 0.0074\alpha_s^{\ 2}\right)\left(1 - 0.987NDVI^4\right) \qquad (5.15)$$

Koloskov (2007) observed that, over a 24-h period, the soil heat flux could relatively be small and can be ignored without introducing significant errors in the computation process. Nevertheless, in this study, the soil heat flux was incorporated in the surface energy balance calculations in order to complete the energy balance with a higher degree of confidence.

5.5.12 Surface roughness height

This is a fraction of the vegetation height used as a physical reference for momentum and heat flux calculation (Parodi, 2002). It affects the shear stress between the vegetation and atmosphere which influences the turbulent characteristics near the surface including the momentum of heat and water vapour exchanges between land and atmosphere. There are several methods in literature for retrieving

this parameter. The applicability and suitability of either of the methods depends primarily on the availability of the required data. In this study, the method described in Moran (1990) and Bastiaanssen et al., (1998a) was used, i.e:

$$z_{om} = exp(-5.54 + 5.87NDVI) \tag{5.16}$$

where Z_{om} is the surface roughness height (m)

5.5.13 Sensible heat flux

Sensible heat flux, H (W.m^{-2}), is the rate of heat loss to the air by convection and conduction, due to a temperature difference. Sensible heat flux is a function of the temperature gradient, surface roughness and wind speed and thus difficult to compute due to the fact that temperature gradient and surface roughness are a function of each other and hence at any time there are two unknowns in this functional relationship. The classical expression for sensible heat flux is given as (Farah and Bastiaanssen, 2001):

$$H = \frac{\rho_a C_p}{r_{ah}} \partial T_a \tag{5.17}$$

$$r_{ah} = \int_{z_{down}}^{z_{up}} \frac{1}{K_h} dz = \left[\frac{1}{ku_*} ln\left(\frac{Z_{up}}{Z_{down}} \right) \right] \tag{5.18}$$

where ρ_a is the moist air density (Kg m^{-3}), C_p is the specific heat capacity of air at constant pressure (J Kg^{-1} K^{-1}), r_{ah} is the aerodynamic resistance to heat transport (s m^{-1}) and δT_a is the temperature difference between two heights Z_{down} and Z_{up} (m), K_h is the eddy diffusivity for heat transport, u_* is the friction velocity (m s^{-1}) and k is the von Karman's constant. Lhome et al., (1994) and Carlson et al., (1995) noted that Equations 5.18 and 5.19 above are only applicable on land surfaces with similar vegetation height and biophysical conditions due to the fundamental assumption made when using thermal infrared images that the radiometric surface temperature (T_{ac}) is equal to the aerodynamic surface temperature (T_{ao}) which does not apply in composite terrain. Bastiaanssen et al., (1998b) suggested another approach where it is assumed that, $T_{ac} \neq T_{ao}$ and taking an arbitrary value of Z_{down}, then the temperature difference δT_a between Z_{down} and Z_{up} can be established from r_{ah} and H without involving radiometric surface temperature T_{ac} and air temperature T_a through an iterative process. In this study, the initial stage of the main iteration process involved establishing δT_a through calibrating an image's surface temperature differences to the energy balance by deriving a linear relationship,

through an intermediate iterative process, between the "wet" and "dry" pixels from an image as described in Bastiaanssen et al., (1998a, 1998b), Bastiaanssen (2000) and Farrah & Bastiaanssen (2001). This relationship was then applied to all pixels after computing the friction velocity from the wind speed at the blending height and the estimated local surface roughness height as outlined in Bastiaanssen (2000), i.e:

$$\frac{1}{u_*} = \frac{1}{ku_{200}} ln\left(\frac{200}{z_{om}}\right) \quad (\text{s m}^{-1}) \tag{5.19}$$

where u_* is the friction velocity (m.s^{-1}), u_{200} is the area-average wind speed at the blending height of 200m elevation (m.s^{-1}) and z_{om} is the surface roughness height (m) for momentum transport. The friction velocity was then used to compute the aerodynamic roughness length, r_{ah}, using Equation 5.18 before computing the initial estimate of H using Equation 5.17. The initial estimate of H was then used to estimate the initial integrated stability correction on the temperature profile for buoyancy effects on the momentum and heat transport as a result of surface heating. This was achieved through using the Monin–Obukhov Similarity Theory (Bastiaanssen, 2000; Mohamed et al., 2004 and Koloskov et al., 2007) where the initial Monin-Obukhov length, L, was estimated as:

$$L = \frac{-\rho_a C_p u_*^3 T_o}{kgH} \quad (\text{m}) \tag{5.20}$$

where g is the acceleration due to gravity (m.s^{-2}) and T_o is the surface temperature (K). This allowed the second improved estimation of the frictional velocity, u_*, using Equation 5.21 by incorporating the stability correction factor for buoyancy effects on the momentum flux, ψ_m, i.e;

$$\frac{1}{u_*} = \frac{1}{ku_{200}} ln\left(\frac{200}{z_{om}} - \psi_m\right) \quad (\text{s m}^{-1}) \tag{5.21}$$

The new and second estimate of u_* was then used to compute an improved estimate of r_{ah} in another version of Equation 5.18, i.e;

$$r_{ah} = \int_{Z_{down}}^{Z_{up}} \frac{1}{K_h} dz = \left[\frac{1}{ku_*} ln\left(\frac{Z_{up}}{Z_{down}} - \psi_h\right)\right] \quad (\text{s m}^{-1}) \tag{5.22}$$

where ψ_h is the stability correction for heat transport. Details on the determination and computation of stability correction factors are highlighted in Kimura et al., (2007). The iteration process was repeated in all pixels until a convergence was achieved in the computation of sensible heat flux.

5.5.14 Algorithm for determining "wet" and "dry" pixels

Through the principle of conservation of mass, evaporation is related directly to the availability of water, i.e rainfall, runoff, irrigation and ground water movements and fluctuation (Farrah and Bastiaanssen, 2001). Jackson et al., (1977) showed that the surface temperature, T_o, is an indicator of evaporation while Nemani and Running (1989) demonstrated the relationship, as reflected on a scatter plot of T_o and NDVI, of the spatial variation of fractional vegetative cover, soil water content, and surface resistance to evaporation. Menenti et al., (1989) proved the usefulness of applying the relationship between T_o and the surface albedo (α_s) in determining dry and wet land surface types. In this study, the NDVI, T_o and α_s values of all the pixels in an image were plotted in a three-dimensional space from where a qualitative approach and interpretation, as described in Farrah and Bastiaanssen (2001), was used to determine the "wet" and "dry" pixels as: low T_o, low NDVI and low α_s indicated bare wet soils and where as high T_o, low NDVI and high α_s represented warm, dry, bare soil pockets. Low T_o, high NDVI and low α_s represent healthy vegetation in good conditions having unstressed transpiration whereas high T_o, high NDVI and high α_s represent vegetation under water stress. The pixels that satisfied the second and third condition were categorized as "dry" and "wet" pixels, respectively.

5.5.15 Latent heat flux

The general expression for latent heat flux ($W.m^{-2}$) is given as (Farah and Bastiaanssen, 2001):

$$LE = \frac{\rho_a C_p}{\gamma(r_{av} + r_s)}\left[e_{sat}(T_o) - e_{act}\right] \text{ (W m}^{-2}\text{)} \qquad (5.23)$$

where γ is the psychrometric constant (mbar K^{-1}), r_{av} is aerodynamic resistance to water vapour transport ($s.m^{-1}$), r_s is the bulk surface resistance to evaporation ($s.m^{-1}$), e_{sat} is the saturated vapour pressure at surface temperature (mbar), e_{act} is the actual vapour pressure (mbar). Stewart (1998) highlighted the difficulty to quantify r_s due to its variability with respect to soil moisture, solar radiation, vapour pressure deficit and air temperature. An easier approach is to compute latent heat flux as a residual of the surface energy balance (Equation 5.1), for each pixel as highlighted in

numerous authors including Bastiaanssen et al., (1998a&b); Hemakumara et al., (2003); Timemermans et al., (2007); Kimura et al., (2007), from which the evaporative fraction for each pixel can then be computed as:

$$EF = \Lambda = \frac{LE}{R_n - G} = \frac{LE}{LE + H} = \frac{1}{1 + \beta} \tag{5.24}$$

where β is the Bowen ratio (*H/LE*). The advantage of using the evaporative fraction over the Bowen ratio is that the former shows less variation during the daytime than Bowen ratio (Farah and Bastiaanssen, 2001; Mohamed et al., 2004) and is equal to its daily value integrated over a period of 24hours. The daily total evaporation was then estimated using Equation 5.25.

$$ET = \frac{\Lambda(R_{n24} - G_o)}{\lambda \rho_w} 86400 * 10^3 \tag{5.25}$$

where *ET* is actual evaporation (mm.d^{-}), R_{n24} is the daily (24 hours) net radiation (W.m^{-2}), λ is the latent heat of vaporization (J.kg^{-1}) and ρ_w is the density of fresh water (kg.m^{-3}).

5.6 Results and discussion

The pixels values of the desired SEBAL outputs that coincided with LAS transect, were compared with the field measurements for the same period of time, i.e 10th May to 11th August 2006. Nine MODIS-AQUA images were obtained and analysed within the 90 days period of field measurements reported herein. The LAS path length more or less coincided and fitted into one pixel of the respective MODIS images given the fact that the resolution of the MODIS bands used in this study was 1km x 1km and the path length was 1.03km. It is useful to note that only cloud-free images were used in this study as a requirement for the SEBAL analysis. Figure 5.4 shows a comparison between the SEBAL estimates of *ET* and field measurements.

For convenience and consistency in this section, the estimates of total evaporation (*ET*) obtained through the analysis of field measurements, i.e net radiation from weather station, soil heat flux from soil temperature sensors and sensible heat flux obtained from the Scintillometer will be referred to as LAS estimates.

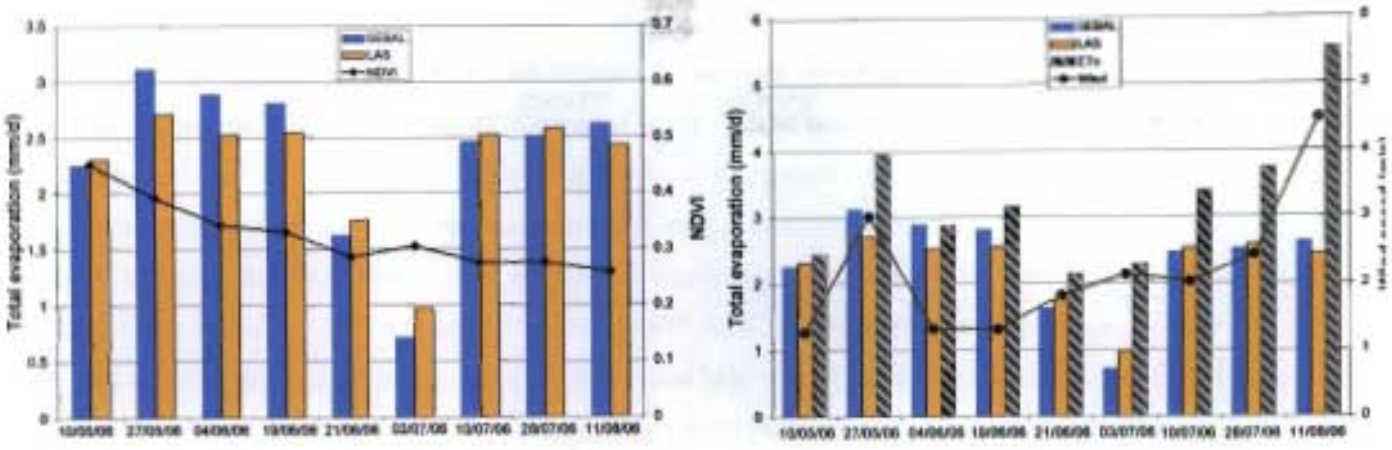

Figure 5.4 SEBAL and field estimates of total evaporation, potential evapotranspiration and biophysical parameters

From Figure 5.4, it can be observed that the SEBAL and LAS estimates of *ET* were comparable and followed the same pattern, with variance being observed on the low *ET* values. The lowest LAS *ET* value, 0.972mm.d^{-1} was observed on 3rd July of which SEBAL estimate was found to be 0.712mm.d^{-1}. This translates to an underestimation deviation of 26.7% (0.26mm.d^{-1}), with the deviation calculated as the depature of SEBAL estimates relative to LAS. The difference between the highest LAS estimate and its corresponding SEBAL estimate was found to be 0.41mm.d^{-1}. This occurred on 27th May where LAS and SEBAL values were observed to be 2.712 and 3.117mm.d^{-1} respectively and hence an overestimation deviation of 14.9%. It was observed that there was a relatively good comparison for both SEBAL and LAS estimates of the range between 0.7 and 2.5mm.d^{-1}. The LAS and SEBAL estimates were compared against the potential evapotranspiration (ET_o) estimates for the study area (Figure 5.4) and which were computed using meteorological data measured at one of the Potshini weather stations and the FAO-56 methodology (Allen et al., 1998; Allen, 2000). The comparison showed that the ET_o estimates were all above the LAS and SEBAL estimates, even though there was relatively less difference on 10th May. In agricultural planning, *ET* estimates have been computed by multiplying the ET_o with a crop coefficient of a respective vegetation types at different growth stages. Such an approach may not be directly applicable in a composite vegetative cover of different stages of growth. Such a challenge is further compounded in land surfaces with both bare soils and composite vegetative covers i.e. in the Potshini catchment. The lowest estimate of ET_o was observed on 3rd July, 2.29mm.d^{-1}, which coincided with the lowest values of both SEBAL and LAS during the study period. The NDVI values for the nine pixels that overlay the measurement transect were plotted against the *ET* values as indicated in Figure 5.4. NDVI is a good indicator of the vegetative condition, with low NDVI values indicating poor vegetative condition. The rain season in the study area usually starts in mid September and ends in April. From Figure 5.4, it can be observed that the NDVI values over the

Potshini catchment were relatively high on 5th May, 0.452, and reduced to 0.259 by 11th August. There was a sharp decrease of the NDVI values between 5th May and 4th June, from 0.452 to 0.343, and this could be attributed to the progressive depletion of vegetation on the smallholder farms in the catchment by the freely grazing livestock, during the winter season (May to August), after harvesting of the main maize crop. The area had received relatively heavy rains and well distributed in the summer season (September to April), with 780mm being recorded between January and April, and hence the vegetative condition in early May was relatively good and hence the high NDVI value. Few rainfall events occurred during the study period as indicated in Table 5.3.

Table 5.3 Rainfall in the Potshini catchment, 2006

May		June		July		August	
Date	Rain (mm)	Date	Rain (mm)	Date	Rain (mm)	Date	Rain (m)
17th	1.5	1st	3	18th	2	2nd	7
23rd	23	2nd	5	24th	10	15th	30
24th	14	23rd	5.5	25th	15		
Total	38.5	13.5		27		37	

From Table 5.3, the months that received the least rainfall were June and July, with 13.5 and 27mm.m^{-1} respectively, while May and August received approximately the same amount of rainfall. A correlation between the *ET* and rainfall observed at least 5 days before the date when the LAS and SEBAL estimates were computed did not indicate direct association save for three rainfall events recorded in May (23rd & 24th) and July (24th & 25th). These rainfall events were of higher magnitude than the others observed during the study period and it is possible to argue that these events were responsible for the relatively higher SEBAL and LAS *ET* estimates that were obtained within 5 days after the rainfall events. The Potshini catchment is characterised by high shallow ground water table ranging between 1 and 3m below surface (cf. Chapter 4), with a seasonal wetland on the upper slopes of the catchment that contributes significantly to the stream flow especially during the winter period. Hydraulic conductivities of the soils in the catchment range from 8 to 120mm.h^{-1} for the upper 300mm of soil. It is useful to note that the each of the MODIS pixels (1km x 1km) that overlay the field measurement transect covered more than 80% of the 1.2 km^2 Potshini catchment including the wetland (cf. Figure 5.1), which could have contributed to the relatively high *ET* estimates from SEBAL and LAS as shown in Figure 5.4.

Several authors, including Allen (1998), have indicated that wind speed is one of the main factors that significantly influence the evapotranspiration process through the enhancement of the atmospheric demand. A plot of the wind speed against the SEBAL and LAS *ET* estimates, Figure 5.4, revealed the correlation of wind speed on occurrence of *ET*, especially in the months of July and August. The rather high *ET* values in July, with low monthly rainfall, may be attributed to the strong winds that prevail in the area between June and August. Such winds have been reported in the past to have enhanced the spread of wild fires in the area leading to destruction of property. The prevailing wind direction in the catchment is South-Easterly, thus blowing from the upper to lower slopes of the catchment across the seasonal wetland and perpendicular to the transect (LAS pathlength) on which field measurements were carried out. The "erosive" and turbulent power of such winds could have lead to the enhancement of the evapotranspiration process over the wetland and whose signature could have been captured by both LAS and SEBAL. Hence, there is a possibility that the fetch over the LAS transect may have influenced the LAS results.

5.6.1 Components of the surface energy balance

A comparison was made on the various components of the surface energy balance obtained from field measurements and the SEBAL estimates. The field net radiation data was obtained from a weather station as described in the methodology section of this Chapter. It is worth noting that the LAS estimates of net radiation and soil heat flux are basically point measurements estimated from different methodologies, whereas the corresponding SEBAL estimates are pixel values for an area covering 1km x 1km. It should also be noted that there are errors in the LAS estimates due to the inherent limitations associated with the various methods used to compute the respective values and this may account for some of the differences in the LAS and SEBAL estimates. Figures 5.5 show a comparison of net radiation, sensible and latent heat fluxes from SEBAL estimates and field measurements (LAS estimates).

There was a relatively good comparison of the SEBAL and LAS estimates of net radiation as depicted in Figure 5.5, even though the field measurement overestimate relative to the SEBAL estimates on most of the days. The highest measured average daily net radiation was found to be 437.2 $W.m^{-2}$, which was recorded on 27th May. The corresponding SEBAL estimate was found to be 376.2 $W.m^{-2}$ and hence the estimation deviation, relative to field measurement, was found to be -13.95%. The lowest relative deviation was observed on 19th June, when SEBAL underestimated the field measurement by 0.38%.

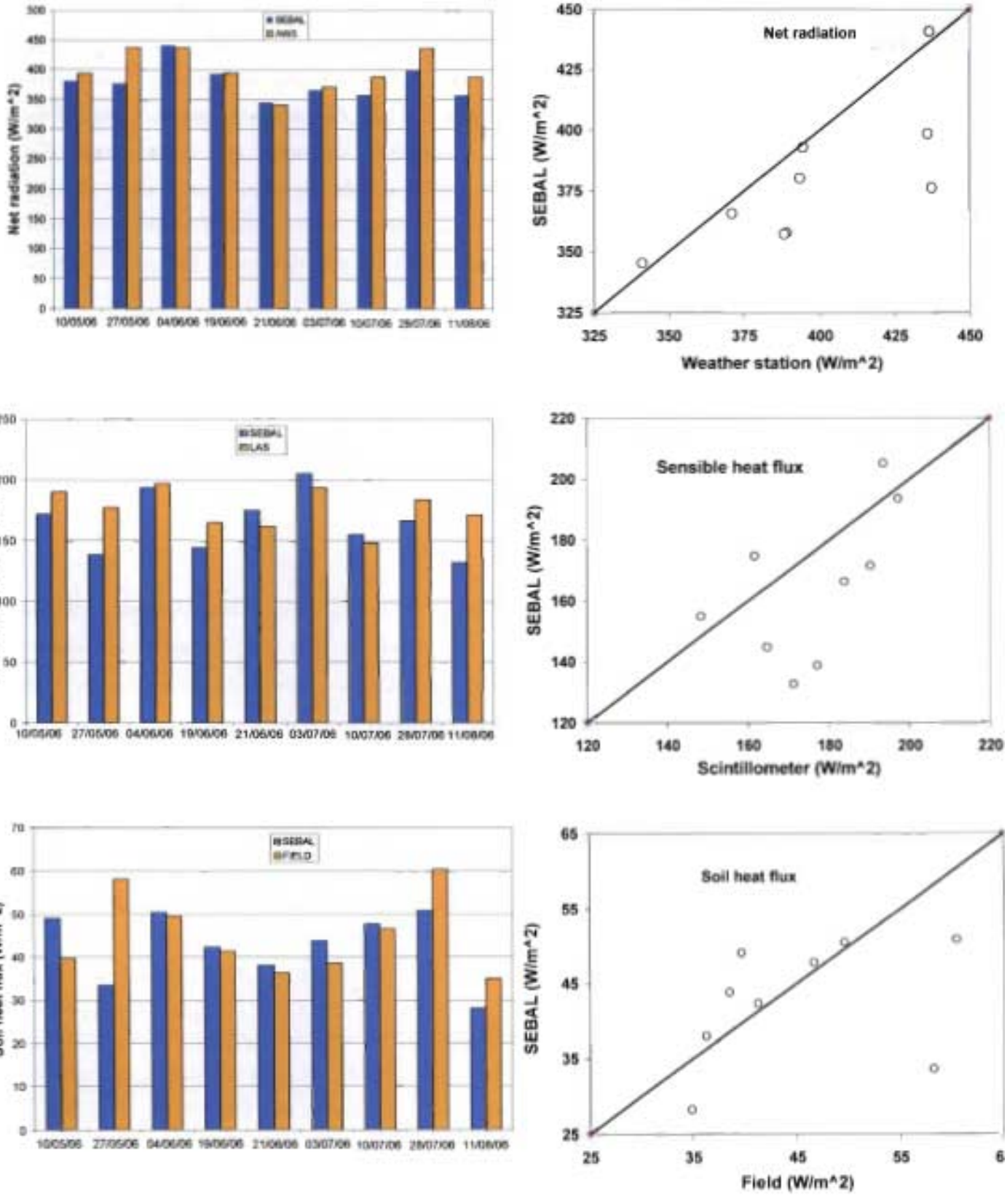

Figure 5.5 Energy balance components at Potshini from SEBAL and LAS

Table 5.4 shows a summary of the relative deviation of SEBAL estimates for the various components of the energy balance including surface temperature (T_o) and the evaporative fraction (E_f) which are derivatives of the SEBAL analysis. There were only two days when SEBAL overestimated the measured net radiation, i.e on 10th May and 4th June, though at an appreciable level of deviation of 3.3 and 1.01% respectively. More variance was observed in the field and SEBAL estimates of soil heat flux as indicated in Table 5.4.

Table 5.4 Components of the energy balance

No	Date	T_o (°K)	T_a (°K)	U_3 ($m.s^{-1}$)	E_f	Relative deviation (%)		
						R_n	G	H
1	10th May	295.012	292.5	1.26	0.430	3.32	-23.76	9.73
2	27th May	297.001	297.22	3.01	0.566	-13.95	42.26	21.52
3	4th June	295.823	290.83	1.32	0.509	1.01	-1.90	1.78
4	19th June	298.426	293.81	1.31	0.500	-0.38	-2.54	12.00
5	21st June	301.667	295.78	1.82	0.293	-1.23	-4.77	-8.21
6	3rd July	302.206	294.7	2.13	0.135	-1.39	-13.74	-6.15
7	10th July	301.497	294.02	2.02	0.468	-7.96	-2.47	-4.47
8	28th July	306.668	298.63	1.70	0.519	-8.54	15.74	9.40
9	11th Aug	307.280	293.76	4.48	0.522	-7.92	19.16	22.37
Average relative deviation						-4.11	3.10	6.44

The highest and lowest relative deviation in soil heat flux was found to be 42.26 and -1.9%, on 27th May and 4th June, respectively. Relatively high variance in net radiation and sensible heat flux estimates was also recorded on 27th May, i.e -13.95 and 21.52% respectively. Such a variance could be attributed to cloud cover sessions during the day given the fact that SEBAL computes instantaneous components of the surface energy balance before integrating for a day based on the evaporative fraction (Bastiaansseen, 2000). It was observed that SEBAL overestimated the sensible heat flux on 6 out of the 9 days. The relative deviation in *H* ranged from 1.78 to 22.37% on 4th June and 11th August respectively. Again, it was observed that more variance was exhibited in *Rn* and *G* on 11th August and hence the cause of the variance could be attributed to cloud cover sessions in the Potshini catchment. The average relative deviation in *Rn*, *G* and *H* SEBAL estimates for the 9 discrete days used in this analysis was found to be -4.11, 3.10 and 6.44%. Figure 5.6 shows the hourly variation of *Rn*, *G* and *H*

as measured in the field on 10th June in the Potshini catchment. 10th June was a typical day in winter with no cloud cover in the catchment, and South Africa at large.

