Modelling of Wetland Processes Impacting Water Resources at a Catchment Scale

Report to the

WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

BACKGROUND

Wetlands in a catchment perform two major ecosystem services in the form of water purification which impacts on water quality in the rivers and stream flow regulation, which has an impact on the water quantity in the rivers, especially during droughts and floods.

Typically catchments have several wetlands of various sizes, types and connectivity to rivers. The importance of wetlands to the catchment hydrological processes and water resources are also varied, with some wetlands being fully connected to river networks, some partially, and some only connected through groundwater and soil water. The impact of wetlands on catchment processes and water resources can be significant when the impact is aggregated at a catchment or basin scale

As the famous statistician George E.P Box stated "essentially, all models are wrong, but some are useful".

RATIONALE

In order to accurately assess wetland impacts on a catchment scale, conceptual hydrological flow models for the different wetland types are essential to improve our understanding of the hydrology of wetlands. The flow models need to take into account the different pathways for water to enter and exit the wetland as well as quantify each inflow and outflow in relation to the other flows.

A critical review of the different hydrological flow models used in Integrated Water Resource Management in South Africa is needed in order to understand the various models and how wetlands are incorporated into the models. Moving forward, a selection of these models will then need to be tested in case studies in order to assess the accuracy in modelling wetlands within a catchment.

PROJECT Aims

The project aims were addressed in full and are reported on in this document. They are to contribute to water resources management through:

1. Improved hydrological understanding of wetlands
2. Improved understanding of how catchment processes impact on a wetland(s) and how wetland processes impact on the catchment.
3. Conceptual modelling of the role of wetlands on water resources at a catchment level, taking into account wetland area and processes as well as groundwater-surface water interactions characteristic of the wetland/river interface.

METHODOLOGY

Conceptual hydrological flow models were created for the different Hydrogeomorphic wetland types of South Africa based on previous work and expert knowledge. These models were reviewed by experts individually as well as presented to wetland experts at the National Wetlands Indaba in 2014.

Hydrological models commonly used in South Africa were critically reviewed as part of the project with particular emphasis on the wetland components, namely the Pittman Model, the ACRU model, the MIKE SHE model, the SWAT model and the Topkapi Model.

RESULTS AND DISCUSSION

The conceptual hydrological models for the different hydrogeomorphic types provide an improved understanding of hydrological flow paths for the different wetland types. From Ollis et al., 2013, the 7 conceptual flow models were expanded to 21 conceptual hydrological flow models.

The conceptual models are grouped into 5 categories:

- Hillslope Seeps (6 conceptual flow models based on different hydrological processes)
- Unchannelled Valley-Bottom Wetlands (2 conceptual flow models)
- Channelled Valley-Bottom Wetlands (1 conceptual flow model)
- Channelled Valley-Bottom Wetlands or Floodplain Wetlands (3 conceptual flow models)
- Pans (5 conceptual flow models)
- Coastal Wetlands (4 conceptual flow models)

In order to understand how wetlands impact on the catchment and how the catchment impacts on the wetland, various hydrological flow models used in Water Resource Management in South Africa were critically reviewed in order to assess how wetlands are incorporated into catchment scale surface water flow models. The scope of the review was to only look at water quantity and not water quality. This was approved by the reference group because the mass transport functions within the different hydrological models are based on a calibrated water quantity model. The findings are summarised below.

Pittman: Although the recent versions of the Pitman model are spatially semi-distributed, based on sub basin divisions with their own climate inputs, the model does not integrate the surface and groundwater systems. The current wetland module mostly accounts for the input-storage-output relationships between the river channel and the wetland.

ACRU: The ACRU has the added advantage of simulating an interaction between surface and groundwater, though the results at a daily scale were less reliable than monthly totals. Nevertheless, in spite of a relatively detailed representation of the wetland module, the actual equations used in the model are not documented.

MIKE SHE: The integration nature and the ability to account for both surface and subsurface flow systems, and their interaction make MIKE SHE well suited in establishing a detailed water balance of wetland systems. Compared to the other three hydrological modelling systems, MIKE SHE is a data intensive system. South Africa has several basins classified as ungauged because they have inadequate hydrological observations, in terms of both data quantity and quality, to enable a computation of hydrological variables -at appropriate spatial and temporal scales- at a level of accuracy acceptable for practical water resource management. There is therefore a tremendous lack of data for a detailed modelling of existing wetlands. This is a concern, considering the recognised large data requirements of an integrated, distributed hydrological model such as MIKE SHE. The subsequent coupling of a MIKE 11 river model to MIKE SHE imposes further data. The use of the MIKE SHE will therefore likely require expensive and extensive field data collections. This is to a certain extent also valid for the SWAT model.

