HYDROLOGICAL PROCESES, CHEMICAL VARIABILITY, AND MULTIPLE ISOTOPESTRACING OF WATER FLOW PATHS IN THE KUDUMELA WETLAND-LIMPOPO PROVINCE, SOUTH AFRICA

A thesis submitted in fulfillment of the requirements for the degree of
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By

Feleke Abiyo Mekiso

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DEDICATION

This Thesis Report for the Master of Science degree is dedicated to my wife Dinknesh and children

“And God said unto Abraham, As for Sarai your wife, you shalt not call her name Sarai, but Sarah shall her name be. And I will bless her, and give you a son also of her: yea, I will bless her, and she shall be a mother of nations; kings of people shall be of her. And God said Sarah your wife shall bear you a son indeed; and you shall call his name Isaac: and I will establish my covenant with him for an everlasting covenant and with his seed after him. But my covenant will I establish with Isaac, which Sarah shall bear unto you at this set time in the next year.”

Genesis. 17:15-16, 19 &21

DISCLAIMER

This thesis is my own work and has not been published on any publication or scientific journal.

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ABSTRACT

The hydrology of the Kudumela Wetland, Limpopo Province of South Africa was studied from November 2005 to April 2007, involving both fieldwork and laboratory analyses. This study presents the results of an investigation of the hydrology of the Kudumela Wetland in South Africa, and its contribution to dry season flow in the Mohlapitsi and Olifants Rivers. Initially, 40 Piezometers were installed along seven transects and water levels monitored in order to understand water table level characteristics (fluctuations) with time. Water levels in transects one, three, the right bank portion of transect four and transect six showed fluctuations. Transect two, the left bank portion of transect four and transect five did not show significant temporal changes. The relationships between piezometer water levels, rainfall in the study area and stream flow observed at a river gauging station are not clear. The river within the wetland is a gaining stream because the water table level elevation is above that of the river. This indicates that the wetland is feeding the river. The northern part of the wetland (T1 and T2) is affected by artificial drains and most of the piezometers closest to the river channel showed the lowest variations. The relationships between rainfall, groundwater, and surface water at this site shows that stream flow did not respond quickly to precipitation as expected, even in months when rainfall increased (for example, 74 and 103mm during 08/02/06 and 18/02/06 respectively), and the groundwater levels did not show fluctuations, indicating that groundwater responds gradually to precipitation, and that the relationship between rainfall, groundwater and surface water is complex.

The environmental stable isotopes (deuterium and oxygen-18) and the radioactive isotope (tritium) were analyzed, along with field observations of electrical conductivity (EC), pH, total alkalinity (Talka) and some major and minor dissolved ion analyses for tracing water dynamics in the study area. A total of 39 water samples was taken and analyzed from boreholes, auger holes, right bank and left bank drains, various points along the river and springs in four sampling visits to the wetland. The results did not clearly provide a temporal record of isotope and

chemical variations in the various sources. Results from the most extensive sampling survey in April 2007 provide the most comprehensive overview of hydrological relationships. Clustering of the stable isotope data suggests that the water samples of upstream and downstream river, auger holes further south and most drains clustered together suggesting a common water source and almost all samples fall above the global (GMWL) and local (Pretoria MWL) meteoric water lines, while some fall between the global and Pretoria meteoric water lines. Six representative water samples were analyzed for major ion concentration. Both cation (Ca, Mg, K, and Na) and anion (HCO_3, SO_4, Cl, and NO_3) analyses in November 2007 confirmed conclusions reached from field observations. The analysis shows that a single type of water (Ca, Mg-HCO_3) is involved in the study area. In almost all major ion plots, the right bank drains, upstream river and downstream river samples grouped together in a single cluster.

As the means for reliable river flow measurements were not available, except for the gauging station at the outlet of the valley, rough, semi-quantitative estimates were made during several field visits. These, suggest considerable losses of river flow into the gravel/boulder beds at and below a gabion dam at the head of the valley. Three major and several other left bank springs and right bank drains at transects T1 and T2 contributed to the river flow at all times. Along with the isotopic and chemical evidence, these observations have lead to a hypothesis that river water enters the wetland and flows back to the Mohlapitsi River through boulder beds underlying the wetland and through drains on the surface of the argillaceous aquitard covering the more conductive boulder beds. Deeper dolomitic groundwater does not appear to contribute to the water balance at least in the northern half of the wetland. Although environmental isotope and hydrochemistry results may not unequivocally prove this hypothesis they do not contradict it.

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My family for their patience and encouragement during the completion process of this document.

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1. PROBLEM STATEMENT

1.1 Introduction

Wetlands are important components of many river basins throughout the world and are also important from a socio-economic point of view in that they support agricultural activities (Ehrlich et al., 1997). The World Conservation Strategy (IUCN, 2008) proposed that wetlands are an important support system on the planet. Unfortunately, many of the world's wetlands are under threat because of changed upstream hydrological and water quality regimes, or through exploitation for agricultural production. The formation, persistence, size and function of wetlands are controlled under natural conditions by hydrological processes (Roulet, 1990). The distribution of, and differences in wetland type, vegetative composition, and soil type are caused primarily by geology, topography, and climate (Scott, 1989). According to Carter (1996) and Scott (1993a) such differences are the product of the movement of water through or within the wetland, water quality, and the degree of natural or human-induced disturbances. In turn, the wetland soils and vegetation alter water velocities, flow paths, and chemistry. The hydrologic and water-quality functions of wetlands, that is, the roles wetlands play in changing the quantity or quality of water moving through them, are related to the wetland's physical setting (Carter, 1996). Wetlands are therefore sensitive natural environments and if they are to be used in a sustainable manner, knowledge of wetland hydrology and quantification of water inputs and outputs are necessary prerequisites to understanding wetland environments and determining their vulnerability to change resulting from man's activities (Roulet, 1990).

Inland wetlands are hydrologically complex as they are influenced by processes within them as well as those in the surrounding catchments. In many of these wetlands the boundary between the wetland and the surrounding area is not well defined (McCartney et al., 2005). There are exchanges of material, including water, between the wetland and upstream and downstream areas. The hydrological processes of groundwater storage and flow generation determine the extent of the inundation of the wetland, and land use changes that can modify these processes (Beven, K. 1983).

1.2 Characteristics of wetlands

Various authors classify wetlands differently. McCartney et al. (2005) characterized wetlands by the presence of the water table at or near the land surface for some part of the year, by soil conditions that differ from adjacent uplands, and by vegetation adapted to wet conditions. Furthermore, they stated that one or more indicators of wetland vegetation, hydric soil and wetland hydrology must be present for an area to be considered a wetland (Nell and Dryer, 2005). Grundling (1999) confirmed that wetlands are usually classified based on their morphology and vegetation, and to a lesser extent, their hydrology. Moreover, Grundling (1999) demonstrated that wetlands develop naturally in response to morphological and hydrological features of the landscape. Based on the above and other classifications, the Kudumela Wetland in the Mohlapitsi River basin, Limpopo Province would certainly fulfil the criteria.

1.3 Wetlands in South Africa – functions and issues

South African inland wetlands cover approximately 20% of the landscape and play a very important role in ecosystem functioning (Masiyandima et al., 2006). These wetlands play provisioning, regulatory, and habitat roles in the landscape. Wetlands are vital for attenuating floods, regulating river flow, recharging groundwater sources, biodiversity protection, tourism, environmental education, grazing, and subsistence agriculture and as a source of food and plant materials for rural communities (Grundling, 1999). Wetland ecosystems, including rivers, lakes and marshes, provide a number of services that contribute to human well-being and poverty alleviation (Millennium Ecosystem Assessment, 2005). Conservation and management of freshwater resources are also roles that wetlands play. In addition, wetlands play important roles in maintaining environmental quality, supporting immense biodiversity, sustaining livelihoods and mitigating unemployment. Recreational and aesthetic qualities and their role in local and regional hydrology, by serving as water-storage areas and reducing flooding, are other important values of wetlands (Dini et al., 1998 and McCartney, 2004).

Many wetlands in the region such as GaMampa Wetland (Jogo and Hassan, 2010) are utilized by the local communities for crop production, fish production, livestock production, natural products harvesting, and domestic water provision (Wood, 2000). The Land use and Wetland/Riparian Habitat Working Group (2000) stated that some land uses within the wetlands have the potential to impact on the surrounding areas due to the fact that wetlands and surrounding catchments are connected. On the other hand, processes and land use changes in the surrounding areas potentially impact on the wetland. Flow generation processes in wetlands are important in determining the role of the wetland in relation to river flows as well as for managing land uses, especially agriculture-related, that impact on the functioning of the wetland (Carter et al., 1979). In spite of their considerable value, some 50% of wetlands in South Africa have already been destroyed due to unsustainable development (Kotze, 2005). Examples of mechanisms leading to their destruction include draining wetlands for crops or housing developments, pollution, building upstream dams, overgrazing and vegetation burning and planting water-thirsty alien trees too close to their edges (Grundling, 1999; McCartney, 2006). Masiyandima et al. (2004) and Grundling (1999) confirmed that wetlands could also be disturbed as a result of natural conditions, such as an extended drought.

Among approximately 1500 wetlands in South Africa, 16 are listed as Ramsar Sites. Figure 1.1 and Table 1.1 show the South African designated Ramsar Sites, designation dates and their identification. The detailed hydrology, geology, hydrogeology, topography, ecological importance, climate, threats and location of Velorenvlei are well documented in www.ramsar.org/index.list.

Even though the Kudumela Wetland plays an important role in the lives of the community by helping them achieve food security during dry seasons, the wetland is still one of the many sites that is not recognized and designated by the Ramsar Convention (1971). The majority of rural people, and some urban dwellers, benefit directly or indirectly from the Kudumela Wetland and its products. However, as with other wetlands in South Africa, it has been subject to pressure, some as a result of natural events, such as a major flood during 2000, but mostly as a result of agricultural and urban developments during the last decade (Conrad et al., 1999).

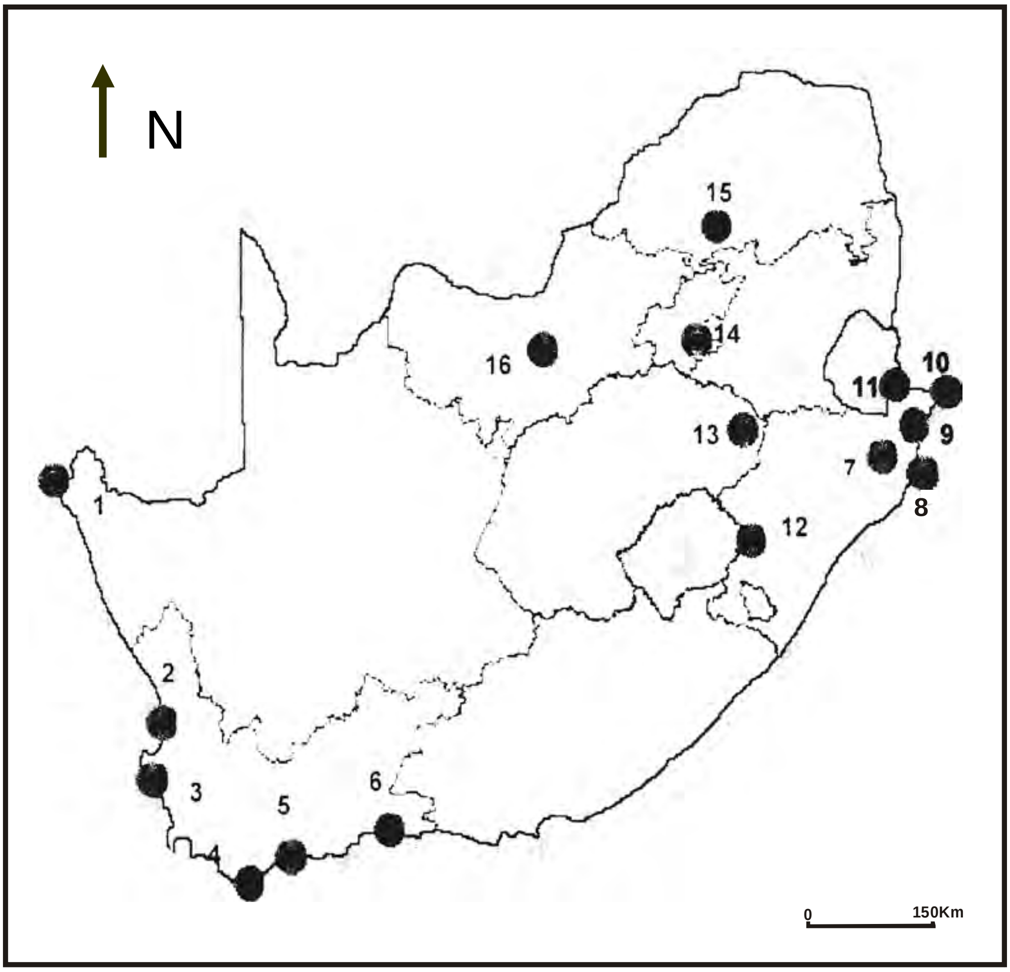


Figure 1.1 South Africa’s designated Ramsar Sites, including natural wetlands, coastal and marine ecosystems, coastal lakes with lagoons, freshwater marshes, parks, estuaries, flood plains and mangroves (Sources: www.ramsar.org/index.list and www.ngo.grida.no/soesa/nsoer/resource/wetland/ramsar_map.htm).

Table 1.1 List of South African Ramsar sites (for locations and reference, see Figure 1.1)

Number	Wetlands	Area (ha)	Designated date
1	Orange Mouth Wetland-delta mouth-braided.	2 000	1991
2	Verlorenvlei-natural wetland.	1 500	1991
3	Langebaan-lagoon, entirely marine.	6 000	1998
4	De Mond State Forest-an estuary wetland.	918	1985
5	De Hoop Vlei.	750	1975
6	Wilderness Lakes-coastal lakes with lagoon.	1 300	1991
7	St.Lucia System-lake	155 500	1989
8	Turtle Beaches & Coral Reefs of Tongland.	39 500	1986
9	Lake Sibaya-natural fresh water lake.	7 750	1991
10	Kosi Bay System-6 large estuary lakes complex.	10 982	1991
11	Ndumo Game Reserve flood plain system.	10 117	1997
12	Natal Drakensberg Park.	242 813	1997
13	Seekoeivlei-seasonally flooded ox-bow lakes.	4 754	1997
14	Blesbokspriut.	1 858	1986
15	Nylsvley Nature Reserve- coastal freshwater lake.	3 970	1998
16	Barberspan	3 118	1975

1.4 Key questions

The brief introduction to the Kudumela wetland provided above raises several key questions that need to be answered before effective management plans can be designed and implemented:

- What is the hydrological function of the wetland in the Mohlapetsi river catchment?
- Is the wetland a regulator of water which sustains the low flows, or is the wetland a net consumer of water?
- What are the impacts of land use practices and land use changes on the hydrological functioning of the wetland?
- Is the wetland becoming wetter or drier?

1.5 Background to the study

A number of different surveys and research studies have been carried out in the study area through the International Water Management Institute (IWMI) for the last eight years (CGIAR, 2005). Most of this research work was in the fields of environmental science, water management for food production, sociology and socio-economics. Three hydrological studies were recorded at the right bank of the wetland and the first one was an MSc thesis on environmental engineering by Sarron (2005). The report was based on the hypothesis that wetlands can be managed in a sustainable manner, achieving a balance between protection and agricultural production, thereby ensuring optimal use of wetlands. The McCartney et al. (2005) and McCartney (2006) reports are the second and the third hydrological studies that focused on the hydrology of the Mohlapitsi River catchment.

However, surface and groundwater generation processes, which are of key importance for understanding the dynamics of the water in the wetland and the conditions of its sustainability, were poorly documented. This research project was aimed at contributing to bridging this knowledge gap. The general objective was to understand the water dynamics within the wetland and whether the Kudumela/Mohlapitsi Wetland is contributing to the flow of the river or it is receiving water from the river.

The author came to appreciate that the shallow groundwater table analysis was, in itself, unlikely to answer the research questions and that environmental isotope tracers might assist in understanding the water flow paths in the wetland. This study was assisted by the Environmental Isotope Group of iThemba LABs that provided funding for the analytical support and a stipend for the author.

1.6 The research project planning

This research project evolved out of the personal interest of the author and was not originally designed as a postgraduate MSc research programme in the normal way, i.e. involving supervision of a senior researcher and critical assessment of the study design. The candidate was attracted by the peculiarity of the hydrology and geology of the study site. With this in mind the author had approached sponsors, and finally iThemba Labs agreed to cover laboratory analyses and field work costs only. Other costs were covered by the researcher himself since he was an employee of a civil engineering consultant in South Africa. Dr. Uwe Horstmann, the iThemba Labs scientist, was interested in this exercise, because he and the author considered that the findings would be of value to the broader scientific community in South Africa. The main result of this arrangement was that the initial project planning, and specifically the programme of field observations and laboratory analyses was constrained by the limited available resources and did not benefit from critical review by a supervising experienced academic researcher. Dr Uwe Horstmann of iThemba Labs suggested to the author that he might consider registering for postgraduate study but this took some time to arrange for various reasons, including a lack of knowledge of the appropriate University Department and the need to continue being employed. In the meantime, the monitoring work discontinued at the end of June 2006 for two reasons. On the one hand, water levels did not change and Dr. Uwe Horstmann left South Africa; and the financial support from iThemba Labs was no longer available.

Simultaneously, the researcher started to communicate with the Department of Water Affairs (DWA), the Department of Agriculture and the Institute for Soil, Water and Climate in order to get information and learn more about the study area. After many communications it was possible to receive the satellite image of the study wetland, some information on soils, maps (from Survey General-Pretoria), weather data from the South African Weather Service (SAWS), and information for the stream flow gauging station. Eventually, the author was accepted as a registered postgraduate at the Institute for Water Research, Rhodes University on the assumption that the data collected are of value and that, despite the limitations of the initial study design, the resulting MSc thesis would make a scientific contribution to the understanding of the dynamics of wetlands in general as well as to the future sustainable management of the Kudumela Wetland. During the preparation and further analysis of the data for the MSc thesis the author more clearly recognized the limitations of the initial study design and that the study would have benefitted from a thorough review of the fieldwork programme, guided by a supervising experienced research scientist, early in the project. Notwithstanding the recognition of these limitations, the data collected are still considered to be valuable given that such data are rarely available for most wetland areas of South Africa. Given this background to the study, one of the key objectives of this thesis is to critically evaluate the fieldwork programme and the information that was collected and make recommendations for the design of future studies in wetlands of this type.

1.7 Aims and objectives of the study

The main aim of this research project is to contribute to the future management of the natural resources of the Kudumela Wetland through developing a better understanding of the hydrology and the mechanisms by which the wetland receives water.

The main aim is supported by the following objectives:

- To contribute to the understanding of the processes of water movement into and within the wetland based on a programme of hydrological monitoring coupled with the collection and interpretation of environmental isotope and hydrochemistry data (from river flow, springs, auger holes, boreholes and drainage channels).
- To critically evaluate the methods used as well as the collected information in terms of its use for understanding the functioning of the wetlands and to make recommendations for the design of future similar studies.
- To assess the impact of the recent wetland area reduction on the hydrological functioning of the wetland.
- To identify the conditions necessary for the sustainability of the remaining wetland area.
- To contribute to new knowledge of the way that wetlands function in terms of their dominant hydrological processes and linkages with surrounding catchment areas.

The main outputs from the study are expected to be an improved climate and hydrological (surface water and groundwater, water quantity and quality) database for the Kudumela wetland, an updated conceptual and quantitative model of the water dynamics of the wetland and guidelines for the future sustainable management of the natural resources of the wetland. The research project results will assist local government, national government agencies and different non-governmental organizations (NGOs) in the region in identifying the likely socio-economic impacts of different types of land use change, and hence assist in planning for future change.

1.8 Structure of the thesis

Chapter 1 has provided some background to the study in terms of the current situation of South African wetlands, especially the threats they face and how they are classified, and describes the issues, aims and objectives, key questions and expected outputs of the project. A detailed description of the physical setting and human modifications affecting the Kudumela Wetland is provided in Chapter 2, together with information about the topography, climate, geology, soils and vegetation as well as a discussion of the relationship of the wetland to the Mohlapitsi River and the available information on springs and drains. Chapter 3 presents a literature review that is focused on previous work related to understanding wetland hydrological dynamics and the contributions that this understanding can make to their sustainable management. Chapter 4 presents the research methods that have been applied and the resources used to achieve the objectives of the project. It includes information about the hydrometric data available from other sources as well as the instrumentation and sampling sites that were established as part of this study (including stream flow and rainfall gauges, groundwater monitoring piezometers, springs, drains and boreholes). Chapter 5 presents the interpretation of the available data, the results of the data analyses and discusses the limitations of both the data and the results. In addition, Chapter 5 also presents the development of the conceptual model of the wetland hydrology and a diagram that summarizes the paths of river water through the wetland environment. Chapter 6 presents a discussion of the implications of the project results for future sustainable management of the wetland, summaries the conclusions of the project and makes some recommendations for future research work or management actions.

2. STUDY AREA

2.1 Location and general description

This study was conducted at the Kudumela Wetland, which lies in the former homeland area of Lebowa in the Capricorn District and in the middle part of the Limpopo basin. The wetland is a riverine system covering an area of 120 ha (Kotze, 2005). The wetland is located in the B71C quaternary catchment (according to South African designation) and geographically on coordinates $24^0$6'0" South and $30^0$6'0" East. Agricultural activities have extensively modified the ecological status of the wetland system under study (Jogo and Hassan, 2010).

The Mohlapitsi River is in Limpopo Province of South Africa and drains southwards from the Wolkberg Mountains into the Olifants River (Figure 2.1). The upper part of the Mohlapitsi Catchment in Olifants Catchment (in Limpopo Catchment) is mountainous with peaks (Figure 2.2) above 2050m and mainly covered by natural forest, whereas the lower reaches are alluvial valleys (Kotze, 2005). At the confluence with the Olifants River, the Mohlapitsi catchment is 49000 km^2 and upstream of the wetland it is approximately 263 km^2.

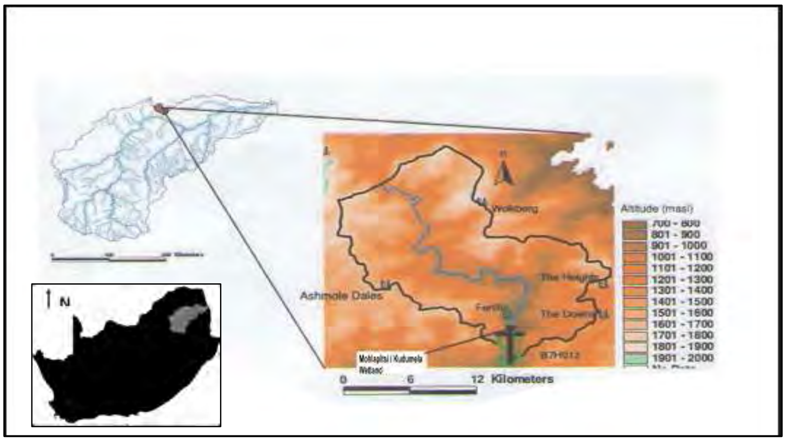


Figure 2.1 Map showing the location of the study area within the Olifants catchment (with an unscaled insert showing the location within South Africa). The more detailed map shows altitude ranges and the positions of the flow gauging station, rain gauges and the Kudumela wetland within the Mohlapitsi River catchment (Adapted from Schulze et al., 1997).

Two minor engineering works were installed in the river in order to assist the community that lost its entire irrigation infrastructure during the 2000 flood. The first is at gabion dam (Figures 2.3 and 2.4), which is located approximately 2.5 km north of transect 1 of the wetland. The purpose of this structure is to increase the head so that more water can be diverted to both Fertilis irrigation canal (right bank canal made from masonry and cement mortar) and Mashushu canal 2 (left bank earth canal) during base flow. During base flow, very little Mohlapitsi River water flows in the Fertilis irrigation canal. The second engineering structure is PVC pipes, which were installed within the right bank of T4 (Figure 2.4) of the Mohlapitsi River in order to convey the river water to a canal (adjacent to the main road). These structures were constructed by the Department of Agriculture in 2002.

Figure 2.2 Google Earth image of the study area illustrating the topography, surrounding hills, and boundary of the wetland (Adapted from Google Earth, 2009).

A significant proportion of the local people use the wetland for crop production due to its ability to store moisture during the dry season and inherently fertile soils which make it possible for farmers to produce crops throughout the year. The use of the wetland for crop production is a mechanism by which many households in the study area mitigate the risk of crop losses during drought periods (Jogo and Hassan, 2010). Sarron (2005) estimated that between 1996 and 2004 at least half the wetland area (about 60 ha) had been converted to cropland. By 2004, the wetland area converted to agriculture had grown to approximately 66 ha (Adekola, 2007).

Figure 2.3 Gabion dam structure at the head of the valley

The wetland occurs in the channeled valley bottom section of the Mohlapitsi River below the Wolkberg mountains. The valley is narrow and confined; with steep hill slopes on the edges of the valley bottom (Figure 2.5).The wetland is divided into four main portions depending on the soil type and saturation (Figure 2.6). Portion 1 is on the western side of the river channel; while portions 2 and 3 are on the eastern side of the channel and all of these areas except right bank part of T4 and western portion of T3 contain extensive organic (peat) soils maintained by permanent inundation and are surrounded by seasonally to temporally waterlogged areas with predominantly mineral soils. Portion 4 is less saturated than the areas upstream and has less organic soils. The saturation of portions 1 and 3 described here seems to be maintained by lateral subsurface inputs from the surrounding catchments.

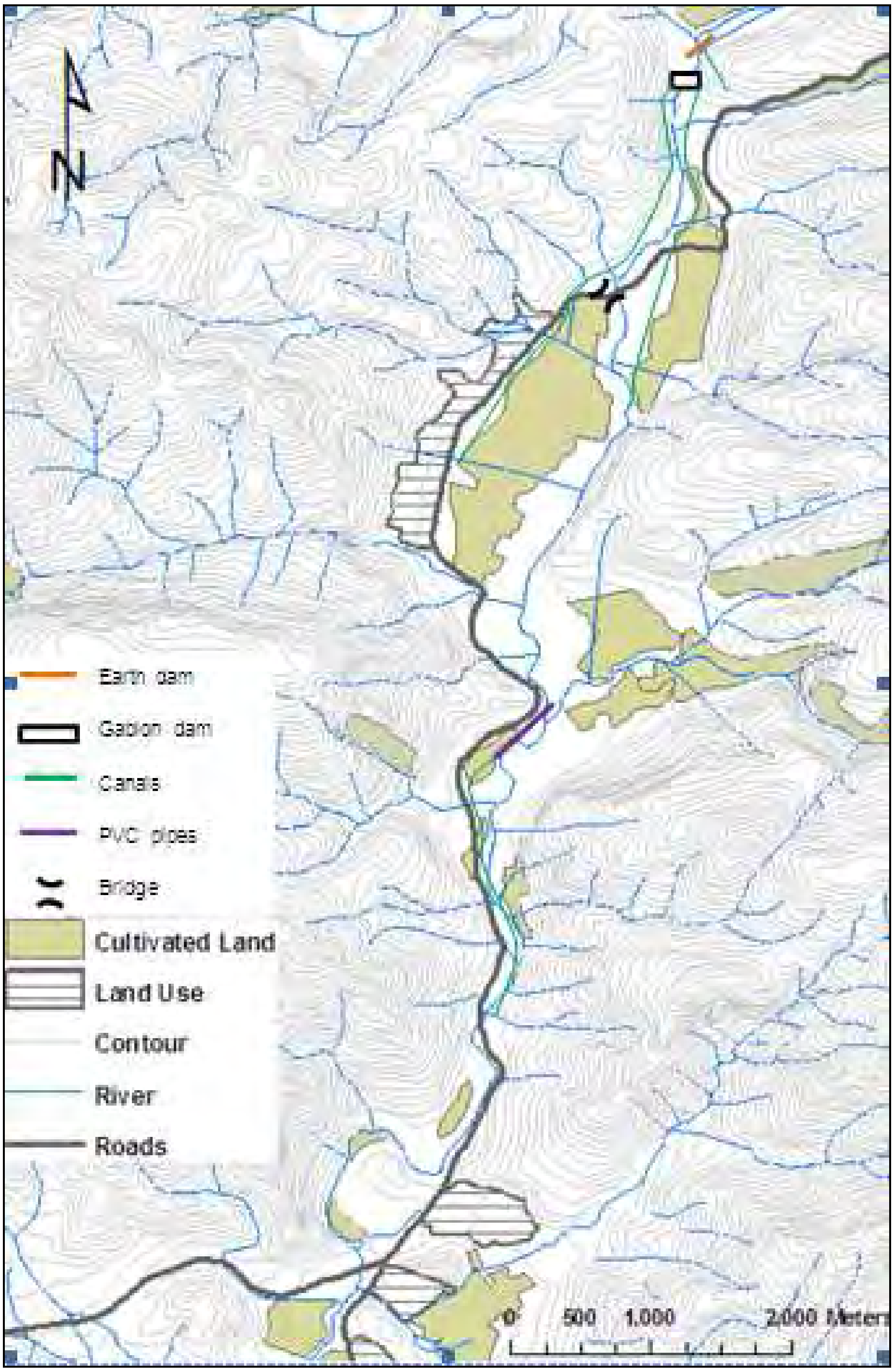


Figure 2.4 Map showing earth dam, gabion dam, canals, PVC pipes, bridge, contour, river, and roads at the study site

The hydrology of the wetland has also been adversely affected by artificial drainage of water by wetland farmers aimed at removing excess water (Figure 2.7) to create favourable growing conditions for maize, the main crop grown in the wetland (Adekola, 2007; Jogo and Hassan, 2010). Besides crop production, the wetland provides other services that support people's livelihoods, such as dry season livestock grazing and watering, domestic water supply, fishing and natural products (reeds, sedges and other edible plants). The hydrological and ecological functions of the study site are driven by wetland activities, and the magnitude of these impacts is not well understood (Kotze, 2005). Because the Mohlapitsi River contributes approximately 10-16% of the dry season flow in the Olifants River (McCartney, 2005), some external stakeholders have the perception that the wetland, regardless of its small size, provides an important regulating ecosystem service, in maintaining dry season flows downstream (Adekola, 2007). Previous work by different authors showed that trade-offs between wetland services occur locally and in the short term between crop production and other local uses of the wetland. At the catchment scale, Jogo et al. (2008) demonstrated that there is a potential trade-off between crop production and the Mohlapitsi River flow regulation and water supply downstream. Finally, in the long-term, continuous use of wetland for agriculture without mitigating management practices may result in irreversible loss of wetland functioning (depletion of organic matter, soil erosion, lowering of shallow water table and reduced contribution to base flow), thus impacting on the wetland ability to provide ecosystem services, including crop production (Adekola, 2007; Jogo et al., 2008).

Figure 2.5 Kudumela Wetland in the valley bottom

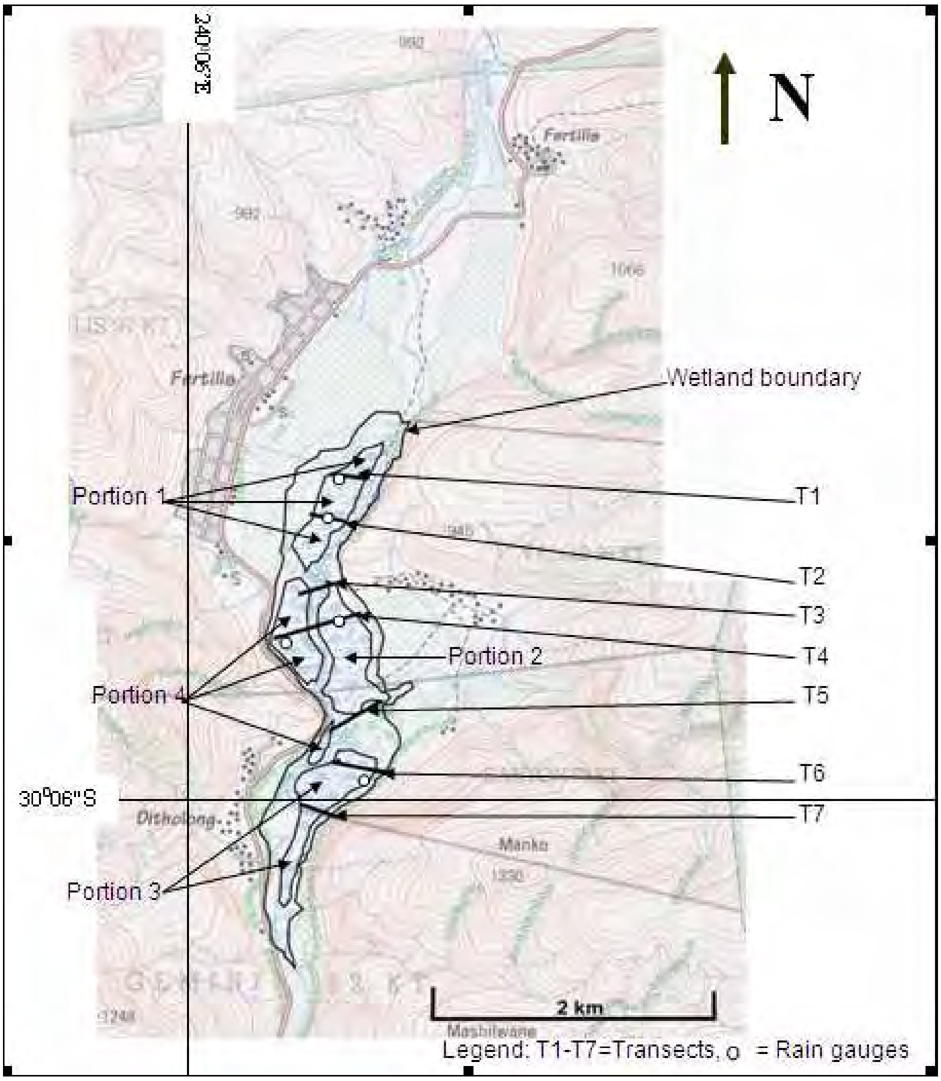


Figure 2.6 Map of the Kudumela Wetland, showing the general topography, the coordinates, the transects (T1-T7) the boundary and the location of the four valley floor portions of the wetland (Adapted from Kotze, 2005). The wetland is divided into sub-catchments in order to understand how water levels in each transect respond depending on soil type. These maps are extracted from base map, and it is not easy to show contour intervals.

Figure 2.7 Artificial drainage ditch at the study wetland

2.2 Climate of the study area

The Mohlapitsi River basin is within the summer rainfall region of South Africa and receives rain between October and April (Chiron, 2005). The mean annual rainfall in the uplands of the Mohlapitsi catchment exceeds 1000 mm, while the long-term average annual rainfall over the wetland (Nell and Dreyer, 2005) is reported to be 511mm, of which 440.8 mm, or 86%, falls from October to March. The wetland site is characterized by seasonal rainfall and experiences frequent drought and floods (for example, the devastating 2000 floods) (Adekola et al., 2007). Mean annual rainfall in the valley bottom, where the wetland is located, is typically 500-600 mm (Jogo et al., 2008). Figure 2.8 illustrates the seasonal distribution of rainfall based on Midgley et al., (1994). The mean annual potential evaporation for the B71C quaternary catchment is 8.33 mm/day. Rainfall information on Figure 2.8 is based on all available gauged data; Potential Evapotranspiration (PE) as regionalized data and stream flow as simulated natural flow using a rainfall-runoff model.

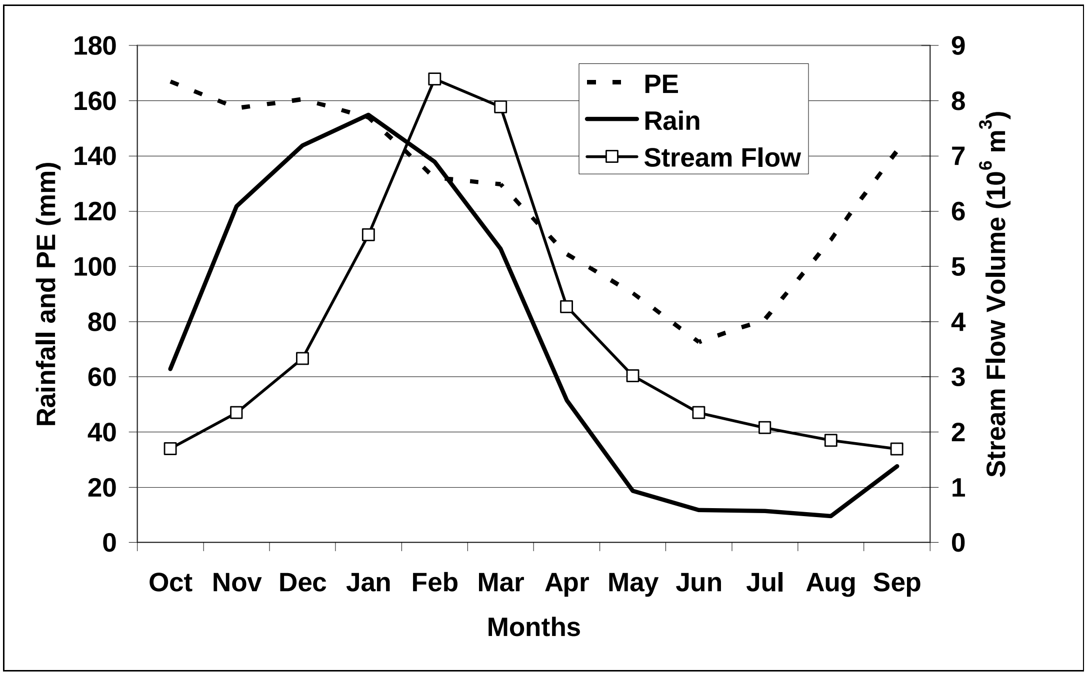


Figure 2.8 Seasonal distribution of rainfall, stream flow and potential evaporation for the period 1920 to 1990, based on data for quaternary catchment B71C taken from Midgley et al., (1994).

The entire Kudumela Wetland has a typical valley climate with warm to hot summers (October-April) and cool winter days with cold nights. Temperatures at the study site vary from an average monthly maximum and minimum of 30.2 ^{0}C and 18.0 ^{0}C for January to 22.0 ^{0}C and 5.2 ^{0}C for June respectively (Nell and Dreyer, 2005). The climate of this part of South Africa is highly variable and the study site has experienced alternating droughts and floods for many years (Nell and Dreyer, 2005). In 2000 a devastating flood a lot of community's property was destroyed, including the irrigation infrastructure.