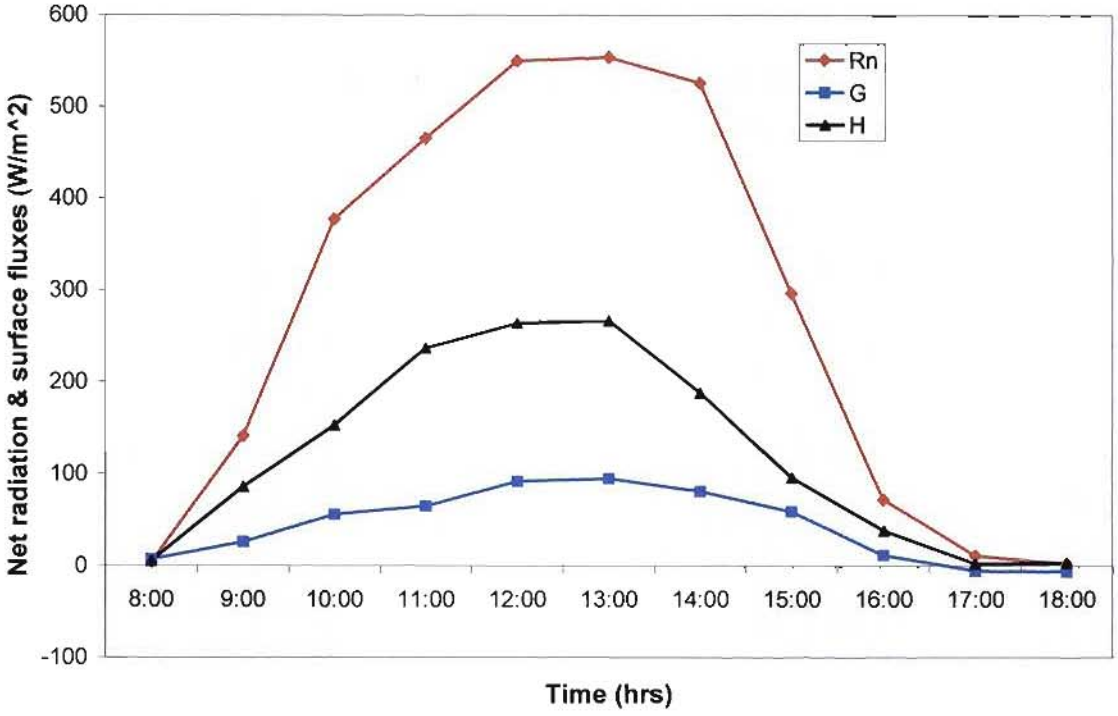

Figure 5.6 Variation of the surface energy balance components on 10th June 2006 in the Potshini catchment

Winter is characterised with shorter daylight and longer dark hours. The variation of the net radiation and sensible heat flux indicate a steady increase and variation from early morning and reaching the peak between 12h00 and 13h00. A similar trend was observed by Hemakumara et al., (2003). In this study, the maximum soil heat flux was 95.4W.m^{-2} while net radiation and sensible heat flux were 554.1 and 267.5W.m^{-2} respectively. It was observed that the soil heat flux maintained a relatively constant level after reaching the peak value until 15h00 when it started to drop down to a negative value at 17h00. Negative values for soil heat flux indicate change of direction of heat flux flow, from lower levels to the upper surface. Such a phenomenon occurs when the upper soil surface is cooler than the lower soil layers. This was not the case with sensible heat flux and net radiation where a sharp decline was observed after reaching the peak value. It is recognised that soil has more capacity to store heat energy than air and hence the relatively constant soil heat flux that was observed after attaining the peak value. A declining trend for net radiation and sensible heat flux was observed to start after 13h00 and reaching very low levels at 17h00. During winter, it is common to have sunset before 18h00 as is depicted in Figure 5.6. Nevertheless, it is useful to note that the magnitude and trend of the

respective fluxes as portrayed in Figure 5.6 will be different during summer where longer daylight is observed (with sunset being as late as 19h00). Hemakumara et al., (2003) noted the effect of cloud cover and rainfall to the variation of sensible heat flux and net radiation in a day, where very low values of H and R_n were recorded on a cloud and or rainy day. It is unfortunate that measurement of sensible heat fluxes could not be carried out during the wet summer season due to breakdown of the LAS as a result of frequent lightning strikes.

5.6.2 SEBAL estimates of *ET* over the Thukela river basin

Figure 5.7 presents the spatial variation of SEBAL *ET* estimates over the Thukela river basin on 1st August 2005 and 29th March 2006 as computed. These dates represent a general overview of the evaporative water use over the river basin during the dry winter season (May to September) and wet summer season (October to April), respectively. A more detailed analysis of the evaporative water use of various land uses in the Thukela river assessed from satellite imagery is presented in Chapter 6. The maximum *ET* on 1st August and 29th March was found to be 5.3 and 6.2 mm.d^{-1}, respectively. Such a variation was expected due to the rainfalls in summer. A sharp contrast can be observed from Figure 5.7 with regard to the spatial variation of *ET* over the basin for the two days. The dominant *ET* in winter and summer ranged between 1 to 2 mm.d^{-1} and 2 to 4 mm.d^{-1} respectively. During winter, the highest *ET* levels were observed to occur on the northern and southern part of the river basin, the latter bordering the Drakensberg mountains and is characterised by commercial irrigated farming and commercial forest plantations.

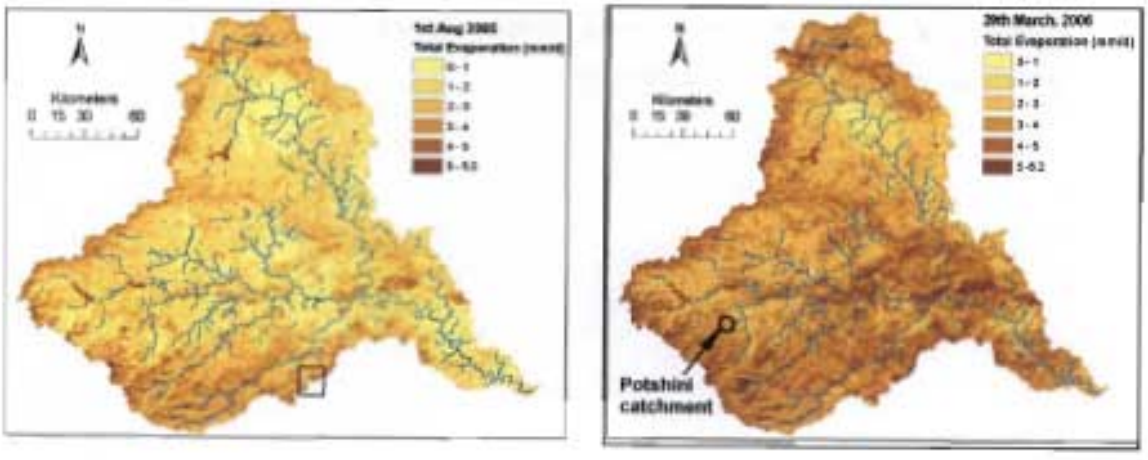

Figure 5.7 Spatial variation of *ET* on 1st August 2005 and 29th March 2006 over the Thukela river basin

5.7 Conclusions

The LAS was used to measure sensible heat flux over a mixed vegetation land cover in the Potshini catchment where soil heat flux and net radiation measurements and other meteorological parameters were monitored. The actual evaporation was computed using the surface energy balance equation based on 1 minute data statistics and compared to the remote sensed SEBAL estimates of actual evaporation in the catchment, derived from MODIS satellite data, and the potential evapotranspiration estimates computed using the FAO-56 method. Generally, the LAS and SEBAL estimates of *ET* were comparable with a relative deviation ranging from -14 to 26%, indicating a reasonable agreement between the two methods. These results compare well with results from similar studies in other countries of different climatic conditions. All the FAO-56 estimates were above the SEBAL and LAS *ET* values, an indication that the latter were within the measurement range considering the fact that the experiment was carried out during the dry winter season. SEBAL estimates of net radiation, sensible and soil heat fluxes were comparable to the field measurements with reasonable relative accuracies. It could be more interesting to compare the *ET* estimates with data from Class A-pan or Lysimeter as another validation strategy for the methods discussed in this Chapter. Nevertheless, it is recognised that no single method of measuring *ET* is without problems and uncertainties due to the many factors influencing its occurrence especially on large spatial scales. However, the ability of the SEBAL methodology to produce reasonable estimates of *ET* provides the potential for practical application on a river basin scale water balance studies by providing estimates of *ET* over large spatial extents. It would be interesting and useful to carry out a detailed analysis, applying both the scintillation and remote sensing techniques, to determine the evaporative water use by the various landuses in the Thukela river basin. Such a study would generate useful information with regard to water productivity and equity in water resources in the basin.

6.0 Evaporative water use of different land uses in the Thukela river basin assessed from satellite imagery

Summary

Evaporative water use of various land use classes (often called Green Water Flows) in the Thukela river basin was estimated using the Surface Energy Balance for Land (SEBAL) methodology and public domain Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images. Twenty-eight images were analysed covering the period between June 2005 and September 2006. The South Africa land use map developed in the year 2000, together with the map of Quaternary Catchments for the Thukela river basin were used to compute the evaporative water use of the respective land uses in 13 Quaternary Catchments on the upper Thukela river basin.

There was a good comparison between the SEBAL estimates of total evaporation and ground measurements from a Large Aperture Scintillometer installed at a site in one of the Quaternary Catchments in the study area. It was observed that the land uses that generated relatively large volumes of green water flows in the study area were forestry (Eucalyptus, Pine, mixed species and indigenous), water bodies and wetlands. Total evaporation rates for all land use classes were high during the wet summer season, with Eucalyptus ranging between 3 $mm.d^{-1}$ during the dry winter season to about $5mm.d^{-1}$ during the wet season. Bare rocks and eroded soil surface land use class had the least evaporative water use. The relatively low evaporation rates over water bodies during the dry winter season could be attributed to the averaging of mixed pixels (wet and dry) due to change in areal coverage and which could not be captured in the 1km x 1km low resolution MODIS images. Thus, the potential for applying remote sensing techniques, using low resolution satellite images, to quantify water use by various land uses in the Thukela river basin was explored with promising results.

6.1 Introduction

Sustainability in water resources management is achieved, when consumptive uses (including abstractions and changes of land use) do not threaten the short and long-term status of the water resource (WaterWatch, 2006). Such a balance can only be achieved through a good understanding of the dominant hydrological processes at the managerial scales in a river basin. In South Africa, for example, the Thukela river basin ($29,000km^2$) is delimited into 86 Quaternary Catchments, which form the lowest level at which water resources strategies are formulated. In spite of the importance of entrenching water resources management principles and practices at the operational scales, the

available database of information on water use by various land uses at these scales is inadequate (Bastiaanssen and Chandrapala, 2003). In sub-Saharan Africa, this is further compounded by the poor state of hydrometeorogical networks and decline in capital investment in their maintenance, despite the importance of establishing "up to date" catchment monitoring networks with the capacity to capture the spatial and temporal variation of dominant hydrological processes in support of decision making in water resources management at the operational scales. Total evaporation is the dominant component of the hydrological cycle in sub-Saharan Africa accounting for over 60% of the incident precipitation, and is thus a major determinant of the net flow in rivers and percolation into aquifers (Rockström et al., 2001). There is little doubt that the success of current and future water resources management strategies in semi-arid regions will include a pragmatic approach of managing the evaporative water use from various landscapes and is thus a challenge to both researchers and policy makers (Jewitt, 2006). The relationship between land use, water use and water supply must be described quantitatively, however this is not straightforward due to the natural heterogeneity and interacting hydrological processes in catchments.

Given the complex nature of mixed vegetation and different land use patterns in a river basin, it is extremely difficult to assess the validity of evaporation and transpiration losses extrapolated from point measurement to catchment scale (Hemakumara et al., 2003). Nevertheless, measuring and monitoring trends in evapotranspirative consumption on the scale required to support judgment about sustainability is feasible through remote sensing techniques, which offer the potential to monitor at river basin scale (thousands of square kilometers in a single satellite image) (WaterWatch, 2006). With remote sensing, it is possible to assess the spatial variability of fluxes, and if the observations are made repeatedly, their temporal variability as well (Schugge et al., 2002). Furthermore, it has been suggested that remote sensing offers the basis for developing and making public indicators of equitable water resources by investigating the intensity of evaporative use and production of biomass at various scales, e.g per unit area or per respective landuse (WaterWatch, 2006). Satellite remote sensing, using the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998a, 1998b), to compute the evaporative water use of various land uses has successfully been applied in several countries under different climatic conditions worldwide, e.g Egypt, Pakistan, Kenya, Sri Lanka and Sudan. Some initial applications of SEBAL in South Africa include studies by WaterWatch (2006) and by the author as illustrated in Chapter 5 of this thesis, with previous studies having assessed the water use by different land uses based on point measurements, small catchment studies or simulation model applications. It is well recognised that these methods have major limitations in assessing water use by different land uses in different parts of a river basin, because of the spatial and temporal scale complexities that arise when trying to extrapolate point measurement to provide

estimates of evaporative water use to the basin as a whole. Nagler et al., (2007) further highlighted the complexity associated with obtaining representative flux measurements in vegetation covers, especially natural vegetation, due to inhomogeneity in both canopy height and spatial distribution.

In this study the remote sensing SEBAL methodology for computing total evaporation on each pixel of a satellite image was applied in the Thukela river basin using the Moderate Imaging Spectroradiometer (MODIS) images for the period between June 2005 and September 2006. The MODIS images have been archived since 1999 and are freely available through the National Aeronautics Space Administration (NASA) and have a daily coverage with pixel resolution of 1km, with some bands having a resolution of 250 and 500m as well. Such a pixel resolution is well suited for monitoring fluxes at regional scale spanning to hundreds of km^2 and is thus considered appropriate for the 29,036 km^2 Thukela river basin.

6.2 Study area

The Thukela river basin is located in the KwaZulu-Natal province in South Africa and extends from 27°25'S to 29°24'S and 28°58'E to 31°26'E. The river basin covers an area of 29,036 km^2 from which the state Department of Water Affairs and Forestry (DWAF) has delineated 86 Quaternary level operational subcatchments (QCs), while other researchers delineated the QCs further into a total of 113 meso-subcatchments (Jewitt et al., 1999) and more recently into 235 subcatchments (Schulze et al., 2005). In this study, the headwater Quaternary Catchments of the upper Thukela river basin, in the vicinity of QC V13D (Figure 6.1) were the main focus of this study due to the availability of comparative data from a Large Aperture Scintillometer installed in the QC V13D as well as the variation in land uses that occur there. The main land uses in the QC are as shown in Figure 6.2 and the areal extents of the QC's used in this study are shown in Table 6.1.

The main land uses covering the 3028 km^2 areal extent of the 13 Quaternary Catchments, as obtained from the National Land use map, developed in the year 2000 by the South African Council for Scientific and Industrial Research (CSIR), are as indicated in Table 6.2. "Unimproved" (natural) Grassland covers 71% of the total area while urban areas and woodlands occupy the smallest area, 0.011%.

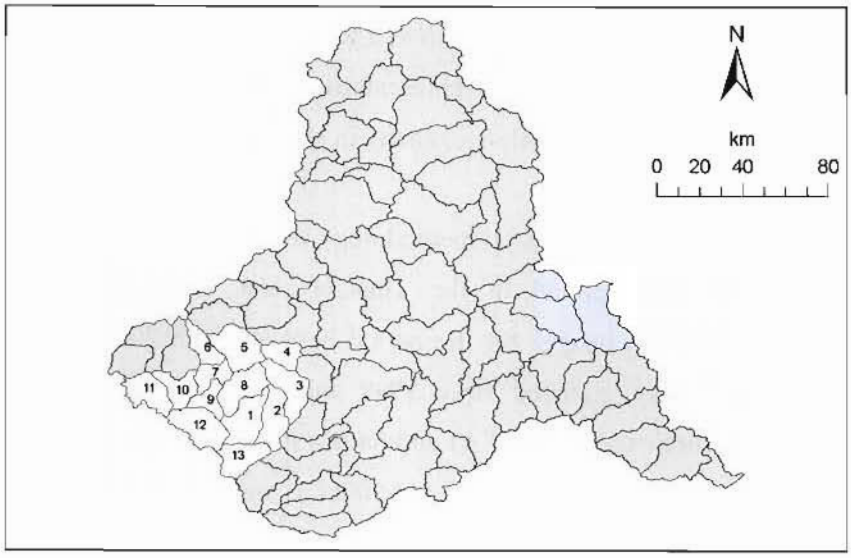

Figure 6.1 Quaternary Catchments in the study area

Table 6.1 Areal extents of the QC. The ID numbers reflects the numbers in Fig. 6.1

ID No.	QC No	Area (km^2)
1	V13B	295.83
2	V13C	257.52
3	V13E	282.98
4	V11M	155.47
5	V11L	313.84
6	V11F	161.74
7	V11J	145.00
8	V13D	285.35
9	V11H	133.81
10	V11E	193.84
11	V11B	254.15
12	V11G	315.52
13	V13A	233.30
	TOTAL	**3028.35**

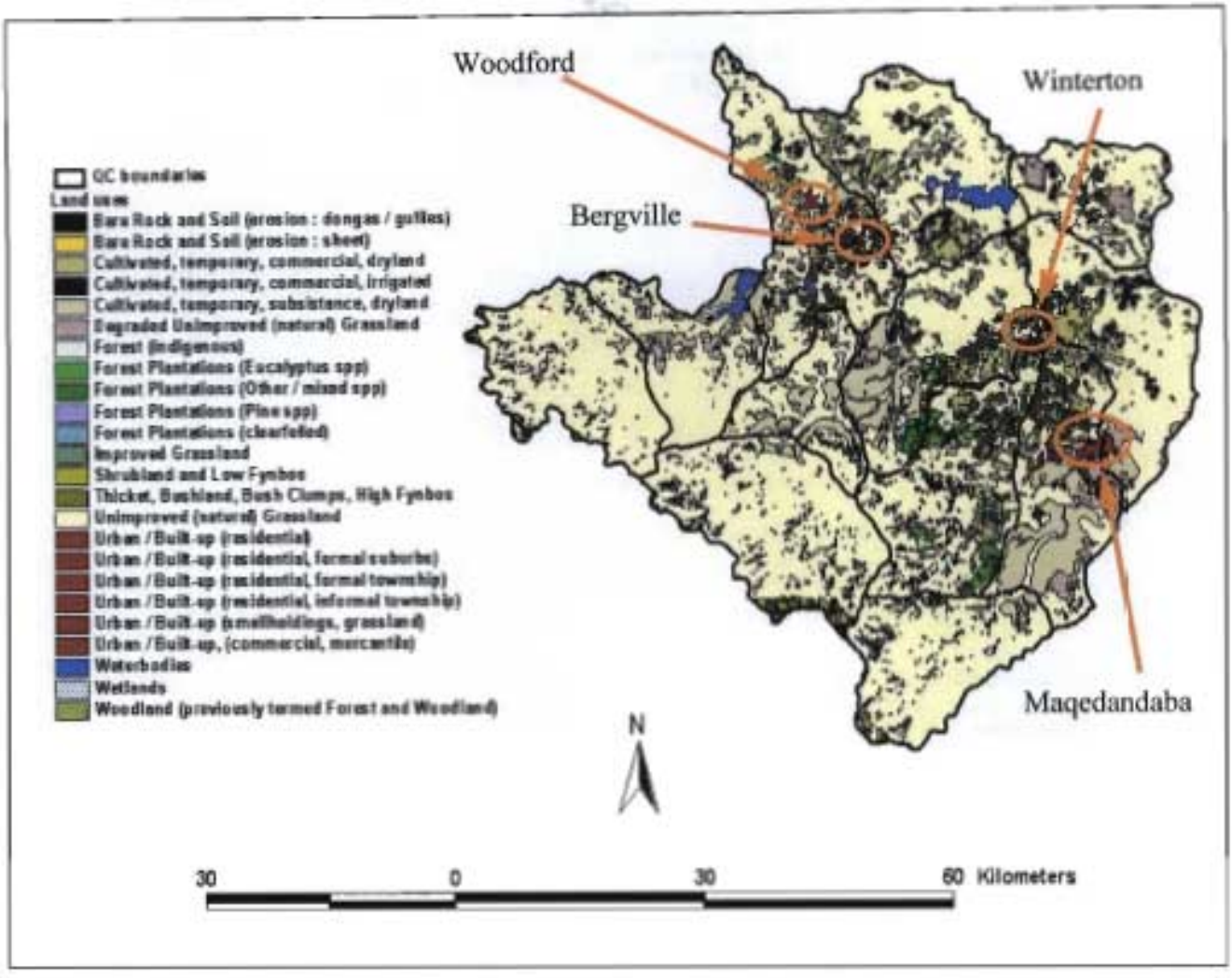

Figure 6.2 Land uses in the Quaternary Catchments and major towns in the study area

6.2.1 Climate

The Thukela river basin exhibits a large variation of rainfall, with Mean Annual Precipitation (MAP) ranging from around 2000 $mm.a^{-1}$ in parts of the Drakensberg mountains, with an altitude of 3000m above sea level, to as low as 550 $mm.a^{-1}$ in lower drier valley regions (Lynch, 2004). An overview and spatial variation of Mean Annual potential evaporation and Mean Annual Precipitation, as highlighted in Schulze et al., (1997) and Dent, (1989) is provided by Figures 6.3 and 6.4, while Figures 6.5 and 6.6 shows the spatial variation of altitude and ecological zones in the river basin respectively.

Table 6.2 Land uses in the 13 Quaternary Catchments

	Land use	Area (km^2)	Percentage of total area (%)
1.	Unimproved (natural) Grassland	2161.743	71.373
2.	Thicket, Bushland, Bush Clumps, High Fynbos	63.394	2.093
3.	Cultivated, temporary, commercial, dryland	246.196	8.129
4.	Cultivated, temporary, subsistence, dryland	214.925	7.096
5.	Bare Rock and Soil (erosion : sheet)	0.568	0.019
6.	Urban / Built-up (smallholdings, grassland)	3.501	0.116
7.	Bare Rock and Soil (erosion : *dongas* / gullies)	12.631	0.417
8.	Wetlands	6.197	0.205
9.	Waterbodies	40.449	1.335
10.	Cultivated, temporary, commercial, irrigated	106.209	3.507
11.	Degraded Unimproved (natural) Grassland	76.309	2.519
12.	Urban / Built-up (residential)	2.271	0.075
13.	Shrubland and Low Fynbos	23.607	0.779
14.	Urban / Built-up (residential, formal suburbs)	1.372	0.045
15.	Urban / Built-up, (commercial, mercantile)	0.237	0.008
16.	Improved Grassland	1.041	0.034
17.	Forest Plantations (Eucalyptus spp.)	35.529	1.173
18.	Urban / Built-up (residential, formal township)	0.331	0.011
19.	Woodland (previously termed Forest and Woodland)	0.331	0.011
20.	Forest Plantations (Other / mixed spp.)	5.724	0.189
21.	Forest (indigenous)	12.300	0.406
22.	Forest Plantations (clear felled)	3.595	0.119
23.	Forest Plantations (Pine spp.)	3.879	0.128
24.	Urban / Built-up (residential, informal township)	6.434	0.212
	Total	3028.354	100

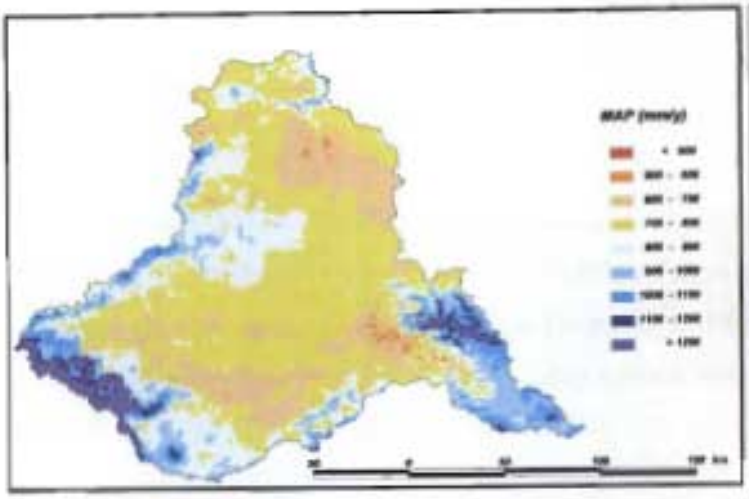

Figure 6.4 Mean Annual Precipitation (after Dent et al, 1989)

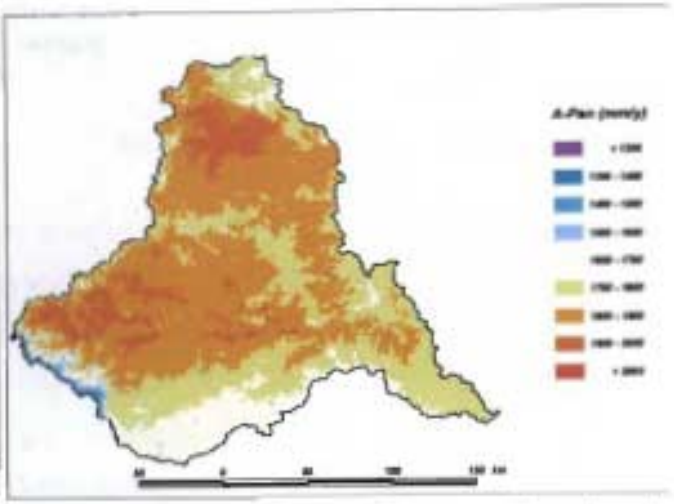

Figure 6.3 Mean annual potential evaporation using A-pan equivalent values as reference (after Schulze 1997)

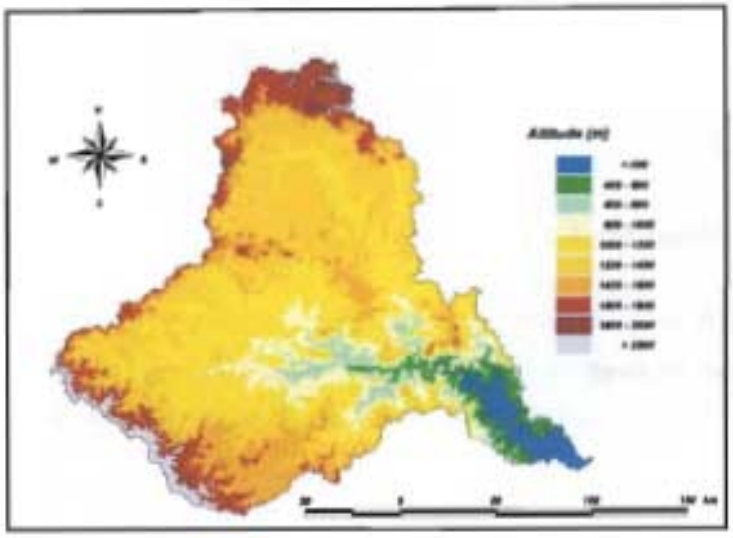

Figure 6.5 Altitudinal zones in the basin (After Dlamini, 2006)

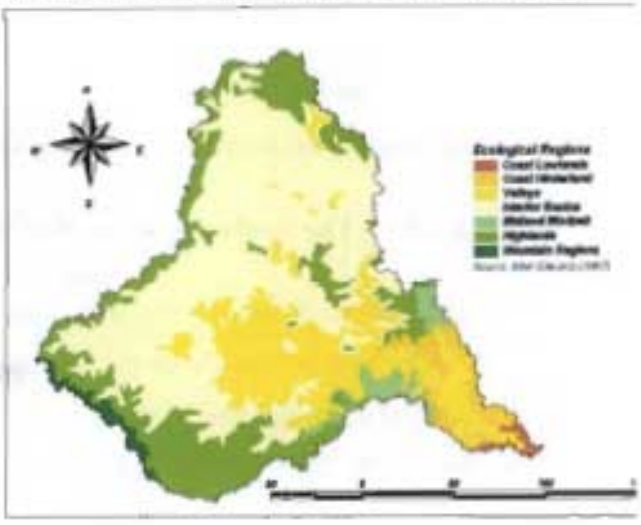

Figure 6.6 Major ecological regions (After Edwards, 1967)

6.3 Material and methods

In this study, twenty-eight MODIS Level 1B images were obtained from the National Aeronautics Space Administration (NASA); Level 1 Atmosphere Archive and Distribution System [http://ladsweb.nascom.nasa.gov/data/search.html] for the period between June 2005 and September 2006. Most of the images were from the MODIS-AQUA imager except for one MODIS-TERRA image, captured on 06/01/2006. Good quality cloud-free satellite images in the southern Africa region are only assured during the winter season (May to September), with the summer season being characterized by haze, clouds and rainfall. This was the case during the months of February and March 2006, when all MODIS (AQUA and TERRA) satellite images covering the study area were

contaminated with clouds. Table 6.3 shows the date of acquisition and time of capture of the 28 MODIS images used in the study.