SWAT: The main limitation of the SWAT model is being a semi distributed, where it divides the watershed into sub basins having homogeneous climate, soil, land cover and management practices. In addition, the surface and groundwater systems are not fully integrated. As a result, the SWAT model fails to represent the surface groundwater interaction.

HYDRUS: can be set up in 1, 2 or 3 dimensions; however it is not suitable at catchment scale although all necessary processes required for wetland hydrology can be simulated

PyTOPKAPI: Although the model is not designed specifically for wetlands, it can potentially be enhanced to cater for most hydrological processes to describe flows in the different HGM wetland types. The model therefore has the potential to become a tool which can be used for modelling flows related to wetland hydrological processes. This could be expanded to quantitative hydrological impact assessments on wetlands and for determining the water quantity component in Wetland Reserve Determination studies.

The project went beyond the ToRs and actually set up, calibrated and ran hydrological models for selected case studies at a catchment scale. This was done in order to assess how the hydrological model was able to model the wetland within the catchment taking into account the wetland area, evapotranspiration characteristics and groundwater surface-water interaction. The current trend in the country's water resources assessments is to ignore wetlands in hydrological modelling and use other parameters to compensate for the inadequacy of the models to account for wetlands processes. Often the modelled results are correct but for the wrong reasons. The result is that wetlands are not incorporated into water resource management at a catchment scale and thus their important contributions to the catchment in the form of ecosystem services and conservation is neglected.

The Pitman Model was applied in two different catchments, the GaMampa wetland (B71C) and the wetlands in the Alma region within the Mokolo River catchment of the Waterberg.

The hydrological modelling in the B71C sub-basin before the inclusion of the wetland sub-model yielded satisfactory results. The model simulated all the low flows well while most of the high flows were not well simulated, probably as a result of the limitations of the flow gauging structure. The inclusion of the wetland sub-model gave poor results, and the observed stream flow, especially the timing of the flows, could not be reproduced. The study thus concludes that the wetland sub-model of the Pitman model in its current form is inadequate for simulations in sub-basins were wetlands are an important part of the hydrology in those basins. The reservoir type conceptualisation of the wetland sub-model in the Pitman model may be adequate for large scale wetlands but is not sufficient for smaller scale wetlands type that are prevalent in the country. Limited attempts by Rhodes University to model some wetlands in the KwaZulu-Natal and Mpumalanga Provinces using the same approach have also not been successful and further research from various institutions is needed to improve the modelling so that it can be applied beyond the scope of academia to integrated water resource management. The reservoir type approach allows for most of the water exchange between the stream and the wetland to occur through 'spillages' which are not necessarily the case in most wetlands where 'seepage' is the dominant process. This difference is significant in the way wetlands are represented in the model and the Pitman model does not currently represent this process properly. Hence, the failures observed in this simple exercise of modelling the wetland.

The GaMampa wetland is a floodplain valley bottom wetland and most of the water is held within the soil as opposed to being a reservoir that gets water and spills it after a particular threshold capacity has been reached. This then creates a challenge for the Pitman to model this type of wetland since their dominant physical processes are not properly represented in the model. This type of wetlands would require more explicit interaction between the soil store and the river, rather than the current filling and emptying sequence currently used. It is thus encouraging to note that the Institute for Water Research at Rhodes University has initiated a programme on understanding wetland processes and developing a better sub-model to represent them in the model. This programme is in the beginning stages and does not cover all the gaps and recommendations highlighted in this report.

Hydrological simulation in the Mokolo catchment before and after the inclusion of the wetland sub-model also yielded poor results. However, it is important to state that in the absence of hydrological data in the Mokolo catchment, it was difficult to estimate the wetland parameters (except for wetland area obtained in topographical maps), hence the use of a hypothetical wetland sub-model.

The interaction between the wetland and the groundwater store is also an area that still needs to be fully investigated and understood. The Pitman model clearly does not simulate this interaction well.