2.3 Stream flow

The river is gauged just below the Kudumela wetland, at station B7H013 and stream flow records for the periods 1970 to 2008 are shown in Figure 2.9.The flow shows both seasonal and inter-annual variation, with mean annual flow is 37.96 Mm^3, equating to about 144 mm of runoff (McCartney, 2006). The coefficient of runoff for the catchment (i.e., the proportion of rainfall converted to runoff) is 0.18, which compares to an average of 0.06 for the whole of the Olifants catchment (McCartney et al., 2004).

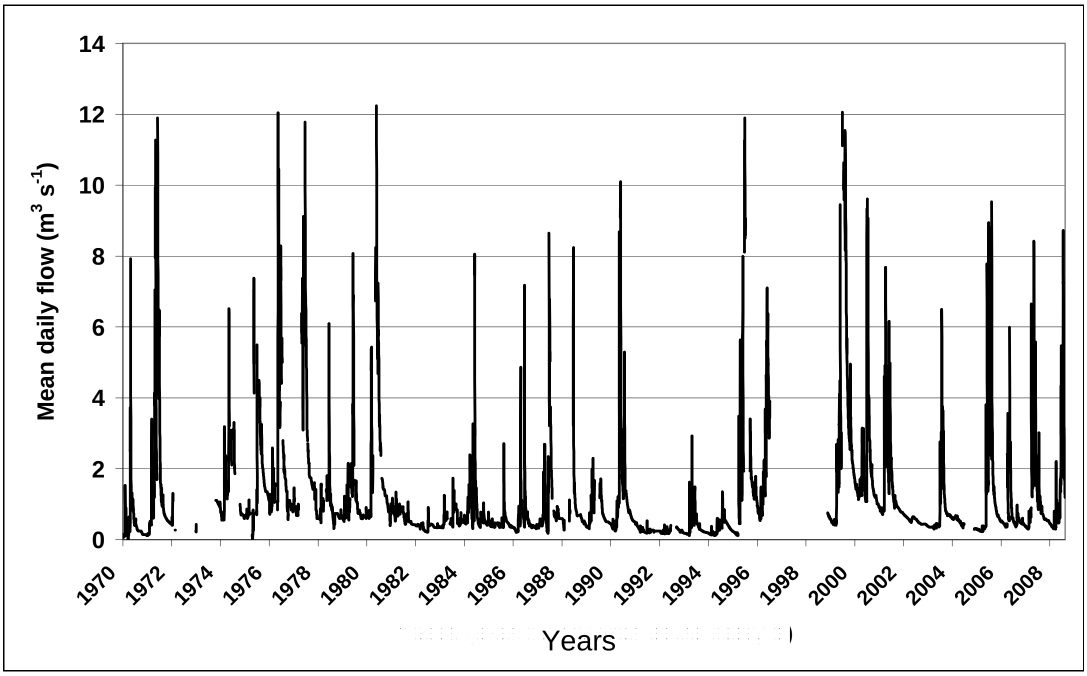
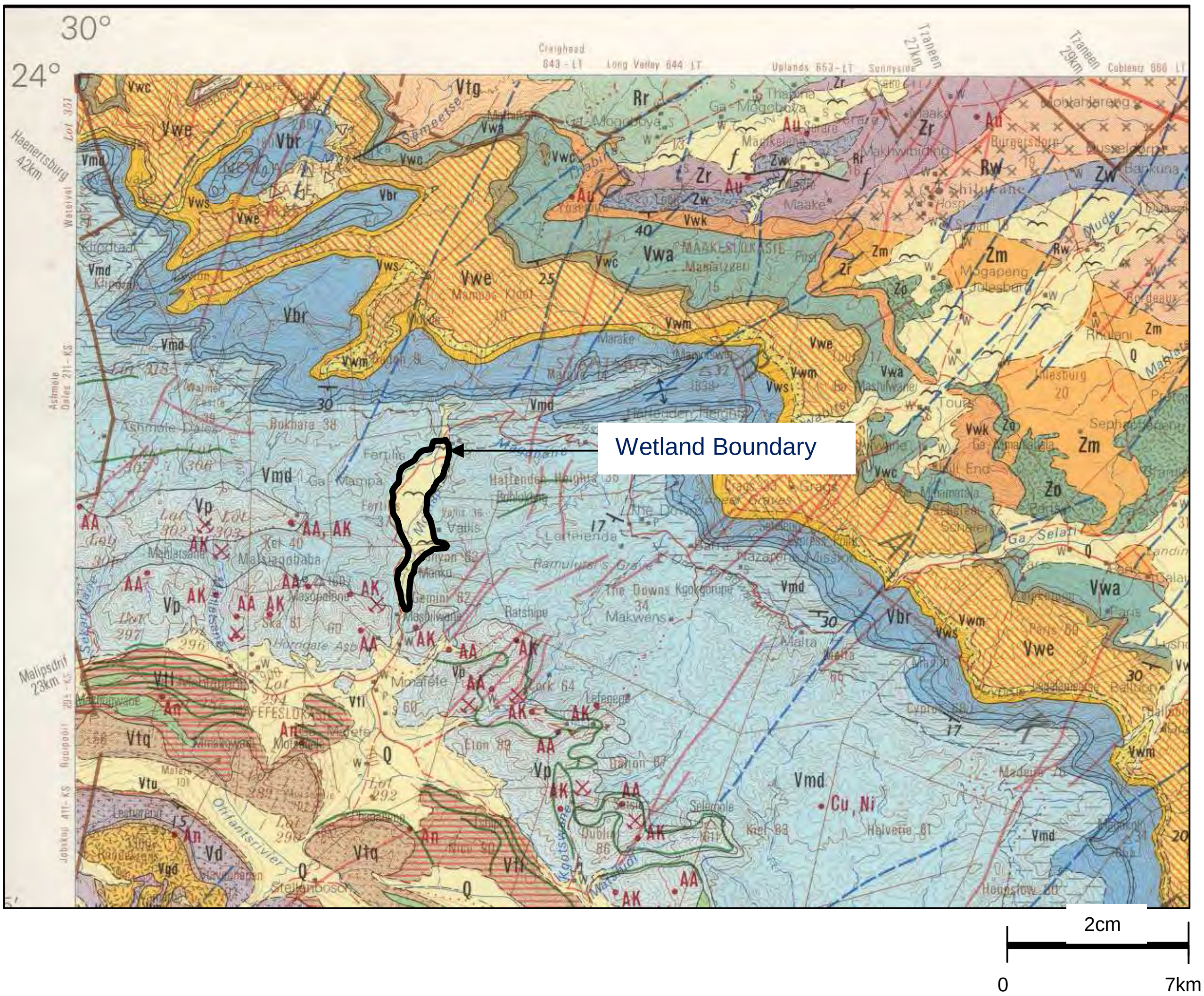


Figure 2.9 Time series of observed stream flow for gauge B7H013 for the period 1970 to 2008 (source: from DWA, 2008)

2.4 Geology

The geology of the region comprises sediments of the Transvaal Sequence and the study area is underlain by the Malmani Subgroup of the Chuniespoort Group (Nell and Dreyer, 2005) which are Early Proterozoic dolomitic rocks of between 2,100 million years and 2,000 million years old (Miyano and Beukes, 1996). The material in this subgroup consists of grey to grayish blue and pink, compact and poorly bedded dolomites and limestone with chert layers (Figure 2.10). The general site geology of the study area was assessed from previous investigations and during field visits. The hills flanking the valley consist of grey dolomite with limestone, chert layers and interbedded quartzite of the Malmani Subgroup (Miyano and Beukes, 1996). It is assumed that the wetland is underlain by the same material. To the north, within the river catchment, is encountered fine to medium grained quartzites, gritty in places with pebble layers (Black Reef

Formation), white grey, fine-grained quartzite with pebble fans and interlayered shale (Sadowa Formation), laminated micaceous and graphitic shale (Mabin Formation), and dark brown well-bedded micaceous shale with lenticular quartzite layers (Selati Formation) of the Wolkberg Group which are 2 600-2 500 million years old (Figure 2.10). The groundwater resources assessment (GRAII) database (Conrad, 2005) suggests that the mean annual recharge to groundwater for B71C is between 24.08mm y^{-1} and 86.50mm y^{-1} depending on the methods used to generate the estimates. Groundwater transmissivities are expected to be approximately 14.71m^2 d^{-1}, while storativities have been estimated as 0.004 and aquifer thickness as 25m.



Geological Legend

Vbr:	Fine-medium grained quartzites, gritty in places with pebble layers	Black Reef Formation	
Vmd:	Grey dolomide and limestone, chert layers, intrerbedded quartzite	Malamani Subgroup	Chenesproot Group
Vwm:	White grey, fine drained quartzite with pebble fans and interlayerd shales	Sadowa Formation	Wolkberg Group
Vwe:	Laminated micaceous and graphitic shale	Mabin Formation	
Vws:	Dark brown well bedded micaceous shale with lenticular quartzite layers	Selati Formation	
Vti:	Dark grey to black well bedded shale with conglomerate	Timeball Hill Formation	Pretoria Group
Vd:	Medium-grained quartzite with gritty and conglomeratic layers and occasional shale layers		

Figure 2.10 Geological Map of the study site (Source: 2430 Pilgrim's Rest)

2.5 Soils

The soils in the wetlands are a mix of fine-textured, poorly drained areas away from the river bank, and less extensively sandy soils located close to the channel (Kotze, 2005). During floods, the Mohlapitsi River carries fine and coarse sediments from the steep catchment slopes with high velocity until it reaches the wetland with gentler slopes. A sudden reduction in flow velocity in the valley has created a changing pattern of braided channels, where it spreads and deposits coarse sediments or bed load (gravel, cobbles and boulders) during very high flood stages (Figure 2.6). These deposits are located near the base of the alluvium. Suspended load (fine materials or sediments such as sands, clays and silts) are deposited at the surface as well as in the intersticies of the deeper coarser sediments (Kotze, 2005).

Soils of the study area are hydric-wetland soils, which have greyish, dark brown to reddish brown, sandy loam top soils and strongly sub-angular structured, sandy clay loam sub soils because of the long periods of saturation (Nell and Dreyer, 2005). Vegetation burning in the catchment is a common practice and this is likely to result in the depletion of soil organic matter (Balesdent and Mariotti, 1996). Chemical and physical properties of soil (soil bulk density, soil porosity, soil structure; moisture holding capacity; diversity and activity of soil organisms, both those that are beneficial and harmful to crop production; and nutrient availability) are influenced by the amount of organic matter in the soil (Balesdent and Mariotti, 1996). Moreover, Benzing-Purdie and Ripmeester (1983) demonstrated that burning vegetation caused a negative impact of soil organic matter and the environment through the oxidation of carbon into carbon dioxide, an anthropogenic greenhouse gas. Parker et al., (2010) and Stone (1971) observed that 21% decline in soil organic carbon resulted in the release of 1446 CO_2 kg ha^{-1} into the atmosphere.

The progressive depletion of soil organic matter poses probably the greatest threat to the integrity and environmental security of the wetland (Stone et al., 1993). Drainage and cultivation could result subsidence in wetland soil organic matter (Ewing and Vepraskas, 2006), which would likely to considerably reduce the volume of soil in the wetland, and alter the morphometry of the wetland and the pattern of flows through the wetland. This, in turn may potentially affect the hydrologic and geomorphic integrity of the wetland. However, it is not possible to predict the magnitude of this effect with any certainty (Stanturf, et al., 2002).

2.6 Hydrology of the wetland area

Stream flow reducing activities are largely absent from the wetland’s catchment, with no tree plantations or dams (except for a gabion dam at the head of the valley) being present (McCartney, 2006). Thus, flow in the channel can be inferred to be largely natural. Abstraction for irrigation is currently absent from the local catchments of the portions 1 and 3 of the wetland (Figure 2.6). However, abstraction from the catchment of portion 2 takes place through diversion of flow (as described in Section 2.1) to flood-irrigated lands in the local catchment of portion 3. This has resulted from a sandbag diversion placed in the natural channel and a diversion channel immediately above the gabion dam (Figure 2.3) that is successfully diverting low flows to flood-irrigated lands in the catchment of the lower wetland portion. This has contributed to the desiccation of a wetland tongue that enters the downstream end of portion 2 (Figure 2.6). However, the remaining part (approximately 90%) of portion 2 appears to have remained well supplied with sub-surface water inputs, with several springs visible feeding this wetland portion even at the end of the dry season.

Heavy grazing pressure (Figure 2.11) and the associated reduction in vegetation cover in the catchment of a wetland may have potentially increased surface runoff and reduced infiltration in the catchment. This, in turn, would lead to less sustained sub-surface inputs to a wetland. However, much of the local catchments are very rocky, with many loose surface rocks. This renders the area fairly resilient and these catchments have not been greatly altered. Settlements, roads and cultivated lands are present in the local catchment of portion 1, although occupying a relatively small proportion of this area (Figure 2.6).

The main catchment feeding the river channel remains predominantly natural, with much of it being a wilderness area. In summary, therefore, it is only about 10% of portion 2 of the wetland (which constitutes about 2% of the overall wetland) that appears to have been subject to marked reduction in hydrological inputs. All three wetland portions have been subject to artificial drainage (Figure 2.7). However, the extent and intensity varies greatly amongst the three wetland portions. The artificial drainage network extends through most of portion 1 and portion 2. Portion 3 is intermediate between portions 1 and 2 (Figure 2.6) in terms of the extent and effect of drains.

Figure 2.11 Animals grazing at T1 (dominated by reeds)

2.6.1 Sources of water feeding the wetland

The present study is aimed at understanding the sources of water that contribute to the wetland, as these are important in understanding the ecological function and hydrological management of the wetland. There are six possible potential sources of water to the wetland: direct precipitation, river water infiltration from upstream, springs, and runoff from the surrounding uplands (eastward and westward), direct flow from the river channel during high river stage, and movement of ground water into the wetlands in response to river-stage changes and aquifer recharge. The river water has been infiltrating to the wetland at the gabion dam (North) through boulder beds as shown on Figure 2.3.This water is trapped in the aquitard below the surface of the valley-the wetland. Then the water leaks vertically to the surface of the wetland and flows back to the river by means of surface drains at the right bank.

Losses of water occur through evapotranspiration, drainage to the river channel (natural and artificial) or deep drainage to the underlying aquifer if the water table drops below the base level of the wetland.

Changes in wetland moisture from direct precipitation depend on the amount of rainfall and the proportion which is intercepted by vegetation and subsequently evaporated. Runoff from the surrounding uplands can provide water to the wetland and thus could increase water table levels in the valley. Direct flow from the river channel during flood can affect the wetland by water logging. Two major and several small springs contribute to the left bank section of the wetland (Figure 4.9). The water from the stream originating in the major Loumauwe Spring is mainly used for irrigation purposes and very little water flows to the confluence of the Mohlapitsi River, and its natural route is not visible during dry period. A significant input to the river on its left bank, a stream derived from the Jordaan Spring some 2 km from the valley, occurs upstream of the wetland (Figure 4.9). It is assumed that this stream does not contribute directly to the wetland but represents a component of the main channel flow. Both natural and artificial drains on the left and right banks of Mohlapitsi River drain the valley bottom/wetland (Figure 4.8). The size of the wetland is decreasing towards south (right bank) due to man made drains (Figure 2.7). More than 7 springs were identified in the left bank of the wetland (T5 environment) in September 2005. The springs indicate the presence of regional groundwater contributing to inflows to the Kudumela Wetland (Kotze, 2005, McCartney, 2005).

2.7 Land use changes in the Kudumela/Mohlapitsi Wetland

The provisional summary of land use changes in the study site is given in Table 2.1. The updated (Department of Water Affairs, DWA, 2004) satellite images revealed the following changes in land use to have occurred between 1996 and 2004 (Figure 2.12);

- +43.2% enlargement of the residential areas/bare soil
- 44.1% reduction of the natural vegetation
- +37% increase in agricultural land and
- Progressive disappearance of the wetlands; hence are generally being converted into agricultural land (-52.2%).

Table 2.1 Land use evolution in the study valley (wetland) between 1996 and 2004 (Source: Troy et al., 2007)

Land use units	1996	1998	2001	2004	Trend
Wetlands (km^2)	0.90	0.82	0.66	0.43	-52.2%
Agriculture (km^2)	1.82	1.87	2.16	2.51	+37.9%
Residential/bare soil (km^2)	0.95	1.13	1.36	1.36	+43.2%
Woodland/uncultivated (km^2)	1.43	1.28	0.92	0.80	- 44.1%
Total (km^2)	5.10	5.10	5.10	5.10	

According to historical accounts, these trends are consistent with changes in local livelihoods over time. Some irrigation schemes destroyed by the 2000 catastrophic floods were abandoned, which explains the occurrence of bare soils or of uncultivated areas in abandoned agricultural areas, as well as the development of cultivation in wetlands. As could be expected, residential areas increased slightly and natural vegetation areas disappeared in favour of settlements and agriculture. The original wetland surface had been reduced by about 60%.

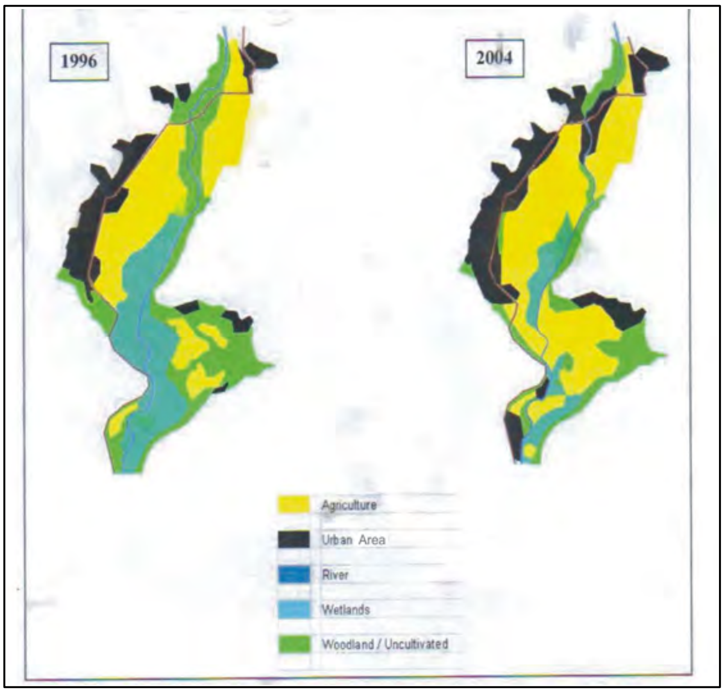


Figure 2.12 Evolution of the land use in the study valley from 1996 to 2004 (Schulz et al., 1997).

2.7.1 Assessment of the potential impacts of land use changes on hydrological change

Changes in hydrological regimes at the outlet of the study catchment may occur for a number of different reasons, for instance:

- Climate changes: As the transformation of precipitation into runoff is far from being linear, minor changes in rainfall patterns and/or in rainfall amount can cause a substantial change in runoff. In the same way, global warming or cooling of the air together with the changes in wind speed patterns could modify evapotranspiration and the water balance of the catchment at large.
- Water use changes: The hydrological regime at the outlet of the stream can be altered in quantity, pattern and quality if the pressure on water resources increases in a catchment.
- Land use changes: The hydrological processes (quick flow, delayed flow, infiltration, soil moisture, evaporation, etc.) are largely influenced by the nature and the density of land cover and the type of land use over a catchment (Troy et al., 2007).

There is no clear information whether climate characteristics in the region of the B71C catchment can be stationary during the considered periods. On the other hand there was no major increase recorded in water use in the study valley during the periods concerned. However, it was established that important land use changes occurred in the valley of the B71C catchment between 1996 and 2004 (Figure 2.12). In particular, the size of the wetland was divided into two namely, cultivated and residential areas. It is verified that the potential impacts of the land use changes are in the magnitude of the hydrological changes (Troy et al., 2007).

Recent findings in hydrology highlighted the importance of water table dynamics in the generation of quick flow (Troy et al., 2007). It is well known in the study region that the 2000 floods were an extreme event, particularly over the Olifants River basin, with estimated return periods of several hundred years for some catchments in the neighboring Kruger National Park. It is likely that there was a dramatic rise in the regional water table, which may have changed the hydrological regimes and increased the production of surface runoff (Masiyandima et al., 2006).

3. LITERATURE REVIEW

3.1 Introduction

The importance of wetlands has not always been appreciated; they have either been considered a nuisance and a source of disease associated with their role as breeding grounds for (mosquitoes and pathogenic organisms), or have been used as dumping grounds for human waste products (Dahl, 1990; Brinson, 1993). These negative views coupled with increased agricultural, commercial and residential development, road construction, resource extraction, impoundments, dredging and waste disposal practices in many parts of the world, have resulted in the rapid disappearance of wetlands from the landscape. Many of those that remain are badly degraded (Mitsch and Gosselink, 1993). Sutula and Stein (2003) showed the severity of the problem in southern California (United States), where about 75% of 53 000 acres of wetlands were destroyed between 1700 and 1870. A large proportion of the international literature on wetlands has focussed on developing systematic approaches to their study and on prioritizing the wise use of these ecosystems.

Converting natural wetlands to agricultural, and sometimes aquaculture, production during the last century was considered to be one of the main wetland management measures (Holland et al., 1995). Kusler (2003) proposed that to achieve such measures, managers used artificial drainage systems as an important tool, because any change in the wetland environment was accepted. The functions and values of these important ecosystems were not understood by indigenous people, academicians, or by natural resources managers (Hollis et al., 1993). Kusler (2006) proposed that once wetland values are understood and recognized, wetland hydrology and water quality can be improved.

Bullock (2003) and Kusler (2003) concluded that there is no single wetland assessment method that best meets the needs of all situations in all geographic areas. According to McCartney et al., (2004) classifying, quantifying, evaluating, measuring their functions and even establishing wetland boundaries are not easy tasks, since wetlands are highly dynamic ecosystems. This short review of the available literature was conducted to obtain an understanding of the hydrological functions of wetlands, specifically the water dynamics and groundwater-surface water interactions. The review also focuses on the methods that have been used to study the hydrological functioning of wetlands.

3.2 Structure of the literature review

The principal objective of this literature review is to illustrate the scientific understanding of wetland processes, the ecology of wetlands and their management. A secondary objective is to focus on wetland identification and investigation, the latter emphasizing the use of environmental isotopes, hydrochemistry and ecological indicators. The review starts with a brief summary of the general concepts relating to wetlands and provides explanations of some of the key terminology relating to wetlands (Sutula and Stein, 2003). While there is not much information available that is directly relevant to the wetland under study, there is extensive literature from South Africa and elsewhere that can contribute to understanding the dynamics of the Kudumela Wetland. While there are a substantial number of wetlands being degraded in South Africa (Grundling, 1999), the existing knowledge does not include descriptions of the measures taken by relevant management agencies to protect the wetlands. There is abundant information available about the use of environmental isotope and hydrochemistry (geochemistry) methods in South Africa and other parts of the world. However there are no reports of the use of these approaches in the Mohlapitsi River basin.

3.3 Key terms and concepts

To assist with the understanding of existing knowledge some of the terminology relating to wetlands is defined and explained below.

Wetlands: There exist different types of wetlands and a variety of ways to define and describe them. The various classification and identification criteria of wetlands are constantly changing (Kusler, 1987). For more than forty years scientists have had difficulty in classifying wetlands since they are not static ecosystems and the various definitions used by wetland scientists and authorities cannot be directly applied in every part of the world. For example, the Ramsar Wetland Convention (1971), the U.S. Department of Agriculture (USDA), the U.S. Army Corps of Engineers (USACE), the U.S. Geological Survey (USGS) and U.S. Fish and Wild Life authority all have different definitions (Cowardin et al., 1979; Craft, 2001). The differences between the definitions are not of cardinal importance, as long as all definitions include wetland hydrology, hydric soil and hydrophytic vegetation and it is considered advisable to concentrate on conceptual descriptions of wetlands (Kusler, 2003). Glenn et al. (1999) demonstrated that wetlands are zones that exist between terrestrial and aquatic systems. Wetlands can remain wet throughout the year or only part of the year (Ramsar Wetlands Convention, 1971) and there is no situation where all parts of a wetland are always wet. They can be fed by groundwater, surface water, precipitation or a combination of any of these sources of water (Jones and Mulholland. 2000).

Aerobic: A situation in which molecular/atmospheric oxygen is a part of the environment (Kusler, 1987). This is a condition where oxygen is available.

Anaerobic: A situation in which molecular oxygen is absent (or effectively so) from the environment (U.S. Army Corps of Engineers, 1987)

Ecology: is the science that deals with the study of the structure and function of nature in a certain locality. It is the study of interactions or relationships between organisms and the environment (Gopal et al., 1982); Kusler, 1987; Zedler, 1987; Hook, 1988; Carter, 1996).

Ecosystems: are dynamic interactions between plants, animals, and microorganisms and their environment working together as a functional unit (National Research Council. 1995; Carter, 1996). They are ecological units consisting of a biotic community (an assemblage of plant, animal, and other living organisms) and the important consideration in ecosystem functioning according to Mitsch and Gosselink, (1993) is mutual living or balance. Kusler (1987) stated that no individual in the community should take more food than it needs.

Isotopes: Clark and Fritz (1997) define isotopes as any of two or more forms of an element having the same or very closely related chemical properties and the same atomic number but different atomic weights (or mass numbers). For example, an atom with 6 protons is carbon and an atom with 8 protons is oxygen. In addition to protons, the atoms of every element (except protium or ^{1}H) contain neutrons (Gat, 1996; Cook and Herczeg, 2000). Isotopes occur when an element's atoms exist with different numbers of neutrons (Epstein and Mayeda, 1953). For example, carbon exists naturally with 6, 7 or 8 neutrons with atomic masses of 12, 13 and 14 respectively (Clark and Fritz, 1997; Baskaran et al., 2005).

Radioactive Isotopes: Epstein and Mayeda (1953); Coplen (1993) described that the stability of each atom's nucleus depends on the ratio of protons to neutrons. Many isotopes have a ratio of protons to neutrons that renders them unstable and, as a result, they are radioactive. Examples include Tritium (^{3}H) and Carbon-14 (^{14}C).

Stable Isotopes: In some atoms, the binding energy (the energy associated with strong force) is great enough to hold the nucleus together (Jacob and Sonntag, 1991). The nucleus of this kind of atom is said to be stable. Fontes and Edmunds (1989) illustrated that stable isotopes are different forms of the same chemical element that vary in atomic mass due to differing numbers of neutrons. For example, Coleman and Brian (1991) demonstrated that ^{16}O, ^{18}O, ^{2}H, ^{13}C and ^{12}C are stable isotopes extensively used in hydrology.

Isotope hydrology: Clark and Fritz (1997) noted that isotope hydrology is a branch of hydrological science that deals with the isotopic signatures of water. Allison (1988) argued that isotope hydrology is a key to understanding the physical, chemical, biological, and climate governing processes occurring in a watershed. It is an important tool for water resources managers that can determine water sources and movements in the catchment (Gat, 1996). Cook and Herczeg (2000) confirmed that isotopes can be used to effectively trace water sources.

Mineral Soil: Mineral matter usually containing less than 20 percent organic matter in a certain soil (Federal Register, 1994).

Muck: Highly decomposed organic material in which the original plant and animal parts cannot be recognized (Craft, 2001).

Organic Matter: Bot and Benities (2005) define organic matter as soil composed of anything that once lived. Similarly, Bauer and Black, **(**1994) defined soil organic matter as any material produced originally by living organisms (plant or animal) that is returned to the soil and goes through the decomposition process. It includes plant and animal remains in various stages of decomposition (Bessam and Mrabet, 2003), cells and tissues of soil organisms, and substances from plant roots and soil microbes (Bell et al. 1999). It provides a carbon and energy source for soil microbes stabilizes and holds soil particles together and therefore reduces the hazard of erosion.

Storage Coefficient of an aquifer is the volume of water released from an aquifer per unit surface area per unit change in head. It is an aquifer's ability to store water (Freeze and Cherry, 1979) and is a dimensionless value. The size of the storage coefficient is dependent on whether the aquifer is unconfined or confined. In a confined aquifer, water derived from storage is related the expansion of water as the aquifer is depressurized (pumped) and the compression of the aquifer (Bazuhair, 1986). The storage coefficient of most confined aquifers ranges from 0.00001 to 0.001. Conversely, in an unconfined aquifer, the predominant source of water is from gravity drainage and the expansion of water and compaction of the rock skeleton is negligible (Singh, 2003). Thus, the storage coefficient is approximate to the specific yield and ranges from 0.1 to about 0.3 for primary unconfined aquifers, but much lower for fractured rock aquifers.

Water Table: Water table can be defined in several ways. The upper surface of groundwater, or that level below which the sub-surface material (soil or rock) is saturated with water. Ellery et al. (2005) state that the water table fluctuates both seasonally and from year to year because it is affected by climatic variations and by the amount of precipitation used by vegetation. It is also affected by withdrawing excessive amounts of water from wells or by recharging them artificially.

Water marks: Kusler (1987) and Brown and Stark (1989) defined water marks as lines on a tree or other upright structure that represents the maximum static water level reached during an inundation event. It is one of the minor indicators in wetland hydrology (Bullock, 2003).

Wetland Identification: The procedure by which an area is evaluated for the presence or absence of wetlands (Cowardin, 1979).

3.4 Wetland indicators

Different wetland identification manuals have been proposed. However, the USACE (1987) have agreed that the presence of wetland hydrology, hydric soil and hydrophytic vegetation are important indicators. USACE (1987) also stated that one of the wetland indicators must be fulfilled in order to identify a land as a wetland.

3.4.1 Wetland vegetation

The hydrology of a wetland is largely responsible for the vegetation of the wetland (Mitsch and Gosselink, 1993). Wetland vegetation can be described as plants that exhibit adaptations to allow, under normal conditions, germination or propagation and to allow growth with at least their root systems in water or saturated soil (Chambers et al., 1992; Chambers et al., 1995). Powell (1990) and Chambers et al. (1995) agreed that wetland vegetation is the plant life that occurs in areas where the frequency and duration of inundation or saturation exerts a controlling influence on the plant species. The area should have plant communities that require standing water for part of the growing season (Laine and Vasander, 1996). Balla (1994) noted that complex dynamic wetland interactions like climate, soil type, and position in the landscape could determine the composition of the plant community. Whitley et al. (1999) illustrated that vegetation indicators of plants growing in wetlands include trees having shallow root systems and swollen trunks.

An indicator of aquatic life can either be visual observation of physical features associated with aquatic life or visual observation of aquatic life (Chambers et al., 1995). Mapaure and McCartney (2001) stated that each wetland community has a variety of plants which provide shelter and food for many of the animals living there. Hydrophytic plants have adapted to survive in wetlands despite the stress of an anaerobic and flooded environment. Unlike common land plants that are able to get oxygen directly into their roots, the hydrophytes have internal oxygen-transporting tubes, the ability to float on shallow water or buttressed trunks to take oxygen down to the roots of the plants. These plants are often the first and most important indicators of a wetland.

3.4.2 Hydric soils

An important characteristic of a wetland is its soil, and soil composition helps to determine the type of wetland and what plants and animals can survive in it. Among the physical characteristics of wetland soils, the resistance to soil erosion hazards is the most important, mainly in the tropical countries (Soil Conservation Service, 1994). Field indicators are usually designed to identify soils which meet the hydric soil definition without further data collection. Field indicators are soil characteristics which are documented to be strictly associated only with hydric soils, and are an efficient on-site means to confirm the presence of wetland soils (Soil

Survey Staff, 1999). The concept of hydric soils includes soils developed under sufficiently waterlogged conditions to support the growth and regeneration of hydrophytic vegetation (Tiner, 1999). The plants that live in wetlands are only those that can adapt to these wet soils. Also, soils that are sufficiently wet because of artificial measures, or soils in which the hydrology has been artificially modified, are hydric (Soil Survey Staff. 1999). The nutrients in the soil often depend upon the water supply. However, if the water source is primarily rain, the wetland soils do not receive as many minerals as those fed by groundwater. Hence, soil in floodplains is very rich and full of nutrients, including potassium, magnesium, calcium, and phosphorus (Environmental Laboratory. 1987).

The presence of hydric soil is one of the three important wetland identifying characteristics (Cowardin et al., 1979; Tiner, 1999; USACE, 1987; National Research Council, 1995). Organic matter content, permeability, texture, drainage and color are important soil properties that play a key role in the development and identification of wetland soils (Soil Survey Staff. 1999) and these properties, and associated morphological characteristics, are unique to each soil type and can be described when examining a soil profile for a particular soil type. Hydric soils can be either organic (peat or muck) or mineral soils (USACE, 1987; National Research Council, 1995). In some bogs (a wetland type that accumulates acidic peat, a deposit of dead plant material--usually mosses, but also lichens in Arctic climates) associated with forests, decaying plant matter fully decomposes and is combined with sediments to form muck. This type of soil is dark and glue-like. To classify as muck, a soil must contain not less than 20 percent organic (derived from living organisms) matter.

Organic soils formed in waterlogged situations, where decomposition is inhibited and plant debris slowly accumulates, are called Histosols (National Research Council, 1995). All histosols are hydric soils, which are freely drained (Folists) occurring on dry slopes where excess litter accumulates over bedrock. Mineral hydric soils are those soils periodically saturated for a sufficient duration to produce chemical and physical soil properties associated with a reducing or anaerobic environment (U.S. Environmental Protection Agency, 1994; Soil Survey Staff, 1999).

Organic soils (Histosols), histic epipedons, sulfidic material, an aquic or peraquic moisture regime, reducing soil conditions, and soil colors are indicators of hydric soil for non-sandy soils. Furthermore, hydric soil indicators for non-sandy soils are Gleyed soils (gray colors), soils with bright mottles and/or low matrix chroma. On the other hand, hydric soil indicators for sandy soils are high organic matter in the surface horizon, streaking of subsurface horizons by organic matter, and organic pans (USDA, Natural Resources Conservation Service, 1994).

3.4.3 Wetland hydrology

This sub-section provides a brief over-view of the hydrology of wetlands, while the dominant hydrological processes are discussed in more detail in sections 3.5 and 3.6. The hydrology of wetlands includes the inflow and outflow of water through a wetland and its interaction with other site factors. It is the hydrological processes that control the formation, persistence, size, and functions of wetlands (Carter, 1996; Glenn et al., 1999). Dahl (1990) and Tiner (1999) stated that wetland degradation has a negative impact on the global hydrological cycle. Dugan (1992) and Mitsch and Gosselink (1993) demonstrated that the major governing force that controls the functioning of a wetland is hydrology, while Chisholm et al. (1997) and De Groot et al. (2006) confirmed that changes in hydrology directly or indirectly affect the shape, size and structure of a wetland. USACE (1987); Price and Maloney (1994) stated that land is identified as having wetland hydrology when the surface of the top soil is waterlogged for several months or throughout the year in order to create anaerobic conditions. There are a number of wetland hydrology indicators, among which are standing or flowing water observed in the area during the growing season, soil water logging during the growing season, and the presence of water marks and debris on trees and other objects (Sutula and Stein, 2003).

Although a lot of research work has been conducted in South Africa on wetlands over the last 40 years (Adams et al., 2001) there is insufficient information on wetland hydrology. As far as wetland identification, wetland threats and status and management are concerned, authors such as Warner (2002) and McCartney (2006) have contributed a lot for the development of this important subject. For example, Grundling (1999) showed wetlands to be vital for attenuating floods, regulating river flow, recharging groundwater, as sources of biodiversity protection, tourism, environmental education, grazing, and subsistence agriculture and as a source of food and plant materials for rural communities. Grundling (1999) also classified wetlands based on their morphology and vegetation and, to a lesser extent, their hydrology. Other authors like McCartney et al. (2005) characterized a wetland by its water table being at or near the land surface for some part of the year, by soil conditions that differ from adjacent uplands, and by vegetation adapted to wet conditions. Parsons (2004) classified wetlands of South Africa as marine, estuarine, lacustrine, riverine, palustrine and endorheic wetlands. Parsons (2004) further showed that one or more indicators of wetland vegetation, hydric soil and wetland hydrology must be present for an area to be considered as a wetland.

3.5 Wetland processes

While wetland processes include hydrological processes, food webs, physical habitat, nutrient cycling, sedimentation trapping and stabilization, this literature review has been limited to hydrological processes. Precipitation, surface-water flow, groundwater flow, and evapotranspiration (ET) are the major components that make up the wetland processes and the hydrological cycle (Roulet, 1990; Freeze and Cherry, 1979). Although the relative importance of each component in maintaining a wetland varies both spatially and temporally, all these hydrological components interact to create the hydrology of an individual wetland (Carter et al., 1979). The water balance of a wetland can therefore be affected by one or more of the following hydrological processes:

- Direct precipitation on the wetland.
- Evapotranspiration losses from the wetland vegetation or surface water.
- Surface, or near-surface (saturated soil water flow or spring flow), runoff from the adjacent hillsides.
- Exchanges with the underlying groundwater body (regional aquifer). These can be upward (groundwater contributing to the wetland), or downward (wetland draining to the groundwater.
- Surface flooding from an adjacent river or lake.
- Surface drainage from the wetland to a river or lake.
- Sub-surface water exchanges with a river or lake through the wetland soils or sediments at the channel or lake margins (i.e. river banks).
- Tidal influences in coastal wetlands (Harvey and Odum, 1990).

De Groot et al. (2006) found that wetland conditions occur when topographic and hydrogeologic conditions are favorable and a sufficient, long-term, source of water exists. Ellery et al. (2005) and De Groot et al. (2006) agreed that the occurrence of wetland in land-surface depressions in drainage basins is governed by favorable topographic conditions. Ellery et al. (2005) added that these depressions may be found in upland areas, along hillsides where there may be a change in slope or geology, in floodplains of streams or rivers. National Research Council (1995) and Bullock (2003) argued that the development of wetland hydrology could be affected by the presence of impermeable bedrock near the land surface. Glenn et al. (1999 and 2006) stated that a persistent, long-term source of water is a prerequisite to the development and existence of wetlands. Moreover, Glenn et al. (1999) explained that the development of wetland conditions depends on a long-term balance between wetland inflow and outflow. Watson and Burnett (1995) showed that the amount of water lost through evapotranspiration may exceed the rate of all water inflow to a wetland. Kadlec et al. (1986), Brown and Stark (1989) and Ridell et al. (2008) confirmed that extreme declines in the water table could result from water loss through evapotranspiration. Kusler (1987), Carter (1996) demonstrated that precipitation and surface water/runoff from the surrounding catchments are the main source for a wetland that is formed in the valley. Individual wetlands will be dominated by different processes, for example some are dominated by groundwater inflow into topographic depressions, while in others groundwater levels are a result of downward drainage of surface water. Some wetlands are dominated by periodic inundation from a nearby river, while others may be dominated by local runoff or seepage from adjacent hillsides (Gilbert et al. (1999).