6.3.1 Field measurements

Hydrometeorological parameters were monitored in a small rural catchment, the Potshini research catchment (E 29.3679^0 S 28.8145^0) located in QC V13D in the upper Thukela river basin, operated by the University of KwaZulu-Natal; School of Bioresources Engineering and Environmental Hydrology as part of the Smallholder Water System Innovations (SSI) research programme (Rockström et al., 2004) in the Thukela river basin. A Large Aperture Scintillometer (Scintec BLS 900), installed over a transect of 1.03km, for measuring sensible heat flux formed part of the monitoring equipment in the catchment. The net radiation and soil heat flux were also measured in the catchment thus enabling the computation of the latent heat flux, and subsequently *ET*, as a residual of the surface energy balance equation. The structure and details of the surface energy balance equation are highlighted in the subsequent section. The *ET* measurements from the field were compared with SEBAL results as discussed in the results section of this Chapter.

6.3.2 The Surface Energy Balance Algorithm for Land (SEBAL)

The SEBAL procedure comprises twenty-five steps for computing a complete radiation and surface energy balance along with the resistances for momentum, heat and water vapour transport for each pixel of a satellite image (Bastiaanssen, 2000). Equation 6.1 describes the surface energy balance, the basis of the SEBAL methodology.

$$\lambda E = R_n - G_o - H \qquad (6.1)$$

Where λE is the latent heat flux ($W.m^{-2}$), R_n is the net radiation ($W.m^{-2}$), G_0 is the soil heat flux ($W.m^{-2}$) and H is the sensible heat flux ($W.m^{-2}$). The latent heat flux is the amount of energy used to evaporate water from surfaces including vegetative landscapes and is calculated as a residual term of the energy balance on the surface. SEBAL requires satellite images with spectral radiance in the visible, near-infrared and thermal infrared part of the spectrum.

Table 6.3 MODIS images used in the study

2005			2006		
Day of the year	Date	Time of capture	Day of the year	Date	Time of capture
161	10th June	12h20	16	16th Jan	08h30
170	19th June	12h15	95	5th April	12h05
183	2nd July	11h45	106	16th April	11h45
192	11th July	12h20	116	26th April	12h20
210	29th July	11h25	118	28th April	12h10
213	1st Aug	11h55	125	5th May	12h15
225	13th Aug	12h20	130	10th May	12h35
238	26th Aug	11h50	147	27th May	11h40
245	2nd Sept	11h55	155	4th June	12h30
254	11th Sept	11h50	170	19th June	11h45
273	30th Sept	12h20	172	21st June	11h35
328	24th Nov	12h25	184	3rd July	12h00
337	3rd Dec	12h20	191	10th July	12h05
353	19th Dec	12h20	209	28th July	11h55

In addition to satellite images, the SEBAL methodology requires a limited number of weather parameters including wind speed, relative humidity and air temperature (Bastiaanssen et al., 1998a, Bastiaanssen, 2000). The surface albedo, surface temperature and relevant vegetation indices were derived from satellite measurements of surface reflectance and emissions after a geometrical correction process of seven reflective and two thermal bands of the MODIS images, and were used together to solve for R_n, G_0 and H. The evaporative fraction, Λ, was computed from the surface energy balance at satellite overpass on all pixels as indicated in Equation 6.2.

$$EF = \Lambda = \frac{\lambda E}{R_n - G_o} = \frac{\lambda E}{\lambda E + H} = \frac{1}{1+\beta} \qquad (6.2)$$

where β is the Bowen ratio ($H/\lambda E$). Computation of evaporative fraction is the last step in the SEBAL algorithm from which other moisture indicators are derived. The advantage of using the evaporative

fraction over the Bowen ratio is that the former shows less variation during the daytime than Bowen ratio (Farah and Bastiaanssen, 2001; Mohamed et al., 2004). The difference between the instantaneous evaporative fraction at satellite overpass and the evaporative fraction derived from the 24-hour integrated energy balance is marginal and may be neglected (Brutsaert and Sugita, 1992; Crago, 1996; Farah, 2001; Farah et al., 2004). For time scales of 1 day or longer, G_0 can be ignored and net available energy (R_n - G_0) reduces to net radiation (R_n) (Ahmed, 2002). At daily timescales, ET_{24} (mm.day^{-1}) can be computed as:

$$ET_{24} = \frac{86400 \times 10^3}{\lambda \rho_w} \Lambda R_{n24} \tag{6.3}$$

Where: R_{n24} (W.m^{-2}) is the 24-h averaged net radiation, λ (J.kg^{-1}) is the latent heat of vaporization, and ρ_w (kgm^{-3}) is the density of fresh water.

6.3.3 Monthly *ET*

The computation of the monthly *ET* involves extrapolating the SEBAL daily *ET*, within a particular month, proportionally to the reference *ET* (Penman-Monteith) where the latter is derived from standard meteorological measurements. The fact that the reference *ET* is from a specific point in the image and does not represent the actual condition at each pixel is not significant for the extrapolation of the daily *ET* image in time since the reference *ET* is only used as an index of the relative change in weather (both reference *ET* and actual *ET*) for the area covered by the image (Morse et al., 2000). The procedure involves determining the cumulative reference *ET* between successive satellite images before computing the ratio, (K_m), of the cumulative reference *ET* to the average reference *ET* over the period. The monthly *ET*, ($ET_{monthly}$), was then computed as follows:

$$ET_{monthly} = \sum_{i=1}^{i=n} (ET_{SEBAL})_i (K_m)_i \tag{6.4}$$

Where ET_{SEBAL} is the daily *ET* image, K_m is a multiplication factor for the representative period, n is the number of *ET* images processed in the respective month.

6.4 Results and discussion

Figure 6.7 shows the spatial variation of total evaporation in the Thukela river basin on 1st August 2005, an output of the SEBAL methodology, with the daily *ET* varying from less than 1 to 5.3mm.d^{-1}. Relatively high *ET* is observed on the high altitude regions in the basin (cf. Figure 6.5) and on forest and water bodies land use classes (cf. Figure 6.2)..

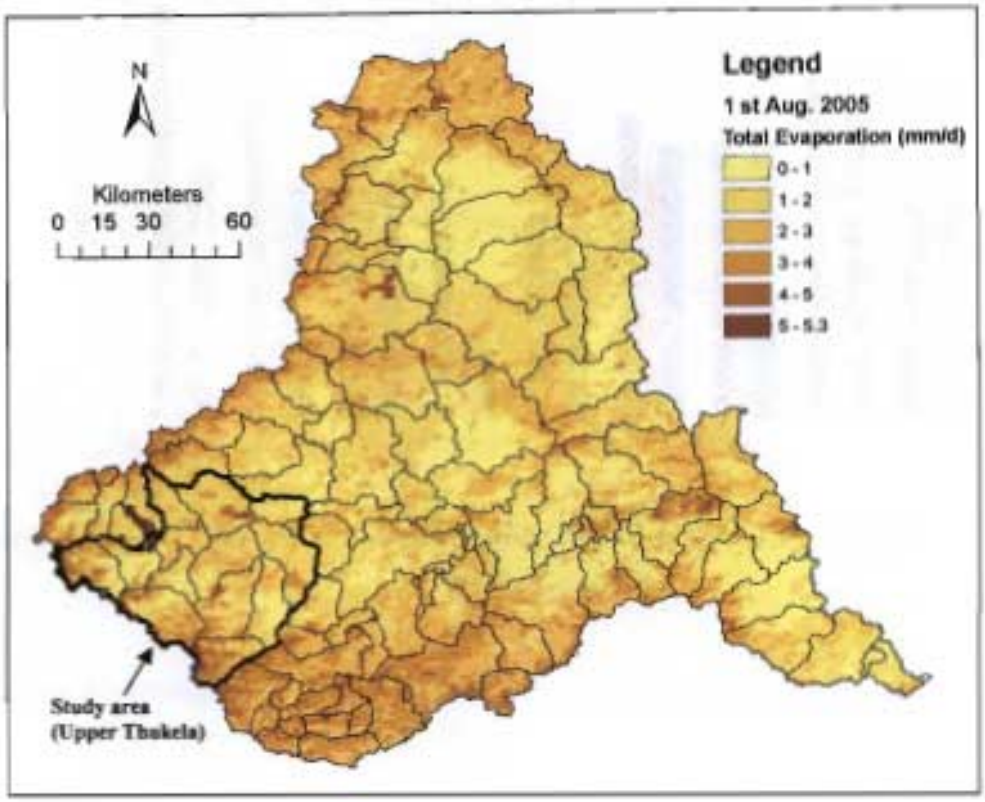

Figure 6.7 Spatial variation of *ET* in the Thukela river basin on 1st Aug. 2005

The *ET* images have a pixel resolution of 1 km, hence land uses with areal extents of less than 1 km^2 (cf. Table 6.2) were not considered in this analysis. The time of capture of 9 out of the 28 images coincided with field measurements of *ET* at the Potshini catchment using the Large Aperture Scintillometer (LAS) together with Penman-Monteith estimates of reference *ET* (FAO-56) derived from weather parameters measured in a weather station in the catchment. The *ET* values derived from the MODIS 1km pixels that coincided with the LAS transect together with the Penman-Monteith estimates of reference *ET* were compared with the LAS measurements of *ET* as indicated in Figure 6.8. The land use along the LAS transect was mainly smallholder farming, the dominant land use in

the Potshini. Crops are only grown during the wet summer season (October to April) with livestock freely grazing on the smallholder farms during the dry winter season thus depleting the standing hay and crop residues on the farms.

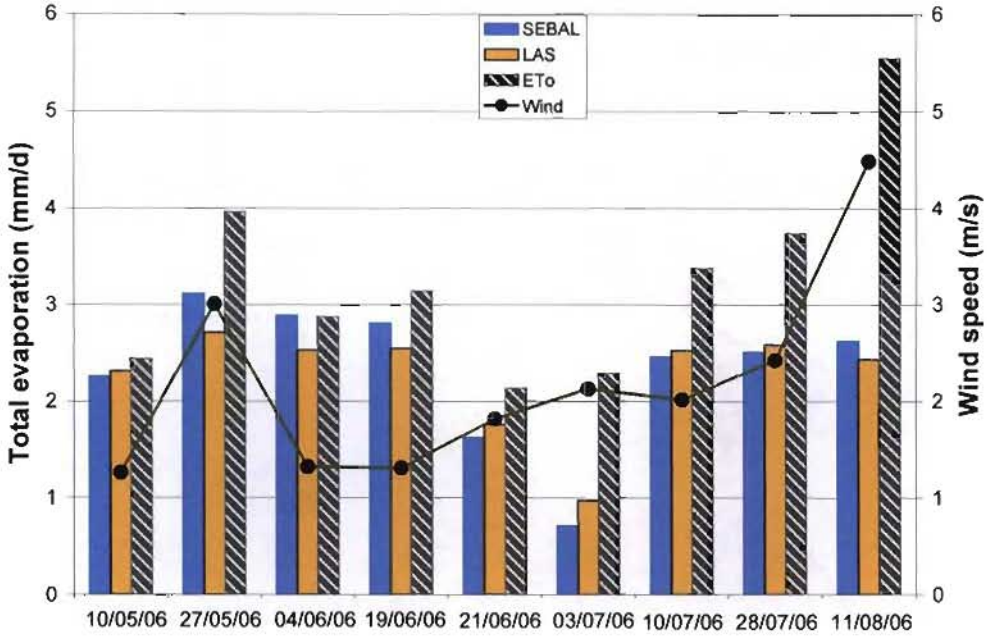

Figure 6.8 Comparison of LAS and SEBAL with reference *ET* results in the Potshini catchment (cf. Chapter 5)

The SEBAL results showed fair to good agreement with the ground measurement in the Potshini catchment, with a deviation range of between -14% and +26% relative to the ground (LAS) measurements, with the actual *ET* obtained from LAS and SEBAL being less than the potential evapotranspiration on most of the days as indicated in Figure 6.8. The lowest *ET* rate of less than 1 $mm.d^{-1}$ was observed in the month of July, which is the coldest month in the year in the study area. The winter season (May to September) is characterized by dry weather conditions and high wind speeds especially in the months of July to September as can be seen in Figure 6.8. Windy conditions increase the atmospheric demand of moisture as evident in the increase of reference *ET* with respect to wind speed as indicated in Figure 6.8. Wind speeds of more than $8m.s^{-1}$ have previously been recorded in the catchment.

6.4.1 Estimating water use of different land uses

The evaporative water use of various land uses in the upper Thukela river basin was then assessed at different spatial and temporal scales from the *ET* images derived from the SEBAL methodology.

Seventeen out of the twenty four land use classes in the study area were analyzed for their consumptive water use. Figure 6.9 shows actual evaporation from five non- agricultural land use classes in the study area, mainly forests, while Figure 6.10 shows *ET* from agricultural land uses including water bodies and grassland for some of the days between August 2005 and April 2006. Only one-good quality MODIS image was available to be analyzed for the months of November and December respectively. Unfortunately, most of the images for the months of October, January, February and March were contaminated with clouds over the study area hence these months are not part of the analysis presented herein. The rainy season in the Thukela river basin starts in October and ends in April (summer), and total evaporation is expected to peak in this period. From Figure 6.9 and 6.10, it can be observed that there is a marked difference in the variation of *ET* rates within land use classes during the dry and wet season, with less variation being observed during the dry and wet seasons for forestry and agricultural land use classes respectively. A likely reason for the relatively high variation in the Forestry land use class during in the wet summer season, apart from the free water-stress soil conditions, could be the contribution of interception to the total evaporation rates with canopies of respective forests playing a crucial role in this regard.

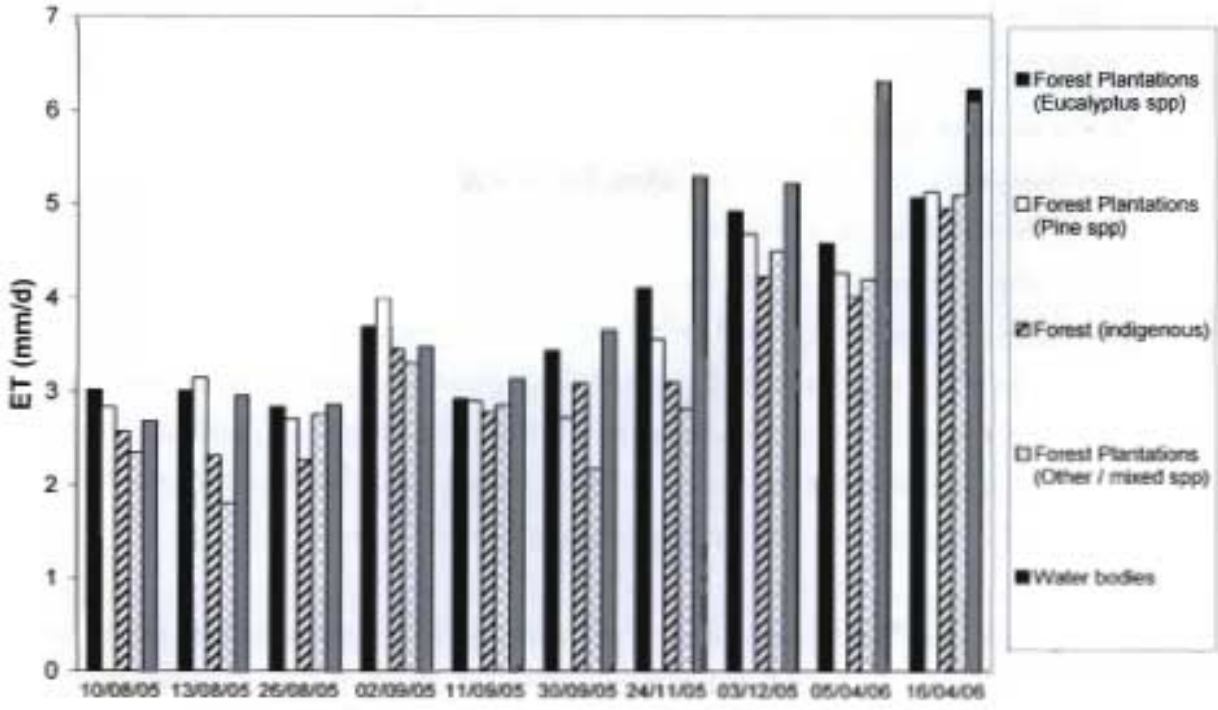

Figure 6.9 Estimated daily *ET* rates of some non-agricultural land uses

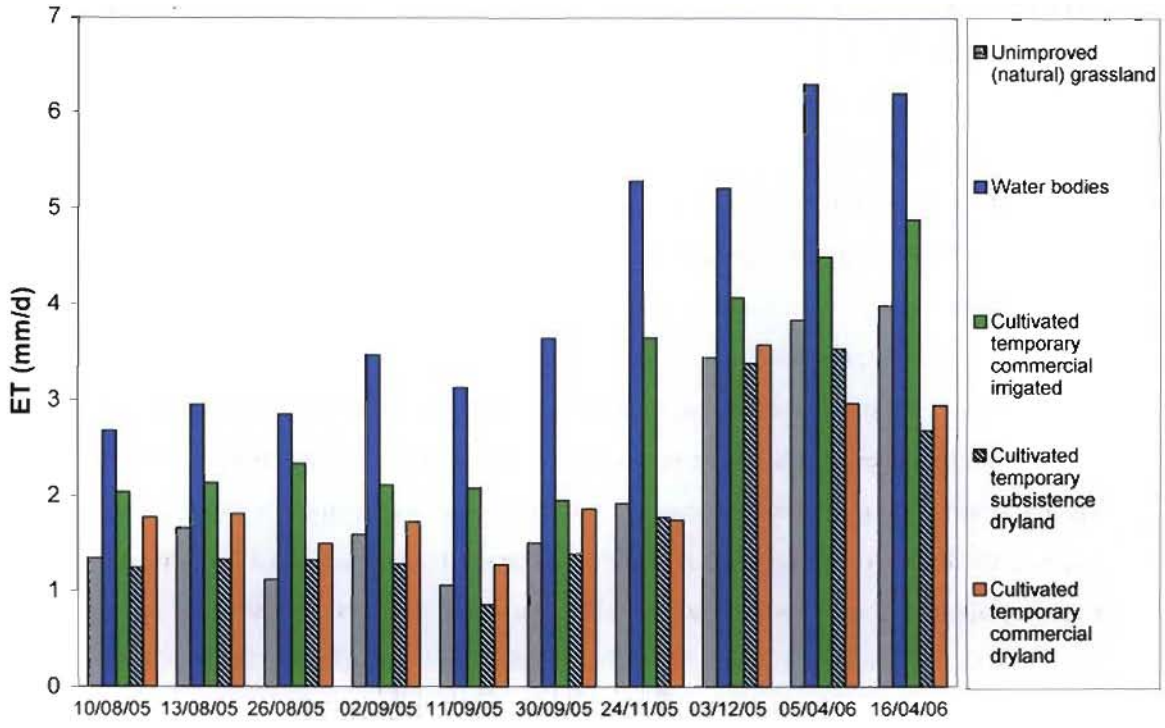

Figure 6.10 Estimated daily *ET* rates of some agricultural land uses including grassland and water bodies

Likewise, from Figure 6.10, the probable reason for the more variation of *ET* rates in agricultural land use class during the dry winter period could be as a result of temporary irrigation practice especially under the Cultivated, temporary commercial, irrigated land use class from which relatively high *ET* rates were observed to be persistent throughout the observation period. Generally, the Cultivated, temporary commercial dry-land farming had relatively higher and persistent *ET* rates compared to Cultivated, temporary, subsistence dry-land farming land use class and the *ET* rates for unimproved grassland are more or less the same as for the Cultivated, temporary, subsistence dry-land farming land use class as depicted in Figure 6.10. The *ET* rate for water bodies during the dry season ranged between 3 and 3.5 $mm.d^{-1}$, and 5 to 6 $mm.d^{-1}$ during the wet season.

It should be noted that the land use class of "water bodies" is inclusive of both natural and man made water bodies that can consist of multiple mixed pixels falling both on land and inside water bodies as can be seen in Figure 6.11. The spatial variation of *ET* during the dry winter season and wet summer season is clearly depicted in Figure 6.11 as can be seen in the change in contrast, with relatively high *ET* being observed over the entire study area during the summer season, e.g on 5th April 2006 compared to the dry winter season, e. g on 1st August 2005. Good quality MODIS images were captured on these dates and hence made good samples for spatial representation of variation of *ET*

over the seasons. The effect of "mixed" pixels is visible in Figure 6.11 (lower pair of figures), especially with the "water bodies" land use class, where it is seen to fall under different pixels with different *ET* values especially during the dry winter season. This could be attributed to the fact that many reservoirs change size during the year, becoming smaller at the end of the dry season, but the classified land use map remain the same, hence the values shown in Figure 6.9 and 6.10 are an average of wet and dried areas of reservoirs, otherwise the *ET* rates from water bodies and wetlands is likely to be higher.

A similar observation was noted by WaterWatch (2006), where the water bodies land use class in the Inkomati catchment in South Africa was observed to have less evaporative water use during the dry season than agricultural land uses, notably irrigated crops. In this study, such an argument is confirmed during the wet season (April), when the *ET* rates from water bodies is seen to be higher than any other land use, when most of the reservoirs are at their full capacity.

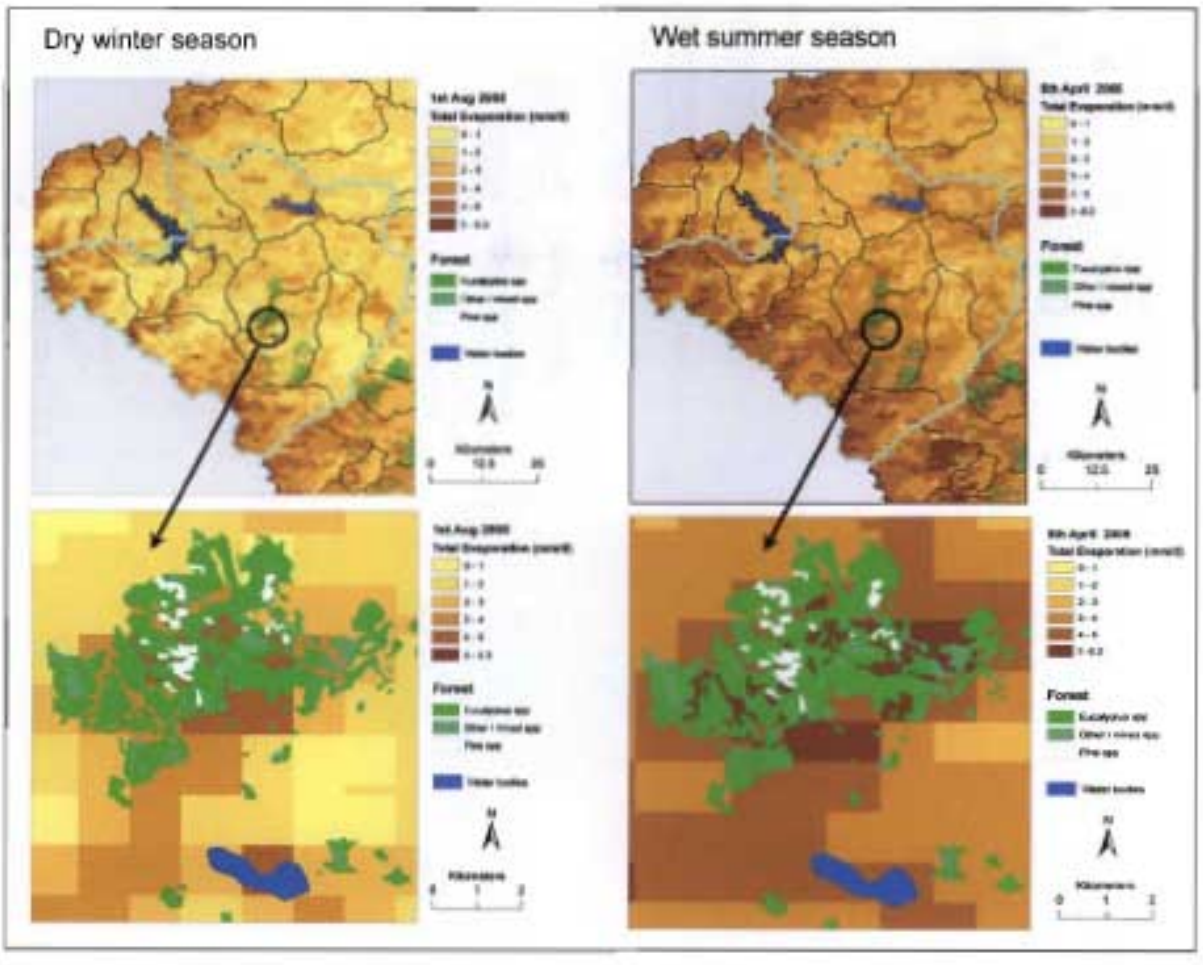

Figure 6.11 Spatial variation of *ET* in winter and summer season in the study area

6.4.2 Monthly *ET*

Figures 6.12 to 6.17 shows monthly *ET* values for 17 land uses in the study area for the months of June, July, August in the year 2005 and April, May and June for the year 2006. It is important to note that the land use classification was generated and based on Landsat images with a pixel resolution of 30m, while the *ET* images were generated from MODIS data with a resolution of 1 km. This has an impact on the evaporative water use analysis in that land uses with small areas (cf. Table 6.2) are considered to be less accurate than when the *ET* is computed from Landsat images.