While the flows in a given sub-basin were simulated with reasonable accuracy, if we do not simulate the correct processes then the results are not good for decision making and management of the water resources. Some of changes in the parameters of the model when wetlands were incorporated are very informative, especially for the way models are used.

The current trend in the country's water resources assessments is to ignore wetlands and use parameters to compensate for the inadequacy of the models to properly account for these important physical processes. This is not ideal and implies that using the results of the modelling would be difficult given that not all processes would have been adequately represented. The most significant effect is therefore that the management and conservation of wetlands and their incorporation into river basin and natural resources management strategies is less than optimal.

The inadequacy of the Pitman model with respect to the simulation of wetlands needs to be evaluated. It is not clear at the moment whether modelling at a finer temporal scale (say on a daily time scale) would be more appropriate. One of the most overriding factors in answering this question would be to assess the purpose of the modelling exercise. If the purpose is for long term water resources assessment and management purposes at the basin scale, then the model would be appropriate. However, for the purposes of research and improving understanding of the functionality and place of wetlands in the catchment, a finer time scale would be preferable. The next logical step for this study would be to set up a model with a finer time step such as the ACRU and evaluate the results. However the finer scale time series requires better input data in order to validate the modelling results. A limiting factor in the collection of water flow data is that an Environmental Impact Assessment is needed in the construction of new weirs and gauges, which is often beyond the scope and expertise of the project team.

CONCLUSIONS

Management of water resources in a catchment scale depends on suitable catchment management strategies and tools which can explicitly handle all the hydrological processes within a catchment. Hydrological models have been used as tools in water resources management to inform decision making. The current trend in the country's water resources assessments is to ignore wetlands processes and use other parameters to compensate for the inadequacy of the models to accurately model these important physical processes in wetlands.

Hydrological models are an approximation of nature, thus accurate results depends on long term hydrological data with minimal missing data. Initial modelling in the Mokolo catchment was done with minimal data and knowledge of the hydrological processes of the wetlands. The findings can be improved by further studies which will investigate and conceptualise the key dominant hydrological processes of the wetlands, prior to modelling, in order to improve the accuracy of the results.

The direction taken by this study to assess the incorporation of wetland process is a step in the right direction, especially in areas of the country where wetlands are an important hydrological process, not only in understanding but also managing the water resources of the relevant basins. Thus, a key finding of this study is that there is an insufficient representation of the underlying hydrological processes of wetlands in current water resources assessments. For a number of sub-basins, the right results are therefore generated for the wrong reasons.

Stable Isotopes provides an accurate tracer for groundwater in freshwater ecosystems. Stable isotopes proved the most useful in the Waterberg case study in order to identify groundwater discharge in the form of baseflow in the streams. Stable isotopes did not perform as successfully in the Wilderness case study as a result of the high evaporative signature of the lakes, although it was successful in identifying the groundwater within the aquifer.

The MODIS ET algorithm produced dubious results for the Wilderness case study with the annual ET estimates being far lower than what was expected. This is likely due to the MODIS algorithm and an incorrect landcover classification for the pixels in which the lakes are located. MODIS proved useful in detecting seasonal trends in evapotranspiration and where this is a lack of field collected data, can be used in water balance equations and hydrological models.

RECOMMENDATIONS FOR FUTURE RESEARCH

A key finding of this study is that there is an insufficient representation of the underlying hydrological processes of wetlands in current water resources assessments. For a number of sub-basins, the right results are therefore generated for the wrong reasons.

- Daily water flow measurements upstream and downstream of each (21 in total) conceptual hydrological flow model produced in this report
- Improved Evapotranspiration measurement results from Remote Sensing
- Plant water use measurements for wetland plant species
- Further collaboration with Rhodes University to refine the wetland component of the Pittman model based on field data for different wetland types
- Further research into the application of PyTOPKAPI and HYDRAS to model wetland processes
- Assessment of groundwater numerical models to model the processes of wetlands linked to regional groundwater
- Refinement of the definition of aquatic ecosystems in the Classification System
- Field Guidelines for the identification of the hydrological processes for wetlands in South Africa