To develop a clear understanding of the dominant wetland processes for a specific site, it is therefore important to be able to quantify the various processes referred to above. Given that they are expected to be variable over time, this is never a simple task, particularly for short-term studies that do not have the luxury of extended data collection periods.

Wetlands lose water through evaporation from soil or surfaces of water bodies and by transpiration by plants. The combined loss of water by evaporation and transpiration is termed evapotranspiration (ET) (Kohler, 1952). Solar radiation, wind speed and turbulence, relative humidity, available soil moisture, and vegetation type and density affect the rate of ET. Evaporation can be measured fairly easily, but ET measurements, are much more difficult (Christiansen, 1983). Evapotranspiration is highly variable both seasonally and daily (Dolan et al., 1984). ET losses from wetlands vary with plant species, plant population, and plant status (whether the plants are actively growing or are dormant). Seasonal changes in ET also relate to the water-table position. For instance, more water evaporates from the soil or is transpired by plants when the water table is closer to the surface.

Obtaining representative observations of surface runoff from adjacent hillsides is very difficult without complex instrumentation. It may therefore be only possible to infer the relative contribution of surface runoff from field observations during rainfall events of different magnitudes and durations. It is also difficult to obtain measurements of saturated soil water flow from hillsides, while the flow rates of concentrated springs can be measured once their location has been established.

Establishing the dynamics of water exchanges between the wetland soils and underlying groundwater can be achieved using shallow piezometers and deeper boreholes. However, while these may indicate differences in water levels and hydraulic heads between the wetland soils and the regional groundwater body (Siegel, 1983), it will be always more difficult to quantify likely flow rates. Vertical drainage (or recharge) rates in wetlands can be much slower than those in adjacent uplands as the upland soils will be generally more permeable than the clays or peat that usually underlay wetlands (Johnston et al., 1990). It was long assumed that the discharge of groundwater through thick layers of well-decomposed peat was negligible because of its low permeability, but recent studies have shown that these layers can transmit ground water more rapidly than previously thought (Chason and Siegel, 1986).

Contributions from flooding of an adjacent river channel can be obtained from time series of either river discharge (preferable measured upstream of the wetland) coupled with a stage-discharge relationship for representative channel cross-sections, or through direct measurements of river water levels. These type of observations may indicate that flooding occurs and the relative degree of severity, but not provide accurate measurements of flooding volumes or the extent to which the floodwaters remain on the wetland or drain back to the river downstream (Copeland et al., 2000). To achieve the latter would require more detailed topographic surveys of the channel and wetland coupled with a two-or three-dimensional hydraulic model (Nolan et al., 1987 and McCarthy, 2005). This would be beyond the resources of most small scale studies. The patterns of flow or surface storage across wetlands during flooding events can be very complex and affected by the topography and vegetation of the wetland surface (McCarthy, 2005).

Exchanges of water between the bed and banks of a river and an adjacent wetland will always be very difficult to monitor, partly because of the large degree of variability in some systems. In many wetlands the exchanges may be reversed depending on the level of flow in the river and the level of saturated storage in the wetland sediments and soils. However, these exchanges (together with the degree of over-bank flooding during high flows) are very important with respect to understanding the impact of wetlands on downstream river flow regimes (Johnston et al., 1990). Contributions to stream flow from wetlands dominated by groundwater inputs tend to be more evenly distributed in time, because natural groundwater levels vary slowly over time (Harvey and Odum, 1990). Storage (and any outflows to river channels) in wetlands fed mainly by surface hydrological processes (hillslope runoff or direct precipitation, for example) will tend to be more variable, particularly in strongly seasonal climates (Gosselink and Turner, 1978; Gehrels and Mulamoottil, 1990). Storage will also be strongly affected by the seasonality of the evapotranspiration regime determined through seasonal climate fluctuations and water demands of the wetland plants.

The occurrence of wetlands in different geologic and physiographic settings helps to group or classify them in such a way as to identify similarities in hydrology. For example, Novitzki (1979, 1982) developed a hydrologic classification for Wisconsin wetlands based on topographic position and surface water-ground water interaction. Gosselink and Turner (1978) grouped freshwater wetlands according to hydrodynamic energy gradients and Brinson (1993) developed a hydrogeomorphic classification for use in evaluating wetland function.

The hydrology of a wetland is mainly responsible for the vegetation of the wetland, which affects the value of the wetland to animals and people. The duration and seasonality of flooding and/or soil saturation, ground-water level, soil type, and drainage characteristics exert a strong influence on the plant density, type, and distribution of plants and plant communities in wetlands. Golet and Lowry (1987) showed that surface flooding and duration of saturation within the root zone, while not the only factors influencing plant growth, accounted for as much as 50 percent of the variation in growth of some plants. Plant distribution is also closely related to wetland water chemistry; the water may be fresh or saline, acidic or basic, depending on the sources.

Peatland type (fen or bog) and plant communities are affected by the chemistry of water in the surface layers of the wetland and the source of water (precipitation, surface water, or groundwater) will largely control the water chemistry and determine the nutrients that are available for plant growth (Siegel, 1983; Siegel and Glaser, 1987). Water moving into wetlands has chemical and physical characteristics that reflect its source. For example, older ground water generally contains chemicals associated with the rocks through which it has moved; younger ground water has fewer minerals because it has had less time in contact with the rocks. Which processes can and will occur within the wetland are governed by the characteristics of the water entering and the characteristics of the wetland itself; its size, shape, soils, plants, and position in the basin (Roulet, 1990).

3.6 Surface water and groundwater interactions

Given the importance of the interactions between surface water and groundwater within wetland systems it has been considered important to include more detail on this aspect of wetland hydrology within the literature review. Winter (1998) and Fetter (1994) pointed out that one of the important aspects of the hydrology of wetlands is their interaction with groundwater. Such interactions play an important role in determining the water balance of a wetland. Winter (1998) and Fetter (1994) further indicated that surface-water dominated wetlands typically have both inflow and outflow streams. Seepage wetlands, on the other hand, are groundwater dominated (Britton and Crivelli, 1993). Bloom (1998) indicated that some wetlands are recharge areas, where excess surface water recharges the water table. However, Bloom (1998) added that other wetlands are maintained by groundwater discharges. For instance, fens are supported by groundwater discharge, whereas bogs could be groundwater recharge areas (Ellery et al., 2005).

Groundwater and surface water are often interconnected, should be regarded as a single resource and involve many physical, chemical, and biological processes that take place in a variety of physiographic and climatic settings (Nyquist et al., 2008). Groundwater contributes to rivers in many physiographic and climatic settings, even, at times, in situations where streams are primarily losing water to groundwater. Some rivers may receive groundwater inflow during some seasons. The quantity of stream flow that is derived from ground-water inflow varies according to physiographic and climatic conditions (Freyer et al., 2006).

USGS (2003), Harvey et al. (2000) and Brodie et al. (2005) conducted several studies on the interaction of surface water and groundwater extensively. However, interactions between surface water and groundwater are complex and unique to a specific location (Hornberger et al., 1998). Kalbus et al. (2006) argued that despite the fact that studies of the interaction of groundwater and surface water concentrated primarily on the interaction of groundwater with streams in alluvial systems, sound analytical solutions have not been developed. Todd (1980), Todd and David (1993), Harvey and Bencala (1993) and Gardner (1999) suggested that studies of the interaction of groundwater and surface water have expanded in scope to include studies of headwater streams, lakes and wetlands. There are many gaps in our knowledge and understanding of groundwater-surface water interactions, particularly site-specific knowledge, and the conceptual understanding of these processes needs continual improvement (Harvey and Wagner, 2000; Seward and Baron, 2001).

Groundwater and surface water interact in a variety of ways (depending on the prevailing physiographic and climatic landscapes) because they are not isolated or independent resources (Sophocleous, 2002; Harvey et al., 2002; Hayashi and Rosenberry, 2002). Hence, development or contamination of one affects the other (Hayashi and Rosenberry, 2002) and an understanding of the basic principles of interaction between groundwater and surface water is needed for effective management of water resources (Fetter, 1994; Winter, 1999; Vegter, 2001 and Parsons et al., 2001). Harvey and Wagner (2000) and Sophocleous (2002) suggested that subsurface lateral flow through unsaturated soil horizons can also contribute to stream flow, however, in most situations this will be negligible compared to flow from saturated zones. Except for some of the perennial rivers in the north-eastern parts of the country, most rivers of South Africa do not have large groundwater contributions (Lerner, 1996; Parsons, 2004). Parsons (2004), Woodford and Chevallier (2002) and Harvey et al. (2004) pointed out that processes that govern groundwater interaction with wetlands are the same as that of rivers and lakes.

Hornberger et al. (1998) and Bates et al. (2001) stated that analyzing and interpreting the chemistry of water can provide valuable insights into groundwater-surface water interactions. Kendal and Coplen (2001) and Mazor (2004) illustrated that dissolved constituents can be used as environmental tracers to track the movement of water. Environmental tracers can occur naturally or may be released into the general landscape by human activities (Winter et al, 1998). In most water resources studies, electrical conductivity or pH; major ions such as calcium, magnesium, sodium, chloride and bicarbonate; stable isotopes in the water molecule of oxygen-18 (^{18}O) and deuterium (^{2}H); radioactive isotopes such as tritium (^{3}H) and radon (^{222}Rn) are extensively used (Epstein and Mayeda, 1953; Fontes and Edmunds, 1989). Several studies have used a combination of these tracers (for example major ions, stable and radioactive isotopes) to assess groundwater-surface water interactions (Crandall et al., 1999; McCarthy et al., 1992; Herczeg et al., 2001; Cook et al, 2003; Baskaran et al., 2004).

The use of tracers has advantages and limitations (Crandall et al., 1999; Gonfiantini, 1986).

Some of the advantages are the development of a conceptual understanding of groundwater flow near a stream and in the provision of information on groundwater evolution, residence times or mixing ratios that would otherwise be difficult to determine (Homberger et al., 1998; Hannula et al., 2003). The range of hydrogeological processes that can be investigated under field conditions is probably the great strength of this method. In addition, Gonfiantini (1986) and Katz et al. (1997) demonstrated that measurements of an environmental tracer along the stream can be a powerful tool to map the spatial distribution of groundwater inflows. Mazor (2004) further illustrated that water chemistry monitoring is commonly undertaken to complement hydrographical data collection and analysis. For example, Deuterium, ^{18}O and ^{222}Rn are the most commonly used isotopes to investigate groundwater-surface water interactions (Katz, 2000). However, Hooper and Shoemaker (1986) and Coplen (1991) noted that the use of such techniques has some limitations including costs related to the logistics of sampling (Katz et al.,1995a) and laboratory analysis and a requirement for a high level of expertise for sampling and interpretation (Gonfiantini,1986). Moreover, tracers such as deuterium, ^{18}O or tritium can have long lead times between sample collection and the final analytical results (Katz, 2000). Models used to quantify seepage flux from hydrochemical data can require estimates of parameters that are difficult to measure in the field (Katz, 2000).

Field surveys using other water quality parameters may also be useful in characterizing groundwater discharge (Katz, 1997). Mazor (1991) showed that cations (such as calcium, magnesium, sodium and potassium) and anions (such as chloride, bicarbonate, sulphate and bromide) have been used as tracers to determine groundwater inputs to a stream during high and low flow periods. Mazor (2004) and Deocampo (2004) demonstrated that processes such as acid-base reactions, precipitation and dissolution of minerals, sorption and ion exchange, oxidation-reduction reactions, biodegradation and dissolution and exsolution of gases affect hydrochemistry. The key processes that could take place during the movement of water through aquifers and streams can only be interpreted by using hydrochemistry (Sprinkle, 1989).

De Groot et al. (2006) studied the ecology of the groundwater-surface water interface of large rivers in America, such as the Mississippi River for many years. Their studies indicated the importance of biological entities as indicators of the interaction of groundwater and surface water. Most studies of the interaction of groundwater and surface water, in which isotopes were considered, used the isotopes to determine the relative age of water or the proportion of water that had been exposed to evaporation. Coplen (1993) used tritium to determine the bulk of the contaminants, such as halogenated hydrocarbons, in water that seeped from the Rhine River in the Netherlands due to pumping of groundwater within the past two and half decades. McCarthy et al. (1992) used a time series of data on deuterium and oxygen-18 to determine the amount of Columbia River water that contributed to groundwater pumped from an alluvial aquifer near Portland, Oregon. Williams (1997) used isotope tracers to locate occurrences and trace movements in a variety of naturally and anthropogenically recharged waters in aquifers of Orange County, California. In his four distinctive groundwater tracer studies, Williams (1997) compared potential recharge waters of natural and anthropogenic origin, and aquifer waters from Orange County wells. Stable isotope techniques, hydrochemical investigations as well as tritium measurements showed promise for tracing several distinctive recharge waters.

Human interventions affect the distribution, quantity, and chemical quality of water resources and the range in anthropogenic activities that impact on the interaction of groundwater and surface water is broad (Love et al., 2007). Agriculture has been the cause of significant changes in the landscapes of the world, particularly sub-Saharan Africa. Infiltration and runoff are affected by tillage of agricultural lands, and this affects recharge to ground water, delivery of water and sediment to surface water bodies and evaporation (Johnson and Cosgrove, 2001). All of the above processes either directly or indirectly contribute to the interaction of groundwater and surface water. For example, tillage practices have been modified to maximize retention of water in soils and to mitigate erosion of soil from the land into surface-water bodies. Agricultural irrigation and application of chemicals are two activities that play a great role in modifying groundwater-surface water interactions (Johnson and Cosgrove, 2001).

The concentration of chemicals through evapotranspiration can lead to the accumulation of ions in the soil root zone. Within irrigated areas the result can be irrigation return flows to rivers that have substantially higher dissolved-solids concentrations than the original irrigation water (Alley et al., 2002). To minimize excessive buildup of salts in the soil, irrigation water in excess of the needs of the crops is required to dissolve and flush out the salts and transport them to the groundwater system. If the dissolved solids reach excessively high concentrations, the artificial recharge from irrigation return flow can result in degradation of the quality of groundwater and, ultimately, the surface water into which the groundwater discharges (Alley et al., 2002).

Both surface and groundwater resources can be affected by applications of pesticides and fertilizers (non-point sources) to cropland (Nelson-Horchler, 1985). For example, ammonium, being a major component of fertilizer and manure, is soluble, and increases concentrations of nitrates in surface and ground water bodies (Nelson-Horchler, 1985). In addition to the non-point sources of water contamination, point sources of contamination are common in agricultural areas where livestock are concentrated in small areas, such as feedlots. Further examples of point sources include direct discharges from sewage-treatment plants, industrial facilities, and storm water drains (Nelson-Horchler, 1985; Alley et al., 2002). Depending on relative flow magnitudes of the point source and of the river, discharge from a point source, such as a sewage-treatment plant, may represent a large percentage of the water in the stream directly downstream from the source. Contaminants in streams can easily affect groundwater quality, especially where streams normally seep to ground water (Wilson, 2006). Point sources of contamination to groundwater can include septic tanks, fluid storage tanks, landfills, and industrial lagoons. If a contaminant is soluble in water and reaches the water table, the contaminant will be transported by the slowly moving groundwater (Nelson-Horchler, 1985).

3.7 Ecological importance of wetlands

Wetlands are found throughout the African continent, and play a significant role in the livelihoods of rural communities in Southern Africa (Taylor et al., 1999 and Turpie et al., 1999). The ability of wetlands to store water during the wet season and release it during the dry season provides farmers living in semi-arid areas opportunities to grow crops all-year round, thereby improving their food security and incomes. Besides crop production, wetlands provide other services that support human welfare such as livestock grazing and watering, water supply, fishing and natural products (Matiza and Chabwela, 1992).

The largest wetlands include the Okavango Delta, the Sudd in the Upper Nile, the wetlands of Lake Victoria and Lake Chad and the floodplains and deltas of the Congo, Niger and Zambezi rivers. Many wetlands are able to store flood waters and slowly release the stored water, thereby reducing the amount of flood damage caused downstream. By storing the flood water, wetlands reduce the velocity of flood waters and enable some of the stored water to seep into the ground (recharging aquifers). For example, surface water - groundwater interactions in the Okavango Delta of Botswana plays a major role in restricting the formation of salt pans and the general functioning of the wetland ecosystem (McCarthy, 2005). When the seasonal flood advances, the water table in the Okavango Wetland is raised by the infiltrated groundwater (McCarthy, 2005). Glenn et al. (1999) confirmed that wetlands serve as a reservoir for runoff water during heavy rain periods by storing flood waters.

Dahl and Johnson (1991) showed that wetlands act like sponges, slowing the flow of surface water and reducing the impact of flooding. Wetlands also prevent soil erosion and buffer water bodies from potentially damaging land use activities such as agriculture (Millennium Ecosystem Assessment, 2005). Wetlands can remove and store greenhouse gases from the Earth’s atmosphere, slowing the onset of global warming (Kusler, 1999; International Institute for Sustainable Development, 1999). Furthermore, Kusler (1999) noted that they serve as breeding grounds for migrating birds and resident amphibians, permanent homes for fish species, social interaction amongst mammals who congregate there for water, and an escape from the heat of the sun for countless reptiles, amphibians and mammals. Wetlands are seen as the cornerstone of wildlife populations (Craft, 2001). Wetlands are able to filter out sediment, nutrients and toxic chemicals before they reach the water table (Glenn et al., 1999). Cowardin et al. (1979) and Denny (1993) agreed that development around wetlands is a major threat to how they function and their survival in general must be preserved. Sutula and Stein (2003) argued that even though a number of studies regarding the ecological importance of wetlands have been conducted, understanding their functions and values need more investigation.

Hailu (1998), Hailu and Abbot (1999) and Wood (2000) indicated that wetlands are very valuable areas for rural communities in the highlands of western Ethiopia. They directly contribute to food security through the production of green and mature maize and vegetables (Wood, 2000). In addition, they are a source of drinking water (from wetland edge springs) and traditional medicines for many of the rural people (Hailu and Abbot, 1999). The functioning of these sources of relatively safe water is dependent on the water table level which is maintained by the wetland (Brown et al., 1998).

3.8 Values of wetlands

Estimating the value of an individual wetland is not a simple task, as they differ widely and perform different functions. For example, the value of wetlands along the Charles River in USA is estimated as $17 million per annum, which includes contributions to the mitigation of flood damage (The Ramsar Convention on Wetlands, 2000). Some studies have attempted to quantify the economic value of wetland systems in southern Africa (for example, Turpie et al., 1999 and Seyam et al., 2001). However, most of these studies were conducted at the local level due to limited data on the actual extent of wetlands at national and regional levels. In addition, most of the valuation studies focused on quantifying a few key services as some wetland services are difficult to quantify given the available data and resource limitations. For example, Seyam et al., (2001) used a simple approach that takes into account the common problem of data limitations and estimated that the total use value of the Zambezi basin wetlands was US$123 million per year, which was equivalent to 4% of Zambia's GDP in 1990. Adekola (2007) estimated that the direct use value of the main provisioning of the Ga-Mampa Wetland in Limpopo Province of South Africa as US$90 000 per year.

3.9 Threats to wetlands

In spite of their considerable value, some 50% of wetlands in South Africa have already been destroyed due to unsustainable development (Bunting et al., 1998; Paersell and Mulamoottil, 1994; McCartney, 2006). Examples of mechanisms leading to their destruction include draining for crops or housing developments; pollution; building dams; existing and additional obstructions which interfere with natural estuarine and coastal lake dynamics, the clearing of natural vegetation for the extension of agriculture, overgrazing/increases in domestic live stock, particularly goats, increased extraction of underground water for irrigation and vegetation, burning and planting of water-thirsty alien trees too close to their edges (Grundling, 1999; McCartney, 2006). Dixon (2003) and McCarthy (2006) demonstrated that mosquito control is one reason that wetlands have historically been drained and it remains a cause of wetland loss today.

Globally, wetland areas are continually decreasing due to drainage, cultivation and urbanization, and it is therefore necessary to protect and sustainably utilize the remaining wetland areas (Masiyandima et al., 2004; McCartney 2006). Wetlands have been drained and converted to farmland, filled for housing developments and industrial facilities and used as waste dumping areas (Ramsar Wetlands Convention. 1971). Liang and Ding (2004) confirmed that human activities continue to adversely affect wetland ecosystems, while Williams (1995) noted that since the 1600s, more than half of the original wetlands in the 48 United States have been destroyed.

By 1970, 60% of the valuable waterfowl habitat on the coastal lowland of New South Wales and the Swan Coastal Plain of Western Australia had been destroyed. In Tasmania, the button grass mires have suffered the majority of human impacts on wetlands, adversely affected by grazing and burning over many years. In New Zealand it is estimated that about 90% of the original wetland area has been lost (Moser et al., 1996), with wetlands now covering only 2% (5 323 km^2) of the country's total land area (266 171 km^2) (Dugan, 1993). Loss has been due to drainage, gold mining, flood control, land clearance, agricultural development, kauri-gum digging and flax milling (Dugan, 1993). The wetlands of Papua New Guinea are poorly known (Gopal et al., 1995) and Moser et al., (1996) reports that little published quantitative information is available for wetland loss in the South Pacific island nations (New Caledonia, Fiji, Western Samoa, American Samoa, Guam, Northern Mariana Islands, etc) (Moser et al., 1996).

Rates of wetland loss are less well documented in Europe than in the United States, but the conversion of natural ecosystems such as wetlands is believed to be greater due to Europe's high population density and longer history of economic development (Dugan, 1993). The considerable wetland losses in Europe are demonstrated by the example of Finland, which originally had 10.4 million ha of mires (30% of its land area), but has lost 5.5 million ha, due to forest drainage. Loss rates for peat lands in excess of 50% have been reported for 11 European countries (Immirzi et al., 1992). In western and central Europe, the majority of the wetlands were destroyed for the sake of extensive industrialization and agriculture (Dugan, 1993). In Eastern Europe, political changes contributed enormous losses in wetland. For example, in Poland 95% of the original mire area of 1.5 million ha has been exploited. In general, European wetlands have been lost mainly due to drainage and conversion to agriculture and grazing land, and urban and industrial development.

According to the report made by Dahl and Johnson (1991), there were approximately 90.2 million ha of wetlands in the contiguous 48 states of the USA prior to European settlement. At least half that area has disappeared (United States Environmental Protection Agency, 2001), due to wetland drainage for crop production. Nearly 656 000 ha of wetlands on non-Federal lands were converted to other uses, according to the 1992 National Resources Inventory (NRI). Frayer et al. (1983) estimated that millions of hectares of drained wetlands are now poor-quality agricultural land in the eastern United States. Frayer et al. (1983) and United States Environmental Protection Agency (2001) also concluded that agricultural and forest lands are being converted to commercial and residential development. Mostly because of drainage (Jones, 1993a and 1993b), many wetland and aquatic wildlife species have declined in this area although wetlands and riparian areas support a higher diversity and abundance of wildlife species than other farmland habitats (Mitsch and Gosselink. 1993).

Not more than 60 percent of the original wetlands in the lower Atlantic Flyway still exist (Brown and Stark, 1989). The remaining wetlands are declining in quality due to nutrient loading, altered hydrology and urban encroachment (Dahl, 1990). Moreover, wetland wildlife species have experienced long-term declines and loss and degradation of the south aquatic system and loss of much of the native fauna contribute to the decline of global biotic diversity (Holland et al., 1995). Dahl (1990) and Dahl and Johnson (1991) stated that the loss and decreased quality of existing wetlands have resulted in declining wildlife populations. Significant loss and degradation of estuaries in the Gulf Coast have occurred because of saltwater intrusion from canal construction and development and other developmental pressures along the coastal regions (Watson and Burnet, 1995). Smith (2003) also demonstrated that drainage for crop production has severely reduced wetland area and most of the wetland acreage that remains is either forested or degraded. According to Shaw and Fredine (1956), nearly 60 percent of the rural land in this region is cropland and pasture. Erickson (1979) found that declines in many wetlands in the United States are mainly caused by wetland drainage and other alterations of associated uplands. In addition, population levels of certain species of waterfowl and other migratory birds are declining and the recreational and economic impacts of wetland loss are a major concern (Dahl and Johnson, 1991). Wooten and Jones (1955) and Dahl and Johnson (1991) stated that this area, although one of the most altered ecosystems in the USA is still one of the most ecologically rich regions in the world. Of nearly half of the original wetlands remaining, most are cropped when the weather permits (Wooten and Jones, 1955). The Wisconsin Department of Natural Resources (1990) added that agricultural practices often result in sedimentation and addition of pesticides and fertilizers, resulting in degraded wetland vegetation, water quality, and wetland habitats. Frayer et al. (1983) investigated that livestock grazing is the most prevalent agricultural use in this area. Furthermore, Frayer et al. (1983) suggested that losses of wetlands in arid areas are particularly detrimental to wildlife and Dahl (1990) noted that wetlands in California's Central Valley have been reduced from more than 1 640 000 hectares to about 123 000 hectares.

Wood (2000a) and Dixon (2000, 2003) demonstrated that wetlands in Ethiopia are at a critical point in their history, due to a new government policy that attempts to address the increasing food security problems. Wood (2000b) stated that the wetland policy has instructed Ethiopian farmers to intensify wetland agriculture and to start cultivating plots that are currently left to restore naturally. Wood (2000) and Hailu et al. (2000) agreed that farmers' indigenous hydrological management knowledge can be sustainable, while the government ultimately possesses the power to change the way that wetlands are managed.

3.10 Wetland management

There are a growing number of opinions expressed in the existing literature that suggest that managing for ecosystem processes may be the key to inland wetland management. This study argues that management strategies are developed at watershed or landscape scales, yet specific guidance about how to relate such strategies back to the site scale, where management decisions are ultimately implemented, tends to be limited (Environmental Protection Authority, 1992a; DWAF, 1999). Barbier et al., (1997) proposed that wetland management generally involves activities that can be conducted within, and around wetlands, both natural and man-made, to protect, restore, manipulate, or provide for their functions and values. Barbier et al., (1997) added that the management goal for natural wetlands is generally constrained by regulatory and other government programme requirements to the protection of existing functions or restoration of degraded functions. Hook (1988) confirmed that the management goal for undisturbed natural wetlands is typically to keep-up existing functions. Kusler (2003) and Baskaran et al. (2004) found that the two major aspects of managing wetlands for protection include stopping human misuse of wetlands and maintaining natural processes in surrounding lands. Payne (1992) demonstrated that the wetland type and landscape position, surrounding land uses, vegetation quality, presence or absence of rare or endangered species, surface water quality (Hughes and Munster, 2000), wildlife habitat, and cultural values are the major issues to account for when establishing a management strategy for a wetland. The goal of protecting a wetland's existing functions can be incredibly complex in the modern landscape, since it involves minimizing the human-induced changes affecting the natural forces that shape and sustain a wetland, such as hydrology, climate, biogeochemical fluxes, fire, and species movement (Wenzel, 1992)..

During this literature review it has been apparent that while the science has advanced in many areas, the improved knowledge has potentially added complexity to management (Dixon, 2001). The stability of wetlands has been undermined by development initiatives that ignore indigenous knowledge in wetland hydrology. Hailu et al. (2000) and Dixon (2001) reported that local or indigenous knowledge develops over time from experience and a detailed understanding of local environmental conditions, and could be modified in response to changing conditions. Furthermore, Dixon (2001) explained that farmers' indigenous knowledge must be recognized and must not be ignored for the sustainability of these important eco-systems. However, there are also some areas where knowledge from scientific monitoring is greater than local knowledge (Hailu et al., 2000). Both indigenous and scientific knowledge are important tools that can help in wetland management (Dixon, 2001 and Ellery et al., 2005).

There are certain problems and some socio-economic changes that are too great for farmers to effectively adapt to. Increasingly, unpredictable climatic conditions are one such issue, while government policy shifts are another (Wood, 2000). Farmers argue that external influences on their management practices have been very small and management techniques, such as drainage design, have been adapted by their communities through generations (Hailu, 1998). While no wetland farmers are experimenting greatly with new management techniques introduced by wetland scientists (Hailu et al., 2000; Wood, 2000), there were many examples of small-scale modifications to existing management practices and tools. Wetland management programmes can only be achieved if the necessary funding is available and where community participation is included (Hailu and Abbot 1998).

Road construction (New Mexico Department of Game and Fish, 2002) is one of the causes contributing to habitat change and disturbance (including traffic noise) and has impacted on wetland habitat populations in some parts of the world (Hink and Ohmart, 1984). The quantity and quality of wetland habitats can significantly be diminished in addition to a reduction in wetland area (New Mexico Department of Game and Fish Conservation Services Division, 2003). For unavoidable road alignments through wetlands, it is, however, possible to reduce the negative impacts during construction (Dixon and Convey, 2000). In addition, efforts should be made during construction to minimize loss of plant communities by making use of existing roads for all transportation, avoiding off-road driving and designing new road realignments to minimize the amount of construction in previously undisturbed areas. All topsoil removed for construction should be stockpiled and used as surface fill during the reclamation of the project area (Rheinhardt et al., 1997). At the completion of the construction works, disturbed areas should be re-vegetated using native species that can grow fast and cover the exposed soil in easily erodible areas and at the same time the wildlife should not be exposed (National Research Council, 2001). Erosion control measures must be implemented during any construction on wetlands to prevent introduction of sediment-laden runoff into surface waters and no material excavated for bridge approaches should be introduced into the stream (Gainey, 1998). Exposed soils, particularly on slopes, must be compacted and stabilized with vegetation as soon as possible to prevent, sheet, rill, and gulley erosion (New Mexico Department of Game and Fish, 2002). Among different landscape conditions that contribute to differences in the stream environment, erosion plays a great role (Bloom, 1998). Drainage control features (culverts, drop structures, energy dissipaters etc) should be designed and constructed to prevent soil erosion and impacts to surface water quality (Roise et al., 2005)

Protective management involves maintaining important natural processes that operate within wetlands by monitoring and controlling human activities in the wetland environment (Dixon, 2003). Despite appreciation among plant ecologists of its important role, fire was always viewed as an entirely negative phenomenon in the early days of wetland management by land management agencies (Conway 1938, Cox 1939; Hanson and Gorbach 1997). Wells (1942) and Garren (1943) identified fire as responsible for the development and maintenance of several wetland communities in the Southeast USA, while Griffith (1941) and Smith (1942) described the value of burning in Atlantic coast marshes (Lay and O'Neil, 1942; Cartwright, 1942; Garren (1943) described several "types" of burn in Gulf coast marshes, suggested their potential value in managing other types of marshes, and identified the need for further study of fire in marshes. Contrary opinions suggest that fire destroys the organic matter of soil, increases the weed population and reduces native plants (Tiedemann et al., 1979; Burrows, 1998; Horwitz et al., 1999). Many wetland types are adapted to periodic burns, but development avoids fire of any sort (Garren, 1943). Controlled burning is a management strategy that mimics the natural process in developed landscapes and promotes marsh plant diversity and eliminates undesirable vegetation (Klijn and Witte 1999).

The sustainable use of wetlands for agricultural production according to Dixon (2003) needs a special management emphasis and critical thinking. Masiyandima et al. (2006) confirmed that a balance has to be found between the environmental functioning of wetlands and their use for livelihood purposes. Sustainable wetland management regimes are found in various situations. Usually they involve minimal conversion of the wetland and limited degradation of the catchment (Edward, 1992). In general terms, sustainable management involves managing wetland functioning in order to get multiple benefits (Edwards, 1992; Masiyandima et al., 2004) and it is clear that an integrated wetlands and catchment approach is needed to ensure that these two elements are linked (Wood, 2000).

3.11 Methods of investigation

3.11.1 Wetlands water budget

Water budgets provide scientific information for evaluating availability and sustainability of a water supply (Healy et al., 2007). A water budget shows the rate of change in water stored in an area (watershed) and is balanced by the rate at which water flows into and out of the area (Changnon, 1993). It is a water management tool that helps to understand hydrologic processes and provides a foundation for effective water-resource and environmental planning and management (Lerner et al., 1990). The main components of the natural water balance of a wetland are given below and quantifying the importance of each component helps to understand the dynamics and functioning of individual wetlands:

- Inflows from river channels originating from the upstream catchment area.
- Inflows from adjacent hillsides, springs and tributaries flowing into the wetland.
- Inflows from groundwater lying below the wetland.
- Inputs from rain falling directly on the wetland.
- Outflows to downstream river channels.
- Drainage to groundwater (recharge from the wetland area).
- Evapotranspiration losses from the wetland area.
- Changes in storage (surface pools, soil moisture and groundwater below the wetland).

In the GaMampa Valley (Limpopo Province of South Africa), Masiyandima et al., (2006) reported that runoff from the local catchment and groundwater components of the water balance were effectively nil. Masiyandima et al., (2006) argued that the peat soils in the valley suggest that there is no direct runoff to the river, although it is possible that some runoff may occur when the soil is saturated. It is therefore not easy to develop a fixed water budget that can be applicable in a watershed (McCartney, 2006). Unmetered extraction, evaporation, ungauged tributary flows, overbank flooding losses, flood return flows, human activities, errors in instruments and weather variability are some of the uncertainties associated with water budgets (Winter, 1981). Moreover, Winter (1981) states that errors in measurement of individual rainstorms due to gauge placement and spacing can be up to 75 percent. It is therefore clear that while water budget methods can be extremely useful for developing an understanding of the dynamics of wetlands, they are not simple to quantify and errors made in quantifying one of the components can lead to false conclusions about the hydrological functioning of wetlands.

3.11.2 Isotopes and hydrochemistry

Reference has already been made to the use of isotope and geochemical tracers for understanding surface – groundwater interactions. This section of the literature review summarises the approaches to using isotopes and hydrochemistry in understanding wetland processes in more detail. Clark and Fritz (1997) as well as Coplen et al. (2000) defined isotopes as forms of a given chemical element that have different atomic masses. For a particular element, Clark and Fritz (1997); Coplen and Kendall (2000) indicated that the isotopes have the same numbers of protons, and therefore the same atomic number, while each isotope has a different number of neutrons and therefore a different atomic mass.

3.11.2.1 Stable Isotopes

Stable isotopes are those isotopes that do not undergo radioactive decay, so their nuclei are stable and the masses remain the same (Dansgaard, 1964; Gat, 1996; Williams, 1997 and Coplen, 1994). The common stable isotopes extensively used in hydrological studies are H, C, N, O, S, B, and Li (Hooper and Shoemaker, 1986). For example, oxygen has three stable isotopes, ^{16}O, ^{17}O, and ^{18}O and hydrogen has two stable isotopes, ^{1}H (protium) and ^{2}H (deuterium) and one radioactive isotope-^{3}H (tritium) (Gat and Kemndal, 1994; Clark and Fritz, 1997). The stable isotopes of ^{18}O (oxygen-18) and ^{2}H (deuterium) are frequently used to provide information on hydrological processes, including groundwater-surface water interactions (Winter, 1999 and Sophocleous, 2002; Harvey, 2005).

The isotope fractionations that accompany evaporation from the ocean and other surface water bodies and the reverse process of rain formation account for the most notable changes (Gat, 1996). One naturally occurring example of kinetic fractionation is the evaporation of seawater to form clouds (Gat and Gonfiantini, 1981). Most of the water molecules in the ocean contain an O^{16} atom, in which a very small proportion of those molecules contain an O^{18} atom. When seawater evaporates, it forms water vapour and, the water molecules consisting of O^{18} tend to stay in the ocean instead of evaporating into the atmosphere because they are slightly heavier. So the proportion of O^{16} in water vapour is higher than seawater. Over time, ocean water gets slightly enriched in the isotope O^{18}. The warmer the ocean water is, the stronger this difference becomes (Gat and Gonfiantini, 1981; Coplen, 1994; Rozanski et al., 2001).

The average relationship between hydrogen and oxygen isotope ratios in natural terrestrial waters, expressed as a worldwide average can be calculated by applying the Global Meteoric Water Line (GMWL) equation : $\delta D = 8\delta^{18}O+10$ (Craig, 1961b). Craig (1961b) also demonstrated that a meteoric water line can also be calculated for a given area, and used as a baseline within that area. Kinetic fractionation will cause the isotope ratios to vary between localities within that area.

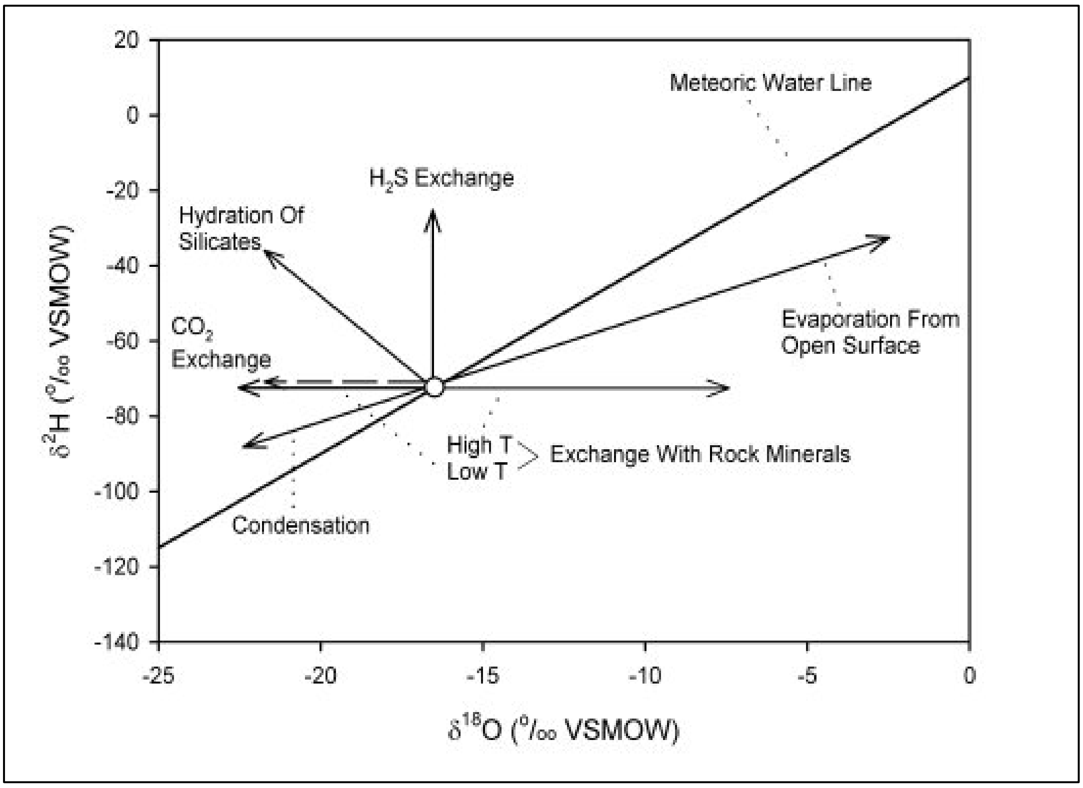


Figure 3.1 Processes that could alter the water's signature as a result of differences in the degree to which the various isotopes participate in chemical and physical processes (Evaporation from open surface, H_2S exchange, hydration of silicates, CO_2 exchange, high/low temperature exchange with rock minerals), or due to the rates of interaction (source: Harvey, 2005).