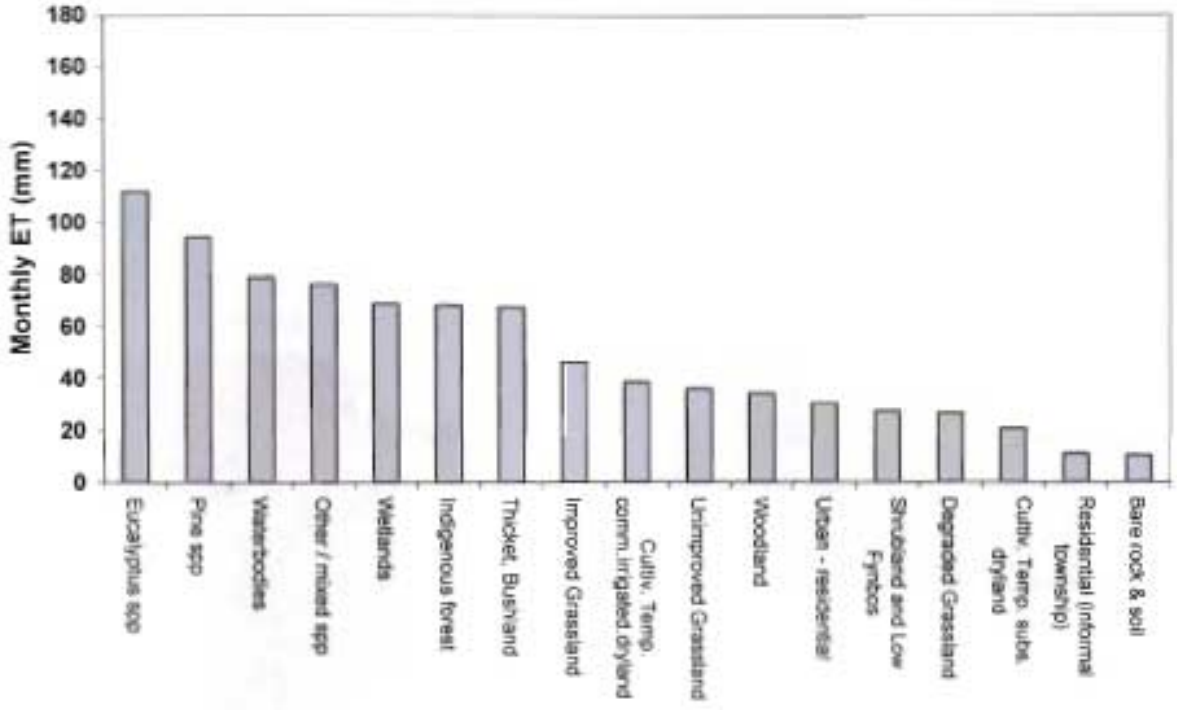

Figure 6.12 June 2005

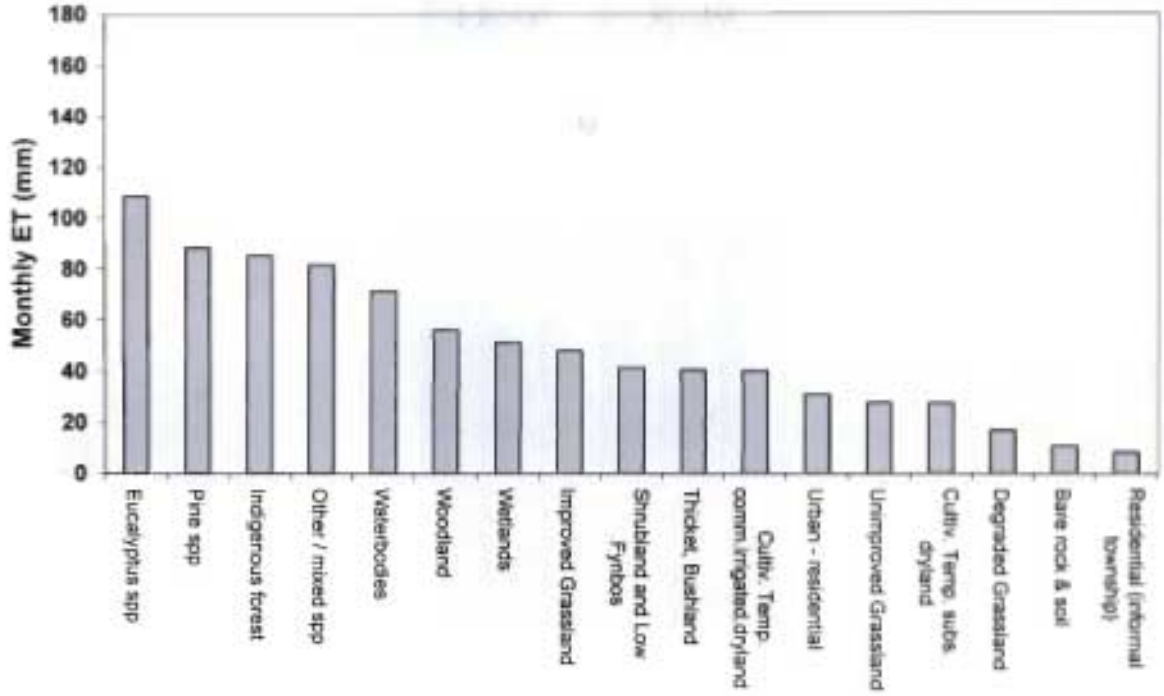

Figure 6.13 July 2005

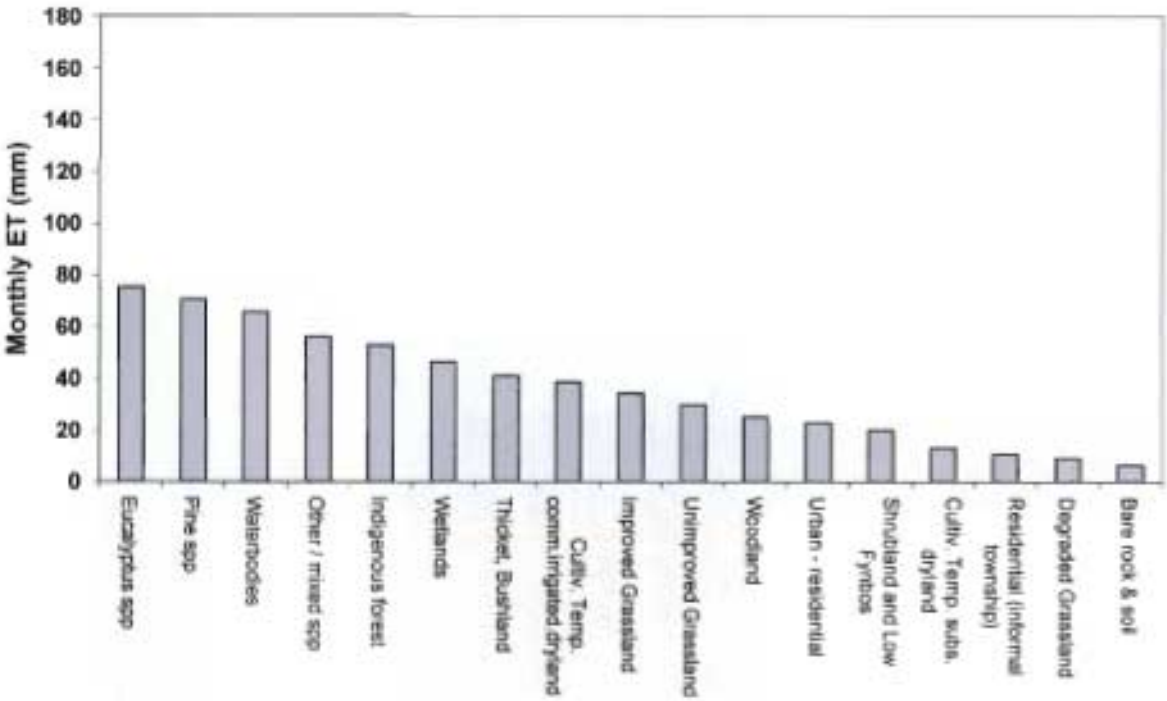

Figure 6.14 August 2005

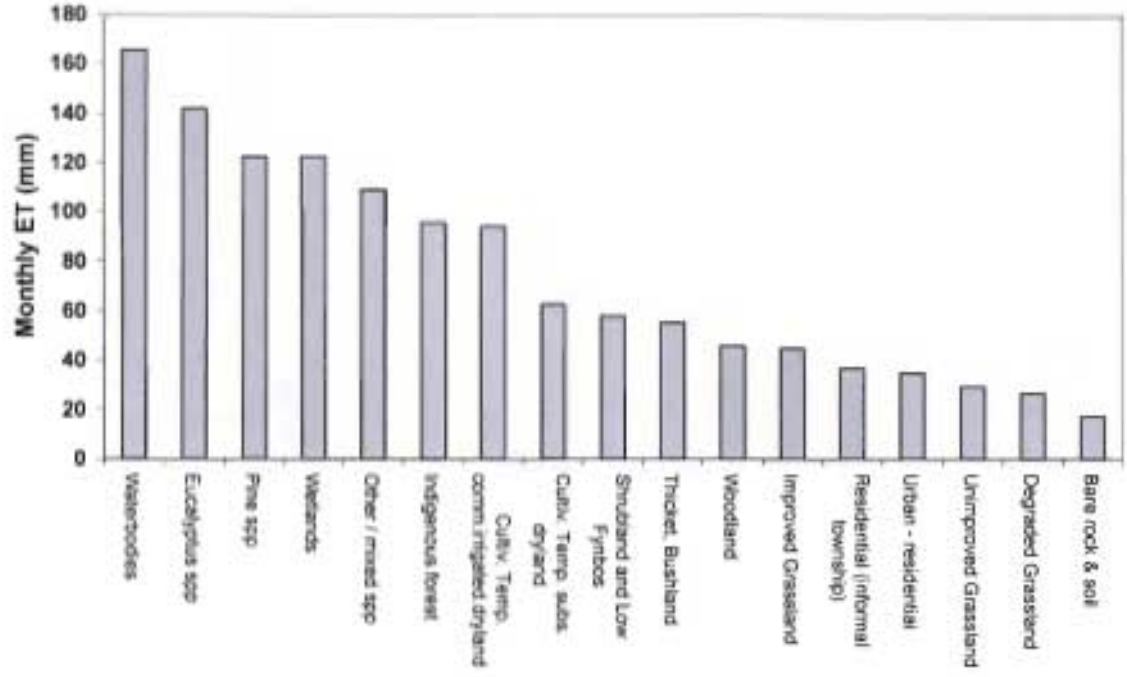

Figure 6.15 April 2006

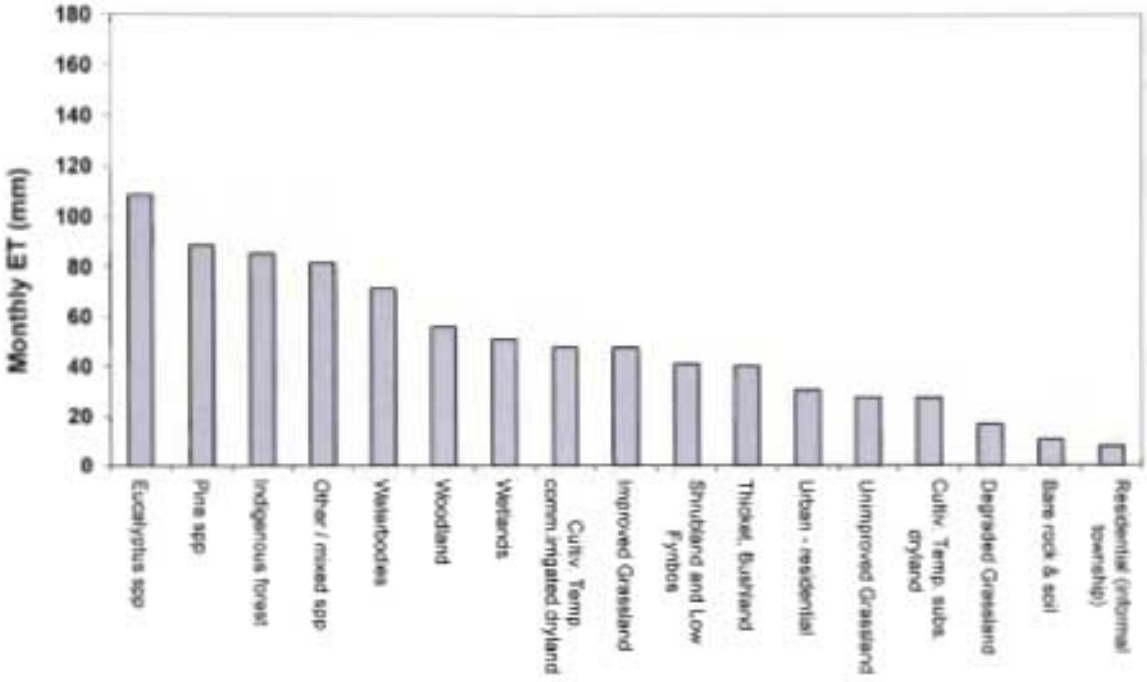

Figure 6.16 May 2006

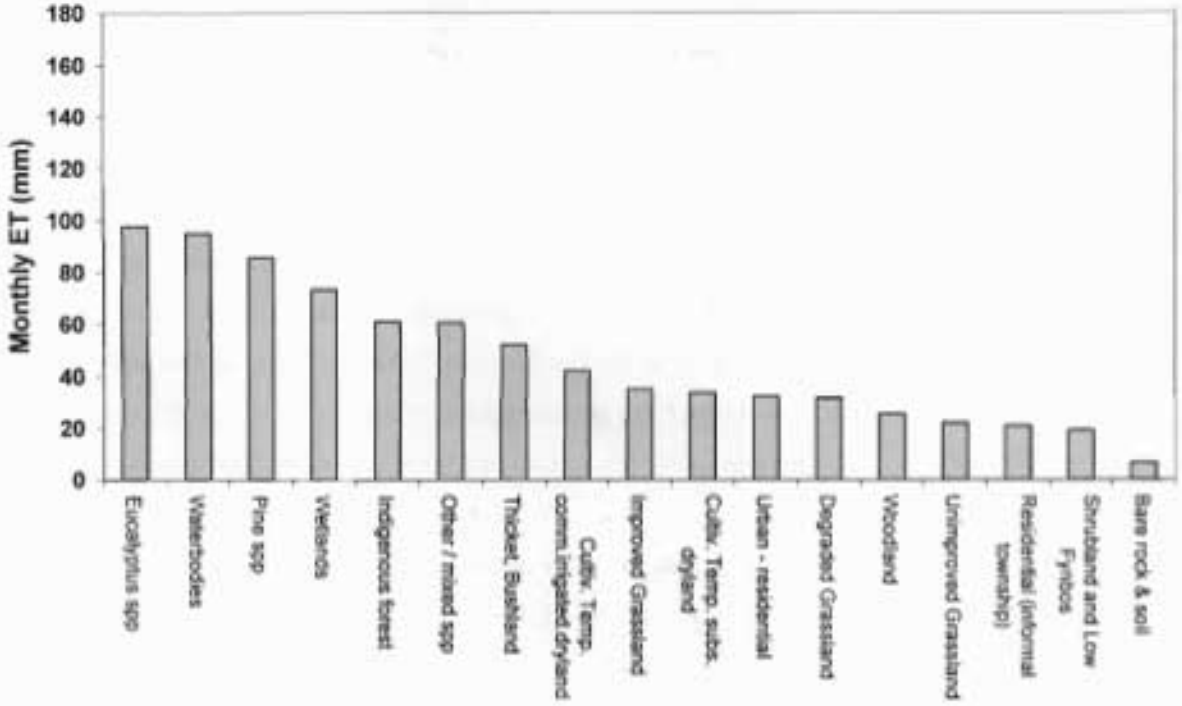

Figure 6.17 June, 2006

The suggested minimum number of *ET* images for computing monthly *ET* values is two (Bastiaanssen, 2006). Nevertheless, in this study, three or four images were used save for the month of June 2005 where only 2 MODIS images were available. The lowest monthly *ET* values were observed in the month of August 2005, with the Eucalyptus forests having the highest monthly evaporative water use of 76mm while bare rocks and eroded soil land use class ranking the lowest with a monthly water use of less than 10mm. From Figures 6.12 to 6.17, there is progressive reduction in the monthly evaporative water use through the dry winter season for all land use classes. Nevertheless, the relative water use for the various land use classes for all months mimics a conservative pattern with minor deviations, with Eucalyptus and Pine forest being the main water users. The deviations could mainly be attributed to land management practices within a land use and localized soil water limitations. For example cleared forests will have less *ET* rates than actively growing, with stage of growth influencing the water uptake by the trees. The month of April 2006, within the analysis period, had the highest monthly *ET* values for all land uses as indicated in Figure 6.15. The water bodies ranked the highest in evaporative water use, with a monthly total of 165mm. Eucalyptus ranked second, with a monthly total of 140mm followed by pine and wetlands with 123mm each. Figure 6.18 shows the variation of monthly rainfall and reference *ET* as monitored in the Potshini catchment, located in the Quaternary Catchment V13D. During the winter season, monthly potential *ET* exceeds the monthly rainfall, with a similar trend being observed when actual *ET* from most of the land uses (Figure 6.12 to

6.17) is compared to the monthly rainfall. The most likely source of water to offset the deficit in the water balance due to the evaporative water use of the various land uses is the soil water. This is either in the form of water stored in water bodies such as wetlands, and in the soil which the deep rooted land uses such as forests, are able to access.

Even though the observed rainfall and potential *ET* at the Potshini catchment is not representative across the entire 3028km^2 study area, they give an indication of the temporal variation of these fluxes in the study area. The weather station at the Potshini catchment is located in the midst of smallholder farms in a local community and hence the potential *ET* at this site may not be the same for other land uses under different altitudes and soils. The month of March and April 2005 received 189 and 16mm of rainfall respectively and hence the relatively high *ET* rates in April could be attributed to the antecedent soil moisture from the previous wet months. Hydrological measurements at the Potshini catchment during the month of April 2005 indicated moist soil conditions with high ground water levels, the later being a significant contributor to the stream flows in the catchment especially during the dry season as described in Chapter 4.

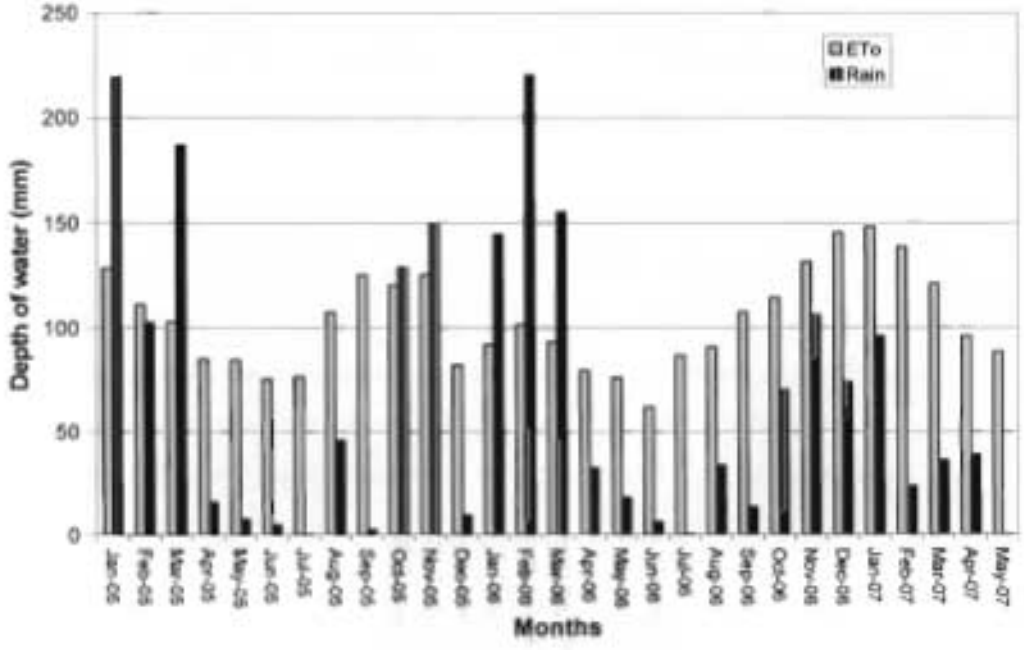

Figure 6.18 Rainfall and reference *ET* in the Potshini catchment

The actual monthly *ET* for all land uses (cf. Figures 6.12 to 6.17) mimics the monthly rainfall, with Thicket and Bushland land use class often having higher monthly actual *ET* values than the temporary cultivated subsistence land use class. One could argue that, the Thicket and Bushland land use class could be changed to temporary cultivated subsistence without significant effect on the monthly water

balance of the area. Nevertheless, it is recognized that there are other factors to be considered before making such a decision.

Indigenous forests often had the lowest monthly *ET* value compared to other forest land use classes (Eucalyptus, Pine and mixed species), with the lowest value being 53mm in the month of August 2005, with Eucalyptus and Pine using 70 and 75mm respectively. Naturally, indigenous forests tend to adapt to availability of water, with less transpiration and shedding of leaves during the dry season to cope with the water stress. This is not the case with non-indigenous tree species which are evergreen, thus continuously abstracting water from the sub-surface.

There is a remarkable difference in the water use by the various categories of grasslands in all months, with, degraded grasslands having the least evaporative water use. Unimproved grasslands, with the largest spatial coverage of 2161 km^2 (71%), had less evaporative water use compared to improved grasslands which had an area of 1.04 km^2. Nevertheless, it is useful to note that the unimproved grasslands had the highest gross water use in absolute terms considering the spatial coverage, though it is not clear from the CSIR land use map whether the improved grasslands are irrigated or not. An interesting scenario evolves when one projects the implications of upgrading the unimproved and degraded grasslands to improved grasslands with regard to water resources management. Similar scenarios on impacts of land use change to water resources at a larger catchment scale, based on evaporative water use, could be assessed. For example, the cultivated, temporary, commercial farming and cultivated temporary subsistence farming are the second largest land uses in the study area with a spatial coverage of 246 and 214 km^2 respectively. The temporary commercial farming had monthly *ET* values of 94mm in April while the subsistence farming 63mm and a significant impact could be registered if the areas of the two land uses were to be swapped or the subsistence agriculture to be upgraded. Such a scenario analysis exercise could be useful to assist water resources managers in understanding the possible implications of land use change, or the impact of upscaling certain land uses, to the water resources in a catchment and river basin at large. Table 6.4 indicates monthly volume of evaporative water use for different land use classes in the study area, which was estimated by multiplying the monthly *ET* by the area of the respective land uses. In absolute terms, the unimproved grassland had the largest volume of water use followed by cultivated temporary commercial irrigated dry land and cultivated temporary subsistence dry land farming. Although Eucalyptus had the highest monthly evaporative water use (Figure 6.12 to 6.17), it often took a lower rank on the list of land uses with the largest volumetric water use due to its relatively small areal extent. Thus, the general observation from Table 6.4 is that the areal extent of the land uses has a significant impact in the absolute volumetric water use of respective land use classes and hence

supporting the importance of carrying out a scenario analysis to assess the impact of land use changes, e.g intensification, swapping of areal extents etc. to water resources in a catchment and river basin at large.

Table 6.4 Monthly volumes of water use for different land uses in the upper Thukela river basin

Land use	Area Km^2	Volume of water use (x1000m^3)					
		June '05	July '05	Aug. '05	April '06	May '06	June '06
Eucalyptus spp.	35.529	3970	3848	2683	5039	3848	3472
Pine spp.	3.879	366	343	274	475	343	343
Indigenous forest	12.3	839	1049	649	1178	1049	1049
Other/mixed species	5.724	438	468	322	624	468	468
Water bodies	40.449	3200	2884	2662	6698	2884	3847
Wetlands	6.197	426	317	288	759	317	317
Thicket/bush land	63.394	4274	2560	2612	3524	2559	2559
Improved grassland	1.041	48	50	36	47	50	50
Cultivated temp. commercial irrigated dry land	246.196	9494	9868	9571	23142	11818	11817
Cultivated temp. subsistence dryland	214.925	4492	5931	2837	13498	5931	5932
Unimproved grass land	2161.743	77823	59982	65153	63523	59982	59984
Shrub land and low Fynbos	23.607	647	975	479	1369	975	974
Bare rocks and eroded soils	0.568	130	135	83	219	135	135

Maize, wheat and pulses are the main crops in the study area and grow actively during the wet summer season (October to April), with harvesting taking place between May and June. This explains the rather low monthly *ET* values for the cultivated temporary commercial irrigated land use class especially during the winter season when most of the land is left fallow, with irrigation mainly being used to supplement the intra seasonal crop water requirements deficits. Again it, should be noted that changes in land management practices within a predetermined land use class could adversely affect the surface flux signatures and consequently impact the average *ET* computed from the SEBAL analysis.

Wetlands had relatively lower monthly *ET* values than the forest land use classes especially during the dry winter season. The most likely explanation could be the existence and influence of mixed pixels, dry and wet, in the delineated land use on *ET* images as a result of change in the areal coverage with time, not withstanding the low spatial resolution of the *ET* images.

6.5 Conclusions

This chapter demonstrates the application of a remote sensing technique to quantify the evaporative water use of various land use classes in the upper parts of the Thukela river basin. The SEBAL methodology was applied to the freely available MODIS images. The SEBAL *ET* results were complemented with field measurements from the Large Aperture Scintillometer installed in a catchment located in the Quaternary Catchment V13D, of which the SEBAL estimates and field measurements were comparable. Twenty four land use classes were found in the study area comprising thirteen QC's, with unimproved grassland occupying 71% of the total area, 3028km^2. The land uses with the highest evaporative water use was found to be commercial forest plantations, with Eucalyptus and Pine generating the highest green water flows. High evaporation rates over water bodies were observed during the wet summer season when both the natural and man made water bodies were likely to be at full capacity.