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LIST OF ABBREVIATIONS

ACRU – Agriculture Catchments Research Unit

AVG – Average

CF – channel Flow

CoV – Coefficient of Variation

CSIR – Council for Scientific and Industrial Research

DWA – Department of Water Affairs

EIS – Ecological and Importance Sensitivity

ESRI – Environmental Systems Research Institute

ET – Evapotranspiration

GWL – Groundwater Level

GWR – Groundwater Recharge

HGM – Hydrogeomorphic

MODIS – Moderate Resolution Imaging Spectroradiometer

NFEPA – National Freshwater Ecosystems Priority Areas

OF – Overland Flow

P – Precipitation MCWAP – Mokolo and Crocodile (West) Water Augmentation Project

PES – Present Ecological Status

SANBI – South African National Biodiversity Institute

STD DEV – Standard Deviation

SWAT – Soil Water Assessment Toil

WA – Wetland Area

WR2005 – Water Resources 2005

1 INTRODUCTION AND OBJECTIVES

1.1 Background

Wetlands in the catchment perform two major ecosystem services in the form of water purification which impacts on water quality in the rivers and stream flow regulation, which has an impact on the water quantity in the rivers, especially during droughts and floods.

Typically catchments have several wetlands of various sizes, types and connectivity to rivers. The importance of wetlands to the catchment hydrological processes and water resources are also varied, with some wetlands being fully connected to river networks, some partially, and some only connected through groundwater and soil water. The impact of wetlands on catchment processes and water resources can be significant when the impact is aggregated at a catchment or basin scale.

The broad aim of the project is to contribute to water resources management through:

1) improved hydrological understanding of wetlands;
2) improved understanding of how catchment processes impact on wetlands and how wetland processes impact on the catchment; and
3) conceptual modelling of the role of wetlands on water resources at a catchment level, taking into account wetland area and processes as well as groundwater-surface water interactions characteristic of the wetland/river interface.

Two study sites have been identified, namely the Mokolo River in the Waterberg and the Wilderness estuarine lakes in the Gouritz Water Management Area. Models are an effective tool for evaluating the hydrologic characteristics and impacts of wetlands in detail, however most models were not developed to assess the hydrologic role of wetlands in the catchment but to fulfil other hydrologic objectives. Most of the hydrological models used in South Africa are not readily applicable for simulations of the hydrological consequences of wetlands.

1.2 Definitions

Chapter 1.1 of the National Water Act, Act No 36 of 1998 lists the following definitions:

National Water Act, Act No 36 of 1998- Definitions and Interpretation "aquifer" means a geological formation which has structures or textures that hold water or permit appreciable water movement through them;

"wetland" means land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil.

"water resource" includes a watercourse, surface water, estuary, or aquifer;

"watercourse" means--

a) a river or spring;
b) a natural channel in which water flows regularly or intermittently;
c) a wetland, lake or dam into which, or from which, water flows, and
d) any collection of water which the Minister may, by notice in the Gazette, declare to be a watercourse,
e) and a reference to a watercourse includes, where relevant, its bed and banks;

Ollis et al. (2013) published the Classification System for Wetlands and other Aquatic Ecosystems in South Africa, referred to as the "Classification System" as an update to the SANBI (2009) National Wetland Classification System. The Classification System adopted the following definitions for wetlands and aquatic ecosystems:

BOX 1: WHAT IS THE DIFFERENCE BETWEEN A WETLAND AND AN AQUATIC ECOSYSTEM?

The following definitions have been adopted for the Classification System:

Wetland—land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil (from the South African National Water Act; Act No. 36 of 1998).

Aquatic ecosystem—an ecosystem that is permanently or periodically inundated by flowing or standing water, or which has soils that are permanently or periodically saturated within 0.5 m of the soil surface.

Based on these definitions, for the purpose of the Classification System, wetlands are considered to be a type of aquatic ecosystem because it is the presence of water at some stage (either permanently or periodically, sometimes rather ephemerally) that distinguishes a wetland ecosystem from a terrestrial ecosystem. Besides wetlands, as defined above, aquatic ecosystems are taken to also include rivers; lakes, ponds, dams and other open waterbodies; estuaries; and (shallow) marine systems (see Section 2.1 for a more detailed description of the broad types of Inland Systems included in the Classification System). In terms of the legal definition (National Water Act, 1998), it is sometimes difficult to determine whether a particular aquatic ecosystem is a 'wetland'. This does not hamper the use of the Classification System, however, because you do not have to make such a distinction in the application of the Classification System.

In essence, the ecosystems included in the Classification System (i.e. all aquatic ecosystems, including wetlands, except for deep marine systems) encompass those that the Ramsar Convention defines, rather broadly, as 'wetlands', namely, "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres" (cited by Ramsar Convention Secretariat 2011).