Gat et al. (2003) found that comparison of the stable isotope data for surface water and groundwater samples relative to the global or local meteoric water lines can provide information on processes. For example, isotopically light water molecules evaporate more efficiently than isotopically heavy water molecules (Rozanski et al., 2001; Gat and Gonfiantini, 1981). Due to this variability, Rozanski et al., (2001) indicated that in isotopic vapour pressures, evaporation produces residual water enriched in the heavier isotopes relative to the initial isotopic composition. Therefore water that has undergone evaporation lies to the right of the local meteoric water line due to this enrichment (Coplen, 1993). The trend line for evaporation from surface water tends to have a slope between 4 and 6 (Figure 3.1), with a slope less than 4 indicating evapotranspiration of soil water in the unsaturated zone (Allison, 1988; Harvey and Welker, 2000).

According to Butler, (1998), water samples collected for isotopic analysis should be stored in bottles with tight closures, such as caps with conical plastic inserts. Neal et al., (1990b) collected water samples in 1000ml polyethylene (HDPE) narrow-mouth round bottles for both isotopic and chemical analyses. Prior to sampling, brand new HDPE bottles were rinsed with stream water at least three times, were filled (with no air gaps above the liquid) to minimize post-sampling alteration in water isotopic composition and were stored immediately in a paper box (Rozanski et al., 1993).

Coplen (1993) and Cook and Herczeg (2000) reported that oxygen and hydrogen stable isotopic ratios are measured by isotope mass spectrometry. Hydrogen analysis is done on hydrogen gas obtained through high-temperature reduction of water on metal (Kendall and Coplen, 1985). Oxygen analyses are done on carbon dioxide that has equilibrated with water at a constant temperature (Epstein and Mayeda, 1953). Oxygen and hydrogen isotope compositions are commonly reported relative to an agreed sample of ocean water, referred to as the Standard Mean Ocean Water (SMOW), representing the largest and most homogenous (salty) water body. Stable isotope ratios of deuterium/hydrogen ($^{2}H/^{1}H$) and $^{18}O/^{16}O$ of water are conventionally expressed as units of parts per thousand (per mil, ‰) deviation from SMOW (Gat et al., 2003; see Figure 3.2).

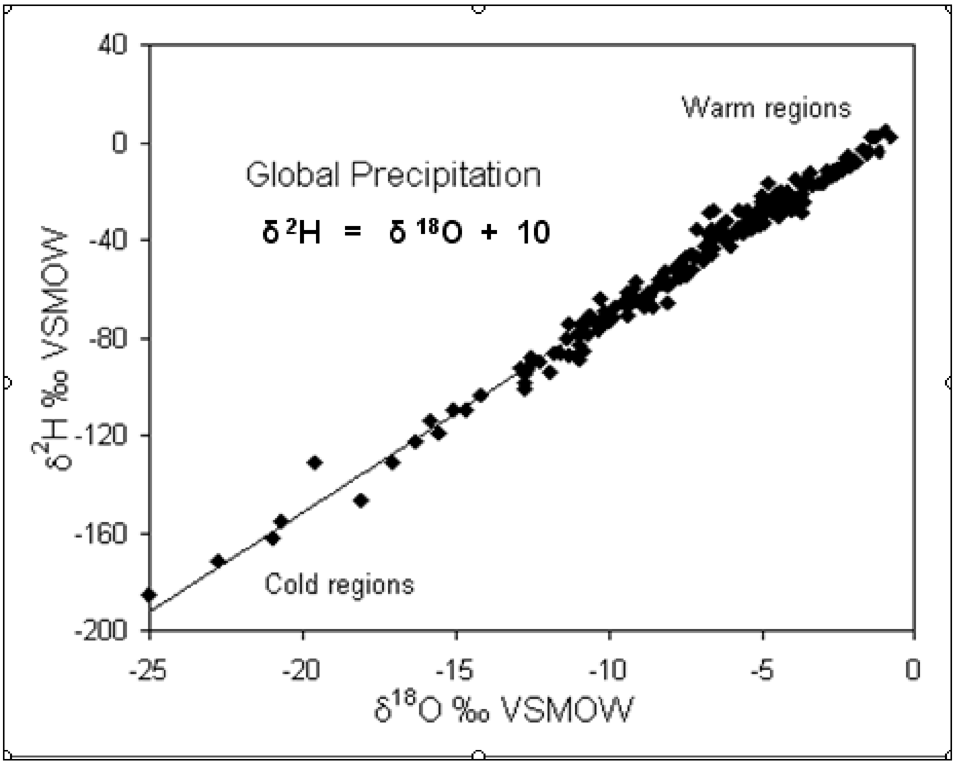


Figure 3.2 The meteoric relationship for ^{18}O and ^{2}H in precipitation (Source: Craig, 1961b).

3.11.2.2 Radioactive isotopes

Gat (1996) defined radioactive isotopes as nuclides that have unstable nuclei that decay, emitting alpha, beta, and sometimes gamma rays. Such isotopes eventually reach stability in the form of non radioactive isotopes of other chemical elements, termed radiogenic daughters. Decay of a radionuclide to a stable radiogenic daughter is a function of time measured in units of half-lives (Coplen, 2000). According to GNIP (2005), radioactive isotopes are useful indicators of the time that water has spent in the groundwater system. For example, tritium (^{3}H) is a well-known radioactive isotope of hydrogen that had peak concentrations in precipitation in the mid-1960s as a result of nuclear testing conducted at that time (Clark and Fritz, 1997).

Cook and Herczeg (2000) reported that ^{222}Rn is a radioactive daughter isotope of ^{226}Ra that has a half-life of only 3.8 days. It is produced naturally in groundwater as a product of the radioactive decay of ^{226}Ra in uranium-bearing rocks and sediments and the concentration of ^{222}Rn is generally much higher in groundwater than it is in surface water. Radon concentrations in groundwater depends on the presence of the radioactive isotopes in the aquifer matrix, and can vary from <2 Bq/L within clastic sediments to >200 Bq/L in igneous and metamorphic rocks (Lee & Hollyday, 1993). Several studies by Ellins et al, (1990), Crandall et al, (1999), Pritchard et al, (2000) and Cook et al, (2003) have demonstrated that radon can be used to identify locations of significant groundwater input to a stream. Radon was also used in a study in France to determine stream water loss to groundwater as a result of groundwater withdrawals (Bertin and Bourg, 1994). Radon is a gas, and natural radon concentrations in the atmosphere are so low that natural waters in contact with the atmosphere will continually lose radon by volatilization (Bertin and Bourg, 1994). Any significant concentration of radon in a stream or river is a sensitive indicator of local inputs of groundwater. Kraemer and Genereux (1998) provide a detailed discussion of ^{222}Rn mixing models and the use of ^{222}Rn to determine areas of groundwater discharge to streams. Kraemer and Genereux (1998) used ^{222}Rn to determine the discrete points of groundwater inflow to a river in Japan and it was also used by Ellins et al. (1990) to quantify groundwater inputs to a stream in Puerto Rico. In the reach of interest, the study revealed that the stream gained 1.2 m s^{-1} but that it also lost 0.5 m s^{-1} to groundwater. In a similar study in Tennessee, Lee and Hollyday (1993) and Gibson et al. (2005) used ^{222}Rn to determine that 36 % of the low flows of Carters Creek was contributed by groundwater.

3.11.2.3 Hydrochemistry

Hydrochemistry plays a key role in the biological, chemical and physical processes in small catchment water movement (Jeffries et al., 1988 and Hooper et al., 1990). It is associated with terrestrial processes, including plant decomposition, soil cation exchange, chemical weathering, biological uptake and mineralization (Hooper et al., 1990). In hilly areas of the Karoo, Adams et al. (2001) determined that $Ca\ (HCO_3)_2$ type waters are prevalent, while the dominating water types in topographical flat areas are NaCl. Saline soils are formed in areas where water is close to or at the surface and salts are leached to the subsurface during significant recharge periods (Adams et al., 2001). Neal et al., (1990b) confirmed that these important findings are good tools for identifying suitable locations of future groundwater developments. Sprinkle (1989); Gat (1996) and Katz (1997) demonstrated that major ions data may be presented in graphical format, of which the most useful plots are the trilinear diagram that show the total major anion or cation composition on separate or combination (Piper) diagrams (Figure 3. 2).

Gonfiantini, 1986; Coplen, 1991 and Mazor (1997) indicated that major anions (chloride, bromide and sulphate) can be determined by ion chromatography and major cations (calcium, magnesium, sodium and potassium) by atomic absorption spectrophotometry (AAS) or by inductively coupled plasma - atomic emission spectrometry (ICP-AES). These are routinely undertaken in most analytical laboratories and the accuracy must be demonstrated both by the use of appropriate standards and also by use of the ionic balance to check electrical neutrality (Coplen, 2000).

3.12 Ecological indicators

Mapaure and McCartney (2001) concluded that the most common ecological indicators are aquatic plants, phreatophytes and hyporheic biota. According to these authors, specific vegetation communities or biota can indicate groundwater discharge to surface water features. Changes in the composition and accumulated biomass of submerged aquatic plants can relate to groundwater seepage. Kotze (2005) also indicated that the near-stream presence of phreatophytic plants, which are deep-rooted and that access groundwater, can indicate a shallow water table. The extent and composition of biota that habitat the hyphoreic zone, can also describe the processes of near-stream groundwater and surface water mixing. According to Mapaure and McCartney (2001), certain plants and animals can be used to identify the nature and extent of groundwater-surface water interaction.

3.13 Summary and conclusion

This chapter has reviewed the available scientific literature about the importance of understanding the functions and value of wetlands and its hydrological processes, including threats, groundwater interactions, and management. The existing knowledge focuses on wetland and groundwater interaction and wetland managements aspects, because this information is needed by water resources and wetland managers. The different conclusions reached by various authors about both the functioning and the management of wetlands indicate that there is still more to know about wetlands. There seems to be general agreement that for an area to be defined as a natural wetland three main components must be included:

- Wetlands must have water present throughout the year or part of the year, either at the surface or within the plants root zone.
- Wetlands must have unique soil conditions that differ from the adjacent upland.
- Wetlands must support water tolerant plants (hydrophytes).

Even though these individual component definitions (or requirements) are relatively straightforward, combining them to make one general definition is not that easy because the detail of the individual components vary from wetland to wetland. Perhaps more importantly, the three variables are not independent of each other. Each wetland's hydrology, soil, and plants vary from season to season and from year to year, making it hard to define strict boundaries of any wetland. Each wetland also has its own unique hydrology, soil and plants according to its location. In addition, defining a wetland is subject to individual or professional interpretations. Thus a geologist, hydrologist, biologist or ecologist will each define a wetland according to their professional experience and understanding.

For centuries, wetlands were disturbed and diminished in the whole world, mostly in the United States, Western Europe and Africa. These threats were caused by humans, because they assumed that wetlands were lands to avoid in their natural state. Human activities like agriculture, road building, residential and industrial building, construction, etc. are the major reasons for the reduction of wetland areas in the world. Part of the process of establishing agricultural developments includes the construction of ditches or drainage channels to remove excess water, completely altering the hydrological water balance of a wetland. After destroying at least half of world wetlands, the positive uniqueness of wetlands has caused scientists to understand their values in the ecosystem. Since people have gained a better understanding of wetlands and how they benefit the environment, today's view is quite different and wetland rehabilitation has occurred in many countries. The lack of natural wetlands and recognition of the beneficial role that they can play have led to the construction of man-made wetlands, particularly in urban environments. As with the definition of a wetland, managing both natural and constructed wetlands is not a simple task. There is no uniformly applicable approach that can apply to all wetlands, because they are all different and located in different ecological, hydrological and climatological zones. Even though wetlands are hard to define because of the variations among the hydrology, hydric soil, and hydrophytic plants, most people have recognized that wetland protection and management is important.

In situations where ecological protection as well as community use is dual management objectives, the principles of adaptive management appear to be appropriate. Typically, this involves understanding the dynamics of a wetland, evaluating the results of management actions and adapting such actions to achieve a defined set of objectives. This can only be achieved by involving the local community who will be affected by the management decisions that are taken and must include a monitoring programme to assess the socio-economic, hydrological and ecological impacts.

4. METHODOLOGY

4.1 Introduction and programme of site visits

The investigation was undertaken on the Mohlapitsi catchment (quaternary catchment B71C) in an attempt to develop an understanding of the hydrological processes in the Kudumela Wetland. Three preliminary visits were made in order to identify the research problems and determine which strategies to apply. The first visit took place between 1-3 November 2005 the purpose being to become familiar with the study site, the community, estimate the resources needed for the study and to gain a basic understanding of the hydrology of the wetland (Table 4.1). This visit included an investigation of the natural route of the river and why, for example, the water disappeared from about 200m upstream bridge (Figure 4.7) for approximately 1.5 km towards the wetland. The locations of drains, the river course, springs and boreholes were determined by a Global Positioning System (GPS). During the second visit from 7-10 November 2005, the wetland boundary and water sampling sites were identified (Table 4.1, Figures 4.3, 4.7, 4.8, 4.9 and 4.10). During the third visit from 15 November 2005 – 10 January 2006, seven transects (Figure 2.5) were established, piezometers were installed in the wetland and preliminary data were recorded (Figure 4.3). In addition the sites for new hydrometric instruments such as the piezometer tubes (PVC pipes), rain gauges and water level indicators were identified and the instruments installed. The exact location of the stream flow gauging station at B7H013 (Department of Water Affairs code) was established by GPS during the third visit. River flow velocities (Figure 4.6) were determined using a stopwatch and floating material. Field observations of the general geology, soils, topography, vegetation and an assessment of existing borehole (Figure 4.7) characteristics were carried out. To obtain weather information, the nearby South African Weather Service stations were identified using the agricultural extension agent of the community. The third visit was also used to train the technical assistants who would be responsible for the field data collection.

Table 4.1 Schedule for the completion of research project at Kudumela Wetland

Item	Description of works	Nov.05	Dec.05	Jan.06	May.06	Dec.06	Apr.07
1	Site visit: to familiarize with the study site community, locate drains, springs, and boreholes by means of GPS						
2	The wetland boundary and water sampling points are to be identified by GPS	▬					
3	Seven transects to be established, preliminary data collected, piezometer and rain gauge sites to be identified, installed and the stream flow gauge site and other hydrometric instruments will be located & installed	▬	▬	▬			
4	The first set of samples for the environmental & water analysis will be collected				▬		
5	The second set of samples for the environmental & water analysis will be collected					▬	
6	The third set of samples for the environmental & water analysis will be collected						▬
7	Rainfall data from South African Weather Service (SAWS) will be collected	▬	▬				

Table 4.1 Continued

Item	Description of works	May.07	Setp.09	Nov.09	Dec.09	Jan.10	Feb.10	Mar.10
8	Collecting all data and prepare spreadsheets and the necessary diagrams				■	■		
9	Contents and thesis preparation	■	■					
10	Submission of thesis chapters to the supervisor			■	■	■		
11	Thesis Compilation						■	■
12	Final thesis submission							■

Notes: No horizontal and vertical scales are used for the preparation of the research project.schedule

4.2 Piezometer installation

As the current knowledge of the groundwater situation of the area is limited, piezometers were installed to gain a better understanding of subsurface-surface water interactions (Table 4.1). Kotze (2005) planned to place three transects in the wetland and eight piezometers were to be installed in the transects. However, to gain a more detailed understanding of water movement, the number of transects and hence, the number of piezometer was increased (Figure 2.6). Piezometers were made from PVC with an internal diameter of 65mm, and no bottom and top caps were provided (Figure 4.1). In November 2005, piezometer holes were made using a Dutch Auger (Figures 4.2 and 4.4) and all tubes were installed at different time. It was planned to install all piezometers at a spacing of 50m within a transect. The lateral distance between transects differs due to the wetland orientation (left bank and right bank position). The surface elevation of each piezometer was obtained from profile surveying using a dumpy level. Two benchmarks namely, one at T1 and the second and the last one at T7 were established on permanent structures. After the first surveying, the candidate carried out two more surveying on the same piezometers by starting the first round from benchmark (BM2) at T7 and the last check-up from first bench mark (BM1) in order to see any errors.

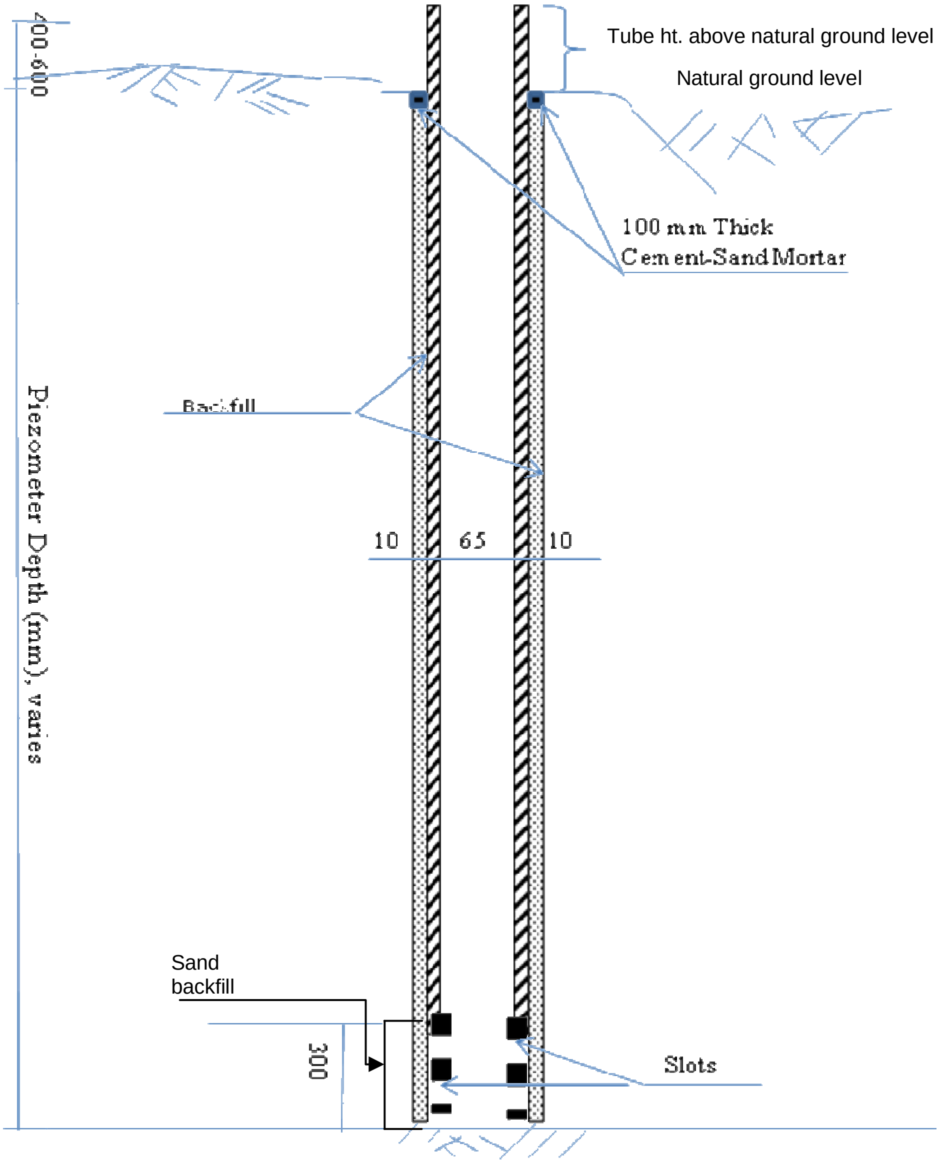


Figure 4.1 Cross-section of a PVC piezometer at the Kudumela Wetland (units in mm)

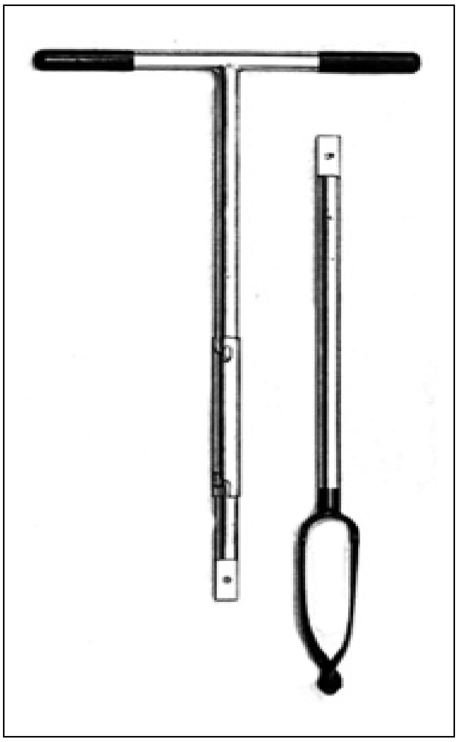


Figure 4.2 Edelman Dutch Auger with extension

Initially it was planned to install a total of 47 PVC piezometers in the seven transects. However, the depth of each hole and the spacing were constrained by the occurrence of boulder beds beneath the surface and a few of the augers were broken during augering due to the presence of the impermeable layer. The spacing was adapted to accommodate this feature and until sub-surface water was reached in each hole. In all transects, the piezometer depth was less than 3.19m. Slots were drilled in the lower 300mm of the piezometer and the slotted part was installed as shown in Figure 4.1. The slots were covered with coarsely textured sandy material. None of the piezometers were capped. The backfill material around the tube was placed using a mason's trowel. A gentle manual compaction was applied around the piezometer after pouring cement-sand mortar.

Groundwater monitoring started in November 2005 and water table levels were recorded daily following rain events. During other days (summer and winter seasons) recording was made every other day. In order to monitor water level in the piezometers, a water level indicator was used (Durham Geo Slope Indicator, http://www.slopeindicator.com - Figure 4.4). It consists of a probe, a cable with laser-marked graduations, and a cable reel. An LED located in the hub of the cable reel illuminates (and a beeper sounds) as soon as the probe contacts the surface of the water in the piezometer tube.

Figure 4.3 Augering for piezometer installation at Kudumela Wetland, Limpopo Province

Figure 4.4 Water Level Indicator (Source: Durham Geo Slope Indicator, Website: http://www.slopeindicator.com)

4.3 Rainfall

Long-term rainfall data were obtained from five stations of the South African Weather Service (SAWS) in the vicinity. Table 4.2 and Figure 4.5 show the names and locations of each station, length of recording period and mean annual rainfall (mm). Among the five daily rainfall stations that are available to characterize the rainfall over the basin, three are located on the top of the mountain near the watershed (Wolkberg, The Heights and The Downs); while the Fertilis station is located at the top of the Kudumela valley and Stellenbosch is in the valley immediately downstream from the B71C catchment.

Table 4.2 Details of rainfall stations in the Mohlapitsi River basin (Source: computed from SAWS data).

Station number	Station name	Location	Altitude (mamsl)	Record period	Record length (yrs)	Mean annual rainfall (mm)
0635873	Wolkberg	24.02S 30.08E	1580	1972-1989	17	844
0636135	Stellenbosch	24.25S 30.08E	750	1967-2005	38	441
0636157	Fertilis	24.13S 30.10E	780	1959-1988	29	570
0636276	The Heights	24.10S 30.18E	1250	1929-1972	43	1 067
0636308	The Downs	24.13S 30.18E	1350	1913-1973	60	941

The duration of the records is variable and none of the stations are currently active and reporting data. The highest rainfall was recorded at The Heights while Wolkberg Station is at the greatest altitude. The Fertilis Weather Station is located approximately 3 km upstream of the wetland, with a mean annual rainfall of 570 mm (Table 4.2). In November 2005 a further five manual rain gauges were installed within the wetland (Figure 2.5) on transects T1, T2, T4 and T6, two gauges were installed on T4 because it is the largest transect. These gauges were read after each rainfall by the field assistants.

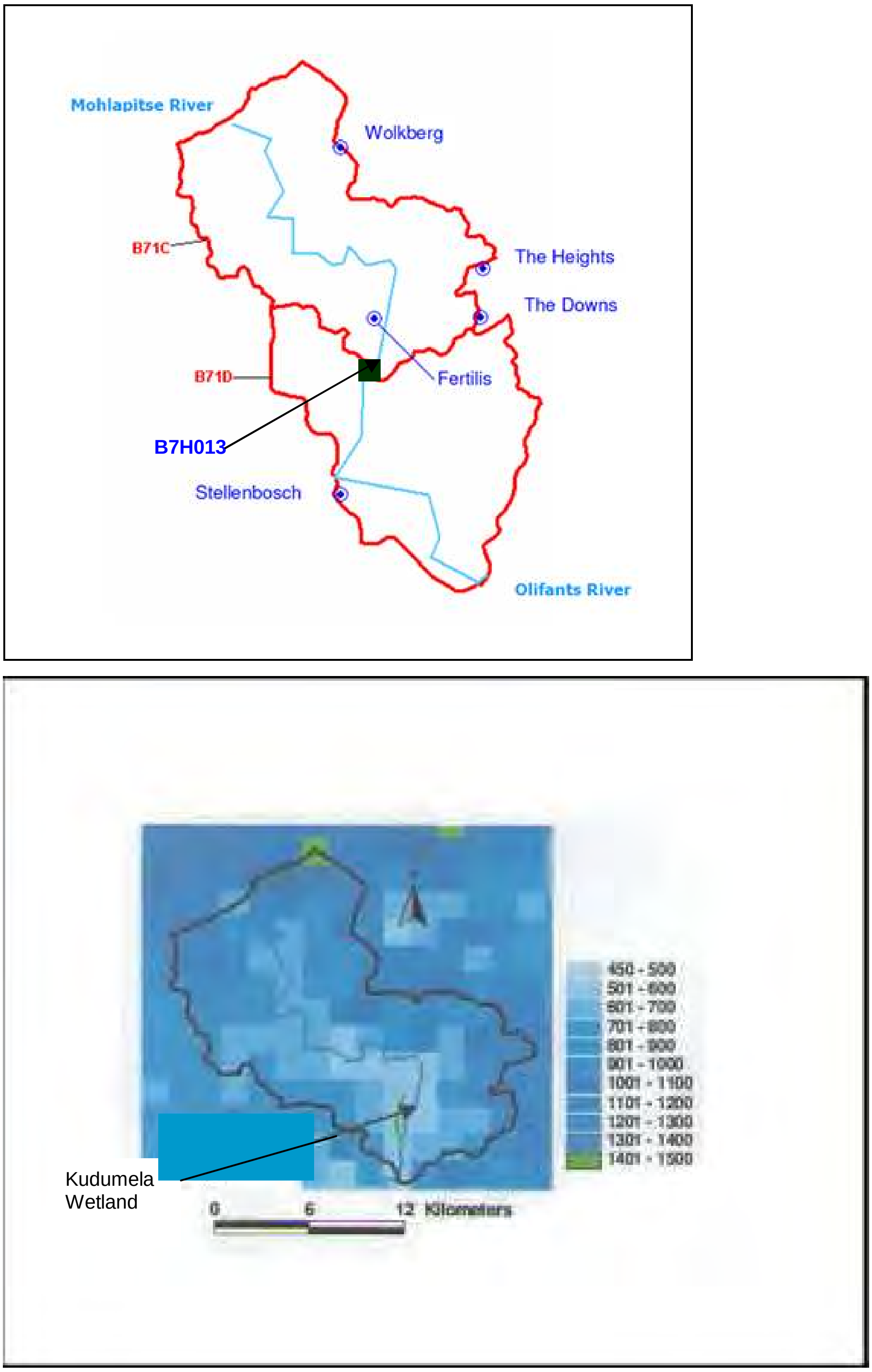


Figure 4.5 Location of rain gauges, rainfall variability with altitudes, and flow gauging station in the Mohlapitsi catchment (Taken from Sarron, 2005 and Troy et al., 2007)

4.4 Stream flow measurements

Daily stream flow was measured at the only gauging station on the Mohlapitsi River (B7H013), located about 1 km downstream of the wetland. The gauging station weir is maintained by the Department of Water Affairs (DWA) and has been in operation since August 1970. Mean daily stream flow data available from the DWA website (www.dwaf.gov.za) were used in the analysis. For the current study, historical records from June 1990 – September 2008 were used for all calculations in the analysis. Due to a technical problem with the gauging station from 30 May 2006 were found unreliable. Starting in the dry season of 2006 river flow has been measured upstream of the wetland by using a C2 current meter (OTT instruments). Measurements were taken for the months of July and August 2006. Unfortunately, the gauge was washed away during the November 2006 flood after which, no data were collected. Moreover, attempts at performing more accurate fluorescent dye tracing failed as no suitable sections of river could be found along which the basic criteria for such tracing (complete mixing, no stagnant water, a single channel) could be satisfied. All field data were collected by the field assistants and sent to the author on a monthly basis. The data were processed and checked for errors and consistency using a spreadsheet. The rainfall (histogram), groundwater hydrographs of all transects as T1, T2, T3, T4, T5, T6 and T7 and stream flow at gauge B7H013 were plotted in order to compare and understand groundwater fluctuations and their relationships (Figures 5.1,5.3,5.5,5.6,5.8,5.11,5.13 and 5.14).

4.5 Water sampling for environmental isotope, hydrochemistry and field parameter analysis

4.5.1 Stable isotopes

Hydrogen-2 (deuterium or ^{2}H) and oxygen-18 (^{18}O) are stable isotopes that form water molecule (Hem, 1989 and Lachniet and Patterson, 2001). Both deuterium and oxygen-18 are extensively used in tracing water movement in catchments. Clark and Fritz (1997) stated that Deuterium δ^{2}H contains an extra neutron, while oxygen-18 (^{18}O) contains two extra neutrons. The difference in mass is caused by the variation in the number of neutrons (Clark and Fritz, 1997). In this instance, isotopically lighter water molecules (i.e., those with ^{16}O) will evaporate slightly more easily than will the isotopically heavier water molecules with ^{18}O. During the course of this process the oxygen isotopes are fractionated: the clouds become enriched with ^{16}O, the seawater becomes enriched in ^{18}O. Thus, rainwater is observed to be isotopically lighter than seawater. Heavier isotopes favor the less energetic liquid phase of water during evaporation and condensation. Water vapor is enriched with light isotopes relative to sea water. Clouds are depleted of light isotopes relative to water vapor. This results in higher latitude waters being isotopically "light" (Kendall and Coplen, 1985). $\delta^{18}O$ and $\delta^{2}H$ concentrations in rainfall decrease as one goes from the equator towards the poles(Gonfiantini, 1981). Any paired values of $\delta^{18}O$ and $\delta^{2}H$ fall very close to the global meteoric water line (GMWL). The GMWL equation according to Craig (1961) is:

$$\delta\,^{2}H = 8\ \delta^{18}O + 10. \qquad (4.1)$$

A computer controlled GEO 20-20 isotope ratio mass spectrometer (Europa Scientific, Crewe, UK) was used for the analysis of deuterium and oxygen-18. After introducing one ml of water into 5 ml vials in the presence of Pt-on-alumina catalyst, the vials were put on a controlled heating block set at a temperature of 50 degrees centigrade. The vials are flushed with hydrogen for one minute and left for one hour to equilibrate hydrogen with the water sample after hydrogen gas was taken from a high pressure cylinder of 99.999% hydrogen and transferred into the 5 ml vials at a pressure of 2 bars. The hydrogen, which is in equilibrium with water samples, is withdrawn from the vials using a gas-tight needle and introduced to the Isotope Ratio Mass Spectrometry for measurement as described by Kendall and Coplen (1985).

Similarly, the $\delta^{18}O$ values of the water samples were determined using the following IAEA reference materials (1999) procedures. When hydrogen measurements are completed, CO_2 is taken from a high-pressure cylinder of 99.999% CO_2 and transferred into the vials at a pressure of one bar. The flashing time for oxygen is similar to that of hydrogen. After all vials are equilibrated with CO_2 for 8 hours at 50 degrees centigrade, the CO_2, which is in equilibrium with the water sample, is withdrawn from the vials using a gas-tight needle and introduced to the Isotope Ratio Mass Spectrometry for measurement (Kendall and Coplen, 1985).

Three sets of samples were collected for the environmental isotope analyses (Table 4.1, Figures 4.6 - 4.9). A total of 12 water samples were analyzed during May 2006, December 2006 and April 2007 (Table 5.2). Among nine samples three of the right bank spring samples were analyzed from their sources (Figure 4.9). During the second sampling period eight samples were collected. During April 2007, 24 water samples were analyzed for the environmental isotopes (Table 5.2). Among 39 water samples, 12 water samples were collected from the Mohlapitsi River for δD and $\delta^{18}O$ measurement. Ten drain samples (two during December 2006 and eight in April 2007) were collected from T1 and T2 (right bank).

Borehole samples were collected from Vallis and Mashushu villages during April 2007 for isotopic analysis (Figures 4.7 and 4.10) and both samples were taken from the taps (not directly from the boreholes). Mashushu and Vallis villages are approximately 3 km apart (Figure 4.10). All the samples were collected with polyethylene containers. The sample bottles were rinsed several times with water from the site. The bottles were completely filled allowing for expansion due to temperature changes, and tightly sealed. Precautions were also taken to ensure that evaporation is kept to a minimum (Gonfiantini, 1981).

Analytical results were reported as $\delta^{2}H^{0}/_{00}$ and $\delta^{18}O^{0}/_{00}$, relative to VSMOW as described by Gonfiantini (1981) and Paternoster et al. (2007). The δ□□ values ($\delta^{18}O$, $\delta^{2}H$) are calculated using the internationally accepted standard equation given as

$$\delta\ (‰) = \frac{R_{sample} - R_{VSMOW}}{R_{VSMOW}} \times 10^{3} \qquad (4.2)$$

where, R is the isotope ratio $^{2}H/^{1}H$ or $^{18}O/^{16}O$.

The local meteoric water (LMWL) line equation for the Pretoria rainfall station was constructed in order to compare it with what is known as the global meteoric water line (GMWL).