This study has highlighted the heterogeneity associated with spatial variation of *ET* with respect to land use classes and the possibility of applying remote sensing to overcome such a challenge, with more prospects for assessing the impacts of land use change, e.g upscaling or intensifying certain land uses, to hydrological systems. The approach used in this study to estimate the evaporative and subsequently volumetric water use of different land use classes in the upper Thukela river basin has the potential to predict implications on water resources from scenarios of land use changes in catchments and river basins and which is useful in water resources planning. In particular, the ability

to estimate the spatial variation of *ET* over large spatial extents using satellite images adds value to this approach. However, the uncertainty associated with low resolution satellite images for mapping *ET* over small areal extents is still a challenge as illustrated by the irregular results from wetlands and water bodies.

7.0 A conceptual framework for identifying the dominant hydrological determinants across scales

Summary

There is a need to integrate knowledge and science from other relevant disciplines in the mainstream hydrological science especially when addressing scaling issues by establishing a pragmatic conceptual framework which integrates data and information from other science disciplines. A conceptual framework is not a theory, but a means of organizing knowledge to facilitate description, explanation and prediction of a pattern or a process. In this Chapter, a conceptual framework is proposed for integrating geophysical measurements, isotope tracers and remote sensing at different scales, to complement the classical hydro-meteorological monitoring, of which the latter is typified by point measurements. Basically, this Chapter endevours to integrate the methodological approach and scientific evidence derived from previous Chapters in this thesis into a framework, with a potential to enhance better understanding of hydrological determinants across scales. Each of the above mentioned measurement approaches has its strengths and weaknesses in identifying the relevant hydrological determinants at various scales as highlighted in this Chapter. The suggested framework provides a platform for incorporating such determinants, derived from other scientific disciplines, into distributed hydrological models, thus enhancing their predictive power by reducing the uncertainty associated with point measurements. Its application is illustrated by a case study from the Potshini catchment and the Thukela river basin in South Africa.

7.1 Introduction

The validity of the transfer of research results from small to larger basins, and from one region to another is of practical importance (Pilgrim et al., 1982; Pilgrim, 1983). A large proportion of research has been carried out on small catchments, but larger catchments (river basins) are of practical importance and it is at this scale that the research results are applied for management purposes. Rodriguez and Gupta (1983) highlighted the need to promote the search for an appropriate level of conceptualization of hydrological processes compatible with the scale of the phenomenon observed on the basin as a whole. It is recognized that catchments exhibit spatial variability of land characteristics such as geology, topography, soils, landuse and vegetation, of which governs the partitioning of rainfall and contribute to defining the spatial distribution of soil moisture within a catchment and basin at large (Güntner and Bronstert, 2004). In hydrology, we cannot carry out fully controlled experiments, let alone critical experiments designed to discriminate between alternative hypotheses

(Dooge, 1986). However, this circumstance should not lead us either to despair of discovering the nature of the irregularities in hydrological behaviour or to a denial that such irregularities exist. The relevance and importance of defining and providing large scale description of dominant hydrological processes cannot be overemphasized. Such a drive comes in the advent of progressive development of computing power, where large spatial data sets can easily be processed and archived in user friendly computing frameworks. Advances have been made in process understanding through complementary measurement techniques, e.g using geophysical and hydrometric measurements (Sandberg et al., 2002; Uhlenbrook et al., 2005), applying geophysical and tracer measurements to complement hydrometric measurements (Wenninger et al., 2007). In this study, a conceptual framework is suggested for incorporating classical hydrometric, geophysical and tracer measurements together with surface fluxes retrieved from remote sensed images for better understanding and appreciation of the critical processes across various scales.

This Chapter strives to demonstrate the value of data, especially "new" data sources in the hydrological science, thus directly contributing to the International Association of Hydrological Scientists (IAHS) led initiative on Prediction in Ungauged Basins (PUB) (Sivapalan et al., 2003), whose focus is to improve process understanding across scales thus reducing uncertainty in process description and data capture. This in turn should lead to reduction in uncertainty in process model parameterization, as highlighted in the PUB science focus. The conceptual framework presented in this Chapter supports and encourages the integration of data and the convergence of different forms of knowledge from different science disciplines in addressing hydrological processes, thus departing from the conventional hydrology paradigm, where the latter has been limited to knowledge generated from the hydrology discipline without learning from the immense information derived from the various science disciplines. It is anticipated that this conceptual framework will, among other things, lead to better conceptualization and understanding of hydrological processes, both in space and time, thus defining a better representation of hydrological processes in hydrological models. This will lead to innovative approaches in integrating of new data sets schemes and new ways of considering and communicating uncertainties thus enhancing robustness of hydrological modeling and our understanding of surface and subsurface water interactions among other uncertainties in the hydrological cycle.

Most often, large scale models make use of data extrapolated from small scale measurements thus involving some sort of extrapolation or equivalently, transfer of information across scales (Blöschl and Sivapalan, 1995). Many authors have indicated that extrapolation of processes across scales leads to loss of detail and lack the credibility to depict the actual signature of the process. In this regard, there

is a need to establish a framework capable of capturing the footprints at reasonable scale of occurrence thus circumventing the typified extrapolation theories which has limited hydrological studies for a long time. One of the basic questions that has, and will always, challenge hydrologists is whether it is possible to observe and record fluxes at the actual occurrence scale. This is a fundamental question that needs input from various scientific disciplines given the fact that the occurrence of the various fluxes is influenced by many factors, some of which cannot be explained using the established theories in hydrological science. It is generally accepted that a physical hydrological process is the same across scales, e.g, infiltration at hillslope scale is the same to that at a river basin scale while total evaporation at a catchment scale is the same as at river basin scale. What differs is the magnitude of the respective process across scales as a result of inherent heterogeneities across these scales, of which influences the variability of respective processes as illustrated in Figure 7.1, where the infiltration process is shown to vary across spatial scales due to terrain and morphological changes over the landscape.

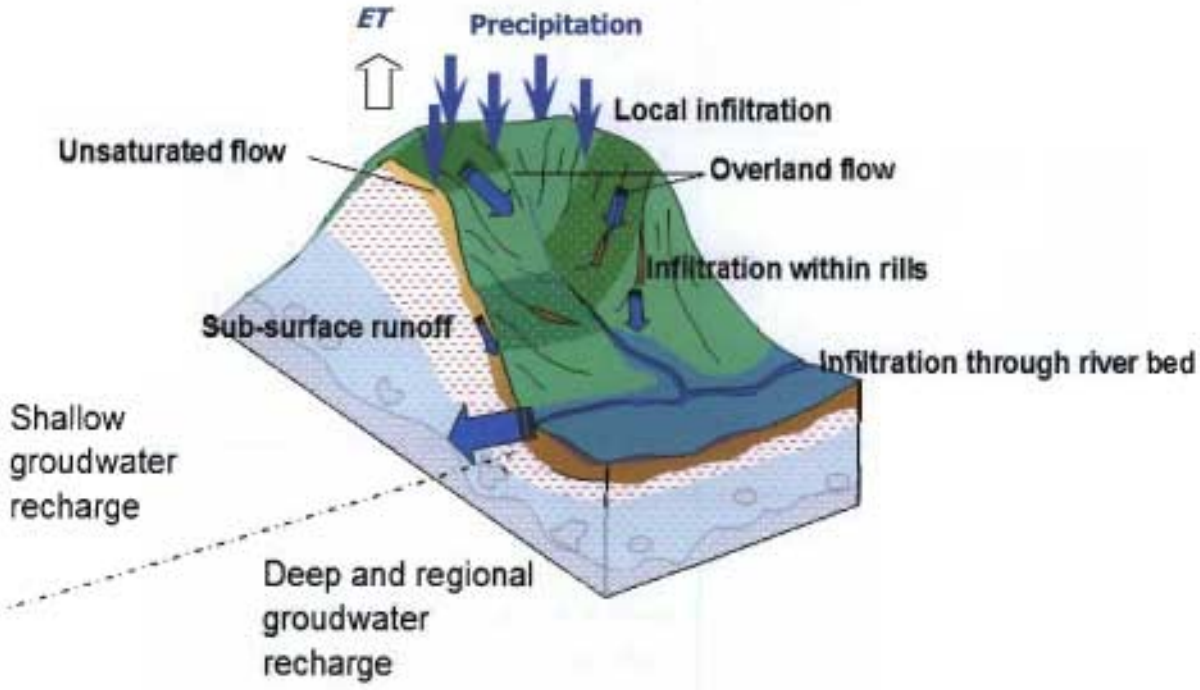

Figure 7.1 Variation of infiltration across scales (Chaplot, 2007)

Figure 7.2 further highlights the temporal and spatial variation of some of the main processes influencing the interaction between surface and subsurface waters. Surface runoff occurs at spatial scales ranging from several m^2 to catchment scale at a temporal scale ranging from seconds to days,

while discharge from shallow ground water (subsurface discharge) occurs at a spatial scale similar to the surface runoff but with a temporal scale ranging from days to years.

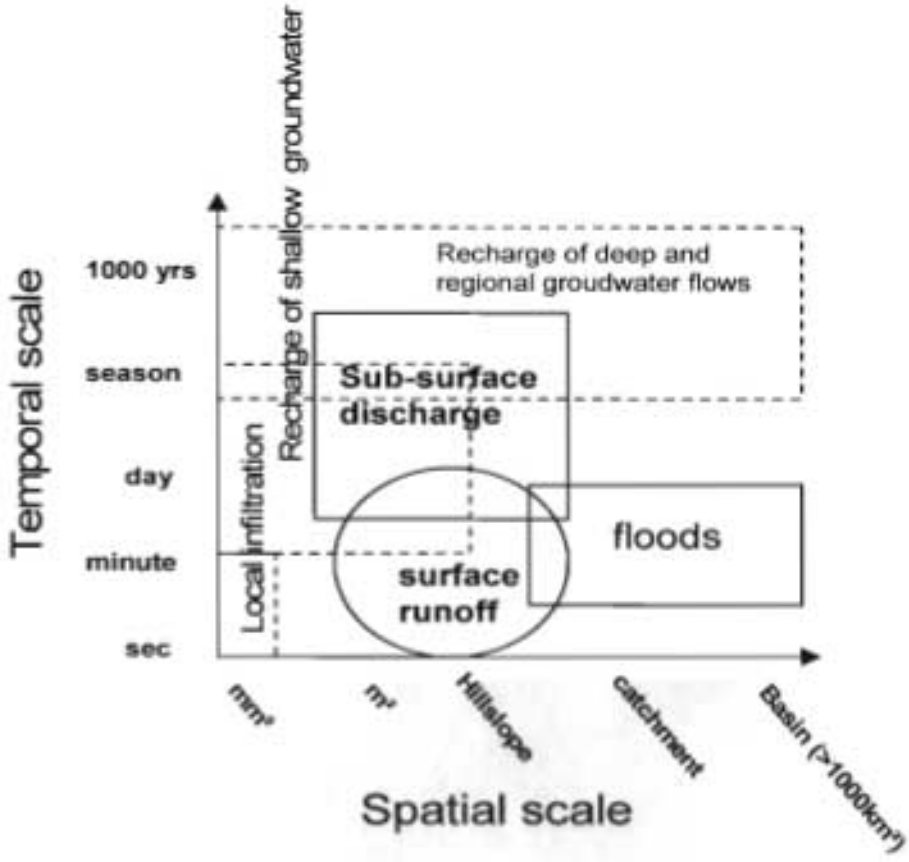

Figure 7.2 Spatial and temporal variation of some of the main processes influencing surface and subsurface water interactions across scales (Chaplot, 2007)

The deep and regional ground water fluxes occur at a larger scale spatial and temporal scale, with a spatial coverage from point to river basin scale and a temporal scale ranging from years to over thousand years.

Thus, the intention of the suggested conceptual framework is to provide for integration of other science disciplines in quest for capturing the dominant hydrological fluxes across scales, from hillslope to river basin scale, by increasing the observation prowess at the occurrence scale of the dominant hydrological process.

7.2 Hydrological models and scale issues

Complexity in a catchment can be modeled using distributed physically-based hydrological models based on the partial differential equations describing surface and sub-surface flows, following the general conceptual framework described by Freeze and Harlan (1969). A model is not a theory but a simpler descriptive of a prototype system and which can produce some but not all characteristics thereof (Dooge, 1986). Silberstein (2006) highlighted three main purposes of models as: (i) They give a framework to assemble our process understanding and to explore the implied system behaviours that come from that understanding (ii) as a mechanism for testing data, to check for inconsistencies and errors, and to fill in missing information. They also give us a method to explore the implications of our measurements (iii) as a tool to explore scenario options.

These may be options for management of a system or exploring possible outcomes under a range of different input conditions. However, it is acknowledged that models are more attractive due to the fact that they are much cheaper and faster than doing real experiments, carrying out observations and seeking for patterns and similarities across scales. They also have the ability to predict things, though with uncertainty, that we may not be able to do in the real world, or perhaps that would not really happen (Silberstein, 2006). As highlighted in Beven et al., (1988), Beven (2001) there are some scientific concerns around hydrological models, despite their data limitations, regarding their basic theories and boundary conditions given the fact that real catchments are heterogeneous in nature with uncertain boundary conditions. Uhlenbrook and Sieber (2005) reviewed some of the fundamental issues regarding physically based models including application of equations derived from laboratory experiments in the model structures and more importantly the concept of equifinality. This concept is elaborated in detail in Beven (1993, 1996 & 2001) and Savenije (2001). Nevertheless, one of the main challenges facing hydrological modeling is the tendency for the model developers to become absorbed with details of their models and neglect the need for objective testing of the model's ability to represent the reality (Silberstein, 2006). Dooge (1986) highlighted that in most cases, the efforts for developing new models have not been matched by the development of criteria for the evaluation of their effectiveness in reproducing the relevant properties of the prototype. Similar sentiments were earlier highlighted by Klemeš (1983) when noting that most hydrological models (both deterministic and stochastic) often develop only in the sense of acquiring more and "fancier Ptolemaeic epicycles" and "hiding more skilfully their hydrological sterility". Silberstein (2006) further added the dimension of data in science by noting that science is founded on observations, that data are science and that models are complement to them but not a replacement for them.

It took the courage of Dooge (1986) to state that, the hydrological science is ripe for a scientific revolution where hydrologists may need to (i) develop new, conceptually simple and radical hypotheses (ii) carry out comprehensive observations capable of falsifying or confirming such hypotheses (iii) develop skills and patience in analysis to bring hydrology to advanced levels similar to the Newtonian synthesis.

Several studies and initiatives have taken up this challenge in the past two decades, most notably the Prediction in Ungauged Basins (PUB) initiative (Sivapalan et al., 2003) through the International Association of Hydrological Scientists (IAHS). The modus operandi in the PUB science plan is to maximize data collection and analysis with a focus on developing new observational tools that will enlighten the hydrological community on the inner workings of catchments and river basins; that hydrologists may better understand and predict their responses to forcing, and thereby better manage for environmental and human outcomes. The role of data across scales in developing hydrological understanding has been emphasized in the PUB initiative and thus the suggested framework herein is aligned with this initiative by providing an approach for considering dominant hydrological determinants across scales. As models gain complexity, or expand the processes represented, the demand for data to calibrate and validate them increases. At the same time, as technology improves and we have the ability to measure more attributes with greater precision, models expand to make use of these opportunities, e.g the potential to incorporat remote sensing data in hydrological models (Schultz, 1993). The suggested conceptual framework strives to consolidate the strengths of various science disciplines with focus on characterizing the nature of the dominant hydrological processes at different scales thus forming a pragmatic conceptual framework upon which the hydrological determinants across scales can be identified. This frame work draws the strength from the following:

i) Classical hydrometeorological monitoring
ii) Geophysical measurements
iii) Remote sensing
iv) Isotope tracers studies

7.3 Monitoring of hydrological determinants

7.3.1 Classical hydro-meteorological monitoring

Catchment research studies using classical hydro-meteorological monitoring have been ongoing for many years in various regions with different objectives, e.g Blackie and Robinson (2007) reported on research catchments established in the late 1950's in the United Kingdom (UK) and East Africa to

investigate the impact of land use change, from grazing to coniferous plantation forestry, on water resources. Lorentz et al., (2007) detailed the establishment of the Weatherly research catchment in South Africa, starting from 1995, with the objective to investigate land use changes associated with stream flow reduction activities by improving the *ACRU* model (Schulze, 1995), a deterministic physically based model, in representing the observed hydrological processes at a range of scales. Chapter 2 of this thesis highlights the establishment of the Potshini research catchment, which started in 2004, on the foothills of the Drakensberg mountains in South Africa to investigate among other things the impact of rainwater harvesting in the catchment. The Potshini catchment was established through a participatory approach where the local community and other stakeholders were involved at different levels of participation. Generally, research catchments are intended to provide quantitative information on the dominant hydrological processes and the interaction of these processes within the framework of water resources management at catchment scale. The catchment response at the outlet is integration of all the processes in the catchment, making it possible to consider flux balances, including water quality issues even though it is difficult to determine the sources of the respective fluxes in the catchment without applying other complementary studies, e.g tracer studies. Most of the measurements under classical monitoring schemes are point measurements, e.g. rainfall, evapotranspiration, soil moisture etc. and many are the times when such information has been extrapolated to larger spatial scales without taking into account the inherent heterogeneities associated with complexities arising from variability of the various hydrological processes across scales and soil properties. The question on how to scale up knowledge gained from monitoring at catchment scale to larger spatial extents of managerial scales has often arisen and it has been a challenge in the hydrological science to overcome this using stand alone information and data from classical hydrometeological networks.

7.3.2 Geophysical measurements

Geophysical measurements provide a very attractive method for soil characterization (Samouëlian et al., 2005). Under normal circumstances the structure of the subsurface material does not change rapidly, with its properties mainly being influenced by hydro-climatological fluxes. The characterization of the subsurface material using geophysical methods (e.g. Electrical Resistivity Tomography-ERT) has gained popularity in hydrological sciences in the past decade due to its ability to profile the properties of the subsurface material and underlying features which influence subsurface hydrology, something which is impossible to achieve with classical catchment monitoring networks. Chapter 4 of this thesis elaborates a detailed account on the application of the ERT methodology in characterizing subsurface material in the Potshini catchment in the Thukela river basin. It is

noteworthy that geophysical measurements at large spatial scales are also possible now days from gravity measurements obtained from remote sensing platforms e.g GRACE mission (Tapley et al., 2004) and airborne mapping.

The ability to carry out resistivity surveys along transects, from few meters to several kilometers, adds value to the collective effort by hydrologists in finding pragmatic tools to address the scale problem. Catchment morphology is a dominant control on the spatial patterns of hydrological response under many conditions. Thus, catchment morphology and hydrological processes are inextricably linked, and water flow pathways depend critically upon hillslope morphology, particularly where surface water or near surface flows are the major mechanisms by which water reaches a stream channel (Beven et al., 1988). However, it is only in the recent past that hydrologists have started paying attention to this interdependence through defining pathways and mapping subsurface formation along hillslopes (Uhlenbrook et al., 2005 and Lorentz et al., 2007) using geophysical methods and linking catchment response to such formations. For example, it is easy to map preferential flow pathways along a hillslope using ERT, with the pathways relatively being associated with rapid response and occasionally large magnitude of subsurface flows. However, there are inherent challenges associated with the use of geophysical measurements in hydrology, most significantly the equipment costs and in many places, the lack of expertise to interpret the measurements to relevant hydrological information. Previous studies including Sandberg et al., (2002), Samouëlian et al., (2005) and Lorentz et al., (2007) have shown the successful application and interpretation of geophysical measurements when integrated with other classical hydrometric measurements, on an event based or seasonal temporal scale. This strengthens a recommendation that geophysical measurements need to be interpreted against other conventional hydrogeological measurements for meaningful and successful application in the hydrological science, as illustrated in Figure 7.3. The derivation of relationships between classical and geophysical measurements, Figure 7.3, facilitates the interpretation and characterization of the subsurface at spatial scales larger than those defined by the classical point measurements.

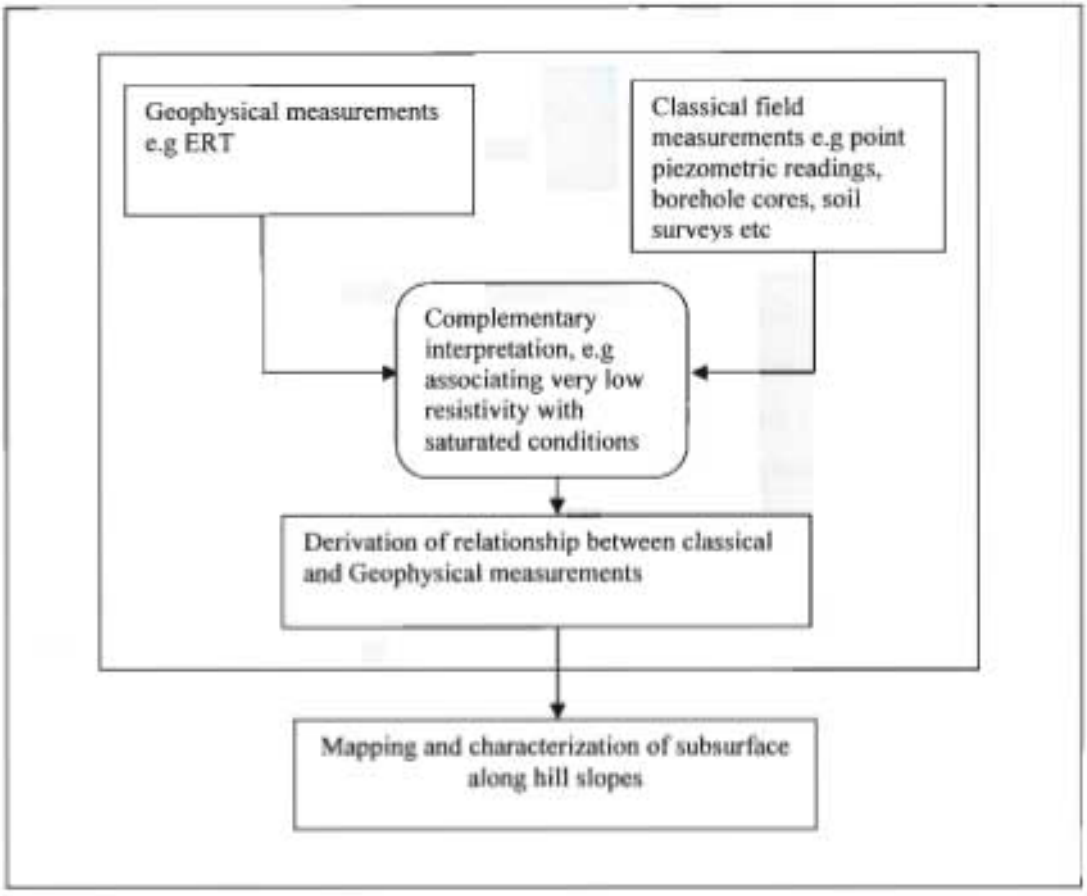

Figure 7.3 Geophysical measurements for mapping subsurface

7.3.3 Remote sensing

The era of satellite meteorology was marked by the launch of the first satellite, Sputnik I, in 1957, which was closely followed by the launch of a similar satellite in 1960, the Television Infrared Observation Satellite (TIROS-1) (Menzel, 2005). Numerous authors in the past decade, e.g Klemeš, (1983), Salomonson and Choudhury (1991), Schultz (1993), have highlighted the significant contribution and potential of remote sensing in hydrological studies especially, the scale issues. Currently, there are numerous satellite imagers in space, both Polar orbiting and Geo-stationary from which the hydrologists are able to obtain the valuable data (real-time and archive), often free of charge. However, the general inherent problems faced by many hydrologists with regard to using remote sensed data, and also highlighted by Schultz (1993), are the fact that:

i) The remote sensed data consist of electromagnetic information instead of the conventional hydro-meteorological data, and many hydrologists do not have skills needed, including resources, to retrieve useable information.

ii) The resolution in time and space of the remotely sensed data is sometimes higher or lower than required. It is appreciated that the resolution of the satellite data is attributed to respective imagers, with coarser data having higher temporal resolution and vice versa.

One of the fundamental advantages of remote sensing is that it provides an appropriate vantage point from which a distinct hydrological behaviour can be recognized at the occurrence scale, and which is occasionally far much beyond our direct experience (Schultz, 1993). The continuous development of remote sensing techniques and satellite technology has gradually facilitated the evolution of the "feel" for hydrologic scales in a similar way as the telescope and microscope helped develop a feel for cosmic and microcosmic scales (Klemeš, 1983). Numerous authors including Shuttleworth (1988) and Schmugge (2002) have highlighted the importance of remote sensing in hydrological sciences including application of remote sensing in estimation of model parameters. Several vegetative and hydro-climatological parameters can be derived from remotely sensed data, and initiatives by the European Space Agency (ESA) and National Aeronautics Space Agency (NASA) have resulted in various useable products, many of which are freely accessible on their respective websites. Thus, it is possible to retrieve some of these hydro-climatological and vegetative parameters on a daily basis from remotely sensed data by use of appropriate algorithms as illustrated in Chapter 5 and 6 of this thesis. Figure 7.4 illustrates a schematic overview of the retrieval of surface fluxes from remotely sensed data. The validation of such fluxes against field observations obtained from measurements at a scale matching with the extent of the resolution of respective satellite data adds value to the authenticity of the retrieved surface fluxes over large spatial scales. A typical example is the validation of remotely sensed total evaporation fluxes using field measurements from a Scintillometer, e.g. Watts et al., (2000); Meijninger (2003) and as described in Chapter 5 of this thesis and illustrated in Figure 7.5, and the comparison of Scintillometer measurements with those from an Eddy Covariance, Bowen ratio and Class-A pan, e.g Savage et al., (2007). Such a framework forms a validation scheme at various spatial scales linking the monitoring of total evaporation at different scales and facilitating upscaling of total evaporation, a dynamic and difficult hydrological parameter to establish across scales.

Scintillometers are expensive, with a Large Aperture Scintillometer costing approximately US $50,000. Relative to analysis of satellite images, scintillometers have less time investment as far as installation, data recording and processing is concerned.