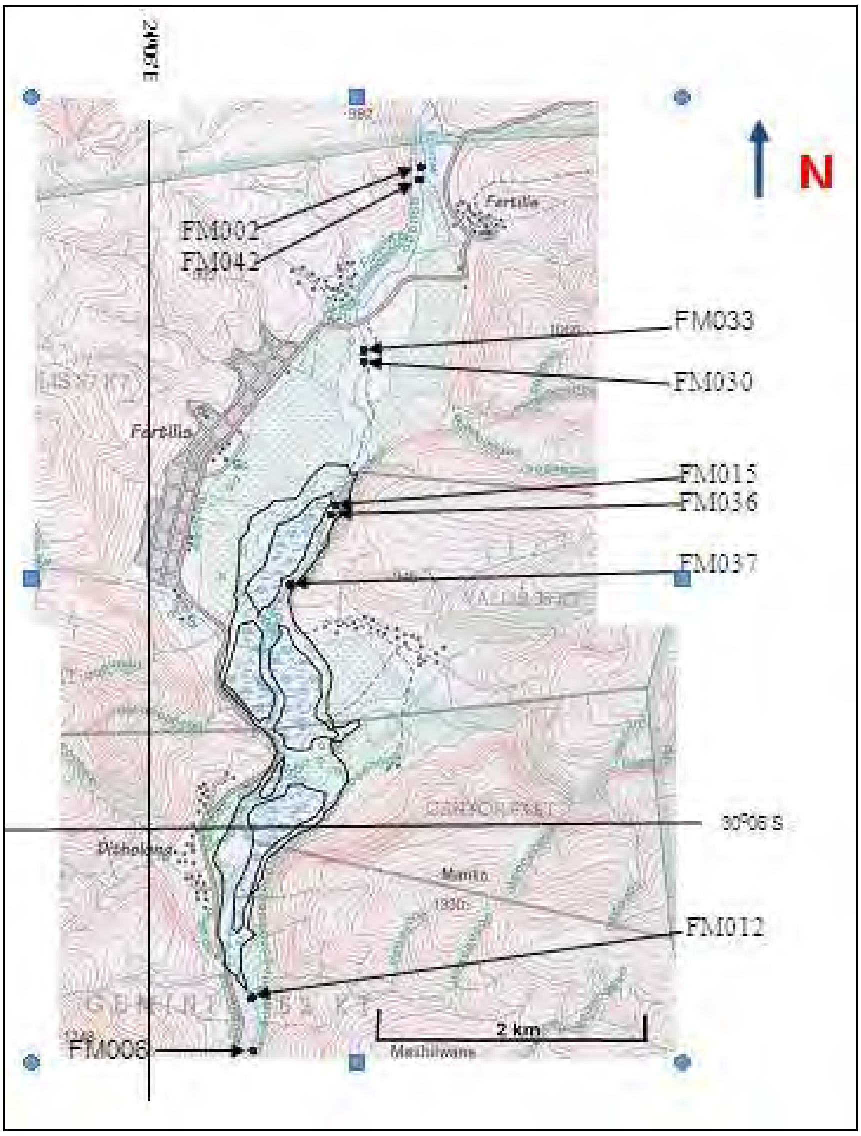


Figure 4.6 Map showing river sampling points (FM002, FM042, FM033, FM030, FM015, FM036, FM037, FM012 and FM006) at the study site

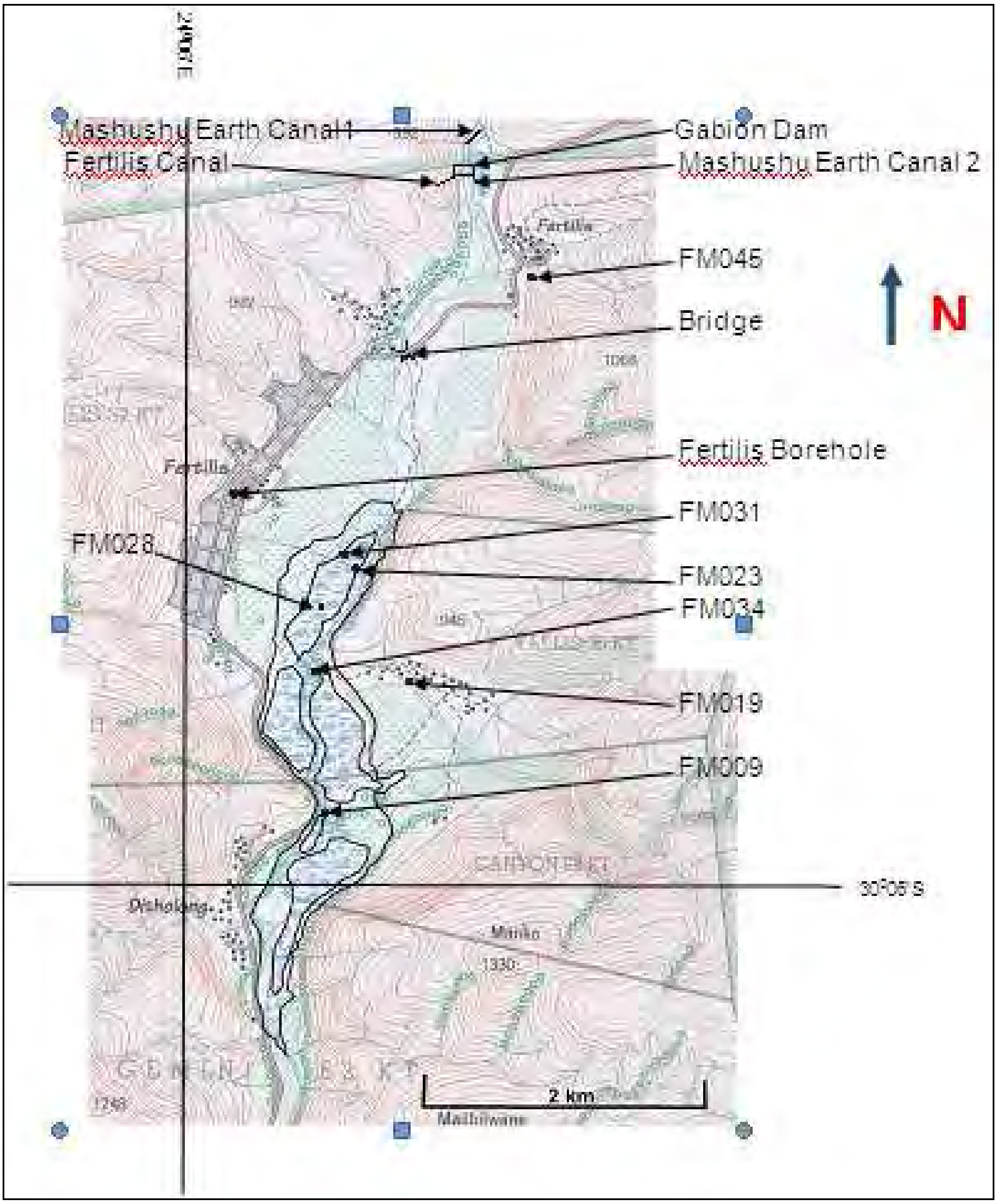


Figure 4.7 Map showing gabion dam, canals, bridge, auger holes (FM031 = Auger Hole near T104, FM023 = Auger Hole at T101, FM034 = Auger Hole at T302, FM009 = Auger Hole at T501 and FM028 = Auger Hole at T2) and Boreholes (FM045 = Mashushu Borehole, and FM019 = Vallis Borehole) at the study site

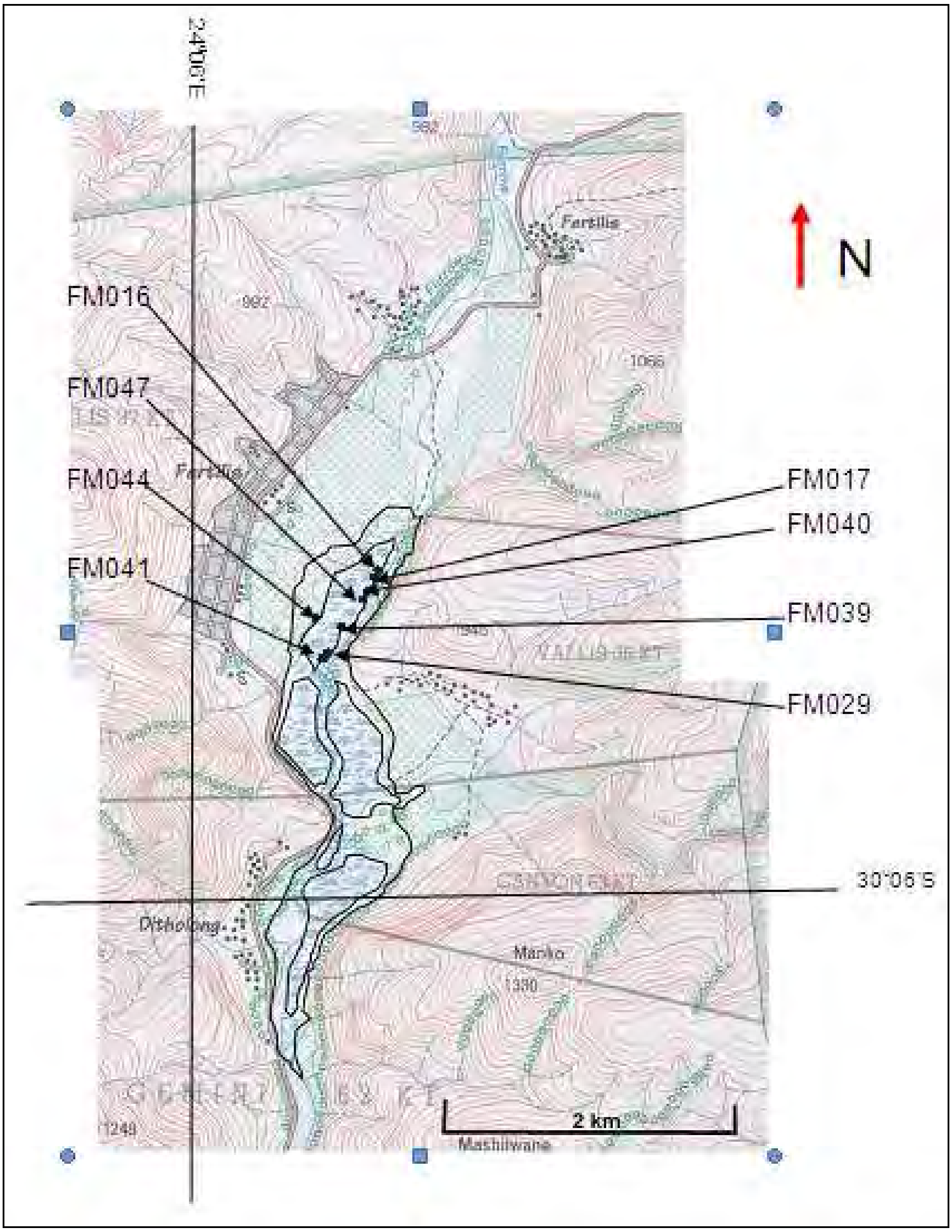


Figure 4.8 Map showing drain sampling points (FM016 = Right Bank Drain1, FM017 = Right Bank Drain2, FM029 = Drain 200m South of T2, FM039 = Drain 200m North of T2, FM040 = Drain 50m South of T1, FM041 = Drain 400m South of T2, FM047 = Drain 200m South of T1 and FM044 = Drain at T206) at the study site

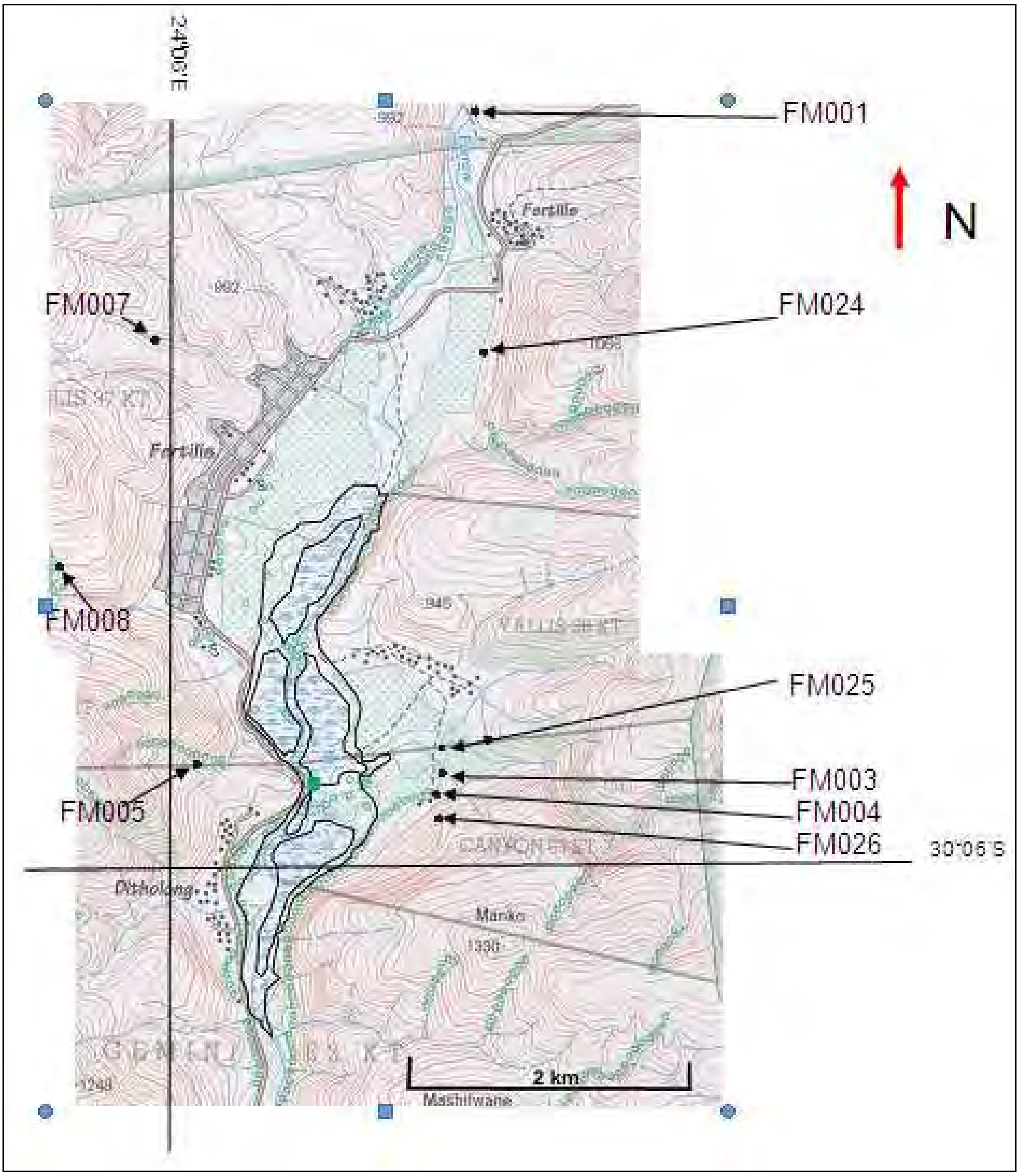


Figure 4.9 Map showing spring sampling points (FM001=Upstream Left Bank Spring1, FM024=Jordaan Spring, FM025=Loumawe Spring, FM003=Left Bank Spring2, FM004=Left Bank Spring3, FM026=T5 Spring, FM007=Right Bank Spring2, FM008=Right Bank Spring3, FM005=Right Bank Spring1 or Ditolong) at the study site

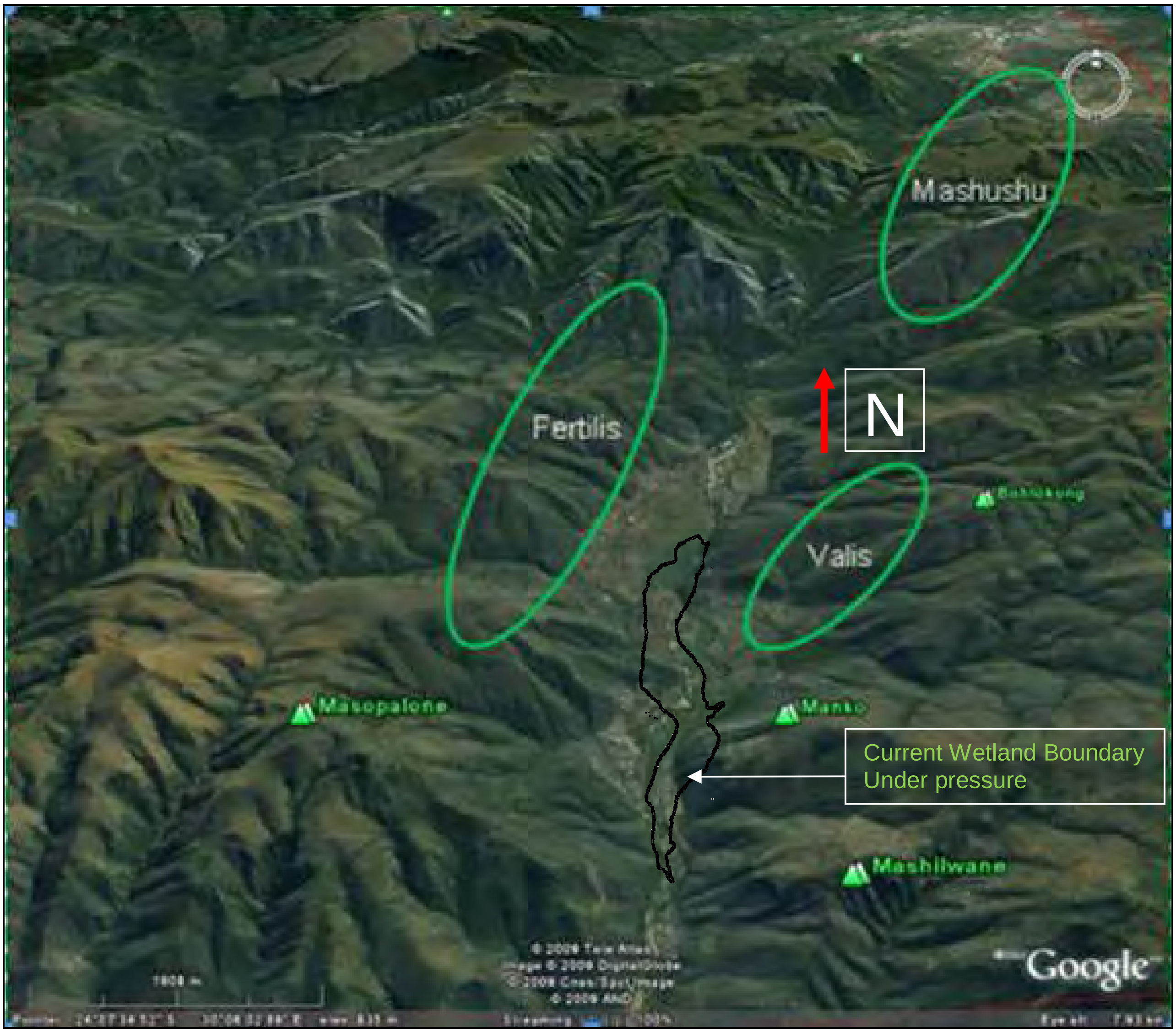


Figure 4.10 Location map showing the three villages of the study area (Taken from Sarron, 2005 and Google Earth, 2008)

4.5.2 Radioactive isotopes

Radioactive isotopes have unstable nuclei that decay, emitting alpha, beta, and sometimes gamma rays. Such isotopes eventually reach stability in the form of non radioactive isotopes of other chemical elements, termed radiogenic daughters. Decay of a radionuclide to a stable radiogenic daughter is a function of time measured in units of half-lives. Radioactive isotopes are useful indicators of the time that water has spent in the groundwater system (Kendall and McDonnell, 1998).

4.5.2.1 Tritium

Tritium is a radio isotope of hydrogen and is usually used to determine the average age of groundwater. Tritium undergoes radioactive decay with a half-life of 4536.95 days (Clark and Fritz, 1997). Naturally, it is produced by cosmic radiation and due to thermonuclear testing between 1950 and 1960, the tritium level increased in the global atmosphere (Hem, 1989 and Clark and Fritz, 1997) contaminating the global precipitation system, hence affecting surface and sub-surface water for approximately 40 years. As a form of hydrogen, it readily forms water molecules, which explains why natural background levels of tritium can be found everywhere in the environment where water is present — including precipitation, surface water, groundwater, ice, soil moisture, animals and plants (Scott, 1992, Bolsunovsky and Bondareva, 2002). It is found in the environment mostly as tritiated water (HTO)

Tritium is the main radioactive component of liquid releases and gaseous discharges of nuclear plants, which contaminates the biosphere not only at a nuclear power plant site but also globally. For instance, the Yenisei River in Russia used to receive both the tritium released by the Mining and Chemical Combine (MCC) and the global fallout tritium (removed from the water catchment area of the river basin) (Bolsunovsky and Bondareva, 2002). Nowadays, tritium concentration could be elevated as a result of radioactive wastes, which are partly deposited in the storage facilities and open ponds (which are close to the nuclear weapon plant sites) (Bolsunovsky and Bondareva, 2002). Tritium concentration in the Yenisei River basin did not exceed 4 ± 1 Bq l^{-1} after the nuclear reactor plant was stopped by the Russian Government, and the results today are consistent (Bolsunovsky and Bondareva, 2002). The tritium concentration decreased after a test ban treaty, which was signed in 1963 by most countries. According to Clark and Fritz (1997), the tritium concentration could not completely return to its former level due to its contribution through other anthropogenic sources, such as landfill activities, nuclear reactions and biomedical research (Butler, 1998). Tritium is measured with a liquid scintillation spectrometer. The following IAEA isotope laboratory procedures were adopted for the analysis of tritium (^3H).

All the glassware such as volumetric flasks were completely dried and kept in an oven at a temperature of 150^0C before any new water sample was introduced. Condensers were rinsed with alcohol followed by acetone. For the first distillation step, a 500ml water sample was used and samples were kept at minimum atmospheric exposure during the distillation process and the joints on both ends of the condensers were made to fit the distillation and receiving flasks tightly. The second step was vacuum distillation that repeats the procedures mentioned above. The vacuum distillation flasks are heated with a gas flame and when the distillation process was over, an initial screening of the tritium concentration was carried out. The samples were then placed in a Packard Tri-Carb 2770TR/SL Low-Level liquid scintillation analyzer, and counted for at least 3 cycles of 4 hours.

After distillation, a volume of some 500 ml of water sample was mixed with 4 gm of sodium peroxide and introduced into the electrolytic cell. A direct current of about 10-15 ampere at 12 V was passed through the cell (due to heat generation). After approximately 5 days, the electrolyte volume was reduced to nearly 20 ml. This volume reduction of about 25 times produced a corresponding tritium enrichment factor of about 20. Samples of standard known tritium concentrations (spikes) were run in one cell of each batch to check the enrichment attained.

For liquid scintillation counting, the enriched water sample was directly taken from the highly concentrated electrolyte. A 10 ml volume of this distilled water sample is mixed with 11 ml Ultima Gold LLT LSC cocktail in a counting vial. The sample is then placed in the packard Tri-Carb 2770Tr/SL Low-Level liquid scintillation analyzer and counted for 2 to 3 hours. The detection limit taken is 0.2 TU for enriched samples. In this way, a total of 30 samples were analyzed for tritium concentration. Tritium concentrations are expressed as absolute concentrations, using tritium units (TU) and, no reference standard is required.

4.5.3 Hydrochemistry

4.5.3.1 Major ions

In November 2007, 10 samples were taken and only six representative samples were selected for major ion analysis and sent to the UIS chemistry analytical laboratory in Johannesburg. In order to understand the movement of water in the study area, surface water (river, drains and springs) and groundwater input to the river during high flow and low flow periods, cations (such as calcium, magnesium, sodium and potassium) and anions (such as chloride, bicarbonate, sulfate, nitrates and bromide) were used as tracers. Cation (positive ions) and anion (negative ions) concentrations for each water sample were converted to total meq/L and plotted as percentages of their respective totals in two triangles (Figures 4.11 and 5.18). To facilitate the interpretation of the chemical analysis, Piper diagrams and Schoeller diagrams were used in this study (Figures 5.18 and 5.19). The cation and anion relative percentages in each triangle were projected into a quadrilateral polygon that describes the water type or hydrochemical facies. Finally, the cation-anion balance percentage was determined by using the equation

$$\{(\boldsymbol{\Sigma}_{\text{cations}} - \boldsymbol{\Sigma}_{\text{anions}}) \div (\boldsymbol{\Sigma}_{\text{cations}} + \boldsymbol{\Sigma}_{\text{anions}})\} \times 100 \qquad (4.3)$$

The concentrations were calculated in milliequivalents per liter, meq/L. In the Piper diagram, the relative abundance of cations with the % meq/L of Na^+, K^+, Ca^{2+} and Mg^{2+} was first plotted on the cation triangle (Hem, 1989 and Mazor, 2004). Then the relative abundance of Cl^-, SO_4^{2-}, and HCO_3^- + CO_3^{2-} was plotted on the anion triangle (Figures 4.11and 5.18). Furthermore, the two cation and anion triangles were combined into the four-sided polygon that shows the overall chemical property of the water sample (Mazor, 1991).

4.5.3.2 Field parameters

Electrical conductivities (EC), total alkalinities (TA) and pH analyses were performed for 41 samples in the field.

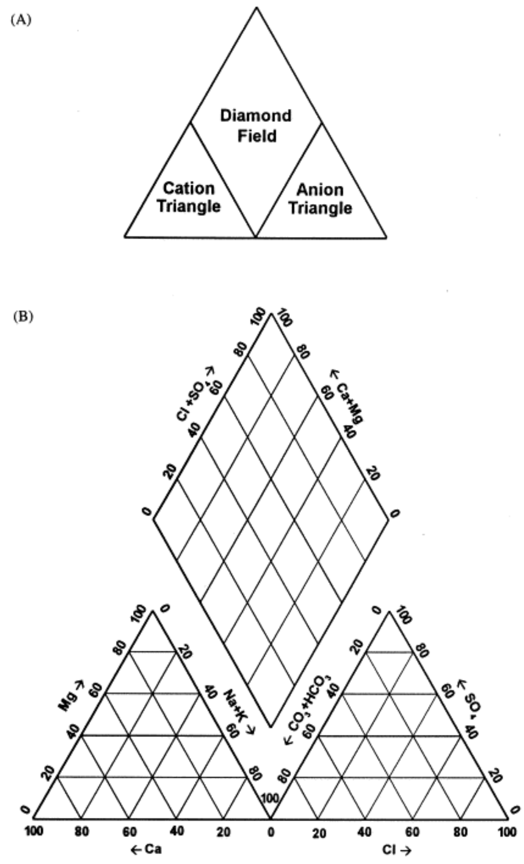


Figure 4.11 The Piper Diagram with two simple triangular plots on the right and left side of a 4-sided diamond field. In the triangular plots, the axes runs from 0 to 100 on each of the three sides. In the right triangle, the axes increase in a counter-clockwise direction--the axis restarts to zero at each apex; in the left triangle, the axes increase in a clockwise direction--restarting at zero at each apex. For each sample, there are three variables to determine the plotting position in each triangular plot, for example the axes may be the three major cations namely, Ca, Mg, Na + K (left) and anions namely, Cl, SO_4 and CO_3 + HCO_3 (right) and the variables are the cation/anion composition of the sample. Classification of Water Quality (Taken from Goltz et al., 2008, Ranjan K R, Rumi M, 2008
and Srinivasa 1998, http://www.sciencedirect.com/science)

5. RESULT AND DISCUSSION

5.1 Rainfall and stream flow

Figure 5.1 illustrates the relationship between rainfall measured over the wetland and stream flow at the DWA gauging station (B7H013) downstream. The accuracy of the measured flow data at the hydrological station B7H013 is expected to be about 5% in the range 0 – 5 $m^3\ s^{-1}$ and 10% for flows higher than 5 $m^3\ s^{-1}$. Moreover, when the water level exceeds 1 meter at the gauge (which corresponds to 12.8 m3 s-1), water overtops the weir and no stage-discharge relationship is available. Therefore, no high flow data are available and such a situation appears as observation gaps in the records (Troy et al., 2007).

The rainfall data plotted are averages of the 10 day accumulations measured at the 5 rain gauges installed as part of the project (Figure 2.5). There were very small differences between the rainfalls measured at the five gauges suggesting low spatial variability of rainfall inputs over the wetland area. The technical assistants indicated that no rainfall was measured for the periods before 29/11/2005 and after 28/02/2006; however, the stream flow response at the end of the study period suggests that rainfall did occur within the catchment of the wetland. The agricultural extension office; which is about 1 km away from the study site, did measure rainfall after February 2006 and these records have been used to extend the rainfall record observed by the technical assistants. However, there is a generally poor relationship between the rainfall measured in the valley bottom and the gauged stream flow (Figure 5.1), suggesting that rainfall patterns in the catchment area could be very different. Unfortunately, data for the South African Weather Service (SAWS) rain gauges referred to in chapters 3 and 4 were not available for the study period as they had been closed down.

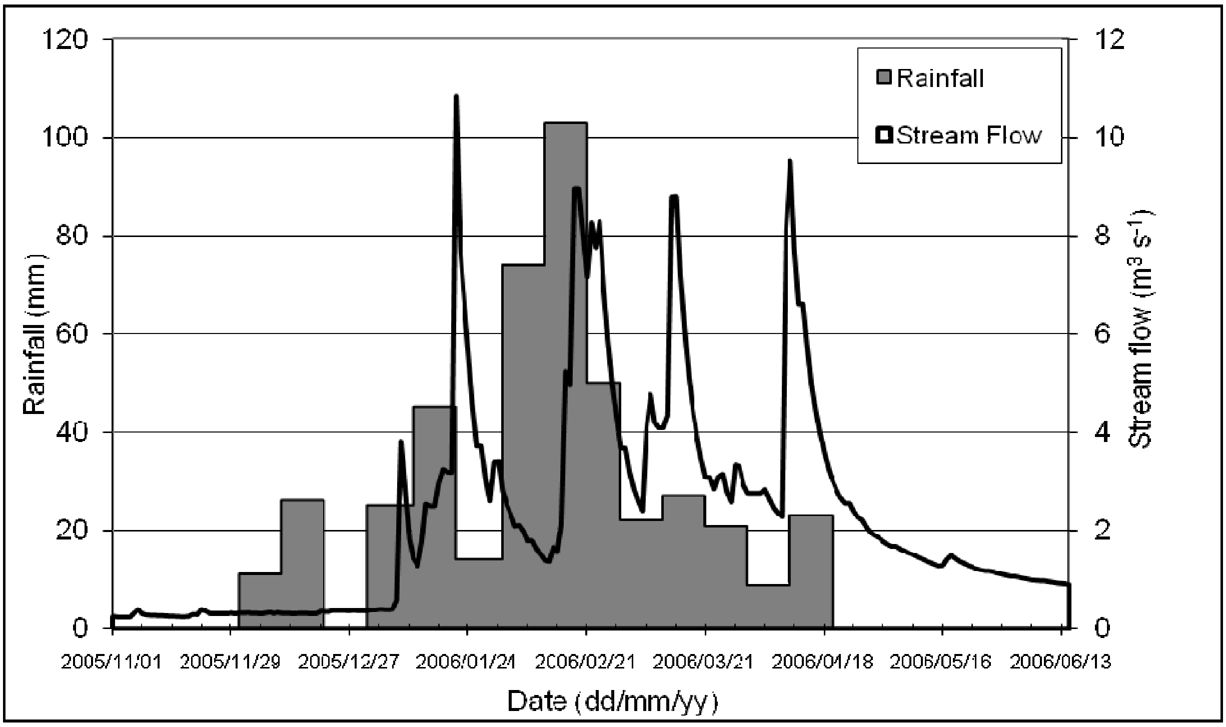


Figure 5.1 10 day accumulations of rainfall over the wetland and daily stream flow observations at B7H013.

The limited programme of stream flow observations from upstream and within the wetland area suggests that the Mohlapitsi River can lose approximately 50% of its flow after the gabion dam (Figure 2.3) during moderate to low flows. For example, in November 2007 the flow upstream of site FM001 (Figure 4.7) was measured as 4.2 $m^3 s^{-1}$. At a site 300m upstream of the bridge the discharge had reduced to 2.2 $m^3 s^{-1}$, while downstream of the wetland the discharge was estimated to be 2.5 $m^3 s^{-1}$ (a similar flow to that recorded at B7H013 on the same date). It is assumed that this reduction in flow in the river represents a positive contribution to the water balance of the wetland related to the artificial diversion of water at the gabion dam.

5.2 Piezometer observations

This section presents the results of the piezometer observations and attempts to interpret them in terms of the rainfall and stream flow observations. The objective is to identify any relationships between the groundwater levels within the wetland and patterns of local rainfall and stream flow in the adjacent channel. The lithological characteristics of the first 6 transects

(T1 to T6) are presented in Figures 5.2, 5.4, 5.7, 5.9, 5.10 and 5.12, while the time series of piezometer observations for all 7 transects are presented in Figures 5.3, 5.5, 5.6, 5.8, 5.11, 5.13 and 5.14. The lithology information has been interpreted from the material removed during the augering for the installation of piezometer tubes, while the groundwater levels shown on these diagrams represent mean levels for the study period. Augering stopped in all transects when water began flooding the holes, hence none of the piezometer holes hit the presumed bed material (dolomite). All piezometers were installed 24 hours after augering to allow for the equilibration of water levels after initial disturbance. It was not possible to auger all the holes and install all piezometers on the same day and the starting dates of water level observations are indicated in Figures 5.3, 5.5, 5.6, 5.8, 5.11, 5.13, and 5.14. The existence of a boulder bed was assumed when the auger encountered a large object. Such materials are observed along the banks of the river, for example at transects T4 and T5.

The graphical rainfall and stream flow data from Figure 5.1 (i.e. excluding the axes labels) have been added as a background image to all the piezometer elevation time series graphs to facilitate comparisons. It should be noted that the stream flow data are sourced from the Department of Water Affairs (DWA) gauge (B7H013) that lies downstream of the wetland and that the variations in flow could reflect variations in discharge from the catchment area upstream of the wetland, as well as inputs from some of the tributary channels within and downstream of the wetland. Groundwater level data are available for a 7 month period that includes the 2005/2006 wet and dry seasons and show the short term variation in the water levels in the shallow aquifer associated with the wetland. Due to no significant fluctuations in the water tables, the monitoring period after May 2006 has not been included in the analysis.

5.2.1 Transect T1

In T1, sandy loamy clay soil (1.2m depth) dominates the top part of T1 and is underlain by approximately 30 cm of boulder bed. Compacted clay with minor gravel material (≥ 1m) was found while augering before the piezometer was buried (Figure 5.2). After the water table was reached, augering continued for a further 50 cm in all piezometers in order to observe the water table fluctuations. Water table monitoring started 24 hours after the installation of the piezometers.

Except for MRB101 (the piezometer closest to the river), the water levels showed a rapid response at the start of the wet season (Figure 5.3). However, there is very little correlation with the patterns of local rainfall during the main part of the wet season. The early season increases in water level are approximately 0.75m, which would imply a 'storage coefficient' of approximately 5% if the increase is to be attributed to the local rainfall of 37mm. In this context 'storage coefficient' refers to the material pore space available before saturation. This would seem to be somewhat too low for un-compacted surface soils, the implication being that the increase in water levels is likely to be caused by other inputs. Although not explicitly part of the measurement programme, other possibilities include diversions from the upstream main channel or inflows from the valley side slopes or minor tributaries. A further possibility is a rise of the regional groundwater level, although the relatively rapid response at the start of the wet season would tend to negate this as an option.

None of the piezometers responded to the large amounts of rainfall recorded during the first three weeks of February 2006 (10 day accumulations of 74 and 103mm) (Figure 5.3). MRB103 and MRB105 show some response to the final stream flow event of the season (end of March 2006), but no clear responses to any of the other stream flow fluctuations during the wet season. Variations in groundwater levels in MRB101 (Figure 5.3) show the closest relationship with variations in stream flow, an expected result given that this piezometer is closest to the channel. The assumption is that the groundwater is draining towards the channel and that the wetland is probably contributing to stream flow, however, the source of the increments to wetland groundwater is not very clear from the available data.

It is interesting to note that most of the piezometers do not show a great deal of variation at the end of the wet season and yet the groundwater levels (and hydraulic gradients toward the river) are substantially higher than at the start of the 2005/2006 wet season (Figure 5.3). Without recent rainfall data it is difficult to reach firm conclusions, and unfortunately the data for B7H013 are missing during the 2004/2005 season. However, the closest alternative flow gauge (B7H010 in the Selati River catchment) suggests that the previous wet season was very dry, which may account for the differences in groundwater levels at the start and end of the study period.

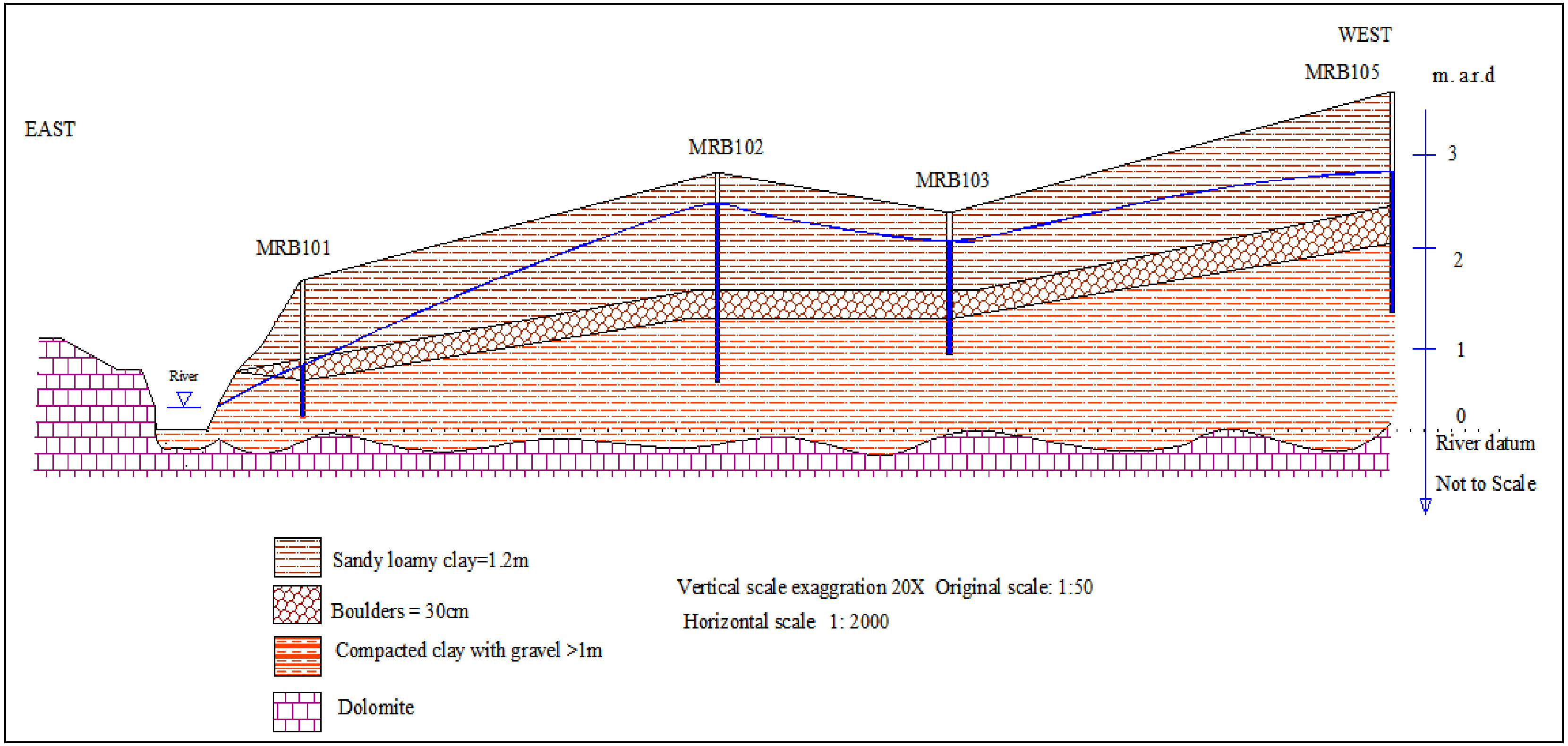


Figure 5.2 Lithological sections of piezometers at T1 (the mean water table level is shown in blue

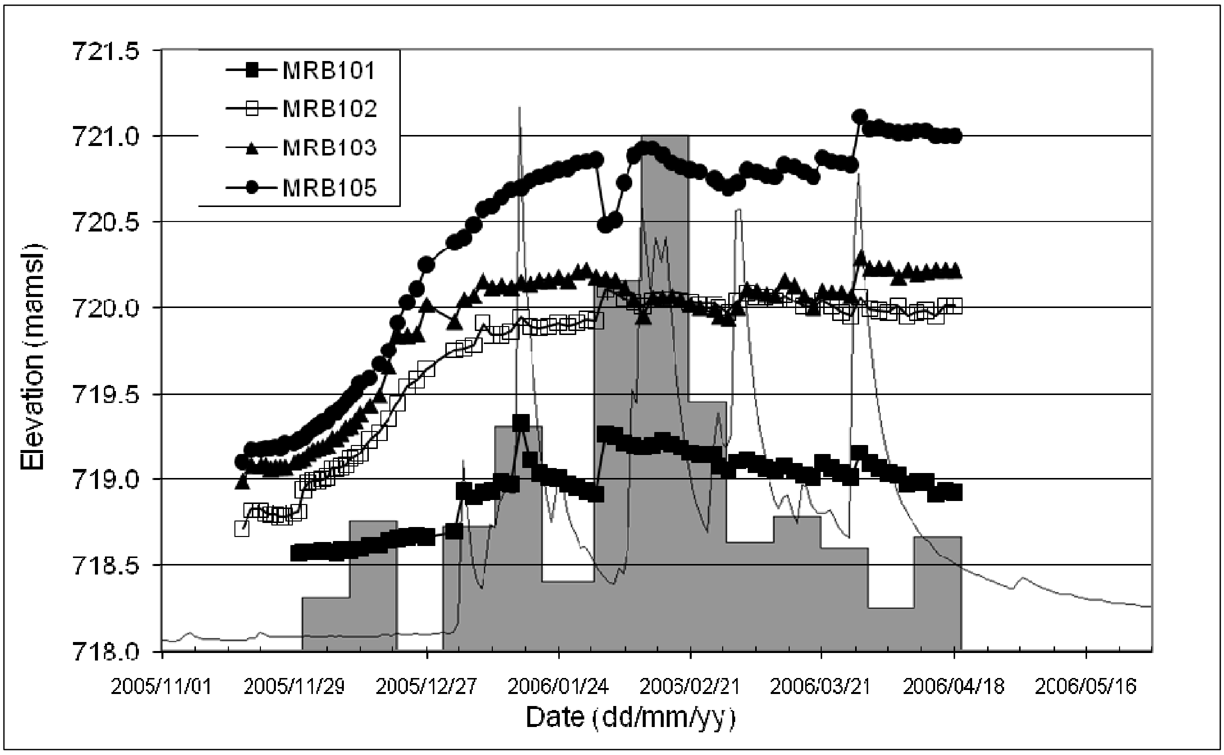


Figure 5.3 Groundwater table fluctuations November 2005 to May 2006 for T1 (refer to Figure 5.1 for the scales associated with the rainfall and stream flow data).

5.2.2 Transect T2

In T2 the depth of the boulder bed was observed to be approximately 0.2m and water table measurements in all piezometers started on 30 November 2005 (Figure 5.4). Most of the piezometers in T2 show a relatively small response throughout the wet season, although MRB206 responds rapidly to the high rainfalls that started at the beginning of February 2006 and, as with the T1, the piezometer closest to the river (MRB201) approximately follows the patterns of stream flow variation (Figure 5.5). MRB206 also shows a response at the same time as the last flow event of the year (at the end of March 2006). If the increase in water elevation of 0.89m in MRB206 in early February is caused by local rainfall a ‘storage coefficient’ of 22.7% would be required. While this might seem reasonable for the type of soil, there is no explanation for the lack of response in the other piezometers.

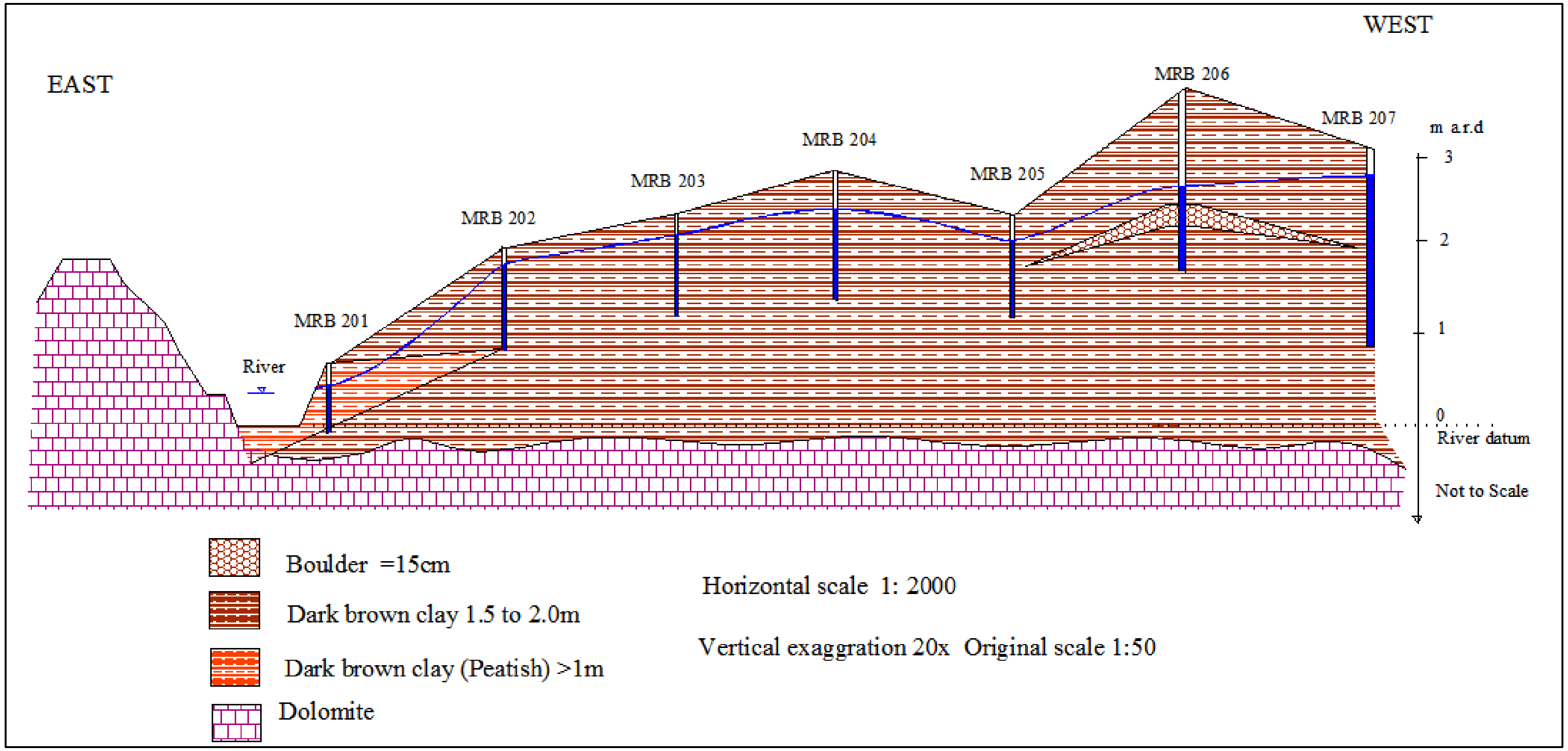


Figure 5.4 Lithological sections of piezometers at T2 (the mean water table level is shown in blue)

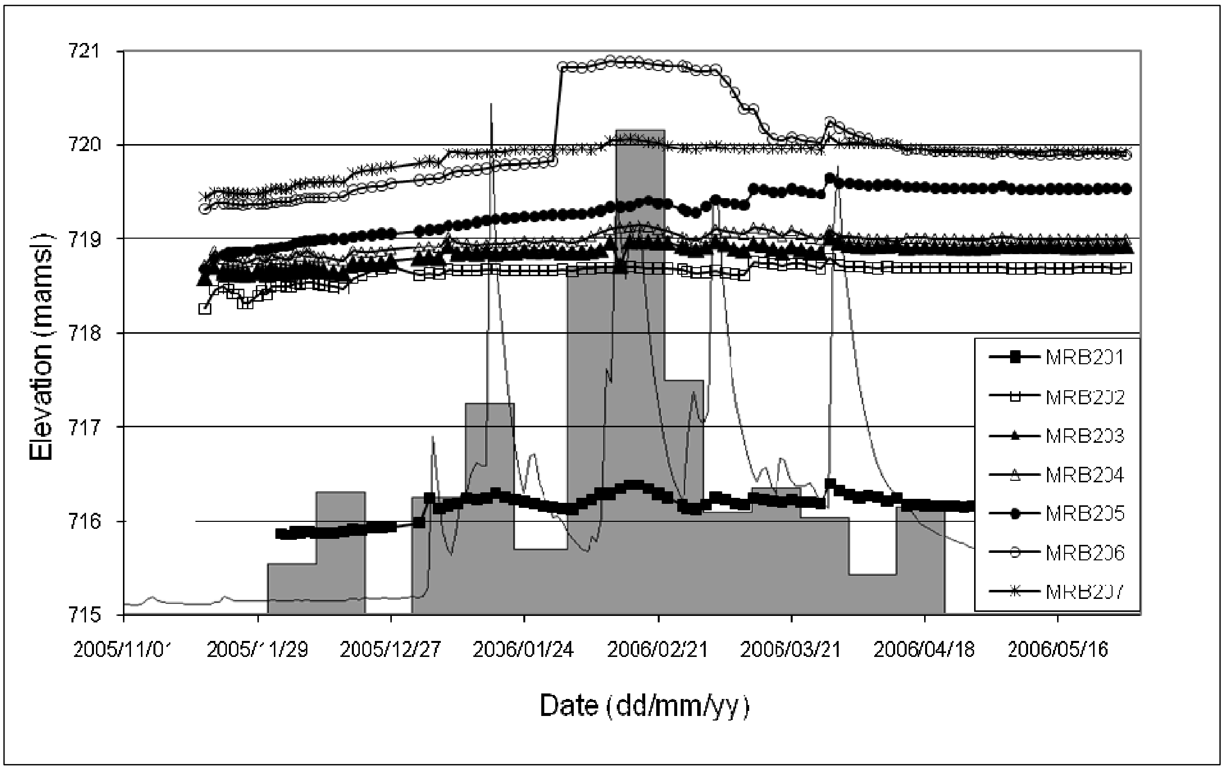


Figure 5.5 Groundwater table fluctuations November 2005 to May 2006 for T2 (refer to Figure 5.1 for the scales associated with the rainfall and stream flow data)

5.2.3 Transect T3

The lithology of transect three (T3) is more complicated than the others. Its top (surface) material is loamy clay; followed by approximately 0.3-0.4m deep boulders and 0.3m thick sand bed (Figure 5.7). The gradient of the water table is generally towards the depression at MRB304 and the river at MRB301. Piezometers MRB304 and MRB306 are the quickest to respond at the start of the wet season, with the water level in MRB304 increasing by 0.28m (Figure 5.6). Except for MRB302 and MRB301, all the sites respond quite rapidly to the rain at the start of January 2006 and continue to respond to the rainfall later in the season. Despite the data gap between the end of February and early April 2006, there are indications that these more remote (from the channel) sites respond to rainfall at the end of the season that is missing from the local records. MRB303 is the most responsive piezometer and this may be related to its position within a depression (Figure 5.6).

The hydrographs (Figure 5.6) of MRB301 and 302 (close to the river) showed nearly the same pattern throughout the study period and with generally less response than the other sites, with a possible exception during the high rainfall and flow in mid-February, when the gradient was slightly away from the river. Although no information is available about the water level in the adjacent channel, it is possible that this reversal of gradient is evidence for flow from the river into the sediments of the wetland.

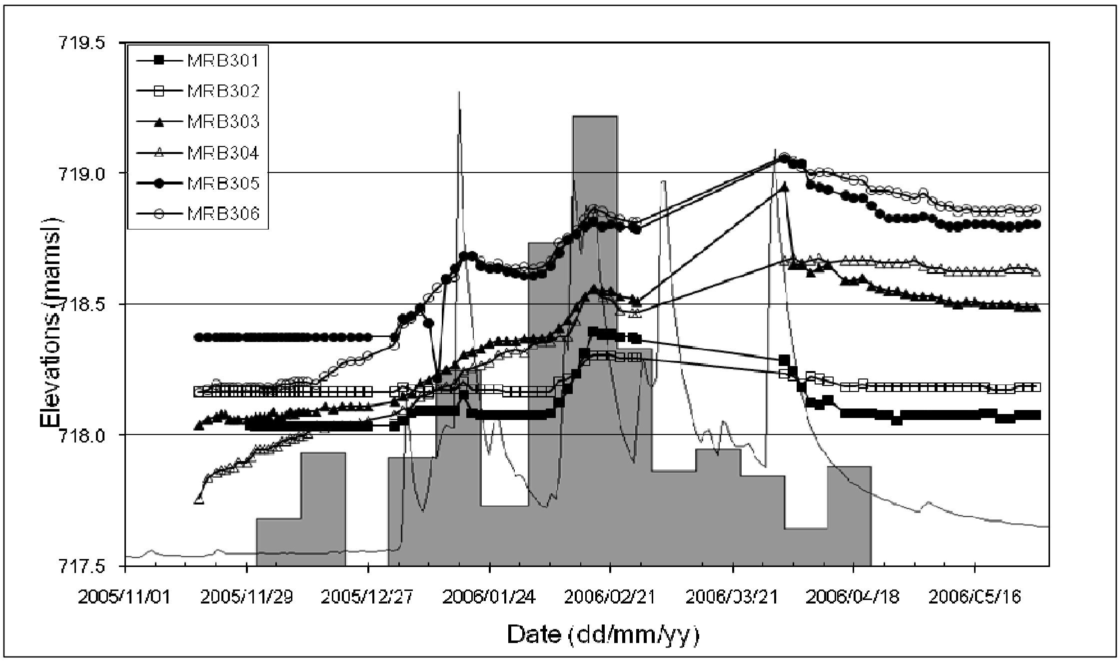


Figure 5.6 Groundwater table fluctuations November 2005 to May 2006 for T3 (refer to Figure 5.1 for the scales associated with the rainfall and stream flow data)

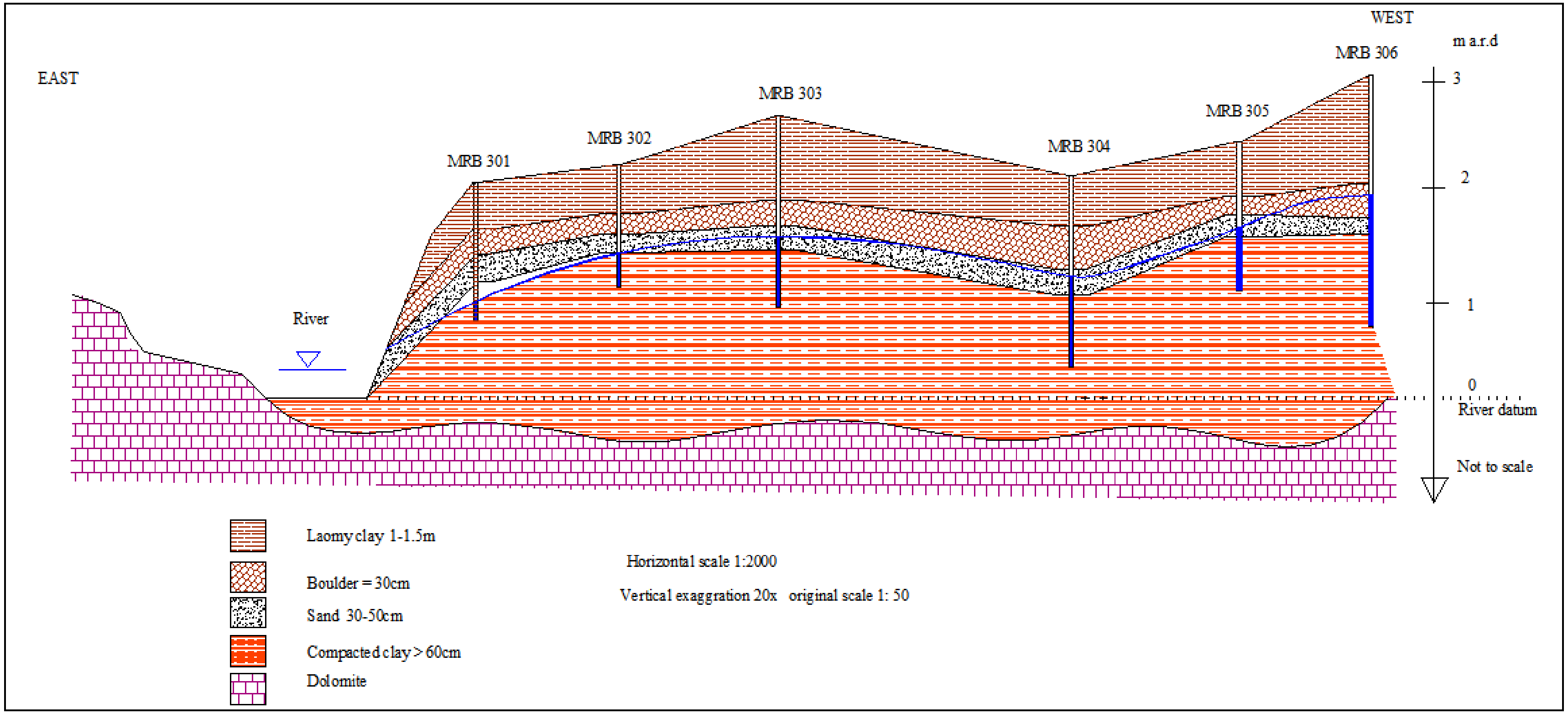


Figure 5.7 Lithological sections of piezometers at T3 (the mean water table level is shown in blue)

5.2.4 Transect T4

T4 is the widest transect in the study area, with a width of 597m and is the only transect that the river crosses (Figure 5.9). A total of 11 piezometers were installed, 5 were removed by vandals and 7 were operating until the end of the study period (Figure 5.9). The river is known to be migrating within the valley bottom, branching and braiding after every flood event. For example, the river’s current flow channel is approximately 150 m to the east of the location before the 2000 flood. The gradients on both banks are predominantly towards the river at all times, however there is a local gradient towards site MLB407 which lies within a depression (Figure 5.8). On the river side of this site the gradient is often weak to non-existent (Figure 5.8). Unlike any of the other transects, many of the piezometers on T4 show a drying tendency at the start of the wet seasons and water levels only start to rise at the beginning of January 2006. There is no obvious explanation for this phenomenon. For most of the remainder of the wet season all the sites exhibit fluctuations that are partly a refection of the variability in the stream flow and local rainfall. There is one unexplained rise in water level at site MLB409, but this could be related to data collection errors.

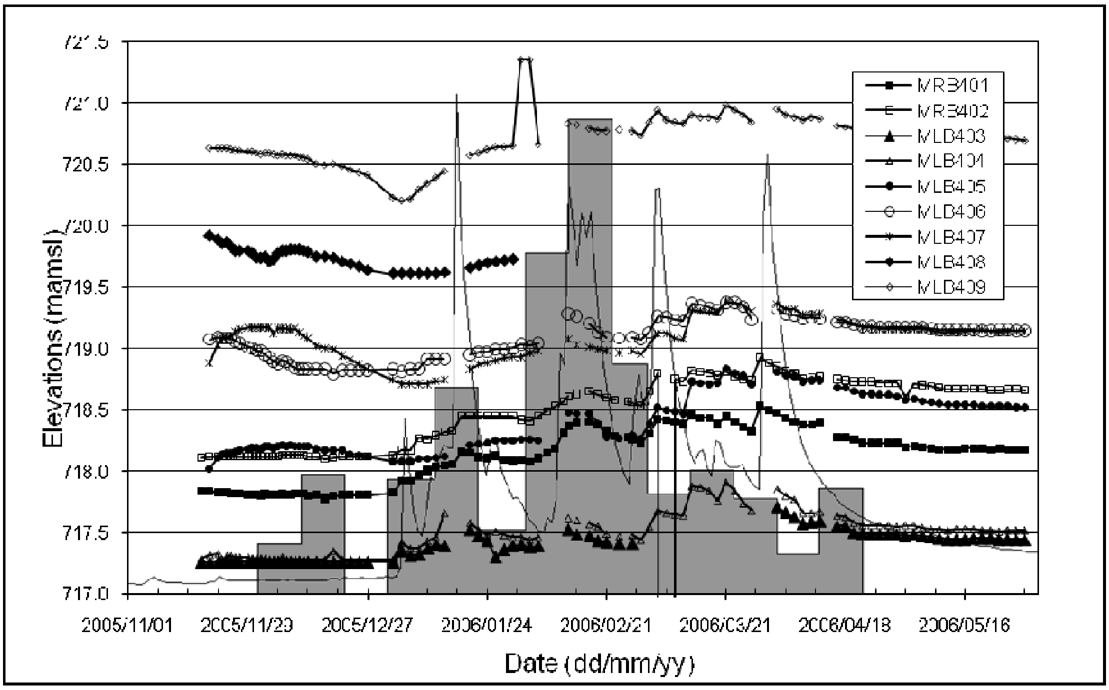


Figure 5.8 Groundwater table fluctuations November 2005 to May 2006 for T4 (refer to Figure 5.1 for the scales associated with the rainfall and stream flow data)

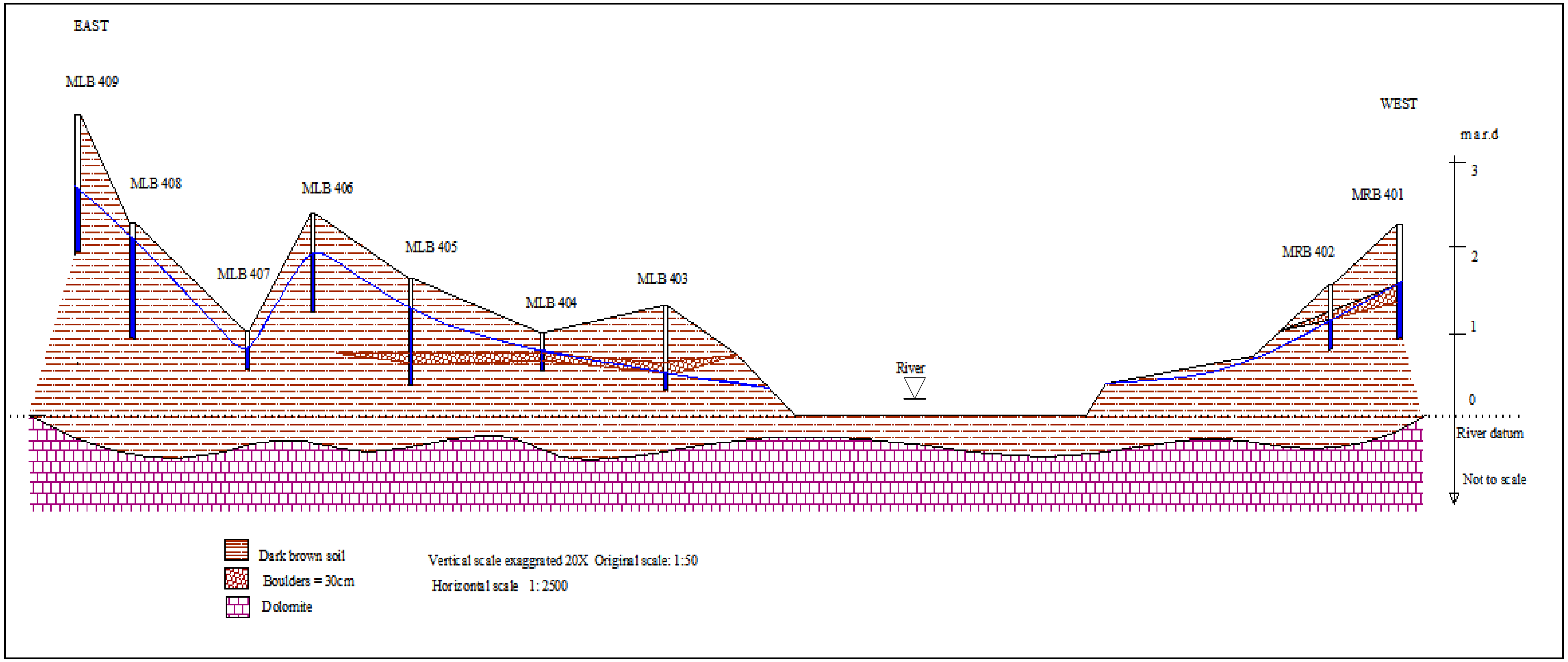


Figure 5.9 Lithological sections of piezometers at T4 (the mean water table level is shown in blue)

5.2.5 Transect T5

T5 is located at the left bank and is 451m wide with eight piezometers. Dark brown clay dominates T5 with 300mm thick boulders beneath (Figure 5.10).This portion of the wetland is located at the foot of a dolomite hillside and is within approximately 20ha of marshy land. Several springs were observed to exist at the foot of the hillside, even during dry seasons. As with T4 some of the piezometers (MLB502, 504, 505, 506 and 508) show a drying tendency at the beginning of the wet season (Figure 5.11). However, MLB507 shows a strong initial wetting and these differences are difficult to explain. In other respects most of the water levels show variations which are weakly related to the variations in stream flow and local rainfall. Site MLB505 has the greatest fluctuations, but does not seem to correlate particularly well with any known driving forces (Figure 5.11). While these fluctuations may be associated with its location in a depression they are still difficult to explain. The elevations for MLB501 are very high given its location close to the river channel and this suggests a reverse gradient away from the river, while the gradient across most of the transect is towards the river. It is, however, possible that an error was made in the original surveyed elevation of the ground level at this point. T5 was flooded in early February (08/02/2006) and again in late March (29/03/2006) and it was not possible to take any readings. Only MLB502 and 503, show any significant reaction to the second flooding event, while most piezometers show at least some reaction to the first. However, none of the piezometers show any signs of complete saturation soon after these events, suggesting that either the flood waters do not fully penetrate into the subsurface material, or that rapid drainage occurs soon afterwards.

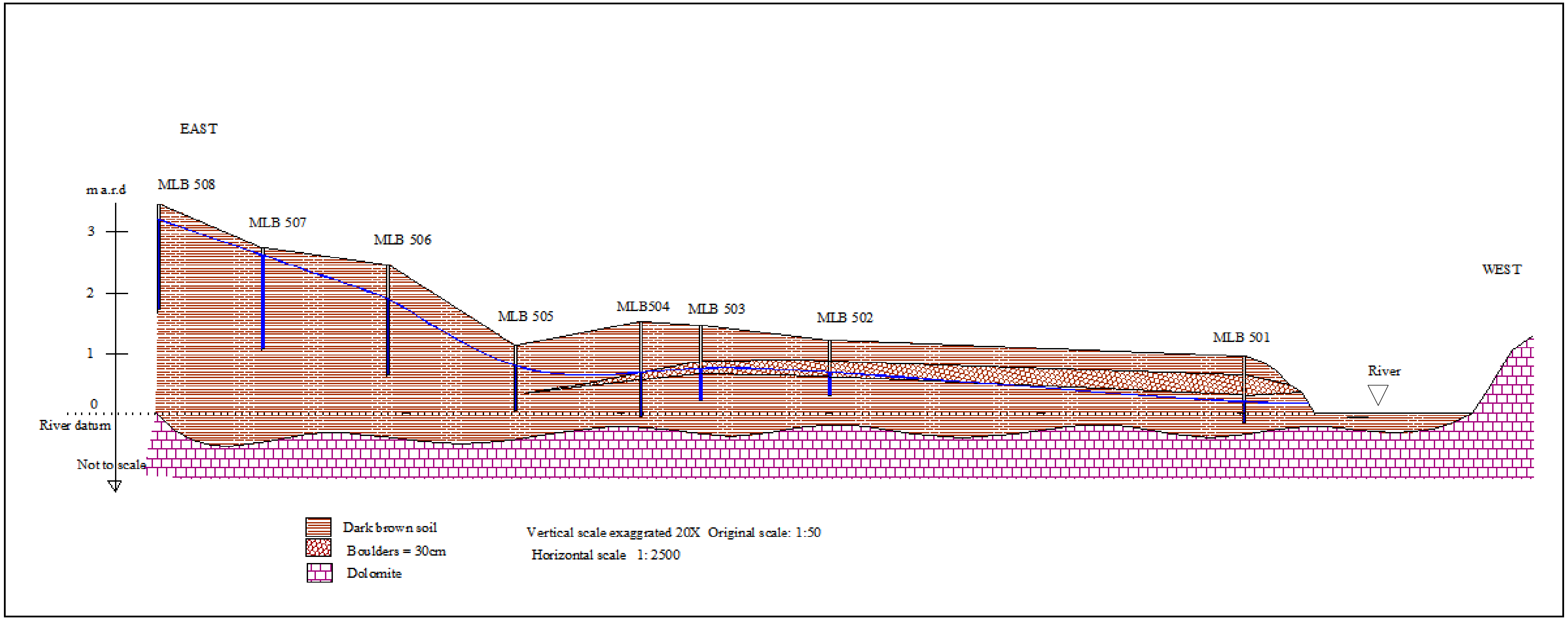


Figure 5.10 Lithological sections of piezometers at T5 (the mean water table level is shown in blue)

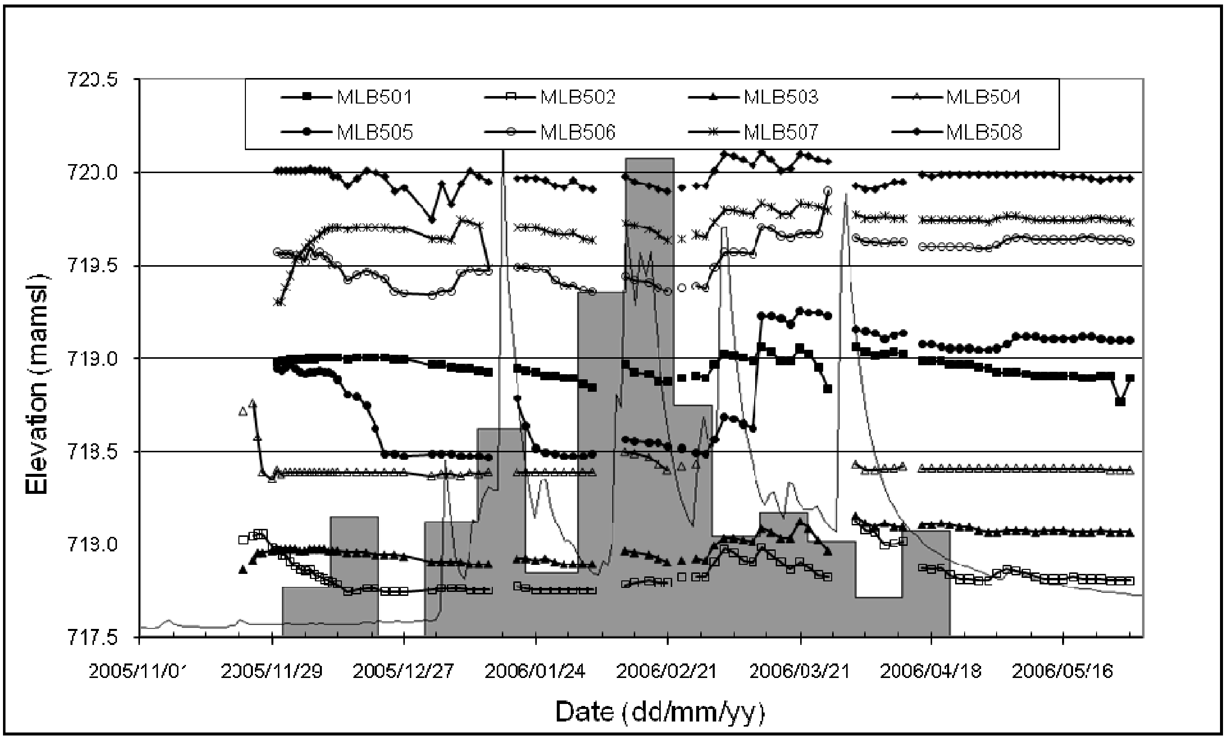


Figure 5.11 Groundwater table fluctuations November 2005 to May 2006 for T5 (refer to Figure 5.1 for the scales associated with the rainfall and stream flow data)

5.2.6 Transect T6

Figure 5.12 illustrates the lithology of T6, while Figure 5.13 indicates that the water levels across this transect fluctuate more so than many of the other transects. These fluctuations are also quite well correlated with the variations in stream flow downstream at the gauging station, except at the start of the wet season. There is always a positive gradient towards the river channel and unlike some of the other transects the fluctuations in the piezometer closest to the channel are greater than further away. Part of this result may be related to the fact that the gauged stream flows are a better reflection of flows in the channel at the transect than in some of the upstream transects, but this is impossible to confirm without more data. Figure 5.13 suggests that there may have been a wetting influence before the study started collecting data and this was followed by a drying period immediately after the first period of observed rainfall.

The response to the second rainfall period (early February) was more or less immediate with water levels rising between 0.4m in MLB601 and a little more than 0.2m in MLB603 (Figure 5.13). Ignoring any effects of drainage or evaporation, and given the 70mm of rain that was measured during this period, ‘storage coefficients’ of between 18% and 35% would be required to account for these increases in water level. These values are within the range that might be expected for the type of material that is present. The responses to later events in the wet season are also relatively immediate, but not always as clear and there appears to be a gradual accumulation of groundwater during the whole period, despite frequent, but relatively short periods of drying. These are presumably caused by drainage or evaporation, or a combination of these two processes. The recession in groundwater levels at the end of the wet season also reflects the pattern of stream flow recession, a result that is not as evident in all the previous transects. The implication is that the groundwater in this transect has a greater connection to the channel than in the other transects.

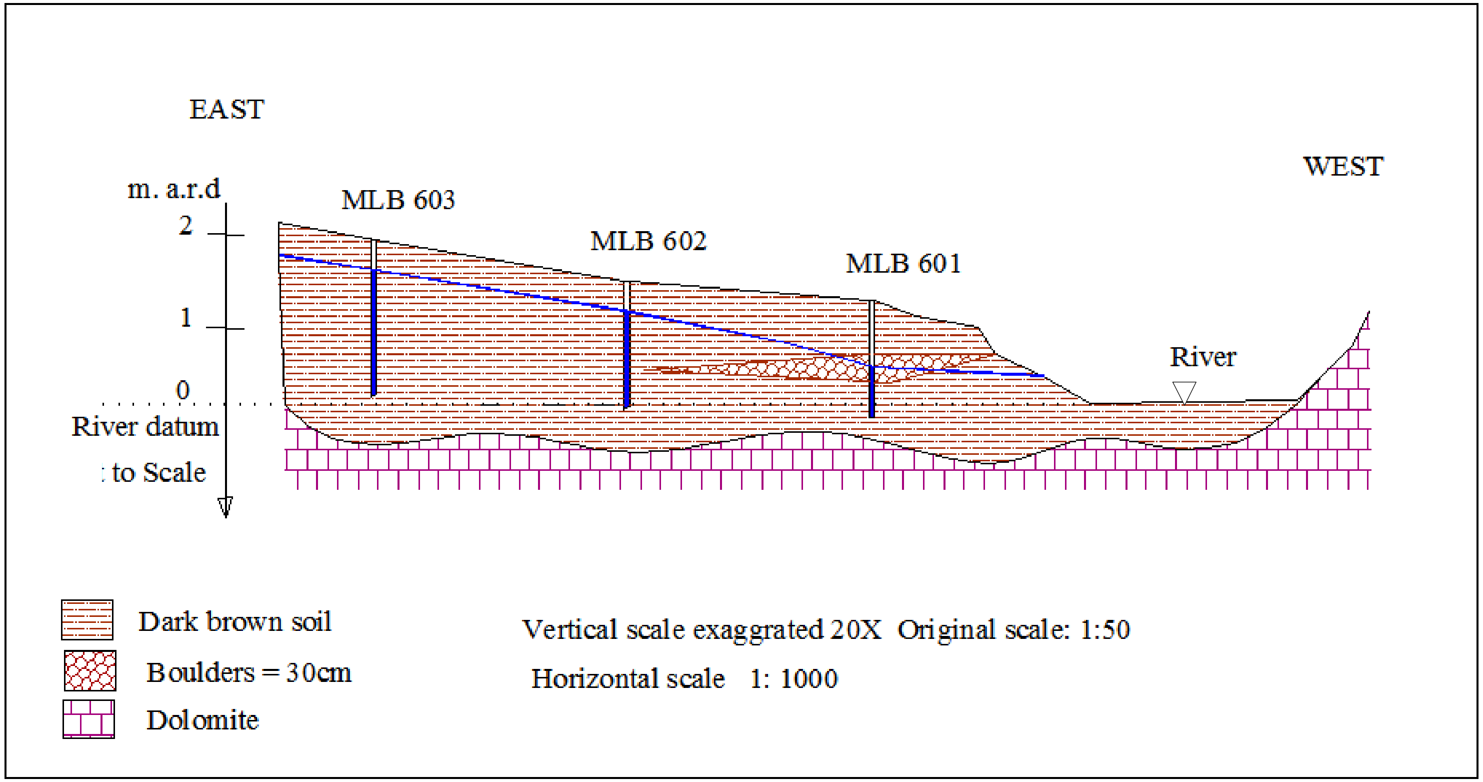


Figure 5.12 Lithological sections of piezometers at T6 (the mean water table level is shown in blue)

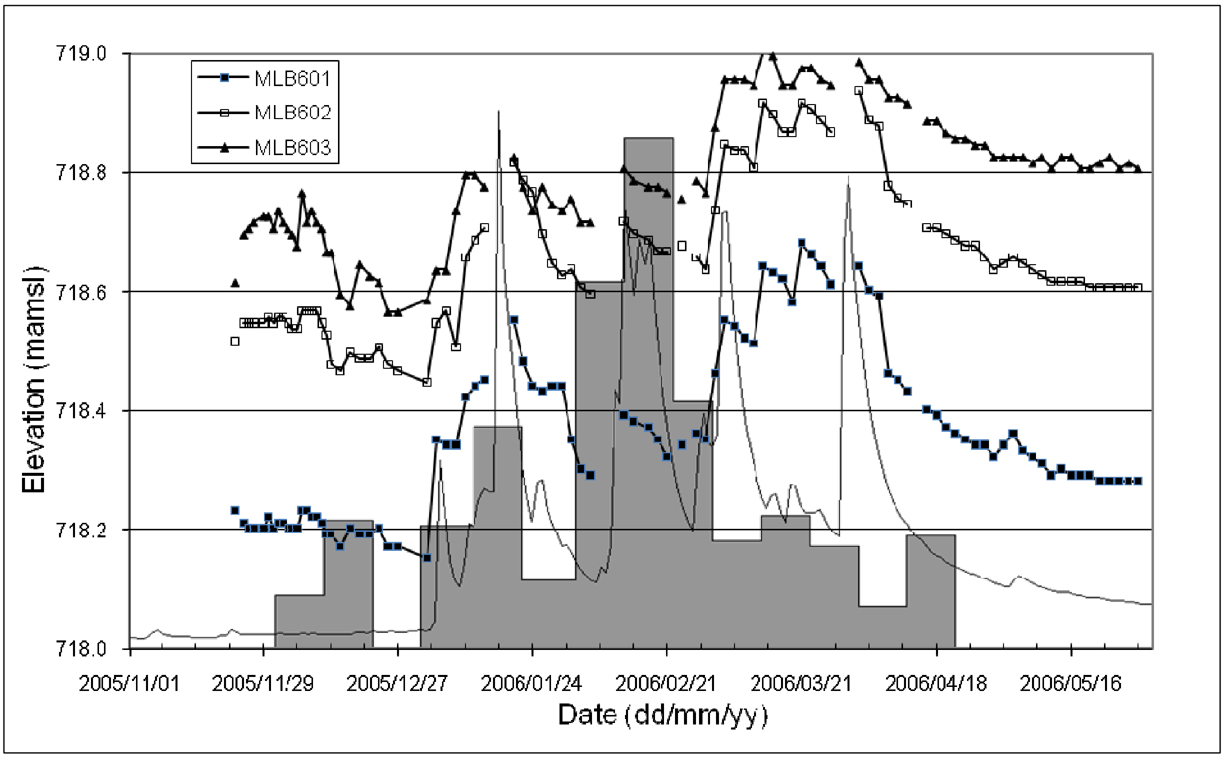


Figure 5.13 Groundwater table fluctuations November 2005 to May 2006 for T6 (refer to Figure 5.1 for the scales associated with the rainfall and stream flow data)

5.2.7 Transect T7

The water levels in transect T7 show similar patterns of variation to transect T1, rising gradually during the start of the wet season and then remaining high with relatively minor fluctuations that do partially reflect patterns of stream flow and local rainfall. As with some of the other transects, the water levels during the 2006 dry season are much higher than the levels at the end of the 2005 dry season.