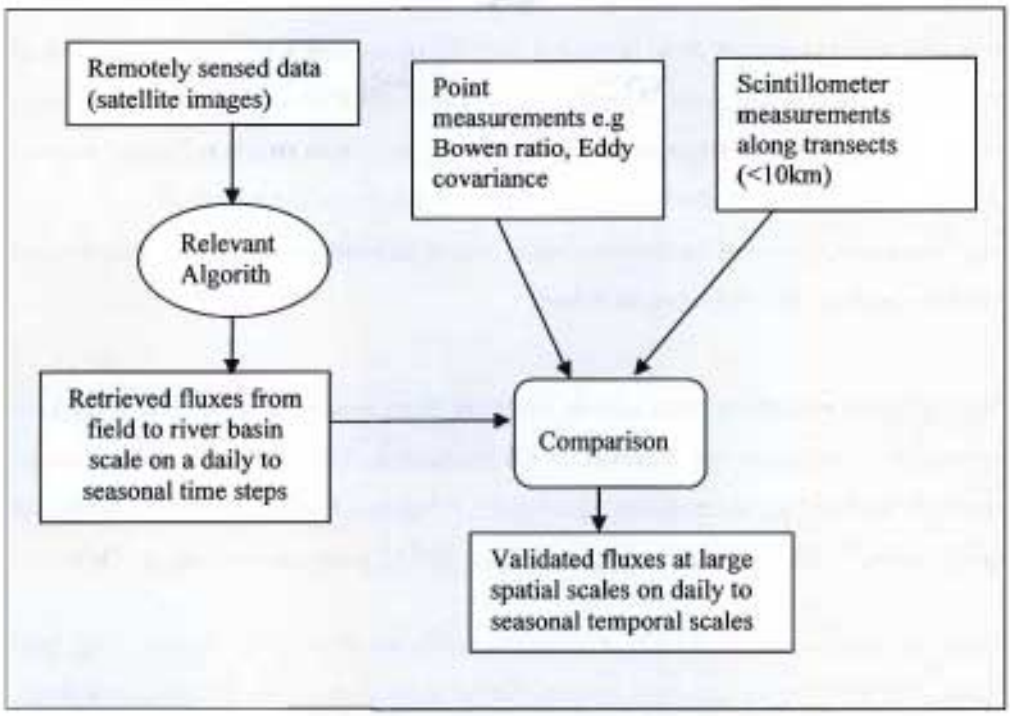

Figure 7.4 Retrieval and validation of fluxes from remotely sensed data

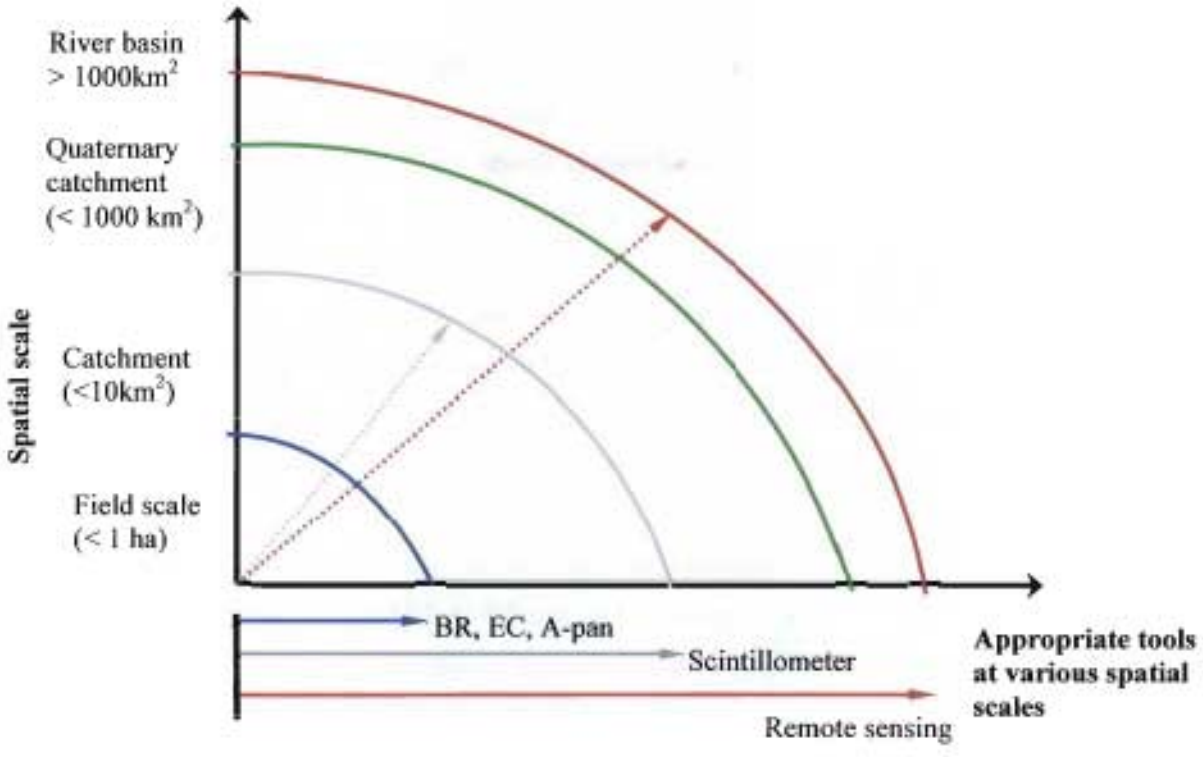

Figure 7.5 Validation strategy of remotely sensed total evaporation fluxes using the scintillation techniques. BR: Bowen Ratio; EC: Eddy Covariance; A-Pan: Class A-pan

Retrieval of total evaporation from remote sensed images using some of the available methodologies, e.g the Surface Energy Balance Algorithm for Land (SEBAL) methodology (Bastiaanssen et al., 1998a), the Surface Energy Balance System (SEBS) (Su, 2002) etc. is relatively less expensive as far as monetary investment is concerned (i.e computing hardware, image processing software etc), with accuracy being compromised by the resolution of the satellite images. However, the time investiment in SEBAL to analyse different images is high.

Other hydrological parameters that can be retrieved from remote sensing data include rainfall (Nezlin and Stein, 2005), soil moisture indicators (Salomonson and Choudhury, 1991; Vischel et al., 2007), net radiation, land surface temperature (Kerr et al., 1992 and Kerr et al., 2000), Normalized Difference Vegetation Index (NDVI) (Farah and Bastiaanssen, 2001), interception among others.

Soil moisture indicators are mainly monitored from satellite observations using passive or active microwave and infrared temperature sensors while most of the other hydro-climatological parameters are mainly obtained from multi-spectral imagers on board the Earth Observation System (EOS). One of the most common and conventional applications of satellite data, especially Landsat ETM, is in land use classification which is an important attribute in both hydrological studies and land use management. However, if we are to make a significant contribution to the scale issue in hydrology it is suggested that the main thrust in application of remotely sensed data in hydrological studies should be on quantification of spatial variation of surface fluxes rather than their identification. These spatial estimates ultimately form better input to distributed hydrological models of which has been and remains a challenge to achieve. Through remote sensing, it is also possible to retrieve rainfall from satellite data thus the monitoring of its spatial and temporal variation and which is a key information and input in most of the distributed hydrological models. Rainfall is a dynamic process, constantly changing in form and intensity as it passes over a given area thus the advantage of remotely sensed rainfall data over hydrometric measurements is that they provide relatively consistent spatial and temporal coverage of rainfall information. The monitoring of rainfall, especially in the tropical regions, is made possible through the combination of the geostationary MeteoSat second Generation (MSG) (Infrared channel) and the orbiting Tropical Rainfall Measuring Mission (TRMM) Microwave channel) satellite data (Microwave channel) through a regression function associated with a threshold as an upper cloud temperature limit where rain occurs. The temporal and spatial resolution of the TRIMM is 15 minutes and 3km pixels respectively. It is worthy noting that there has been progress in developing new remote sensing strategies for monitoring of rainfall at small scales e.g $1km^2$ through airborne remote sensing using X-Band rainfall radar. Nevertheless, it is acknowledged that there are numerous challenges in using remote sensing to confidently monitor spatial variation of rainfall and

hence more effort is required to validate the available methods while seeking for pragmatic remote sensing approaches and techniques.

7.3.4 Isotope tracers

Numerous studies in various regions, e.g Kendall et al., (1999); Uhlenbrook and Leibundgut (2002); Wenninger et al., (2004), Wissmeier and Uhlenbrook, (2007) have shown the potential for applying tracer techniques, notably the stable natural tracer isotopes (Oxygen-18 and Deuterium), in hydrological studies for determining flow pathways, sources of water in a catchment and the relative contribution of each source to the integral stream flow (hydrograph separation). Oxygen-18 (^{18}O) belongs to the group of stable environmental isotopes, (Table 7.1), occurring naturally in water has been widely used to separate storm flow into its various components (Herrmann, 1996; Leibundgut, 1999). The ^{18}O is part of the water molecule and hence behaves conservatively, with no chemical or physical retardation during the flow in a hydrosystem, with the concentrations being given in delta units (δ) and defined by the following expression (Uhlenbrook and Hoeg, 2003):

$$\delta^{18}O = \frac{R_{sample} - R_{standard}}{R_{standard}} * 1000 \qquad (7.1)$$

where R_{sample} and $R_{standard}$ are the $^{18}O/^{16}O$ ratios for the water sample and the standard respectively, with the reference standard for water being the Vienna Standard Mean Ocean Water (V-SMOW).

It is noteworthy that meteorologist have used isotope methods to carry out large scale simulations at continental scale in climate studies and the challenge is to downscale this information to appropriate scales of interest to hydrologist and water resources managers. Nevertheless, such information needs a framework to verify such results at the desired scales, e.g at hill-slope, catchment, river basin.

Residence times, reservoir volumes, and the hydraulic characteristics of subsurface flow systems can be quantified if long-term tracer data are available (Maloszewski et al., 1983). Tracer methods provide suitable tools for investigating runoff generating processes and the knowledge of process and flow pathways is crucial for evaluating the vulnerability of surface and ground water systems (Leibundgut et al., 1998). This ultimately facilitates the development of a conceptual process model for a catchment. The fundamental assumption of the hydrograph separation method is that the geographic source, the flow pathway, and the residence time of a runoff component control the water chemistry. Based on this premise, Uhlenbrook and Hoeg (2003) demonstrated the potential for applying tracer

methods to quantify two, three and five components of a hydrograph. Table 7.1 shows available tracers that can be used in hydrological sciences and other fields. It is important to recognize that each isotope tracer has inherent pros and cons with regard to its practical application and hence multiple tracers are advised for better and systematic analytical results.

Table 7.1 Available tracers (After Leibundgut, 1999)

Natural tracers		**Artificial tracers**			
Environmental isotopes		**Radioactive**		**Inactive**	
Stable		Tritium	^{3}H	**Soluble substances**	**Drifting substances**
Deuterium	^{2}H	Sodium-24	^{24}Na	**Salts**	Lycopodiumspores in different colours
Oxygen-18	^{18}O	Chromium-51	^{51}Cr	Na^{+} Cl^{-}	Bacteria
Carbon-13	^{13}C	Cobalt-58	^{58}Co	K^{+} Cl^{-}	Fluorescent particles
Helium-3	^{3}He	Bromine-82	^{82}Br	Li^{+} Cl^{-}	Viruses
Sulphur-34	^{34}S	Iodine-131	^{131}I	HBO_2	Fungi
		Gold-198	^{198}Au		
Radioactive		**Activatable**		**Fluorescence tracers**	**Special**
Tritium	^{3}H	Bromine		Uranine	Magnetic tracers
Carbon-14	^{14}C	Indium		Eosine	
Silicium-32	^{32}Si	Manganese		Amidorhodamines	
Chlorine	^{36}Cl	Lanthan		Rhodamines	
Argon-37	^{37}Ar	Dysprosium		Naphtionate	
Krypton-81	^{81}Kr			Pyranine	
Krypton-85	^{85}Kr			Tinopale	
				Flavines	
Chemical components					
Conductivity	µS /cm				
Sodium	Na				
Others eg.	Si,				
Pollution tracers		e.g. Chloride, heavy metals, detergents, radioactive substances, ^{222}Rn, etc.			

Even though tracers have the potential of measuring fluxes directly, compared to geophysical measurements and some of the classical hydrometric measurements, (e.g ground water levels, soil moisture changes etc.), they need to be used and interpreted against other relevant field measurements, including biogeochemical data, for better description of a process. The main challenge in applying isotope tracers in mainstream hydrological sciences, especially in developing countries, is the cost of analytical instrumentation which is exacerbated by lack of laboratories for analyzing samples. This is further compounded by lack of expertise in the field of tracer isotopes in many parts of the world, more severe in developing countries, even though good regional and global data sets for precipitation and large rivers are available through the International Atomic Energy Agency (IAEA) and other studies in literature (e.g Talma et al., 2004).

7.4 Different observation scales

Observation scales are the extents which humans choose to study natural phenomenon, e.g on a temporal time step of daily, weekly etc. Usually, these scales are chosen by the observer even though most of the time these scales are imposed by perceptual capabilities or by technological or logistical constraints (Jewitt and Görgens, 2000). Blöschl and Sivapalan (1995) defined an observation scale as being characterized by a collection of finite number of samples and which can be defined in terms of (i) spatial or temporal *extent* of a data set (ii) spacing between samples (*resolution*) (iii) the integration volume of the sample, often referred to as the *grain*. Figure 7.6 illustrates the definition of observation scale, with the *extent* and *grain* defining upper and lower limit of resolution of a study (Jewitt and Görgens, 2000).

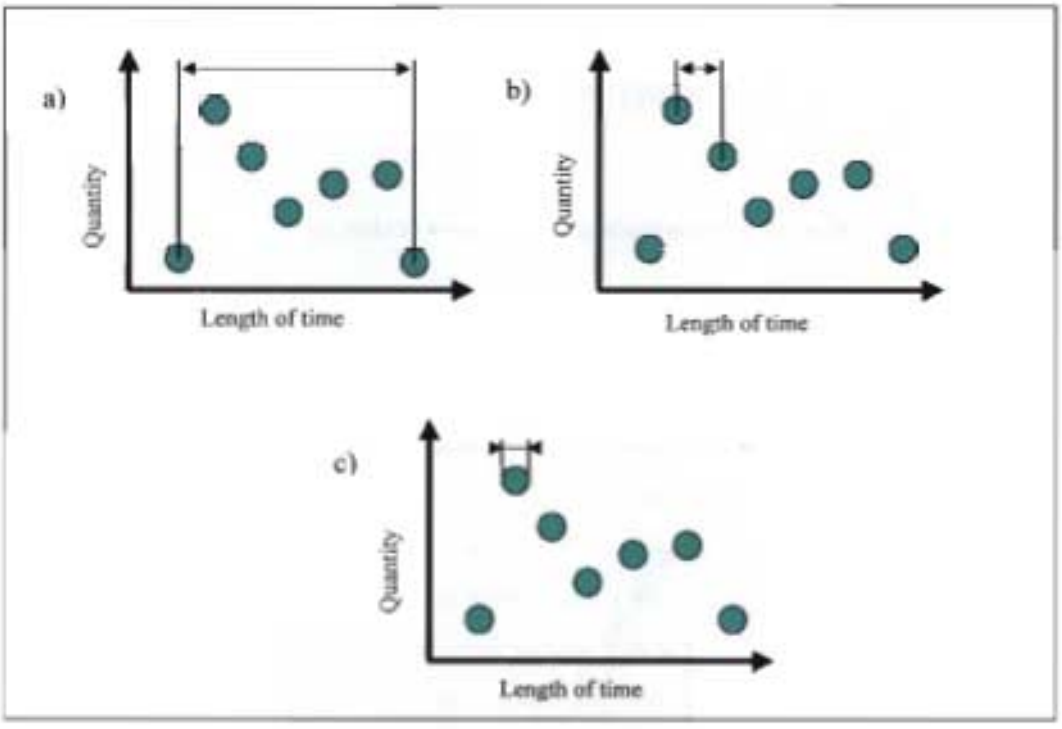

Figure 7.6 Three alternative definitions of observation scale in space and time: a) spatial or temporal extent; b) spacing or resolution; and c) integration volume of the sample (adapted from Blöschl and Sivapalan, 1995)

A summary of the applicability of the observation techniques for monitoring hydrological determinants as highlighted in this framework, across spatial and temporal scales, is illustrated in Figure 7.7. Remote sensing covers the largest spatial scales, with a spatial scale spanning from few

square meters to river basin scale and a temporal scale of less than a day (i.e several image scenes captured over a day) to seasonal and annual scales.

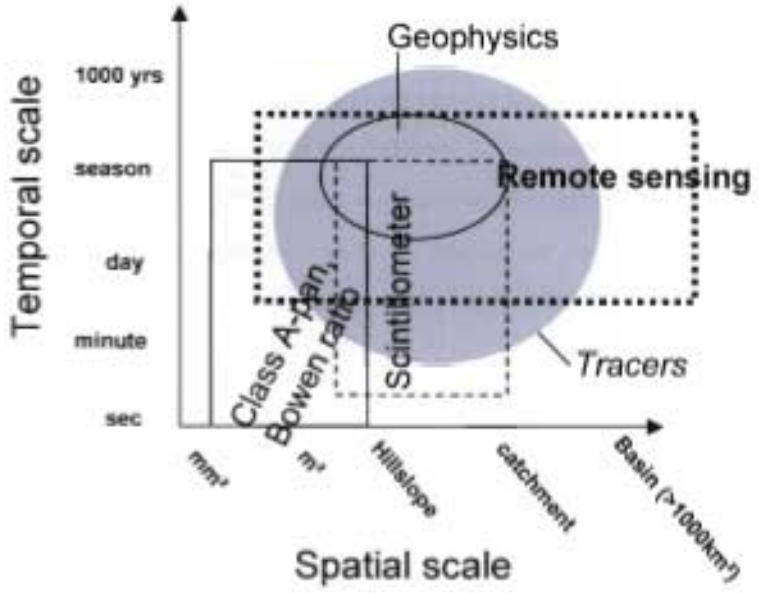

Figure 7.7 Summary of monitoring tools across scales

Geophysical measurements are more applicable at spatial scales ranging from few m^2 to catchment scale and mainly at temporal scales above a day, e.g in distinguishing variation of subsurface over events and seasons. Tracers have a relatively wide range of application scales, with a temporal scale ranging from minutes to thousands of years and a spatial scale from few m^2 to Quaternary Catchment. Bowen ratio systems and Class A-Pans are more appropriate at spatial scales less than hillslope for monitoring total evaporation with a temporal scale of less than a minute to seasons. Scintillometers are well suited for intermediate spatial scales, between hillslope and catchment scales, with a temporal resolution range between minutes and seasons, and hence a useful calibration tool for remotely sensed estimates of sensible heat flux and total evaporation at these scales.

7.5 Conceptual framework

A conceptual framework is not a theory, but a means of organizing knowledge to facilitate description, explanation and prediction of a pattern or a process (Dollar et al., 2006), by providing more perspective and drawing input from various sources. Several authors including He et al., (2000), Thwaites et al., (2000), Jewitt and Görgens, (2000), Niemeijer and de Groot (2007), Ryan et al.,

(2007) have highlighted the usefulness and application of conceptual frameworks in various studies including ecology and land and water resources management. Such a framework, in the context of this study, provides a means for identifying hydrological determinants across scales and understanding the heterogeneity of hydrological systems and which has a direct influence on hydrological response at various scales. The suggested conceptual framework provides a platform for integrating information from remote sensing, geophysics, and tracer isotopes in mainstream hydrological science and notably in identifying the dominant hydrological determinants across scales. Table 7.2 shows a summary of the key issues to be addressed at various spatial scales and the practical approaches, combining various techniques, which can be used to address the respective issue. Figure 7.8 further illustrates the linkages between various forms of data and their integration in defining water balance at across scales.

The proposed framework creates a platform for addressing some of the fundamental practical concerns in hydrology and water resources management of which are influenced by scale issues as discussed in a case study herein.

7.6 Application of the conceptual framework: a case study of the Potshini catchment and the Thukela river basin in South Africa

7.6.1 The Potshini catchment and the Thukela river basin

In this Chapter, the application of the suggested conceptual framework is demonstrated in identifying the dominant hydrological determinants at different scales in the Potshini catchment and the Thukela river basin in South Africa. In this case study, the framework has been applied on issues related to land use change and quantification of surface fluxes in the Potshini catchment and the Thukela river basin, based on analytical and scientific evidence accrued from previous Chapters of this thesis. Parameterization of hydrological models is discussed as another possible application of the framework based on results and information from other studies. An overview of the Potshini catchment and the Thukela river basin has been highlighted in previous Chapters of this thesis, especially Chapters 2, 3 and 4.

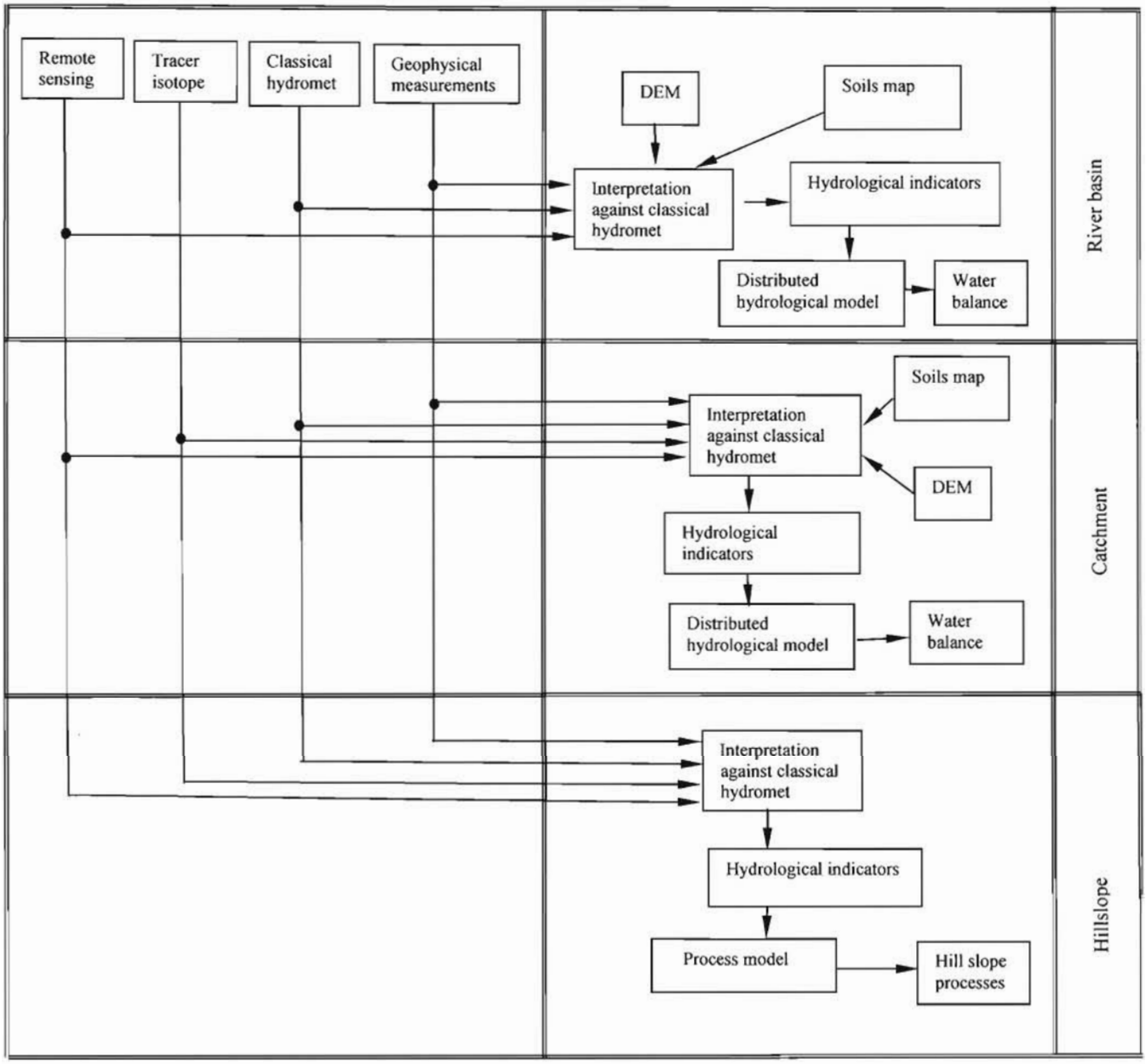

Figure 7.8 Integration of various forms of data in the conceptual framework

Table 7.2 Levels of application of the conceptual framework

Spatial scale	Key issues (some examples)	Applicable tools	Error propagation
Field scale (<1 hectare)	• Water balance • Land use	• Geophysical measurements • Process models • Classical hydrometric	• Electrode spacing in Geophysical measurements • Choice of protocol in geophysical measurements • Spatial and temporal resolution of satellite images • Diffuse sources of baseline concentration of isotopic signatures
Hill-slope	• Identification of flow paths • Solute transport • Soil hydraulic characteristics	• Geophysical measurements • Isotope tracers • Classical hydrometric • Process models	
Catchment	• Surface-subsurface water interactions • Hydrograph separation • Water quality and solute transport • Soil characterization • Land use classification • Water balance	• Remote sensing • Geophysical measurements • Classical hydrometric • Isotope tracers • Distributed hydrological models	
River basin	• Water resources assessment • Water quality and solute transport • Water balance studies • Land use classification • Land use change	• Distributed hydrological modeling • Remote sensing • Isotopes tracers • Classical hydrometric	

7.6.2 The Potshini catchment monitoring network

The Potshini catchment monitoring network comprises various gauging structures and instrumentation as indicated in Figure 7.9, mostly automated, for measuring and monitoring various hydrological parameters from field to catchment scale as described in detail in Chapter 2.