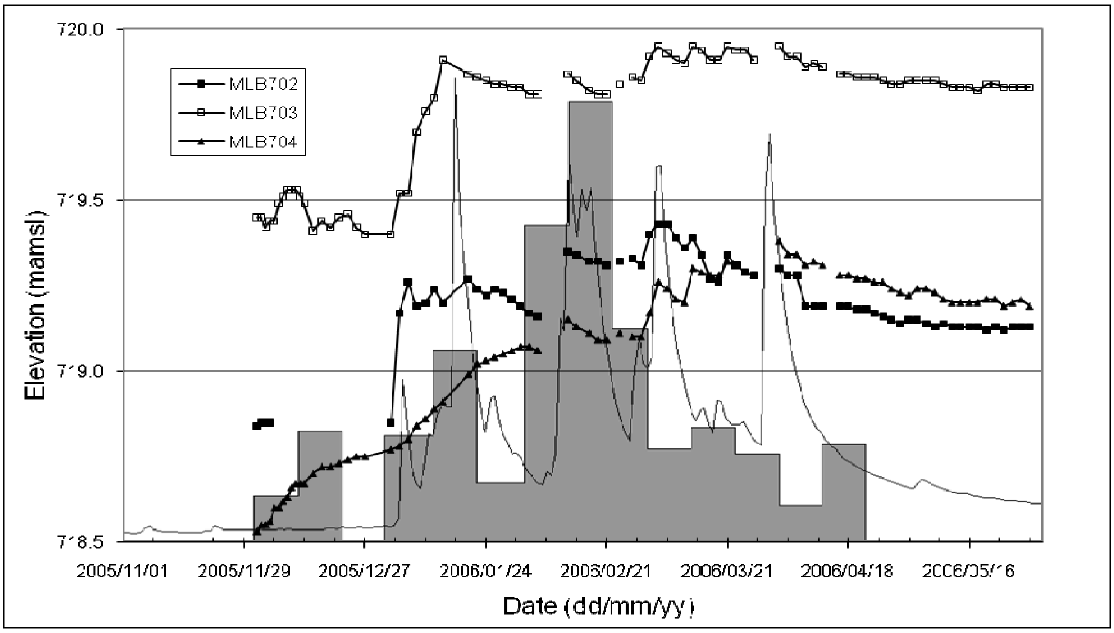


Figure 5.14 Groundwater table fluctuations November 2005 to May 2006 for T7 (refer to Figure 5.1 for the scales associated with the rainfall and stream flow data)

5.3 Discussion of groundwater level changes

Groundwater monitoring on all piezometers did not commence on the same day due to the fact that drilling all holes manually could not be done the same day. In addition, boulders beneath the soil did not allow some holes to penetrate as deeply as others. However, these constraints have not affected the interpretation of the results as the main wet season groundwater response has been captured within all transects. The deepest piezometer (3.19m) is MRB306 (farthest from the river), which is located at the end of T3 (Figure 5.7); while the shallowest (0.75m) one is MLB404, located at the left bank of T4 (Figure 5.9).

One of the first observations is that some of the interpretation of the results is hampered by some problems with the experimental design. The author was very reliant upon the field technicians to collect the data accurately and while this appears to have been generally successful, there are some gaps that impact on the interpretation of the data. Specifically, there is some evidence to suggest that the local rainfall did not end at the beginning of March 2006 and the records have been extended using the more distant (1 km from the wetland area) observations from the Agricultural Extension office. While there were insufficient resources available to the study to measure channel flow at each transect at the same time as the groundwater level observations, in retrospect it would have been useful to measure channel water levels at the same time as the piezometer water levels were monitored. This information would have helped to better understand the variations in flow in the channel through the wetland during the whole of the wet season.

At the start of the 2005/2006 wet season the variation in water levels across some of the transects was relatively low, while the variation at the end of the season was much greater (T1 and T3). However, in other transects (T2, T4 and T5, for example) the variations during the wet season were relatively minor. Most piezometers showed a gradual increase in water table level at the start of the wet season, while some others showed a drying tendency. Almost all transects show a flow gradient towards the river, while in some cases there are local gradients towards depressions in the wetland surface. The fluctuations in the water level varied from transect to transect as well as within transects. Transect 1 showed the greatest variations (between 1.1 and 2.0m, with the exception of MRB101 next to the channel), while T5 showed the lowest range of variation (mostly between 0.3 and 0.6m). Most of the sites closest to the river channel showed the lowest variations. The soils near the river channel are sandy and well drained in nature (Kotze, 2005) and these smaller variations in water level possibly reflect the presence of rapid lateral flow processes.

The fluctuations in water level appear to be more strongly associated with the stream flow variations reflected at the gauge (B7H013) located downstream of the wetland. The lower part of the wetland is characterized by sandy and more permeable soils, allowing for more rapid movement of water, both vertically and laterally. In this part of the wetland, any increase in storage in the wetland due to rainfall may be lost shortly after the event through lateral flow to the river. This may be one explanation for some of the rapid water table surface elevation changes observed for T6 (Figure 5.13). A further possibility that is difficult to explore in more detail without more data is that the river flow from upstream is influencing the water tables in some of the transects. It has already been noted that some of the moderate to low flows generated upstream of the wetland are diverted at the gabion dam (Figure 2.3). This water is assumed to infiltrate into the wetland environment through boulder beds and then flow back to the river through drains or subsurface flow. This is in agreement with the results of the stable isotope (^{2}H and ^{18}O in Figure 5.15) and hydrochemistry analysis (Figure 5.18) in that the drainage water reflects the isotope and chemical signatures of the river water. These processes could have affected water levels in some of the upstream transects (notably T1 and T2). There are also many small tributaries that flow into the main channel across the wetland and depending on the spatial patterns of rainfall over the surrounding hill sides, these could have runoff responses that are very different to those reflected at the B7H013 gauge. These tributary inflows could also be affecting the water levels in some of the transects.

The mean water table surfaces in all transects (Figures 5.2, 5.4, 5.7, 5.9, 5.10 and 5.12) show gradients in the water table along the transects towards the channel, suggesting inflow from the slopes. Whether this inflow is derived from surface runoff onto the wetland surface, or as subsurface flow is difficult to determine from the available data. The upstream part of the wetland is affected by artificial drains (Figure 2.7), although the exact location of these with respect to the transects has not been recorded. The influence of these drains could be partly responsible for the relatively low degree of variation in most of the piezometers of T2. Further details of the local conditions within each transect are provided in Table 5.1.

Monitoring shallow water levels by piezometers is standard hydrological practice; however, it is difficult to determine if the results have been affected by any deterioration in the performance of the tubes during the duration of the project. Butler (1998) confirmed that piezometers can be partially filled with soil, either as a result of vandalism or collapse of the tube. Every effort was made during the installation of the piezometers to avoid such problems and the assumption is that they have not substantially affected the observations over a single wet season.

Table 5.1 Summary of water level variations in the study area during November 2005 to May 2006

Transects	Water table characteristics	Location characteristics
T1	Shows a relative rapid increase at the beginning of the wet season, after which the levels are highly variable. MRB101, close to the river shows lower variations but has a more significant recession at the end of the wet season, relative to other piezometers.	Drained by three natural drains; dominated by reeds at western side, river is very close to the ground surface, farming towards, the river, and subsurface material with many cobbles and boulders.
T2	Initially gentle increase followed by variable increase (except MRB206), finally none showed increase/decrease after March 2006.	Highly waterlogged portion; two natural and two man-made drains, reeds dominate, undulating terrain; dark brown soil.
T3	Water level increased in some piezometers at the start of the wet season, the rest showed no change until the initiation of main channel stream flow. No evidence for an end of season recession.	One of the drier portions of the wetland
T4	The right bank of the transect shows some drying tendency at the start of the wet season with fluctuations thereafter. At the end of the wet season all sites show a gentle recession towards similar levels at the start of the season.	Right bank: Boulders and other sediments; reeds, no drains, bank erosion, farming, river braiding and branching, domestic fishing Left bank: receives runoff from dolomite hill, dominated by reeds and water logging, farming.
T5	MLB505 is the most responsive site, which may be linked to its location in a depression. Groundwater levels do not show an obvious response to two instances of surface inundation. No real recession at the end of the season, but water levels finish at similar levels as the start of the season.	Left bank of the river, boulders underneath, bank erosion, farming close to the river, many springs and about 20 ha marshy land at the foot of dolomite mountain.
T6	Variations in water levels closely reflect variations in observed stream flow. The only transect to demonstrate a clear recession in water levels at the end of the wet season.	Left bank: farming dominates; not many reeds, totally waterlogged, boulders and pebbles towards the river, no drains, stagnant water, hence, domestic fishing

This investigation has attempted to show whether there are relationships between groundwater, surface water and rainfall at the Kudumela wetland site, but there are many confusing signals within the available data. Some of the confusion is related to the fact that it was not possible to collect key items of information. However, the importance of some of this information only became evident when the results were analyzed. Some of the confusion is almost certainly associated with the complexity of the surface and subsurface interactions prevailing in this wetland. Very few of the piezometers show any clear relationships with the measured local rainfall inputs, suggesting that other processes are playing equal or more important roles. These processes could include inflows from the adjacent hill slopes (either surface or subsurface or both), interactions with flow in the channel and the effects of artificial drains. There is some evidence within the data for all of these processes, but it is not conclusive.

One of the important observations that has been made is that the research resources required satisfactorily quantifying and understanding wetland processes are substantial. Many valuable lessons have been learned from this study. While the Kudumela wetland is relatively small, it is apparent that the hydrological processes within it are quite complex. Perhaps one of the failures of the initial experimental design was to under-estimate this complexity.

5.4 Environmental isotopes and hydrochemical analysis

5.4.1 Deuterium (D or ^{2}H) and Oxygen-18 (^{18}O) analysis

Three sets of environmental isotope samples (9 samples in May 2006, 8 samples in December 2006 and 22 samples in April 2007) were collected and analysed during the entire study period (Table 5.2 and Figure 5.15). The $\delta^{18}O$ and δD values of 39 water samples from the river, drains, boreholes and springs are listed in Table 5.2. The $\delta^{18}O$ and δD values of these water samples and the global meteoric water line (GMWL), with the equation $\delta D = 8\ \delta^{18}O + 10$ as described by Craig (1960) and the local meteoric water line (LMWL) are shown on Figure 5.15.

Eight of the May 2006 samples line-up above the GMWL and one of the right bank springs (Ditolong) plots on the line. Two of the right bank springs plot slightly to the right of the LMWL, indicating that they are isotopically depleted. All of the December 2006 samples plot far above the GMWL and one of the right bank springs lies to the right of the LMWL for the reasons mentioned above. The downstream river sample (FM006) showed enrichment ($\delta^{18}O$ = -4.81 and

δD = -19.30), while one of the right bank springs (FM007) shows depletion (δ^{18}O = -5.88, δD = -34.30). As with the December 2006 samples, all April 2006 δD and δ^{18}O values line-up above the GMWL. The Auger hole at MRB302 plotted on the LMWL, while the Mashushu borehole (FM045) and river water at T2 environment (after manmade drains) lie very close to the LMWL and the rest are above the LMWL. The Vallis (FM019) borehole sample plots to the right of the LMWL and is depleted (Figure 5.15). Overall, it is observed that the samples in the δD and δ^{18}O diagram are generally far above and slightly displaced to the left of the GMWL

The δD and δ^{18}O isotopic composition for the groundwater at T1, T3, and T5 farthest from the river are different from that of the groundwater closer to the river. In this case, the groundwater at the piezometers (MRB104, 302 and MLB510) farthest from the river has a depleted isotopic signature (more negative) than MRB101. MRB101, with the values (δD = -23.80 and δ^{18}O = -4.70) being more similar to the river isotopic values (δD = -23.90 and δ^{18}O = -4.72) at T1 (see Figure 5.5 for their location). These patterns are consistent with infiltrating river water as the main source of water for the piezometers close to the river. The more depleted signature for groundwater in the piezometers farthest from the river suggests that this water does not originate from infiltrating river water under base flow conditions.

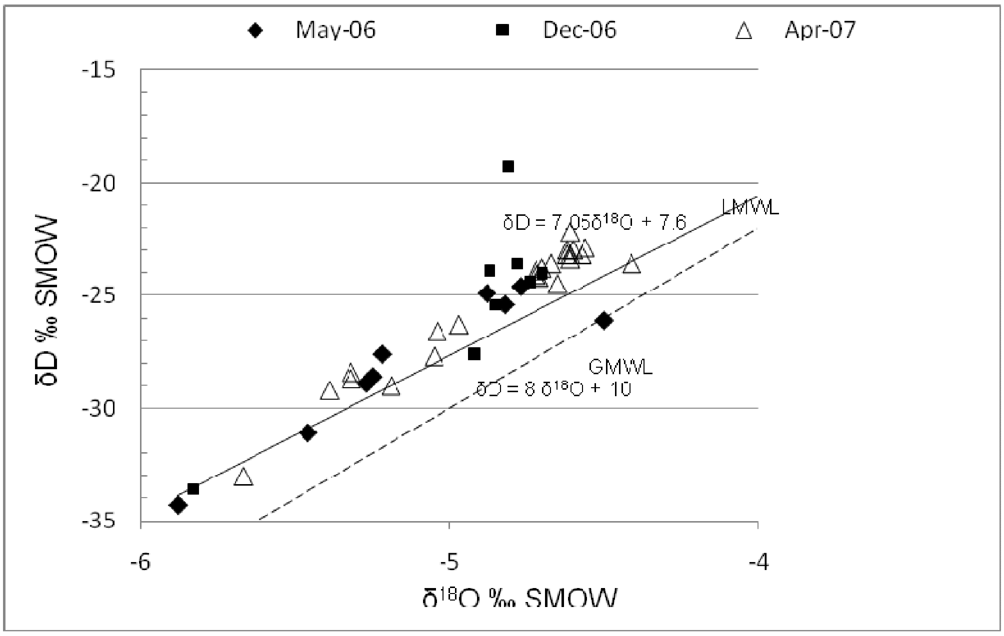


Figure 5.15 Deuterium and Oxygen-18 plot for water samples during, May 2006, December 2006 and April 2007

The isotopic composition of water samples in the study area during low-flow (May 2006 and April 2007) and high-flow (December 2006) periods were similar (Figure 5.13) and no seasonal variations were observed. Regression analyses of δD and ^{18}O yielded:

For May 2006 $\delta D = 7.09\ \delta^{18}O + 8.35$, $r^2 = 0.86$
For December 2006 $\delta D = 9.49\ \delta^{18}O + 21.63$, $r^2 = 0.73$
For April 2007 $\delta D = 9.97\ \delta^{18}O + 23.36$, $r^2 = 0.81$.

This non-seasonal variation and the LMWL equation of May 2006 is similar to the results obtained by Turner et al (1987) in the Salmon Catchment in Australia and International Atomic Energy Agency (IAEA) Pretoria meteoric water line equation ($\delta D = 7.05\ \delta^{18}O + 7.6$) (GNIP). The coefficient of variations (CV) for δD during May 2006, December 2006 and April 2007 are -0.12, -0.11 and -0.09 respectively, indicating that there is no significant seasonal variation.

Figure 5.16 illustrates the different isotopic signatures according to the source of the water. The springs and groundwater samples appear to form a distinct group, albeit with a wide spread, while the drains and river water generally cluster together. The auger hole samples are quite variable with those associated with upstream transects grouping with the drains, while those associated with the downstream transects more similar to the spring signatures. The indications are that the springs have a highly variable signature which may suggest that there are different types of springs to be found in the area, some that are directly associated with groundwater and some that are associated with the drainage of sub-surface water circulating above the general level of the regional water table (Hughes, 2010).

Table 5.2. δD and $\delta^{18}O$ isotopic values during the study period at the Kudumela Wetland

Sample description	Sample ID	May-06		December-06		April-07	
		$\delta^{18}O$ ‰ SMOW	δD ‰ SMOW	$\delta^{18}O$ ‰ SMOW	δD ‰ SMOW	$\delta^{18}O$ ‰ SMOW	δD ‰ SMOW
River upstream	FM002	-4.77	-24.6	-4.74	-24.4	-4.67	-23.6
River downstream	FM006	-4.88	-24.9	-4.81	-19.3		
River 2, downstream	FM012			-4.87	-23.9		
River 3, T1	FM015			-4.78	-23.6		
River after Jordaan Spring	FM030					-4.72	-24.1
River100m above Jordaan spring	FM033					-4.61	-22.2
River upstream from Vallis crossing	FM042					-4.97	-26.3
River upper crossing T1	FM036					-4.72	-23.9
River at Vallis crossing	FM037					-4.41	-23.6
Upstream LB Spring	FM001	-4.82	-25.4				
LB Spring 2	FM003	-5.27	-28.9				
LB Spring 3	FM004	-5.25	-28.6				
RB Spring 1 (Ditolong)	FM005	-4.5	-26.1				
RB Spring 2	FM007	-5.88	-34.3				
RB Spring 3	FM008	-5.46	-31.1				
Jordaan Spring	FM024					-4.71	-24.2
Loumauwe Spring	FM025					-5.32	-28.4
T5 Spring	FM026					-5.39	-29.2
RB drain 1	FM016			-4.7	-24	-4.57	-23.2
RB drain 2	FM017			-4.85	-25.4	-4.65	-24.5
Drain 200m south of T1	FM029					-4.61	-23.2

Table 5.2 continued

Sample description	Sample ID	May-06		December-06		April-07	
		$\delta^{18}O$ ‰ SMOW	δD ‰ SMOW	$\delta^{18}O$ ‰ SMOW	δD ‰ SMOW	$\delta^{18}O$ ‰ SMOW	δD ‰ SMOW
Drain 400m N of T1	FM039					-4.62	-23
Drain 50 m S of T1	FM040					-4.56	-22.9
Drain 400m S of T1	FM041					-4.62	-23.2
Drain 200m S of T1	FM047					-4.61	-23.4
Drain at T206	FM044					-5.04	-26.6
Auger hole at T501	FM009	-5.22	-27.6			-5.32	-28.7
Auger hole at T101	FM023					-4.7	-23.8
Auger hole near T104	FM031					-4.9	-25.3
Auger hole at T302	FM034					-5.19	-29
T2 Auger hole	FM028					-4.6	-23
Vallis borehole	FM019					-5.67	-33
Mashushu borehole	FM045					-5.05	-27.7

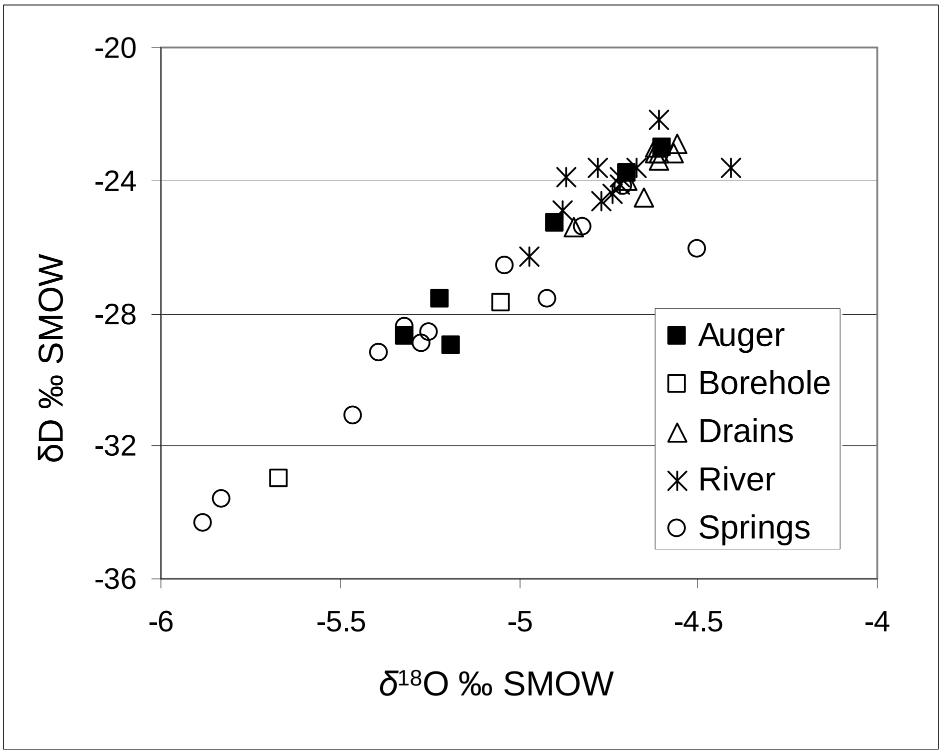


Figure 5.16 Deuterium and Oxygen-18 plot for water samples based on water source

5.4.2 Electrical Conductivity and Total alkalinity

Four sets of water samples (2 sets of samples each in the summer and winter seasons) were planned for the analysis of electrical conductivities and total alkalinities. This is clearly shown on the project planning and schedule table (Table 4.1). The electrical conductivity (EC) and total alkalinity (TA) results for May 2006, December 2006, April 2007 and November 2007 are summarized in Table 5.3. In May 2006, 10 samples were analyzed; while in December 2006, April 2007 and November 2007, 7, 24 and 10 samples were analyzed respectively. EC was high in the Vallis borehole during the high-flow period (November 2007, 681µS/cm and April 2007, 554µS/cm); indicating that some kind of ionic compound was dissolved in the groundwater. However, Mashushu Village borehole (approximately 3km from Vallis borehole upstream) showed an EC of 307 and 291µS/cm during April and November 2007, respectively. This site shows the opposite seasonal trend to the Vallis borehole but the seasonal differences are small and possibly not significant. During May 2006, the lowest electrical conductivities (78 and 83µS/cm) were observed in the upstream left bank spring1 (FM001) and river upstream

(FM002) respectively. The highest EC values (461µS/cm) were observed in the left bank spring (FM004). In December 2006, the lowest EC (120µS/cm) was observed in T101 drain (FM016); and the highest (381µS/cm) was in the right bank spring 2 (FM007).

In all water samples (including boreholes), higher electrical conductivities were observed during the start of the high-flow season (November 2007) than the low-flow season (May 2006 and April 2007), although this is not evident from the December 2006 data (Figure 5.17). A possible explanation is that during the early part of the wet season surface runoff dissolves ions from surface soils (Ecos Environmental Consulting, 2009). In addition, salts from individual septic tanks (there is no common septic tank) and roads during high flows could contribute to the increase in EC. Moreover, agricultural drainage and local catchment runoff could be contributing salts (DLWC, 1998). Evaporation of water from the surface of a wetland concentrates the dissolved solids in the remaining water contributing to higher EC values (Ecos Environmental Consulting, 2009). After the Vallis borehole sample, the next highest EC values are measured in the two right bank springs (381µS/cm and 416µS/cm) suggesting that deeper sub-surface flows have the highest salt concentrations.

Figure 5.17 illustrates that electrical conductivity increases with alkalinity for all water samples. The results of May 2006, December 2006, and April 2007 show very similar trend lines. However, the slope relationship between total alkalinity and electrical conductivity during November 2007 is higher compared to the other samples, and the highest electrical conductivity is observed for Vallis borehole (Table 5.3), indicating that groundwater is more saline than other water samples.

Table 5.3 Summary of Electrical Conductivities (EC) and Total Alkalinities (Talk) during May 2006, December 2006, April 2007 and November 2007 at the study area

Sample Description	Sample ID	May-06		Dec.-06		Apr.07		Nov.07	
		EC (µS/cm)	Talk(meq/l)	EC (µS/cm)	Talk(meq/l)	EC (µS/cm)	Talk(meq/l)	EC (µS/cm)	Talk(meq/l)
River upstream	FM002	83	49	115	68			167	28
River downstream	FM006	193	124	247	168				
River ds (below bridge1)	FM012	241	166						
River at T1	FM015			171	105				
River, 100m ds of Jordaan Spring	FM030					176	107		
River, 100m above Jordaan Spring	FM033					114	71		
River at upper crossing, T1	FM036					163	103		
River at Valis crossing, b/nT2 & T3	FM037					206	112		
River at upper causeway T1	FM042					164	90		
U stream LB Spring1	FM001	78	34					93	27
LB spring 2	FM003	189	129						
LB spring 3	FM004	461	286						
RB spring 1 (Ditolong)	FM005	159	95						
RB spring 2	FM007	288	193	381	254				
RB spring 3	FM008	280	193	416	288				
Jordaan Spring	FM024					150	93	227	42
Loumauwe Spring	FM025					225	120	229	45
LB Spring, T5	FM026					313	200		

Table 5.3 continued

Sample Description	Sample ID	May-06		Dec.-06		Apr.07		Nov.07	
		EC (µS/cm)	Talk(meq/l)	EC (µS/cm)	Talk(meq/l)	EC (µS/cm)	Talk(meq/l)	EC (µS/cm)	Talk(meq/l)
RB drain, T1	FM016			120	76	137	73	138	31
RB drain, T2	FM017			184	127	204	134	198	49
Drain,200m South of T1	FM029					151	85		
Drain between T2 & T3	FM035					310	183		
Drain, 300-400m south of T1	FM039					135	88	307	80
Drain, 50m south of T1	FM040					140	81		
Drain at T2	FM041					204	122		
Drain at T206	FM044					294	178		
Drain, 200m south of T1	FM047					147	78	293	77
Auger hole, T510, LB	FM009	356	200			392	254		
Auger hole, T1	FM023					263	112		
Auger hole, T202	FM028					232	134		
Auger hole at T104	FM031					213	103		
Auger hole at T302, depth=2.80m	FM034					383	234		
Mashushu borehole, tap-water	FM045					307	168	291	76
Vallis borehole, from tap water	FM019					554	337	681	167

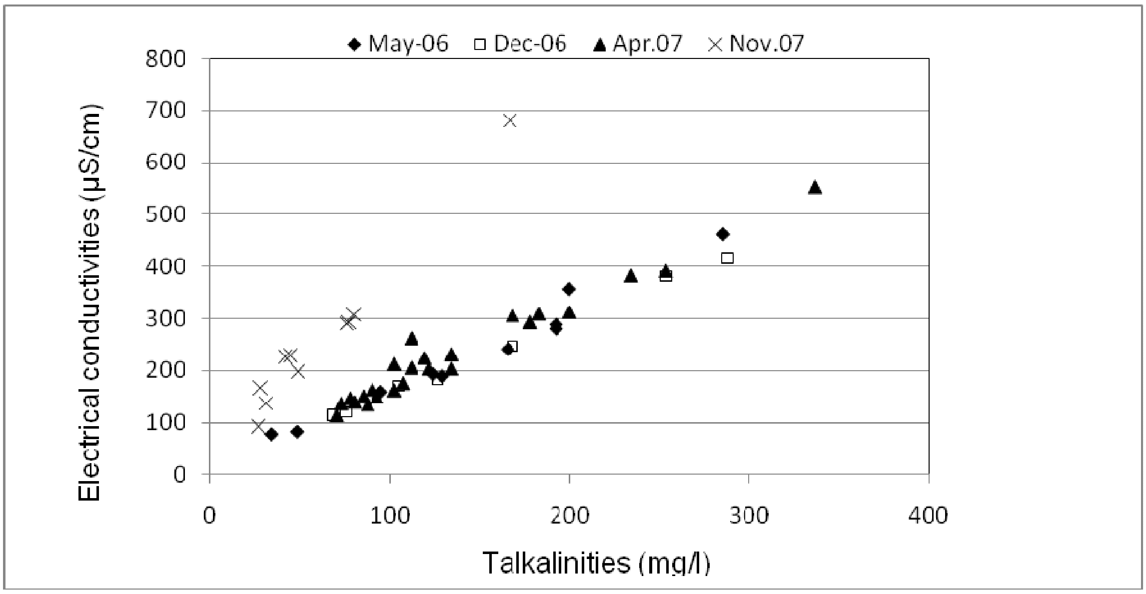


Figure 5.17 Total alkalinity against electrical conductivity during May 2006, December 2006, November 2007 and April 2007

5.4.3 Major ion chemistry

A subset of the November 2007 samples were subjected to more detailed ionic analyses (Cl, SO_4, NO_3, HCO_3, Ca, K, Mg and Na ions) and these results are presented in Table 5.4 and Figures 5.18 to 5.23. The major ion chemistry result shows that HCO_3 is the dominant anion (5.57meq/l) followed by chloride (0.63meq/l). The dominant cation is calcium (3.63meq/l) closely followed by Mg (3.31meq/l). Overall, it was observed that Vallis borehole contains relatively elevated HCO_3, calcium, magnesium, chloride, sodium and SO_4. Since groundwater mostly occurs in association with geological materials (such as carbonate rocks) containing soluble minerals, high concentrations of dissolved salts are normally expected in groundwater relative to surface or near-surface waters (rivers, wetlands, lakes, drains). If springs are associated with the interaction of the water table with the surface they would be expected to have similar chemical signatures. However, if the springs are associated with perched aquifers or fracture zone flow above the general water table (Hughes, 2010) they might be expected to have intermediate ionic signals related to shorter residence times. The latter types of springs appear to dominate within the study area based on the chemistry data, although the isotopic data suggested a mixture of spring types. The type and concentrations of salts in all sub-surface water will depend on the geological environment, the source and residence time of the water

(Hem, 1985). Nitrate values were found to be below the detection limit in four of the six samples. However, the Jordaan Spring and River downstream sites both had nitrate values of 0.02meq/l each indicating possible contamination. In summary, Ca-Mg-HCO_3 type of water was observed at the study sites, with the exception of the T1 drain sample. The samples were clustered together in the cation triangle and fall under Ca-Mg-HCO_3 type of water indicating the same source of origin. The drains reflect river water rather than dolomite water. Tables 5.2 and 5.4 suggest that depleted $\delta^{18}O$/ δD values are associated with higher concentrations of HCO_3, Ca, Mg, Na, Cl, and SO_4.

Table 5.4 Summary of anion and cation analysis during November 2007 at the Kudumela Wetland

Sample Description	Cl (meq/l)	SO_4 (meq/l)	NO_3 (meq/l)	HCO_3 (meq/l)	Ca (meq/l)	K (meq/l)	Mg (meq/l)	Na (meq/l)
River us	0.12	0.05	0	0.9	0.41	0.02	0.4	0.12
T1 drain	0.13	0.04	0	1.03	0.66	0.02	0.61	0.14
T2 drain	0.15	0.04	0	2.67	1.63	0.02	1.51	0.17
Jordaan Spring	0.13	0.03	0.02	1.4	1.17	0.03	1.13	0.14
Valis borehole	0.63	0.34	0	5.57	3.63	0.08	3.31	0.77
River ds	0.13	0.05	0.02	0.93	0.84	0.02	0.82	0.13

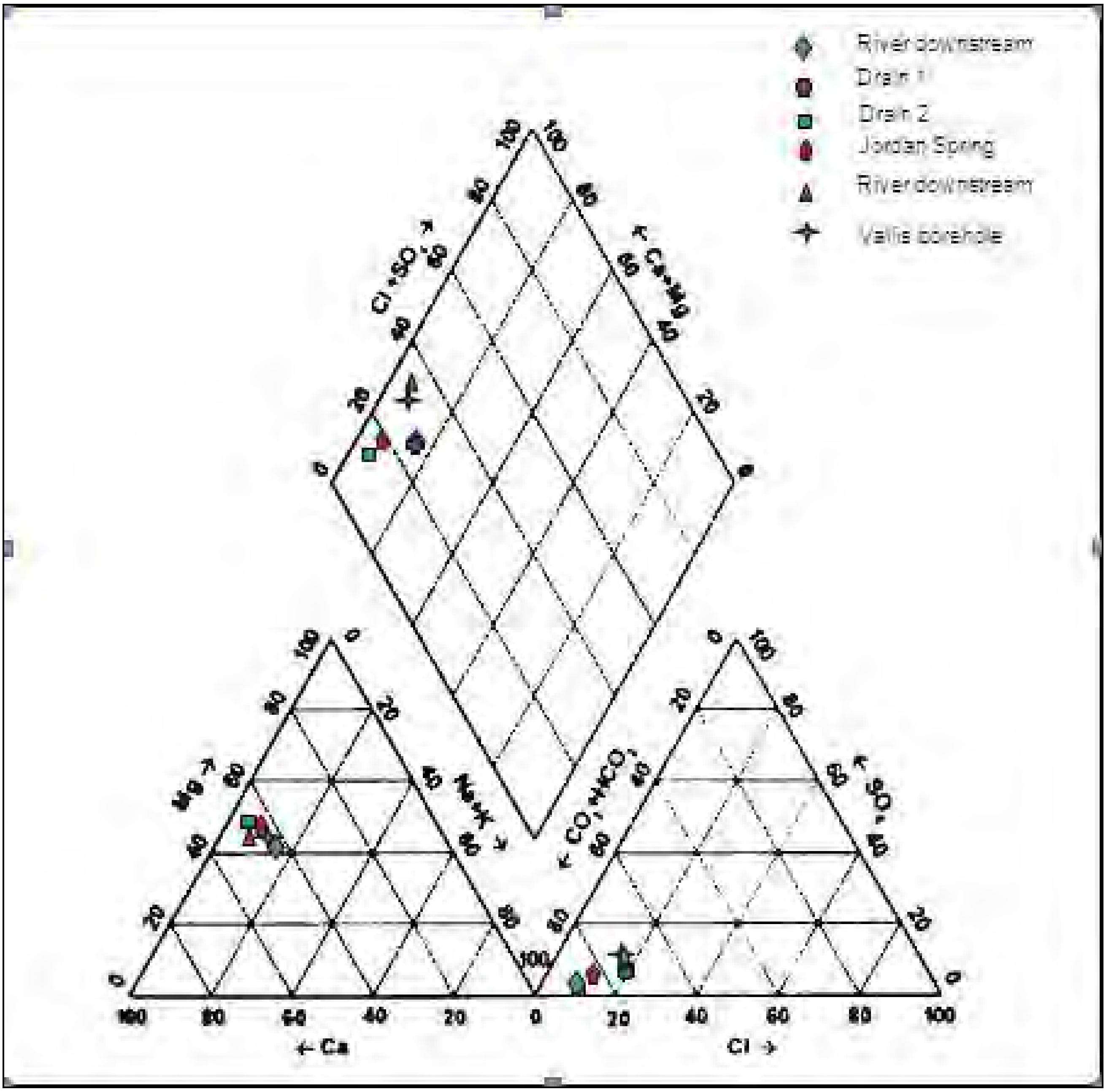


Figure 5.18 Piper diagram for selected water samples

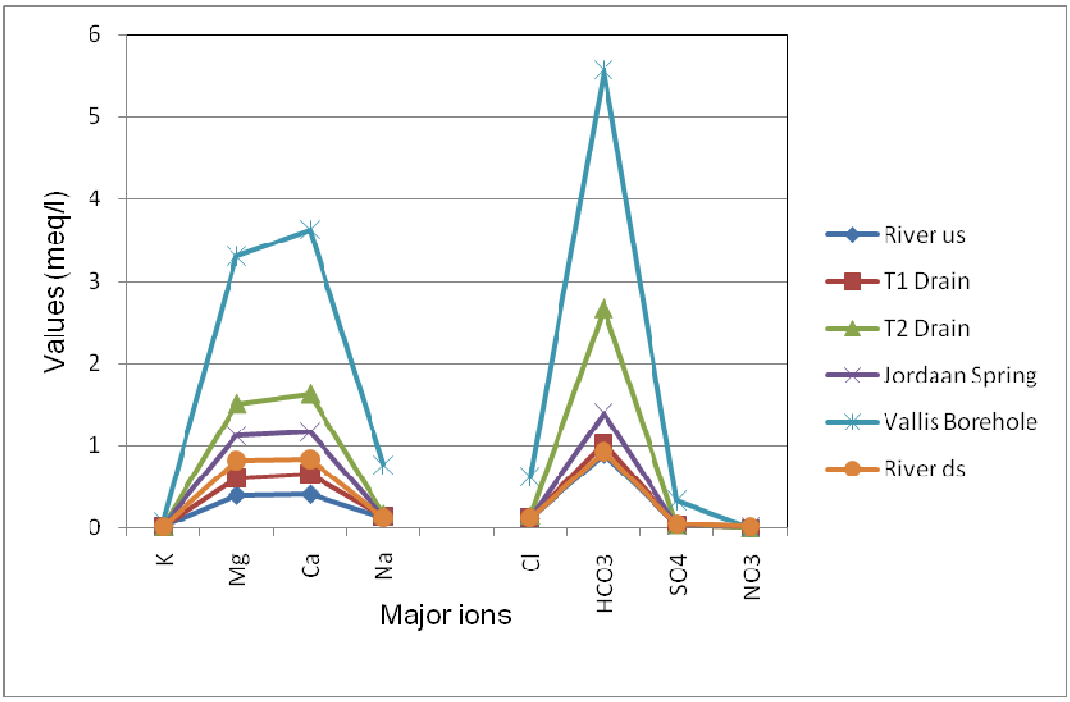


Figure 5.19 Schoeller diagram (River upstream, Drain T1, Drain T2, Jordan Spring, Vallis borehole, and River downstream)

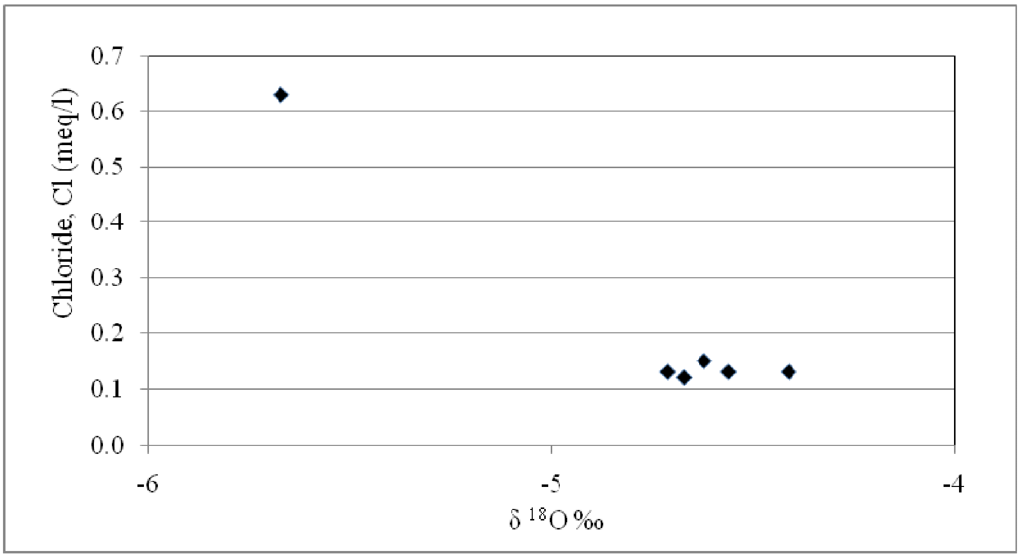


Figure 5.20 Chloride versus δ^{18}O

Table 5.4 and Figure 5.20 show that chloride concentrations for all water samples remain nearly the same (0.12, 0.13, and 0.15meq/l) except Vallis borehole (0.63meq/l). The reason for an elevated concentration of chloride when $\delta^{18}O^0/_{00}$ value is depleted is not clear.

Figure 5.21 shows that for surface waters, as calcium values increase, sulfate concentrations remain much the same, while the highest concentrations of both calcium and sulfate were observed in the Vallis borehole. The relationship between chloride and sodium is very similar for all the sources of water (Figure 5.22). Figure 5.23 show the close relationships between calcium and both total alkalinity and TDS.

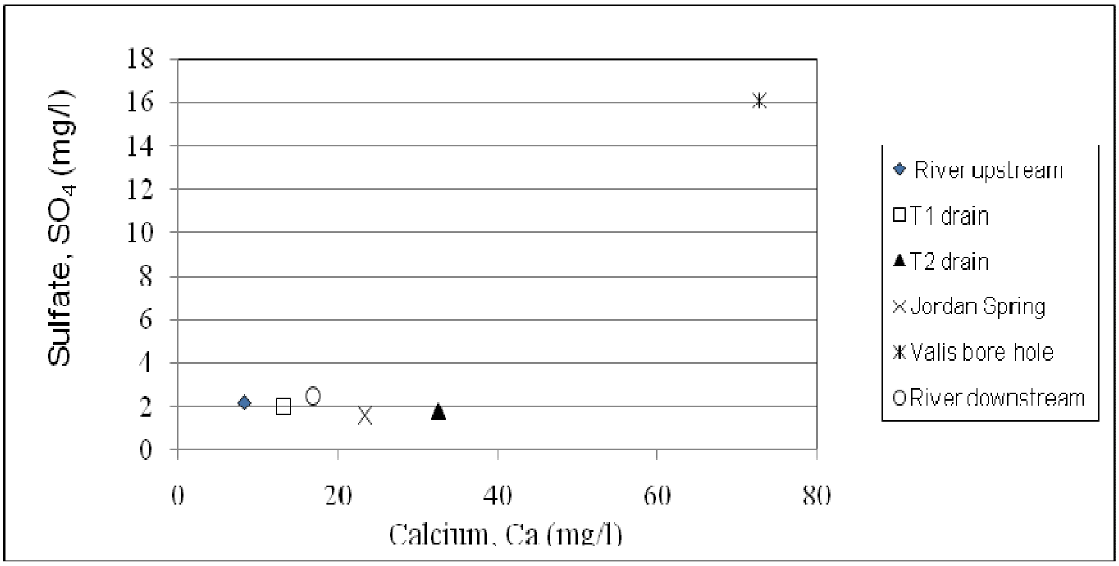


Figure 5.21 Sulfate versus calcium

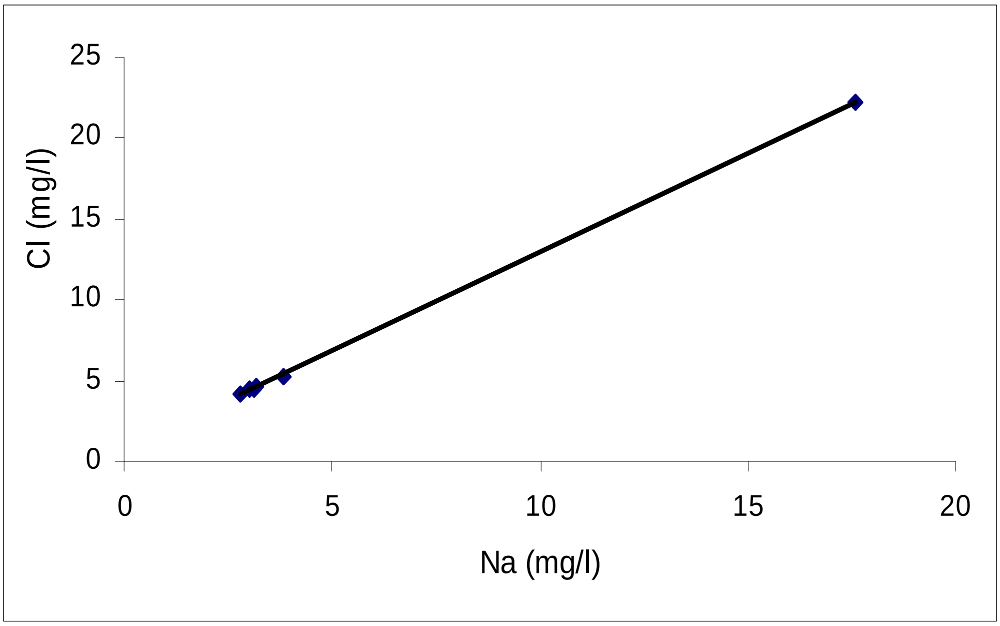


Figure 5.22 Chloride versus sodium

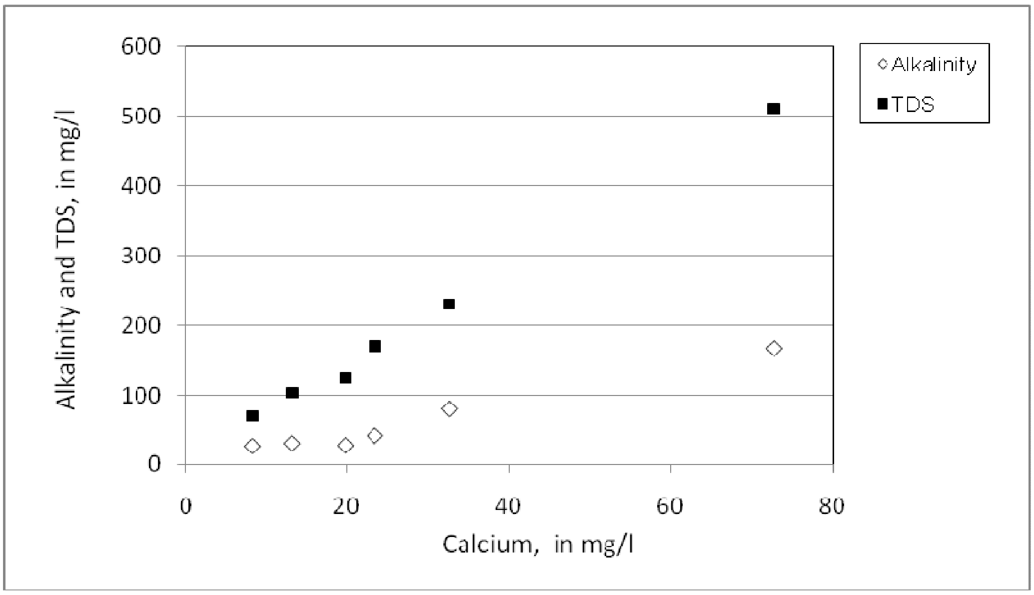


Figure 5.23 Total alkalinity and TDS versus calcium

5.4.4 Tritium Analysis

Tritium values for river, springs, drains, auger holes, boreholes and rainfall samples are shown in Table 5.5 and Figures 5.24 to 5.26. The most noticeable trend within these data are the high variations in tritium values across the various springs that were sampled, which is consistent with the variability in the isotopic signatures of the spring water. This further strengthens the argument that the spring waters come from different sources with different residence times and ages. The cause for high concentration of tritium (3.5 TU) for Spring1 (FM001) during May 2006 could be that during the study period, new rainfall water entered the spring storage and mixed with old water. The tritium values for the river water samples are much more consistent, but do not show any strong seasonal variations, while it might have been expected that the dry season river samples would show up as older water originating from sources with longer residence times.

The single borehole sample appears to be the oldest water (0.3TU), which would be expected as the concentration of tritium in groundwater decreases by radioactive decay (Moran and Hudson, undated; Poreda et al., 1988). The drain samples are of the same order of magnitude as the river water suggesting that the drainage water has a short residence time in the wetland. The majority of the auger hole water samples are also similar to the river water and have relatively high tritium values. However, the sample taken at T5 has a very low tritium value during May 2006, while the sample from the same site during April is more consistent with the other auger hole sites. This may suggest that some spring water is contributing to the wetland subsurface water content during the dry season. However, additional dry season auger hole samples would be needed to confirm this result.

Only comparative ages of water samples are referred to and no absolute aging of water based on tritium has been attempted. While these comparative values have provided some information about the age and possible movements of water in the wetland environment, a more intensive and better planned programme of tritium analysis would have provided a more complete assessment. It may be concluded that this study has therefore demonstrated some potential for the use of tritium water analyses in wetland studies, but that the sampling scheme used within this study does not provide conclusive answers about different ages (and residence times) of different water sources

Table 5.5 Tritium values during May 2006, December 2006 and April 2007

Sample Description	ID	$\delta^{18}O$	TU
May 2006			
Spring 1(LB)	FM001	-4.82	3.5
Spring 2 (LB)	FM003	-5.27	0.7
Spring 3 (LB)	FM004	-5.25	0.8
Spring 4 (RB)	FM005	-4.50	1.4
Spring 5 (RB)	FM007	-5.88	1.0
Spring 6 (RB)	FM008	-5.46	1.7
River upstream	FM002	-4.77	1.9
River downstream	FM006	-4.88	1.2
Auger hole at T5/10	FM009	-5.22	0.8
December 2006			
River downstream-below ds new bridge	FM006	-4.81	1.8
River at ds new bridge	FM012	-4.87	1.7
River, us culvert, N of Fertilis	FM015	-4.78	2.1
River at T1	FM036	-4.72	1.4
Spring(RB)	FM008	-4.92	1.7
Spring(RB)	FM009	-5.83	1.3
RB Drain, Transect 1	FM016	-4.70	2.3
RB Drain,Transect 2	FM017	-4.85	1.6
April 2007			
River ds of Jordaan Spring	FM030	-4.72	1.4
River us of Jordaan Spring	FM033	-4.61	2.4
River Vallis crossing	FM037	-4.41	1.7
River us	FM002	-4.67	1.7
Auger hole, T5/10	FM009	-5.32	1.4
Auger hole, T1	FM023	-4.70	1.6
Auger hole, T2	FM028	-4.60	1.6
Auger hole, T1/04	FM031	-4.47	1.7
Auger hole, T3/02	FM034	-5.19	1.2
Jordaan Spring	FM024	-4.71	1.3
Loumauwe Spring	FM025	-5.32	0.6
T5 Spring	FM026	-5.39	0.7
Vallis bore hole	FM019	-5.67	0.3

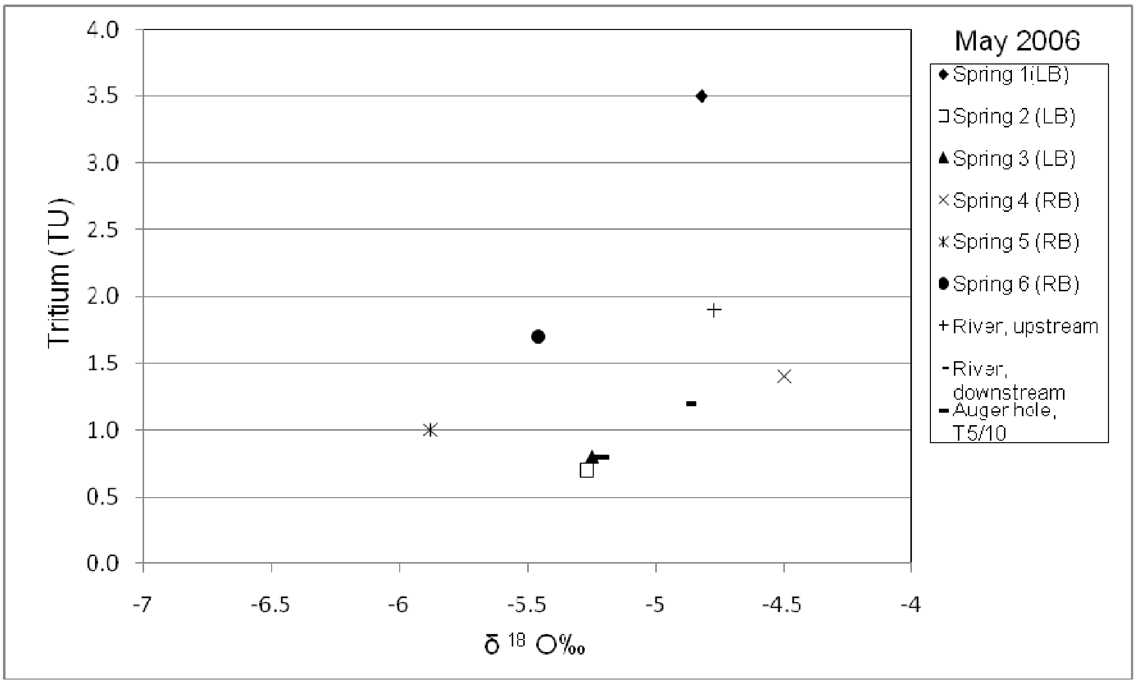


Figure 5.24 Plot of tritium against δ ^{18} O ‰ during May 2006

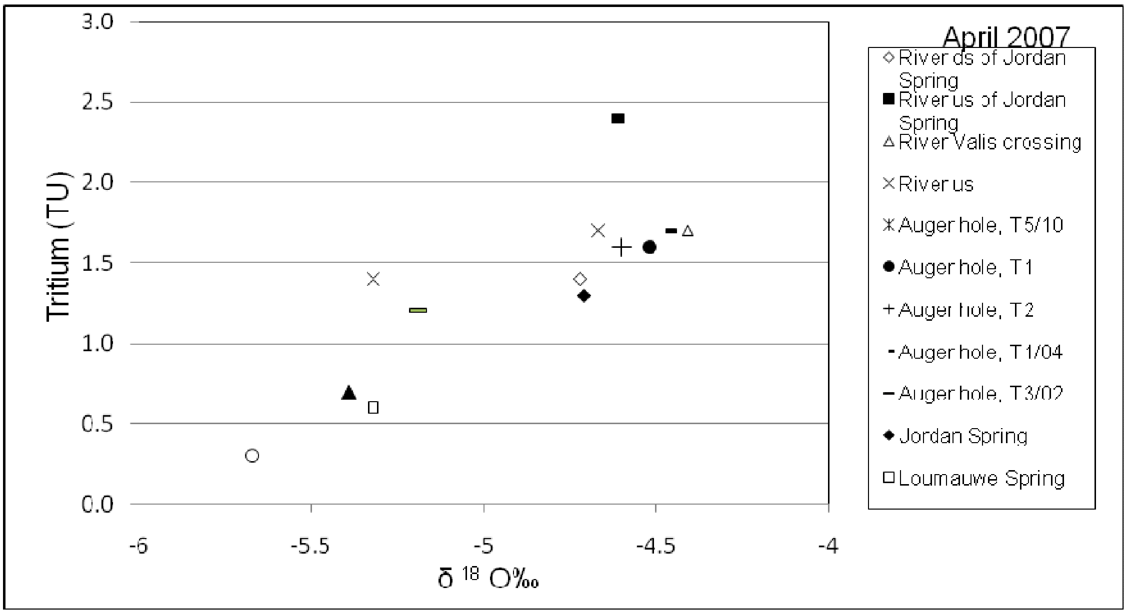


Figure 5.25 Plot of tritium against δ ^{18} O ‰ during December 2006

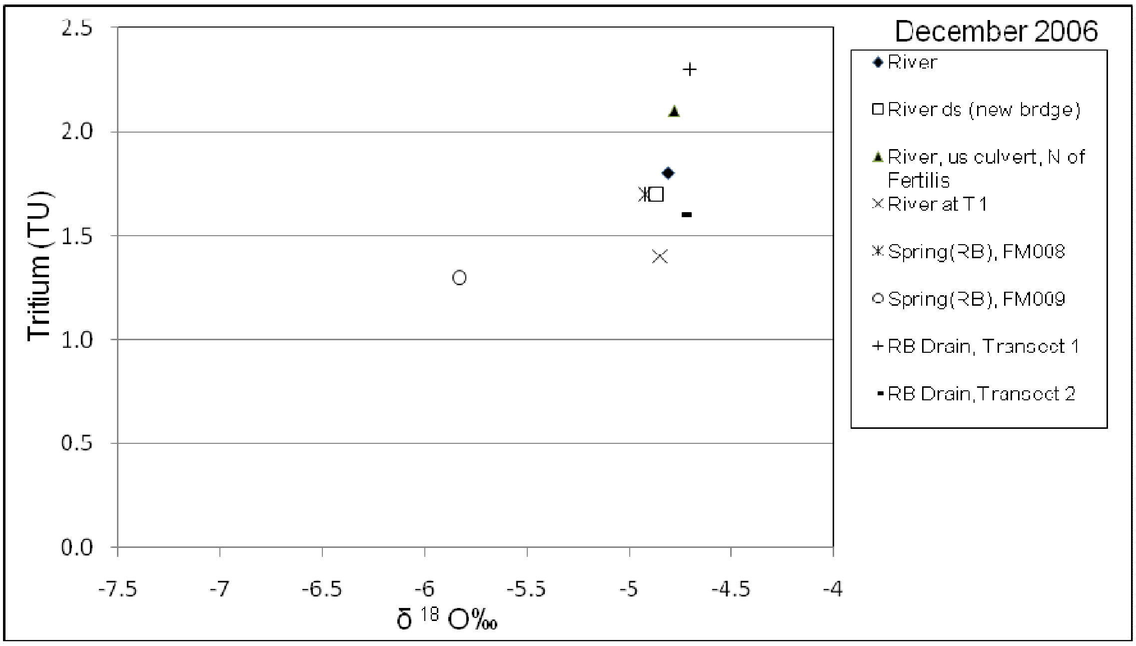


Figure 5.26 Plot of tritium against δ ^{18} O ‰ during April 2007

5.4.5 Discussion

Almost all samples except river at Vallis crossing and a single drain at the end of transect T2 cluster together, indicating that they are from the same origin. This is in accordance with the conceptual model (Figure 5.28) that river water enters the wetland and joins the river within the right bank environment by means of surface drains. Hydrochemistry analysis confirms the environmental isotope results. Piper and Schoeller diagrams (Figures 5.18 and 5.19) indicate that there exists a single water type, dominated by Ca and Mg ions ($CaMg\text{-}HCO_3$). The environmental isotopes and hydrochemistry analysis show that the river water upstream feeds the drains at the right bank of the wetland. Water is lost through Fertilis and Mashushu canals (Figures 4.7 and 5.27), and the same water infiltrates through boulder beds and contributes flow to the wetland. The plots of EC and Total Alkalinity taken during May 2006, December 2006, April 2007 and November 2007 show similar trend lines. This suggests that the major ion analysis in six (6) samples could represent the rest of the samples.

Figure 5.27 Irrigation water loss at Mashushu earth canal, approximately 200m below gabion dam (see Figure 2.5), that could contribute to wetland drains and groundwater

5.5 Water balance of the wetland and conceptual model

Despite gaps in some of the information that is available to quantify the water balance of the wetland a number of observations can be made that are based on the results of the programme of groundwater monitoring, environmental isotope and hydro-chemical analyses. These are illustrated in Figure 5.28 and discussed below.

- Contributions to the shallow groundwater levels within the wetland soils appear to come from different sources depending on the location within the wetland. In the upstream parts of the wetland some water is almost certainly contributed from the artificial diversion (Figures 2.3 and 5.27) of upstream stream flow onto the wetland surface for agricultural purposes, as well as flow from the channel into the upstream parts of the wetland through boulder beds (shown as C-W in Figure 5.28). While local rainfall clearly plays a contributing role, there are some sites where additional contributions from the local catchments draining the valley sides appear to be important. Whether these contributions are predominantly from surface runoff or through shallow sub-surface flow could not be determined.
- Artificial drainage (Figure 2.7) of the wetland soils plays an important role in some transects (notably T1 and T2).
- In most transects the piezometers closest to the river show patterns of water level variations that are similar to the patterns of stream flow variation. This could be interpreted in two different ways; on the one hand it could imply that the river flow is affecting the water levels (i.e. sub-surface flow from the river to the wetland), while alternatively it could suggest that drainage from the wetland is contributing to river flow and that the variation in the amount of drainage closely follows patterns of runoff generation in the rest of the catchment (both processes labelled as C-W in Figure 5.28). Unfortunately, without records of river water levels for each transect it is difficult to determine which alternative is most likely. Two pieces of evidence suggest that the latter is the more likely process. First of all the fluctuations in the piezometers that are remote from the channel in transect T6 are very similar to those close to the channel and while the variations are similar to the measured downstream stream flow, they are not always well correlated (note the water level rises in mid-March). Secondly, transect T5 experienced two inundation events, while the near-channel water levels did not show any corresponding response.

- Over-bank flooding (O-BF in Figure 5.28) from the main channel does not seem to contribute a great deal to the water balance of this wetland and local knowledge suggests that inundation is not a common occurrence. This may be related to the relatively small size of the catchment, which together with the steep topography suggests that flood events will be relatively short lived. The wetland is also crossed by a number of local tributary channels (and artificial drains - Figure 2.7) which will further contribute to short residence times for any inundating water.
- The hydro-chemical data, and to a certain extent the isotope data, suggest that the shallow groundwater in the wetland is not sourced from the regional groundwater (right hand side option for the groundwater level line in Figure 5.28). This conclusion is slightly confused by the differences in the isotope, EC and Total Alkalinity signatures of the two borehole samples, making it somewhat difficult to properly characterize the groundwater. Unfortunately, no observations were made of the regional groundwater table levels and their variations (the water supply boreholes are sealed and could not be accessed with water level sensors), which would have helped to further develop ideas about the links between the regional groundwater and the shallow groundwater in the wetland. It is therefore not clear whether the regional groundwater table is in hydraulic contact (left hand side option for the groundwater level line in Figure 5.28) with the shallow groundwater observed in the auger holes.
- While several valley side springs contribute to the water balance of the wetland, the origin of these springs is somewhat in doubt. Some of them have similar isotope and chemical signatures as the regional groundwater, while others suggest water with lower sub-surface residence times. Figure 5.28 offers three conceptual possibilities for different spring types. S1 type represents springs occurring at the topographic gradient change between the valley slopes and the flatter wetland surface and sourced from the regional groundwater. S2 represents spring flow rising into the lower sediments of the wetland and therefore not visible. S3 represents springs occurring as flow from fracture zones, or perched water tables, above the general level of the regional groundwater table (Hughes, 2010). The evidence suggests that at least S1 and S3 types are present in the Kudumela wetland.

Reports from local people and observations by the author indicate that in November 2005 the river had stopped flowing altogether in the northern part of the study area (approximately 200m above the main road bridge upstream) and that flow recommenced approximately 100m above the Jordaan Spring (FM024, Figure 4.9). When the river flow stopped the Jordaan Spring contributes most of the downstream flow. It is assumed that the river water was infiltrating to the wetland under boulder beds, but no significant flow was observed in the drains at the right bank side. However, in 2006/7 the volume of flow in drains increased significantly and more drains were observed than 2005.

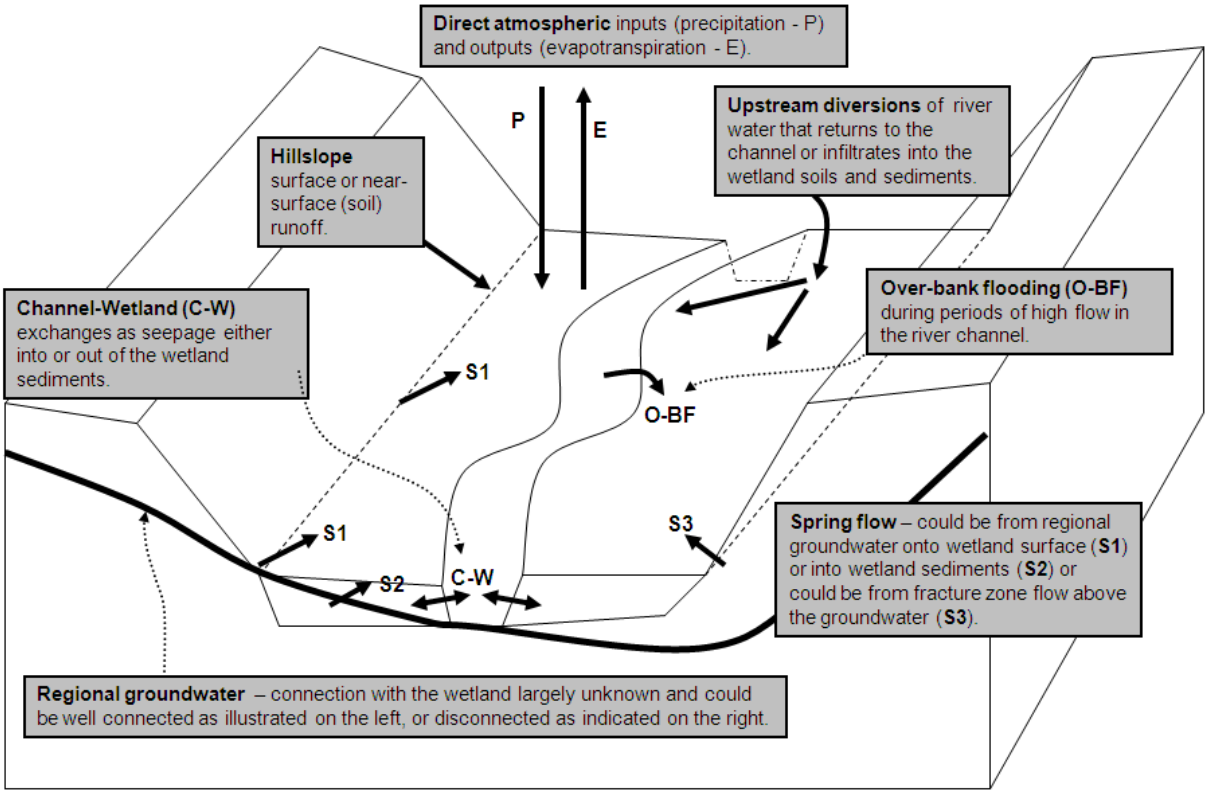


Figure 5.28 Kudumela wetland conceptual model

The close clustering of stable isotope values of water from drains and auger holes in the northern part of the wetland (T2 and T3) and river water samples taken over a period of more than a year indicate that they are fed by one type of water. These values are distinct from those observed in dolomite springs discharging into the valley on both the right bank and the left bank (Vallis area). Tritium values in almost all samples except those from boreholes (could be deeper dolomite water) indicate recent water (less than 20 years). Field parameter measurements on samples on all water sources taken throughout the study period and major ion analysis of selected samples proved a low mineralization Ca Mg-HCO_3 dominant type. From the river (lowest mineralization), there is an increase in concentration of all ions at T1 and T2 drains.

The present understanding suggests that the wetland hydrology is likely to be dominated by local rainfall, surface runoff from the valley sides, and spring flow from recharge on the surrounding hills, evapotranspiration and lateral flow from the wetland to the river (Figure 5.28). Some contributions from channel flow appear to affect the upstream parts of the wetland (via boulder beds) and artificial drains (Figure 2.7) also play a role.

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

To improve the understanding of the hydrology and the origin of water in the Kudumela Wetland, monitoring water table levels, environmental isotope tracers and hydrochemistry were analysed. The results of these analyses, a critical assessment of the gaps in data and understanding and interpretations of the data with respect to the dominant hydrological processes in the wetland are summarised below.

- Tracing shallow water table levels for 7 months indicate that there is no strong correlation with the rainfall data recorded in the wetland during the study period. The relationship between water level fluctuations and rainfall data collected from five rain gauges in the wetland during the study period did not show a strong correlation. Rather the fluctuations of water levels appear to be strongly associated with the stream flow variations reflected at the gauge (B7H013) located downstream of the wetland.
- The relationships between water level fluctuations in the piezometers and flow in the channel could have been understood better if the experimental design had included observations of water levels in the channel adjacent to the transects.
- The existence or non-existence of boulder beds in the lithological sections in all transects of the valley did not account for differences in patterns of water table level fluctuations.
- The elevation of the water levels in all six transects is higher than that of the river datum within the wetland environment, indicating positive hydraulic gradients toward the channel and that the river is gaining flow within the wetland. This is supported by the generally lower fluctuations in the piezometers close to the channel in many of the transects. This conclusion is in agreement with the result of Masiyandima et al. (2006) who reported that the Mohlapitsi River gains flow along the wetland.
- The existence of a hydraulic gradient towards the river, suggests either surface or sub-surface inflow from the adjacent hill sides. Further quantitative information about the hydrological processes in the wetland margins adjacent to the valley sides would have been useful to improve the understanding of these processes.

Most transects showed a gradual increase in water table at the beginning of the rainy season, while some of them indicate a drying tendency which is difficult to explain without more information about events that occurred immediately prior to the study period.

- The water table in the vicinity of transects T1 and T2 rises quickly but does not recede during periods after rainfall events (Figures 5.3 and 5.5). This observation suggests a component of lateral flow from the valley side. The water level responses in piezometers close to the river bank do tend to more closely follow patterns of rainfall, showing increases when it rains and decreases following storm events. However, this may also be a reflection of changes in channel flow closely following changes in rainfall and that the water table levels close to the channel are mainly affected by relatively rapid exchanges with channel water. The soils close to the river bank are sandy and well drained (Kotze, 2005 and Nell and Dryer, 2005) which supports the concept of rapid lateral flow exchanges with the channel. More rapid water level responses are observed in the lower part of the wetland (Figures 5.13), and these appear to be more strongly related to rainfall. This part of the wetland is characterized by sandy and permeable soils, leading to rapid movement of water vertically and horizontally. In the area of transect T6, any increase in storage due to rainfall is lost shortly after the event through lateral flow to the river, as demonstrated by the rapid water table surface elevation changes observed.
- Some of the river flows generated upstream of the wetland at the gabion dam (Figure 2.3) are assumed to contribute to the wetland environment through both channel overflows (largely caused by the artificial gabion dam) and infiltration through boulder beds. At least part of this water flows back to the river through drains or subsurface flow. There is some limited evidence to suggest that this process is influencing the water tables at T1 and T2, but it is not conclusive.
- Measurements of EC and Talk on all water sources collected throughout the study period and major ion analysis on six selected samples proved low mineralization Ca, Mg-HCO_3 type of water.
- The clustering of stable isotope values of water samples from drains, auger holes in the southern part of the wetland and all of the river water samples(except Vallis village crossing) during April 2007, indicated that these water components are derived from a similar source of water.
- The reduction in river flow between the gabion dam and the main road (at upstream bridge) during 2005, the increase of flow in the drains during April 2007, and the clustering of stable isotope values of drains, water tables further south and river water samples, indicate that the upper part of the wetland hydrology is largely driven by inputs from the river water upstream. Field observations, discussions with locals, and the chemical tracer analyses, tend to support this conclusion.

- In other parts of the wetland it is difficult to determine the relative contributions of direct rainfall and inflows of different types (surface or sub-surface) from the valley side slopes.
- Contributions from over-bank flooding do not seem to be important in the hydrology of this wetland, as they do not seem to occur very frequently and even when they do occur they appear to have little impact on the water levels within the wetland soils.
- The results of the groundwater level monitoring programme have demonstrated that both natural and artificial drainage ditches in the wetland contribute to the groundwater fluctuations within transect T2. The relatively low variations compared to other transects suggest more effective drainage processes
- The tritium value during May 2006 for the upstream left bank spring is high (3.5TU). The possible cause for these high tritium values could be that during the study period, some new rainfall water entered the spring storage reservoir and mixed with old water.

The usefulness of environmental isotope tracers and hydrochemistry in tracing water dynamics in the Kudumela Wetland is emphasized in this study. However, there are some limitations related to the costs and logistics of sampling and the cost of laboratory analysis. Secondly, a high level of expertise could be required for sampling and interpretation of the analysis.

6.2 Conclusions

The results presented in this thesis indicate that the wetland is fed partly by the river, partly from local rainfall and partly from lateral inflows from the valley sides. It has not been possible to determine whether the valley side contributions are mainly from surface runoff or from some type of sub-surface flow (i.e. springs). The results of the study do not allow firm conclusions to be reached about the connectivity between the wetland groundwater and the regional groundwater in the dolomitic aquifer. The chemical and isotope analyses certainly suggest that these are different sources of water, while the same data suggest that some of the spring contributions can be derived from the intersection of the regional groundwater with the surface, while others appear to have followed different pathways that may lie within the rocks above the regional groundwater table.

While some of the wetland transects show similar water contents at the end of the 2005/2006 wet season as the beginning, others (T1, T2, T3, T6 and T7) indicate that there are higher quantities of water that are available to drain towards the river throughout the 2006 dry season. While many of these transects also show very small changes in water level at the end of the wet season (except T6), the evidence suggests that the wetland will contribute to sustaining low flows in the river during the dry season. However, the study does not have enough information to be able to quantify this contribution relative to the low flows generated in the upper part of the catchment during the dry season.

With the present level of understanding it is not clear how modifying land-use in the wetland will affect dry season flows in the river. Transect T2 appears to be most affected by artificial drainage and this transect shows the lowest variations in water level of all the transects. It may be tentatively concluded that additional drainage will reduce water level fluctuations within the wetland and therefore possibly affect its ability to contribute to downstream low flows during the dry season. It has not been possible to perform a detailed water balance analysis during the study, as it was not possible to quantify many of the critical components, such as total spring flow contribution, interactions with the regional groundwater and evapotranspiration losses. Remote sensing technologies, such as the use of the Surface Energy Balance Algorithm for Land (SEBAL) can be explored to estimate seasonal evapotranspiration for inclusion into the water balance and more accurate determination of the unknown component of groundwater inflow from the hill slopes.

Due to the enlargement of residential area and wetland converting to agricultural operations, progressive disappearance of the wetland portions at the right bank is clearly observed (see section 2.7). The reason for the recent wetland area reduction could be that groundwater levels decreased as a result of artificial drainage by the wetland users. The satellite images (DWA, 2004) revealed that the wetland area during 1996 – 2004 has reduced by 66%, indicating that in the near future the entire wetland will be converted to agriculture; given that the wetland farmers continue draining the valley bottom.

6.3 Recommendations

It is evident that, in retrospect, there were some serious gaps in the experimental design that have affected the ability of the author to interpret the results that have been obtained. Many of these gaps are associated with the limited resources available to carry out a study of this type. However, this point serves to illustrate the need for careful thought in the design of short-term hydrological field studies which are based on a sound conceptual understanding of the system before the detail of the field monitoring programme is initiated. To achieve the stated objectives of this study, the field data collection design would need to be very carefully planned in order to obtain more quantitative and reliable results that would contribute to an understanding of the functions and processes of the wetland. Therefore, it is recommended that piezometer installation and groundwater monitoring should be strengthened in order to avoid the gaps that currently exist. At the same time it should be recognized that it is not always a straightforward task to develop the conceptual understanding without some field observations.

The seven months shallow water table level monitoring in the transects of the valley improved the understanding of the hydrology of the wetland, but some improvements could be made. The monitoring piezometer holes should be at greater depths to more accurately define the variations, although this does not appear to have affected the results substantially. Installing and maintaining the piezometers needs care. For example, removing any collapsing mud while augering and piezometers must be provided with perforations below and caps on top, and must be protected from human and animal disturbance. Using as many piezometers as possible and monitoring for longer periods can enable a better result in terms of interpreting and understanding the fluctuations of water levels.

Monitoring of water levels in the channel adjacent to the transects should have been included and additional information on the level and gradients in the regional aquifer would also have been useful. More sampling from the existing water sources and analyses (chemical and isotope) should be done in order to obtain a larger sample of environmental isotope tracers and hydrochemistry values. Specifically, repeated samples from the same sources of water may have revealed different patterns of variability, or at least would have helped to conform some of the tentative conclusions that have been reached in this study. One of the data gaps that this study has revealed is the identification of the origin of the water from the various springs in the area. While the data collected have revealed differences, there are not enough data to fully understand the processes involved nor to map spatial variations. Similarly, more field parameters and ion measurements would have helped to achieve higher confidence in some of the conclusions. Water sampling must be done frequently and proper water quality analysis should be carried out in order to understand variations in water quality.

Despite the limitations of the field data collection programme it is suggested that this study has made a substantial contribution to understanding the hydrological dynamics of this type of wetland and specifically to the Kudumela wetland. It is accepted that the improvements in the data collection methods would have contributed to more confident, and possibly more quantitative, conclusions, however, the main processes of water interactions within the wetland have been identified. The results should therefore be able to make a contribution to developing future management strategies for the wetland.

The river banks between transects T2 and T5 (Figures 5.5 and 5.11) are exposed to erosion and the investigation of farmers’ indigenous wetland knowledge has revealed that they do not possess an understanding of wetland hydrological processes such as seasonal patterns of rainfall and water table hydrology. It is recommended that a detailed and frequent training programme should be organized should the farmers continue using the wetland goods and services. The author strongly believes that such training should be conducted on the wetland site.

Wetland protection and management can only be achieved if different specialists (including hydrologists, agricultural scientists, ecologists, biologists, geographers, sociologists) work together with the government management agencies and the community (including non-governmental organizations who may be providing community advice) to understand the functions and values of wetlands and therefore develop a sustainable management approach.

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