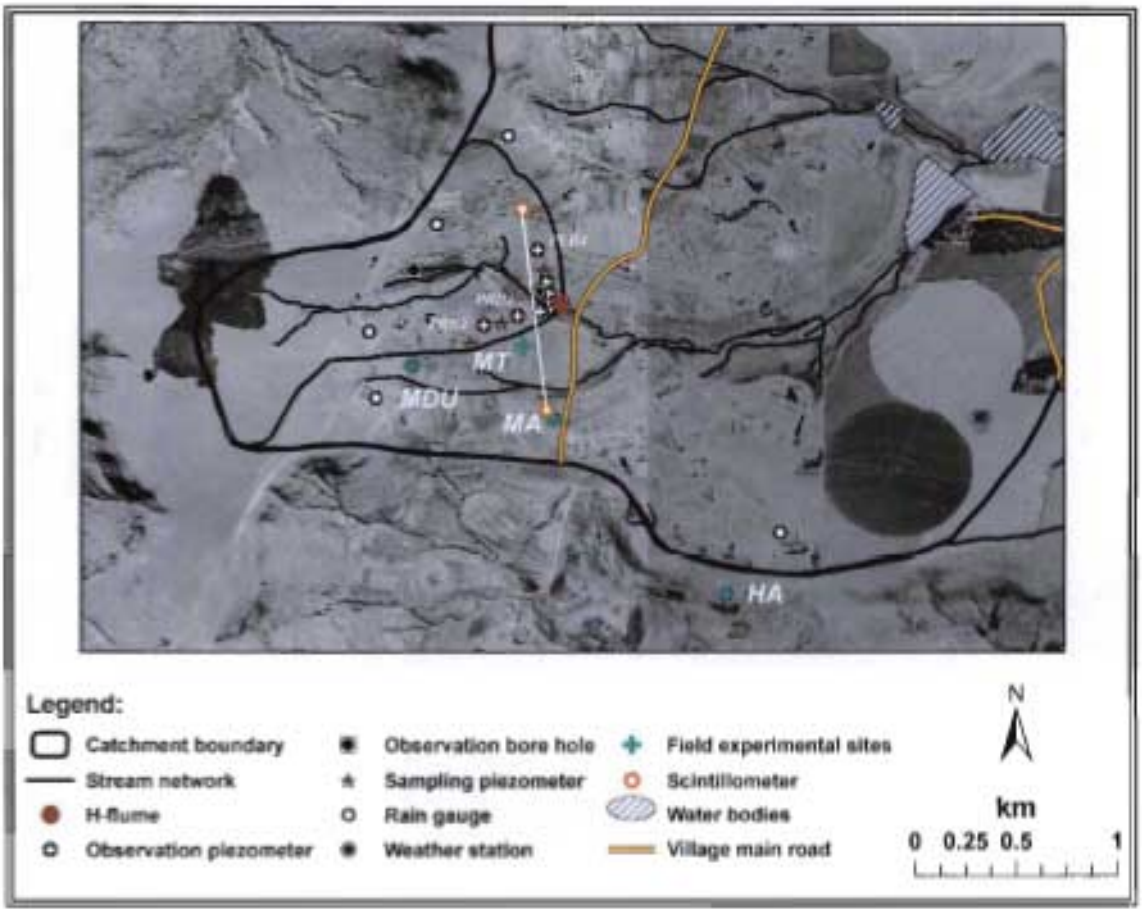

Figure 7.9 The Potshini catchment

The main parameters monitored at the Potshini catchment include stream flows and sediment load, overland flow and volumetric soil moisture content from field experimental plots (sites *HA, MA, MDU, MT* in Figure 7.9), shallow and deep ground water tables, subsurface resistivity using Electrical Resistivity Tomography (ERT), isotopic composition (Deuterium and Oxygen-18) in both surface and subsurface water, volumetric soil moisture content, soil hydraulic parameters, crop transpiration rates and meteorological parameters.

The application of scintillation techniques (Large Aperture Scintillometer) in estimating total evaporation in the Potshini catchment forms an intermediate observation and a validation scale for remote sensed estimates of total evaporation from satellite images in the catchment and the Thukela river basin at large, using the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998a; Bastiaanssen, 2000). The application and basic working principles of the various instruments in the Potshini catchment monitoring network is detailed in Chapter 2.

7.6.3 Land use change impacts

Land use change is a major concern to the hydrological community and water resources planners. Landscape patterns are not static but change over time. Anthropogenic activities are the main drivers of land use change where as landscape structures are artificially manipulated often leading to altered or damaged habitats (He et al., 2000). It is difficult to convincingly and explicitly analyze land use change across scales based on the classical hydrometeorological networks alone, due to their inability to capture the inherent spatial and temporal heterogeneities that exists across scales. The impacts of land use change (e.g change in land management practices, intensification or upscaling of land uses) can effectively be investigated from field scale to river basin scale through the combination of classical hydrometric stations, remote sensing, geophysical measurements and isotope tracers, with additional spatial data from soil maps, aerial photographs and high resolution Digital Terrain Models, as illustrated in Figure 7.8.

In this case study, analyses were undertaken to determine the impact of different land management practices in the Potshini catchment, i.e conventional and conservation tillage systems. Classical hydrometeorological monitoring (cf. Section 7.3.1) was used to monitor runoff generating characteristics from runoff plots installed in the catchment at sites *HA, MA, MT* in Figure 7.9 under different land management systems. Each site formed an experimental trial, with two of them i.e *HA & MA*, being managed by smallholder farmers in the Potshini catchment. A total of six runoff plots measuring 10m by 2.45m were installed in the three sites in the catchment, two on each site and under different tillage systems. At each site, one runoff plot was installed in a field under conservation tillage (minimum tillage) and the other under conventional tillage. A tipping bucket was used to measure the surface runoff intensities from each site and the data were recorded with a HOBO data logger. Rainfall was monitored using an automatic weather station installed in the catchment while manual rain gauges installed at, or close to, the experimental sites complemented the weather station daily total rainfall records. Volumetric soil moisture content was monitored along the soil profile on each runoff plot using a TRIME-TDR probe (TRIME-FM, 2003) at an interval depth of 30cm in

access tubes to depths ranging from 1.2 to 1.5m. Time Domain Refletometry (TDR) method is a geophysical method (cf. Section 7.3.2) that measures changes in soil water content by sending a very high frequency (~GHz) electrical signal into the soil, and the velocity of the reflected signal is used to calculate an apparent dielectric constant, which is a function of soil water content (TRIME-FM, 2003).

Figure 7.10 shows results from one of the field experimental sites, *MT*, in the Potshini catchment, with regard to soil moisture retention characteristics of conservation and conventional tillage systems in the Potshini catchment for the period between 21st April and 25th August 2005.

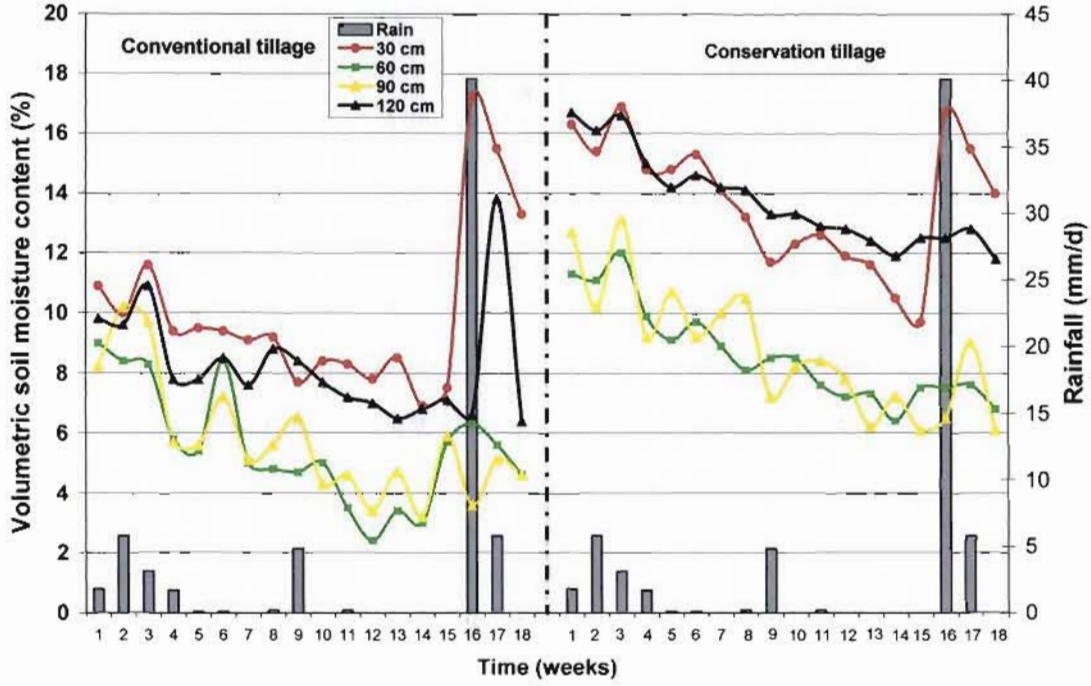

Figure 7.10 Soil moisture profiles under conventional and conservation tillage systems at site *MT* for the period between 21st April to 25th August 2005

The cumulative surface runoff from the runoff plot under conventional tillage over the entire observation period at site *MT* amounted to 1.238 m^3 while 0.45 m^3 was recorded from the runoff plot under conservation tillage practice and hence translating to a percentage reduction of close to 64%. Such results more or less conform to observations made at site *MA* and *HA*, where a percentage reduction in surface runoff was found to be 57 and 46% respectively. The general observation from Figure 7.10, is that conservation tillage system conserves more soil moisture than conventional tillage system where a significant trend in difference in volumetric soil moisture is maintained across the soil profile and throughout the observation period untill the last two weeks of measurements (week 16-17)

in August, when early rains were recorded in the catchment. Relatively high soil moisture content was observed at deeper depths in the plots under conservation tillage practices as compared to conventional tillage practices, as indicated in Figure 7.11, hence raising the possibility of interaction of the excess soil moisture under conservation tillage systems with shallow ground water through recharge. Such an interaction at field scale, even though not analysed in this case study, could be investigated through the application of both geophysical measurements, i.e. the Electrical Resistivity Tomography (Loke, 2003) (cf. Section 7.3.2) and piezometric readings of shallow ground water (cf. Section 7.3.1) in plots under conservation and conventional tillage practices respectively. The ERT measurements provide a characterization of the subsurface material (cf. Chapter 4) and hence volumetric soil moisture content and piezometric readings (shallow ground water levels) from the respective plots could be analyzed together to provide a better perspective on the interaction of soil moisture and shallow ground water at field scale with regard to impacts of conservation and conventional tillage systems (cf. Chapter 3).

Such an analysis could be upscaled to hill-slope and catchment scale (cf. Figure 7.8), where 2-D ERT measurements along transects spanning to several kilometers, or 3-D surveys, in combination with other classical hydrometrical monitoring (e.g shallow ground water piezometric readings along hill-slope transects, soil hydraulic properties, rainfall, stream flows etc) could reveal the interaction of surface and subsurface water at catchment scale as highlighted in the conceptual framework (Figure 7.8) and which was realized in the Potshini catchment. Several 2-D ERT surveys were carried out in the Potshini catchment, using the ABEM© ERT terrameter system, (cf. Chapter 4) on transects spanning from 200m to 500m at different electrode spacing of 1 and 5m., with the latter spacing providing deeper measurements (>50m) at the expense of more detail and resolution of which is a characteristic of the shorter electrode spacing including shallower measurements (<15m). The fluctuation of the shallow ground water in the catchment was monitored using 8 piezometers along 2 transects in the catchment while samples of the subsurface water, for isotopic composition of Oxygen-18 and Deuterium, was obtained from 4 piezometers (shallow ground water) and a 120m deep bore hole (deep ground water) (cf. Figure 7.9). Rainfall was also sampled using a rainfall collector for isotopic composition of Oxygen-18 and Deuterium while the stream flows from the catchment was measured using an H-flume from which samples were also obtained for analysis of suspended solids and isotopic composition of Oxygen-18 and Deuterium.

The fluctuation of shallow ground water in response to rainfall in the Potshini catchment in two piezometers, *PRB1* and *PRB2* in Figure 7.9, is as shown in Figure 7.11, while Figure 7.12 shows the response of stream flows to rainfall.

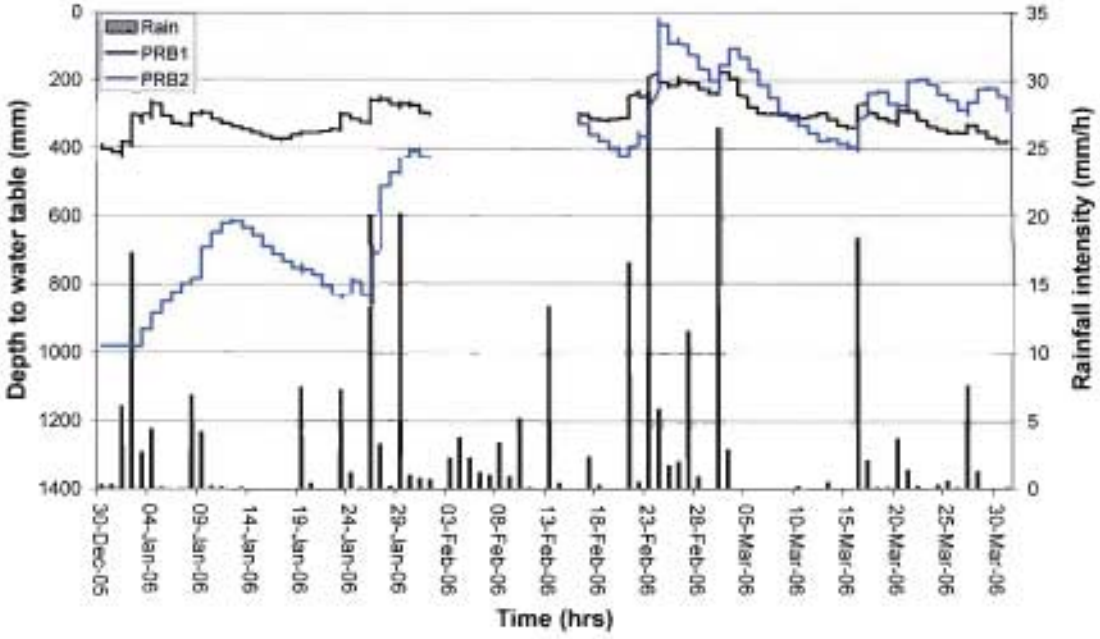

Figure 7.11 Shallow ground water flactuations in response to rainfall intensity in the Potshini catchment

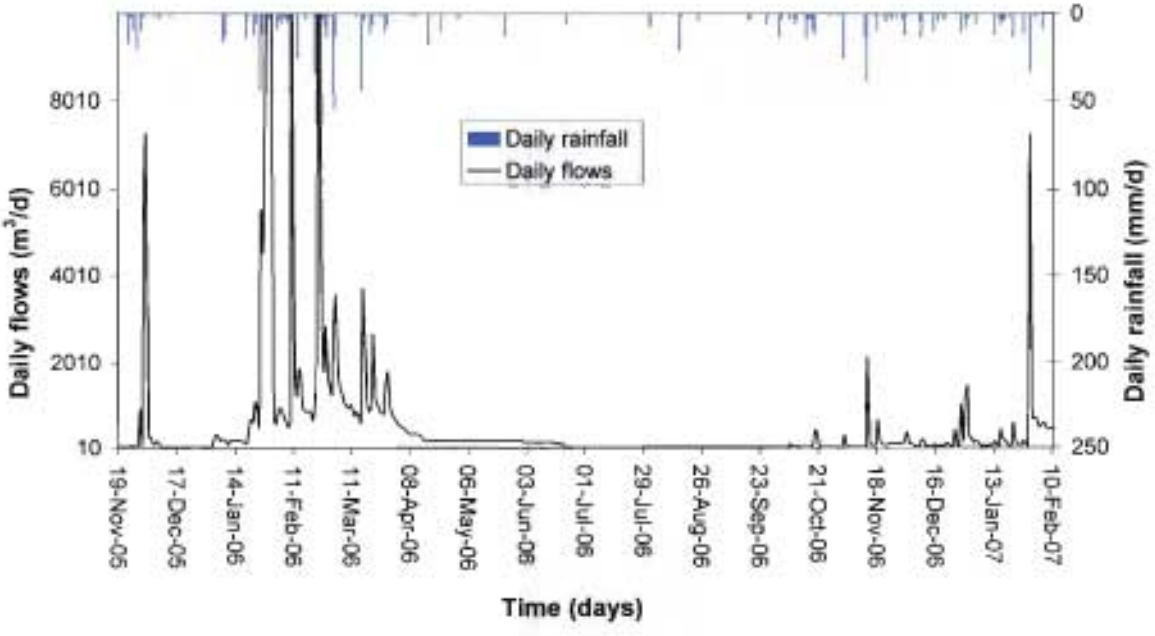

Figure 7.12 Response of stream flow to rainfall in the Potshini catchment

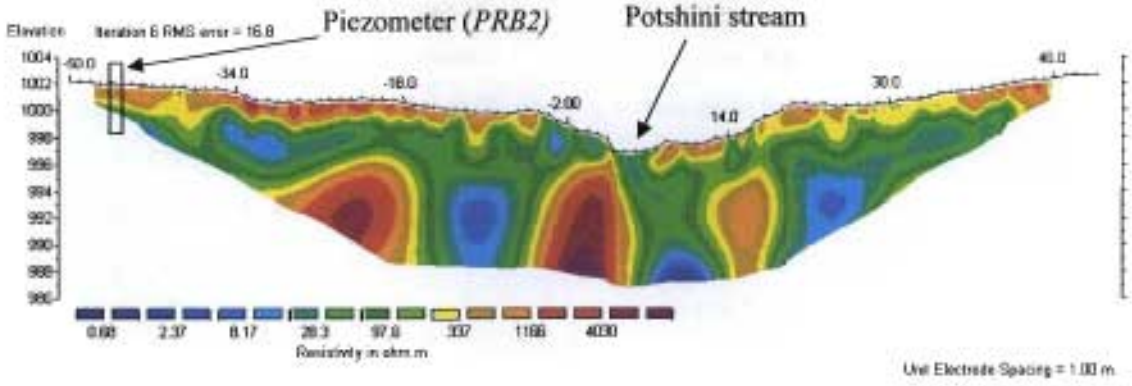

Figure 7.13 ERT survey across the stream in the Potshini catchment

It is useful to note that the numbering of the piezometers in Figure 7.9 decreases towards the stream, with *PRB4* and *PLB4* being located on the upper slopes of the respective hill-slope transect. Figure 7.13 shows resistivity survey along one of the transects in the Potshini catchment. An exclusive account on the interactions of surface and subsurface water in the Potshini catchment is detailed in Chapter 4. It can be observed from Figure 7.11 and Figure 7.12 that the stream flow in the Potshini catchment responds to rainfall much faster than the shallow ground water even though quick response of the latter can be observed on days that received high rainfall intensity. The ERT survey, Figure 7.13, revealed the subsurface characterization along one of the transects surveyed in the catchment, with low resistivities indicating saturation conditions or presence of clay material. The resistivity values along a transect can be related to specific land uses on the same transect after carrying out a detailed correlation exercise. Thus, the impact of conservation and conventional tillage systems to the hydrological regime at catchment scale could be investigated by analysing the interaction of surface and subsurface water through the application of classical hydrometrical monitoring and geophysical measurements (ERT) as highlighted in the framework and further supported by results from the Potshini catchment. The application of tracer isotopes to define sources of flow, pathways and resident time would add more value in such an analysis.

The catchment land use change studies can be upscaled to larger scales, i.e, to river basin scale through the combination of remote sensing (cf. Section 7.3.3) and classical hydrometric measurements (cf. Section 7.3.1) as highlighted in the framework (cf. Figure 7.8). Some geophysical measurements covering large spatial scales can be done from remote sensing platforms e.g gravity data from the GRACE satellite platform, and magnetism measurements from air-borne radars. High resolution remote sensed images, e.g Landsat ETM, SPOT, ASTER, provide land use cover maps from which the

rate and patterns of land use change can be analyzed. For example, it is possible to map areas under conventional and conservation tillage systems in a catchment and river basin at large, after ground truthing, and determine their respective rate of change with a possibility of determining the hydrological impact associated with such a change. Thus, it is also is possible to quantify the rate of land use changes by analyzing the percentage change of respective land use cover over seasons or years. Figure 7.14 shows a land use map for the upper Thukela river basin, where the Potshini catchment is located, developed by the South African Council for Scientific and Industrial Research (CSIR) in the year 2000 using Landsat images, while Figure 7.15 shows the percentage coverage of each land use in the same area.

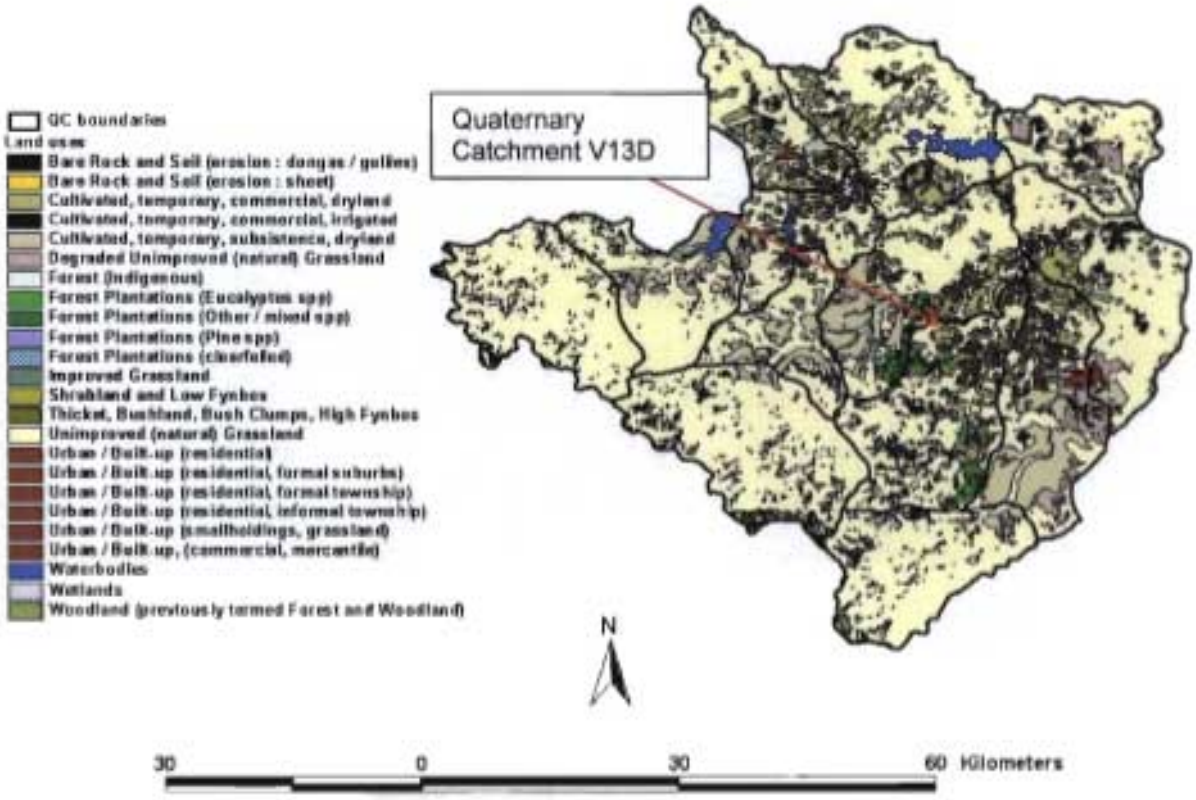

Figure 7.14 Land uses for the upper Thukela river basin derived from Landsat images by the CSIR for the year 2000

A study was carried out to determine the evaporative water use of the different land uses in the upper Thukela river basin using the Surface Energy Balance Algorithm for Land (SEBAL), a remote sensing technique, (Bastiaanssen, 2000) and the Moderate resolution Imaging Spectroradiometer (MODIS) satellite images (with a pixel resolution of 1km) on a monthly time scale as described in Chapter 6. It was observed that each land use had a different evaporative water use as indicated in Figure 7.16.

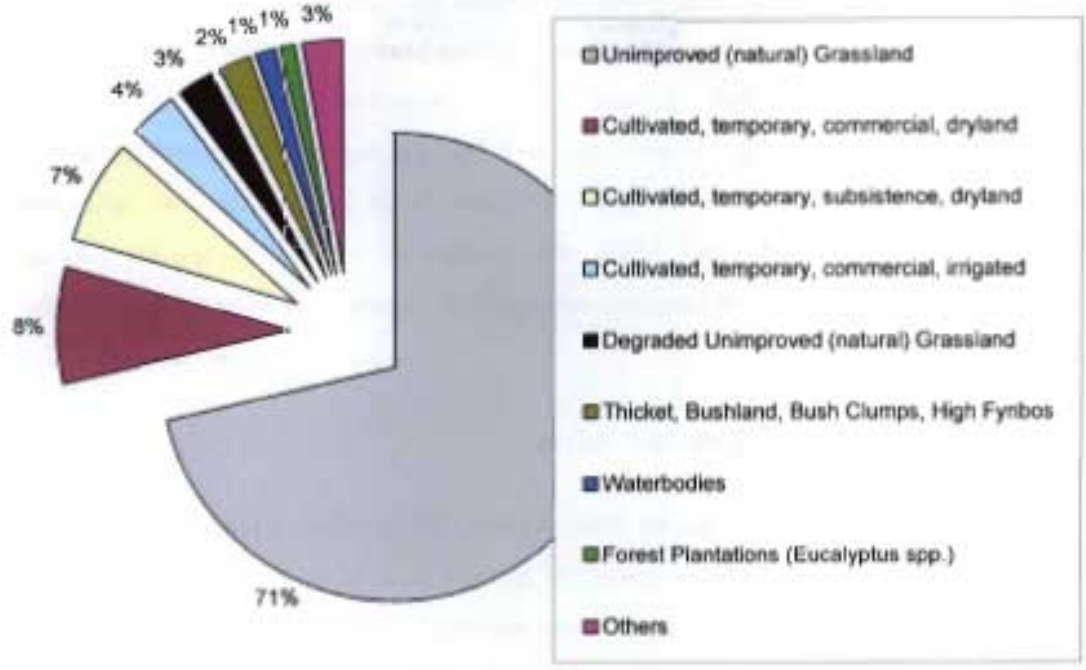

Figure 7.15 Percentage coverage of respective land uses in the upper Thukela river basin

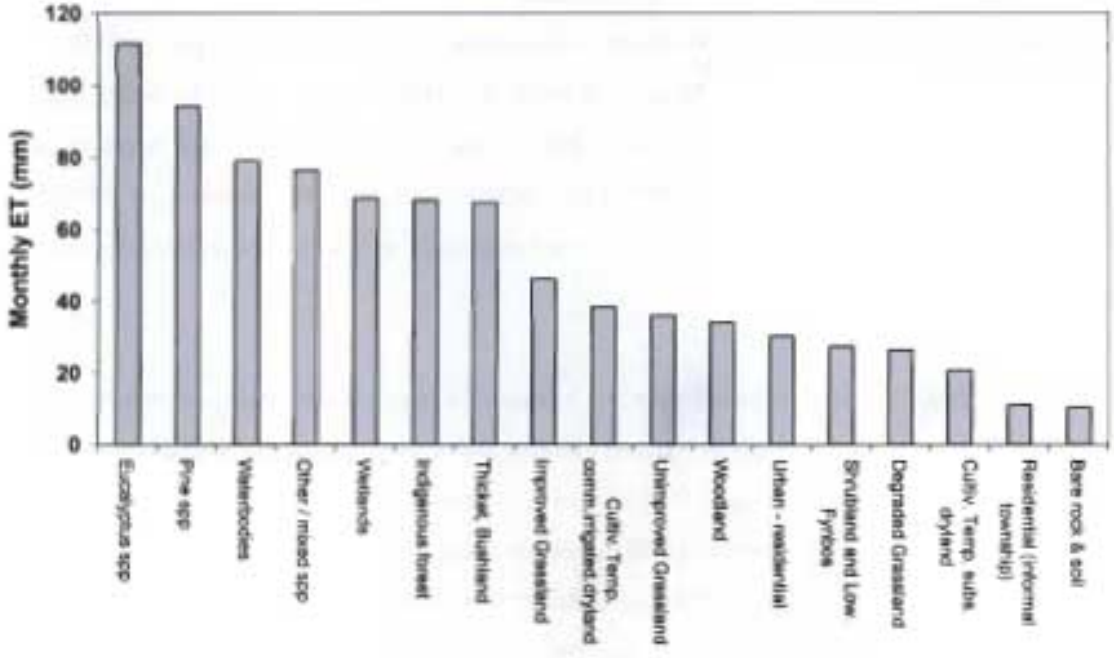

Figure 7.16 Monthly evaporative water use for various land uses in the upper Thukela river basin for the month of June 2005. The Potshini catchment is located in the upper Thukela

In June 2005, the Eucalyptus and Pine forests land use had the highest monthly evaporative water use compared to the other land uses in the study area with each having a monthly evaporative water use of

114 and 96mm respectively. Bare rocks and eroded soils had the least evaporative water use of less than 10mm in June 2005. Hence, the above analysis shows the potential of applying the suggested protocol as illustrated in Figure 7.8 and Table 7.2, across scales to address land use change issues including quantifying the impacts associated with land use changes at different and across scales, e.g if the land uses are intensified or swapped. The latter is of great concern as far as water resources management is concerned and hence this framework adds value to the ongoing efforts in implementing integrated water resources management strategies at different scales in the Thukela and other similar river basins.

7.6.4 Quantification of surface fluxes

The suggested conceptual framework advances and further creates a platform for quantification of the spatial variation of surface fluxes from field to river basin scale through the application of classical hydrometeorological monitoring and remote sensing techniques (cf. Figure 7.8). Quantification of these fluxes over large areas and over time can reveal the relative change of hydrological and environmental indicators (He et al., 2000). For example, total evaporation *(ET)* is a good indicator of plants ability to use water from the environment and thus a measure of adaptation of the plants in response to changes and shifts in structure of landscapes (Mattikalli and Richards, 1996). Thus, *ET* is closely associated with land use change and is the dominant component of the water balance in most semi-arid regions (e.g sub-Saharan Africa) and its management across scales is paramount in water resources management (Jewitt, 2006). This section discusses the application of the suggested framework in quantifying *ET* from field to river basin scale as was applied in the Potshini and Thukela river basin.

The Potshini catchment monitoring network comprise various instruments and structures, (cf. Chapter 2), including 2 standard automatic weather stations and a Large Aperture Scintillometer (LAS), which measures the turbulent intensity function of the refractive index fluctuations of air between a collimated light source (transmitter) and a detector (receiver) (Meijninger et al., 2000). The turbulent intensity functions are then converted to sensible heat flux measured along a transect (typically less than 10km) and which can be used together with soil heat flux (derived from soil temperature difference) and net radiation measurements (from weather station) to estimate total evaporation along a transect using the surface energy balance equation, i.e.

$$R_n = H + LE + G_o \qquad (7.2)$$

where R_n is the net radiation (W.m^{-2}), H the sensible heat flux (W.m^{-2}), LE the latent heat flux (W.m^{-2}) and which can be converted to total evaporation. G_o is the soil heat flux (W.m^{-2}). The LAS in the Potshini catchment was installed over a transect length of 1.03km and the soil heat flux measurements were done at three sites along this transect. Net radiation was measured at one of the weather stations in the catchment, which also measured and recorded other meteorological parameters including air temperature, relative humidity, wind speed, wind direction, soil temperature and rainfall. The Surface Energy Balance for Land (SEBAL) (Bastiaanssen, 2000), a remote sensing methodology for retrieving total evaporation and other surface fluxes from satellite images was used to compute *ET* from MODIS images (with a pixel resolution of 1km x1km) over the Potshini catchment and beyond. The values of the MODIS pixels that overlay the LAS transect at the time of satellite overpass were compared with the *ET* estimates derived as a residual of the surface energy balance equation, (Equation 7.2), using field measurements as variables, i.e sensible heat flux from LAS, soil heat flux estimates from soil temperature difference, and net radiation obtained from a weather station. It is noteworthy that SEBAL uses the surface energy balance equation to estimate latent flux on each pixel of a satellite image and hence the basic principle governing the estimation of *ET* using LAS and other field measurements (field *ET*) and the SEBAL methodology is the same. A good correlation was obtained between the field *ET* and the SEBAL estimates as shown in Figure 7.17 and hence provided good grounds to scale up the estimation of *ET* using the SEBAL methodology to cover the entire Thukela river basin as shown in Figure 7.18.

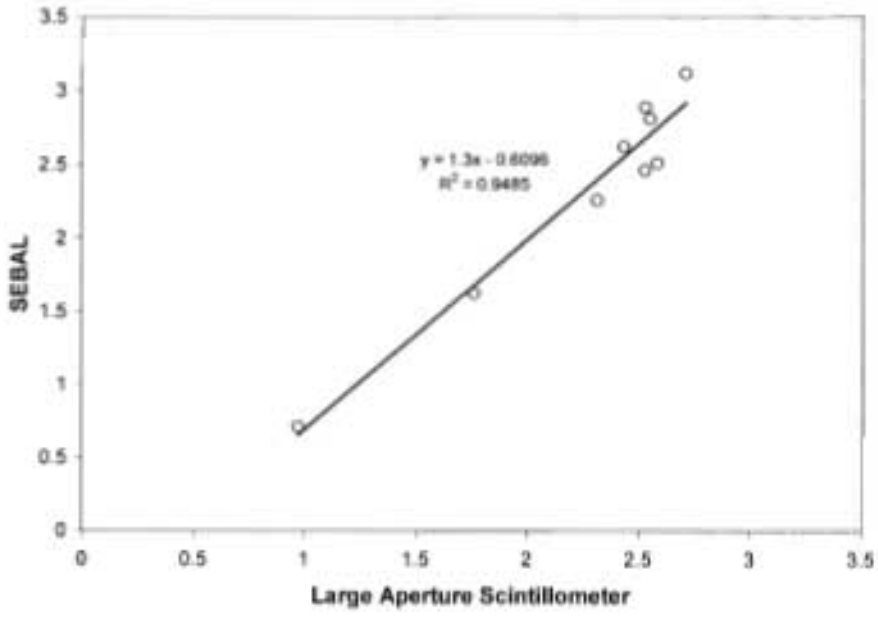

Figure 7.17 A comparison of daily SEBAL *ET* estimates and LAS measurements in the Potshini catchment

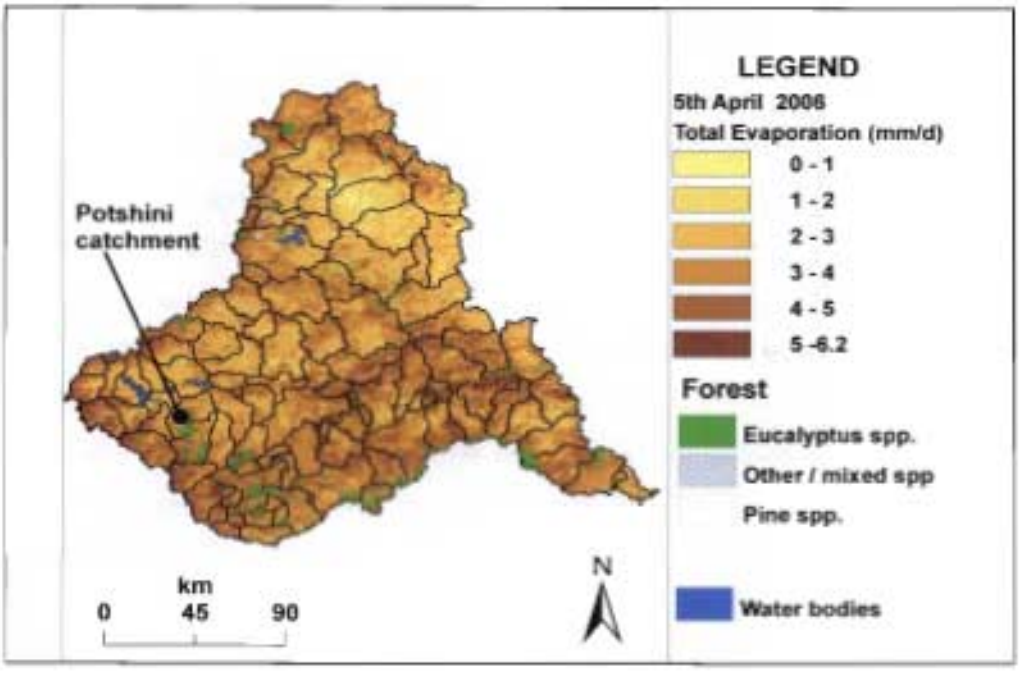

Figure 7.18 Spatial variation of in the Thukela river basin derived from a MODIS satellite image on 5th April 2006

However, it was not possible to validate the remotely sensed estimates of *ET* at other locations under different land uses in this study due to logistical problems associated with moving and operating the LAS in such new sites. Otherwise future research should compare concurrent *ET* measurements from at least two scintillometers under different land uses with SEBAL results for a given satellite overpass. It is noteworthy that there are several remote sensing techniques for quantifying *ET* reported in literature, with all techniques employing the concept of energy balance and mass transfer by associating the evaporative fluxes to the latent heat fluxes, the latter being a residual of the surface energy balance. Some of the documented methodologies include the Surface Energy Balance for Land (SEBAL), (Bastiaanssen et al., 1998a); The Surface Energy Balance System (SEBS), Su (2002); Two-Source Energy balance (TSEB) (Kustas et al., 2004; Mapping EvapoTranspiration with high Resolution and Internalized Calibration (METRIC) (Allen et al., 2005).

7.6.5 Parameterization of hydrological models

Hydrological models are representation of real hydrological systems. The internal functioning of such systems is characterized through field and laboratory measurements from which parametric mathematical relationships, e.g in conceptual physical models, are defined to describe the interactions

of the various hydrological processes. In the real sense, each of the model parameters has physical meaning associated with a particular process hence the need for a robust framework for estimating these parameters with less uncertainty. The proposed framework creates a platform for realistically estimating the respective model parameters given its potential to integrate data and information from various science disciplines across scales but limited to remote sensing, geophysical measurements, tracer studies and classical hydrometric measurements. The platform further has the potential to enable modelers to restructure their models to capture the real structural description of the prototype (field, hillslope, catchment or river basin) given its potential to capture data and characterize a hydrological determinant across scales. It is argued that modeling in the absence of adequate data is not science unless the modelling exercise is meant to develop hypotheses that are to be tested by observations (Silberstein, 2006). Extending this view, it can also be argued that model parameters that are estimated without a robust data-enriched framework to determine their uncertainty and authenticity are flawed. Geophysical measurements (e.g ERT) and isotope sampling, interpreted against hydrometric observations, enable the explicit characterization of the subsurface and subsequently defining the components of discharge in a catchment and hence making it possible to restructure a physical model accordingly including better estimation of its parameters, as demonstrated in Lorentz et al., (2007). It is a challenge to parameterize models at larger spatial scales (meso scales) using hydrometric observation alone and hence the most practical approach is to complement these with remote sensing data. Remotely sensed data such as Landsat-ETM and SPOT in combination with equally high resolution Digital Elevation Models (DEM's) facilitate the spatial estimation of model parameters related to vegetation, infiltration, slope, aspect etc. DEM's have conventionally been created from topographic contour maps and of late from satellite imagers which provide high resolution terrain maps, and which have been used extensively in hydrological studies in defining flow accumulation, channel network, length of channels, slopes, delineating catchments, computing temperature lapse rates, aspect etc. (Schultz, 1993), thus contributing significantly to model parameter estimation. Figure 7.19 shows some of the fluxes and hydrological parameters that can be retrieved from remotely sensed data and a DEM respectively. Other studies e.g Chaplot and Walter (2003) have shown the potential for retrieving a spatial distribution of soil wetness indicator from a DEM, i.e the Compound Topographic Index (CTI).

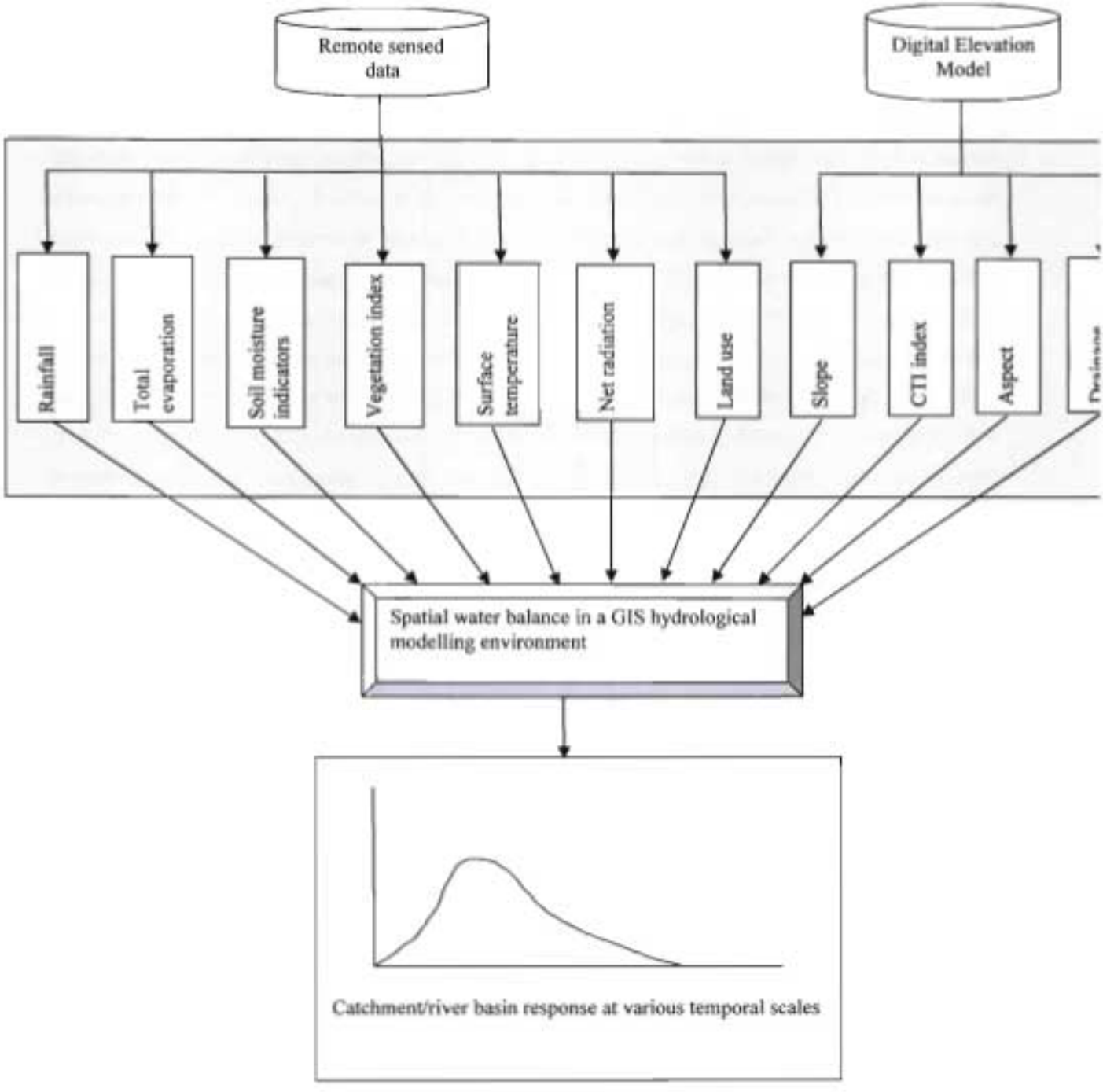

Figure 7.19 Remotely sensed fluxes and hydrologic parameters from remote sensed data and DEM

7.7 Conclusions

The main shortfall of classical hydrometric observation is the fact that the observation scale, (in space and time) does not necessarily match the scale of the dominant hydrological determinants. The conceptual framework discussed herein gives an insight for potential of applying various techniques derived from other related science disciplines to increase the effectiveness of monitoring and identifying the hydrological determinants across scales, but largely spatial. This provides a contribution to the scale issue, by highlighting and appreciating the fact that hydrological processes vary in space and time while providing a pragmatic platform for better description of these processes which integrates concepts and theories from various science disciplines, and thus making use of data from various data sources including remote sensed data, geophysical measurements and tracer isotope sampling.

The contribution of the framework to hydrological modeling is highlighted, especially the possibility of using the framework to realistically estimate model parameters and incorporation of other data sources in process oriented physical models. There is no doubt that the future of the hydrological science will be determined by innovative approaches in both monitoring and modelling, with the latter being the ability to directly integrate and make use of data from various science disciplines. Already, some effort has been made in this innovative approach, e.g. Uhlenbrook et al., (2004), where a process oriented conceptual distributed catchment model incorporates tracer data. Hydrologists have made significant progress in hydrological modelling research, especially in the past two decades. This has been linked to the advent of powerful computers able to make numerous simulations with the capacity to handle large data sets (Silberstein, 2006). This is evidenced by the fact that many publications in the hydrological sciences today emanate from research that applies hydrological modeling tools (at field scale, hillslope, catchment or river basin scale). It can be argued that hydrological modeling has taken a central position in the hydrological science, a position which is better reserved for improved understanding hydrological processes. Such an offset could be linked to the computer era, with rather slow progress in characterizing and understanding of hydrological process, conceptualization of new theories, uncoordinated effort in innovating new paradigms, and lack of integration of other science disciplines in the hydrological science.

The future of the hydrological science will be determined by our departure from preconceived ideas on hydrological processes, our willingness to search for better understanding and conceptualise these processes while defining pragmatic frameworks for identifying their footprints at various spatial and temporal scales. Nevertheless, as much as we encounter and overcome challenges in our innovative

thinking as we apply various techniques and tools in addressing the rather complex scale issue in hydrology, we should not be preoccupied with pointing out our strengths and achievements but rather weaknesses and failures as a way of provoking new ideas from the various disciplines of science in an attempt to understand and conceptualise the complex labyrinth of hydrological processes across scales.

8.0 Conclusion and recommendations

This research is a culmination of 4 years field studies carried out in the upper Thukela river basin in South Africa under the Smallholder water Systems Innovation (SSI) research programme and which resulted in the setting up of a "field hydrological laboratory", a research catchment, in the midst of the Potshini community in Bergville district of KwaZulu-Natal province. The main aim of the research study was to characterize and determine the dominant hydrological determinants across scales in the Thukela river basin river and hence appropriate techniques and tools were tested and applied at various scales in due process from which a conceptual framework with a potential for enhancing better identification and characterization of the main hydrological determinants across scales was devised. The field studies were carried out with the involvement of the local Potshini community and relevant stakeholders at various levels of participation, including provision of labour and resource materials. Such an approach provided an opportunity for fostering good working relationships, with numerous benefits being realised for both researchers and other stakeholders and hence this participatory approach is recommended for any similar research studies.

Process hydrological studies were carried out at field and catchment scale by carrying out classical hydrometric measurements and complemented with geophysical measurements (Electrical Resistivity Tomography-ERT). Field studies on comparison of soil moisture and runoff generating characteristics of conservation and conventional tillage systems in the Potshini catchment highlighted the impact of the respective tillage systems to partitioning of rainfall. There was enough field evidence to support the fact that conservation tillage systems significantly reduces surface runoff and increases soil moisture retention especially at deeper depths. However, this study did not clearly establish whether the increase in soil moisture under conservation tillage practices has any implication or interaction with shallow ground water including solute transport of nutrients into the ground water. Also, the impacts of upscaling these tillage practices on water resources at catchment and river basin scale were not analysed in this study. Thus, this study recommends further research to establish whether conservation tillage practices have any significant impact on shallow ground water dynamics and the hydrological impact of wider adoption of conservation tillage practices to water resources at different management scales. It is recognized that the latter will require agro-hydrological modelling to develop appropriate scenarios.

The ERT measurements at catchment scale facilitated the characterization of the subsurface structure along 9 transects in the catchment, spanning between 150m to 600m, with shorter transects (<200m) having an electrode spacing of 1m while longer transects (>200m) an electrode spacing of 5m. The

subsurface structure of a catchment has an influence on both surface and subsurface hydrological processes thus directly influencing the catchment response. The ERT measurements were interpreted against hydrometric measurements, i.e ground water levels, where it was observed that low resistivity values occurred in saturated zones of the subsurface. Such understanding and interpretation was then used to map saturated and unsaturated zones, subsurface preferential flow paths and subsequently the connectivity of the subsurface water (shallow ground water) with the stream flows in the catchment. The resistivity survey revealed the stratification of the subsurface structure including identification of preferential flow paths towards the Potshini stream and the connectivity of shallow ground water with the Potshini stream. The hydraulic conductivity of the stratified subsurface layers, obtained from in-situ and laboratory measurements, and shallow ground water levels were used to compute the relative contribution of shallow ground water into the stream flows in the catchment of which it was found to be significant especially during the dry winter season. Such analytical information is useful for assisting the wise implementation of current and future anthropogenic activities in the catchment, especially those that may impact negatively on the occurrence of shallow ground water in the catchment, for sustainability of stream flows throughout the seasons. Thus, the integration of geophysical methods into mainstream hydrological studies was explored with success in this study. However, it is useful to note that the resolution of the ERT measurements is affected by electrode spacing, with detailed and finer resolution ERT measurements resulting from shorter electrode spacing at an expense of deeper measurements. This is a compromise which one has to make depending on the objectives of carrying out any ERT measurements. In this study, the inherent limitations associated with the application of Darcy's methodology in quantifying subsurface fluxes and relative contribution to the stream flow was highlighted, especially the inability of the methodology to account for preferential flows and contribution from macro pores. Thus, this study recommends complementary application of tracer studies, notably Oxygen-18 and Deuterium, in similar studies in future given their potential in quantifying and identifying end members of a hydrograph.

Remote sensing techniques were used to integrate the catchment process studies to the larger Thukela river basin scale through the evaporative term of the water balance. Total evaporation is a main hydrological determinant in arid and semi-arid regions in southern Africa although its occurrence is influenced by many factors including meteorological parameters and land surface attributes. In this study, the Surface Energy Balance Algorithm for Land (SEBAL) methodology was used to retrieve the main components of the surface energy balance (net radiation, sensible and soil heat fluxes) and ultimately total evaporation fluxes from the freely available Moderate Imaging Spectoradiometer (MODIS) images, with the latter having an inherent pixel resolution of 1km. SEBAL estimates of net radiation, sensible heat flux, soil heat flux and total evaporation compared well with ground

measurements, obtained from an automatic weather station and a Large Aperture Scintillometer (LAS) installed in the Potshini catchment. The comparison entailed comparing the ground measurements with the respective remote sensed estimates for pixels overlaying the 1.03km LAS transect. The raster images of total evaporation covering most of the upper Thukela river basin, on which the Potshini catchment is located, were used together with a South African land use classification map to compute monthly evaporative water use of different land uses over an area of 3,028 km^2 covering 13 Quaternary Catchments.

The analysis indicated that forestry, water bodies and wetland land use classes consistently had the highest evaporative water use compared to the other 24 land uses in the study area. The estimation of the monthly volumetric water use of different land uses in the upper Thukela river basin highlighted the implication of land use changes including the possible impact of swapping or intensification of respective land uses to water resources. Such information, derived from scenario analysis, is useful in water resources planning at different management scales and hence this study recommends further research to establish and generate this useful information that apparently was not fully covered in the study reported herein. Nevertheless, it is useful to note that the resolution of the respective satellite images is imparted into the remote sensed estimates of surface fluxes and hence coarse resolution images like MODIS may not be useful at catchment scale (less than $10km^2$) but at larger spatial scales with regard to detailed analysis on water resources management, a similar sentiment is also shared in WaterWatch (2006). Thus, it would be prudent to combine high and low resolution satellite images in similar research endeavours in future in an effort to maximize the potential of applying remote sensing techniques at both catchment and river basin scale. Such a recommendation is further supported by the fact that the irregular results of evaporative water use from water bodies is more attributed to the low resolution MODIS images, with the latter being unable to merge with the fine details from the land use map which was derived from high resolution 30m Landsat images. Field measurements of total evaporation from other land uses using scintillation techniques is recommended for better comparative analysis and as a validation strategy of remote sensing estimates of evaporative water use from the same land uses.

Lastly, the opportunity to develop a pragmatic conceptual framework with the potential to address and contribute to the scale issue in hydrological processes across scale by taking advantage of the complementary role of geophysical measurements, isotope tracers and remote sensing to the classical hydrometeorological measurements is suggested and discussed. Each of these techniques has their inherent weaknesses and strengths which together form a useful tool for enhancing our understanding

and conceptualisation of hydrological determinants across scales, with the added benefit of constraining hydrological models to reflect reality.

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