The Classification System defines subsurface water as "all water occurring beneath the Earth's surface, including soil moisture, that in the vadose (unsaturated) zone and groundwater" and groundwater as "subsurface water in the saturated zone below the water table (i.e. the water table marks the upper surface of groundwater systems)".

Simply stated, subsurface water is all of the water beneath the surface and groundwater is only the component of subsurface water that is in the saturated zone. Colvin et al. (2007) stated that when referring to groundwater, hydrogeologists specifically refer to the water that occurs within the saturated aquifers or aquitards, whilst other scientists may incorrectly refer to all water underground as groundwater.

Colvin et al. (2007) in An Introduction to Aquifer Dependent Ecosystems in South Africa list the following definitions within the glossary:

Aquatic ecosystem – defined in the water quality guidelines (DWAF, 1996) as: the abiotic (physical and chemical) and biotic components, habitats and ecological processes contained within rivers and their riparian zones, reservoirs lakes and wetlands and their fringing vegetation. Terrestrial biota, other than humans dependent on aquatic systems for their survival, are included in this definition.

Aquifer – A geological formation which has structures or textures that hold water or permit appreciable water movement through them (National Water Act, 1998). A saturated stratum which contains intergranular interstices, or a fissure / fracture or a system of interconnected fissures / fractures capable of transmitting groundwater rapidly enough to supply a borehole or spring directly (McGraw-Hill, 1978).

Aquifer dependent ecosystems – ecosystems which depend on groundwater in, or discharging from, an aquifer. They are distinctive because of their connection to the aquifer and would be fundamentally altered in terms of their structure and functions if groundwater was no longer available.

Baseflow – the volume of water in the stream when at its minimum or base level of flow; this is the level to which the stream flow returns between storms; in climates with seasonal rainfall it is often treated as the dry season flow; it is commonly viewed as being derived exclusively from groundwater flow or discharge (Ward, 1975, McGraw-Hill, 1978), but may include drainage from deep soil and weathered material; generally synonymous with the term low flow.

Interflow – refers to the (rapid) lateral movement of subsurface water from rainfall through the soil layers above the water table to a stream or other point where it reaches the surface (McGrawHill, 1978); generally synonymous with subsurface stormflow. In the context of this report, interflow is considered as temporarily saturated lateral flow in the unsaturated (vadose) zone.

Groundwater – in common usage includes all subsurface water (McGraw-Hill, 1978) but in this document the use of this term is restricted to water in the zone of saturation. It flows into boreholes/wells, emerges as springs, seeps out in streambeds or elsewhere in surface catchments and is not bound to rock (particle) surfaces by forces of adhesion and cohesion. Generally used for water contained in aquifers.

Groundwater Dependent Ecosystem – an ecosystem which depends on groundwater discharging from or contained within an aquifer, and is significantly altered by changes in the groundwater regime.

Groundwater discharge – the release, or emergence of groundwater from an aquifer into the unsaturated soil or as surface water springs, wetlands or streams (McGraw-Hill, 1978); also called groundwater flow (Ward, 1975). Discharge areas occur in the lower parts of catchments and may comprise springs or seeps, where groundwater contributes to the surface runoff or streamflow. These areas are synonymous with the source areas of rivers.

Perched aquifer – an aquifer that is separated from an underlying body of groundwater by an unsaturated zone (see below).

Perched groundwater – unconfined groundwater separated from an underlying main body of groundwater by an [impermeable layer and] unsaturated zone (McGraw-Hill, 1978, A.G.I. glossary).

Perched springs – springs which are fed by groundwater discharge from a perched aquifer (McGrawHill, 1978).

Perched water table – the water table on an unconfined aquifer separated from an underlying main body of groundwater by an unsaturated zone, generally perched on and impermeable layer. The watertable of a body of perched groundwater (A.G.I. glossary).

Unsaturated zone – the layer(s) of the soil and underlying material where the soil pores are only partially filled with water. Not necessarily composed of soil or regolith only but may also include bodies of fractured bedrock. A subsurface zone containing water under pressure less than that of the atmosphere, including water held by capillary tension. The zone is subdivided into the belt of soil water, the intermediate belt and the capillary fringe (A.G.I. glossary).

1.3 Discussion

There is consensus between the wetland and groundwater literature on the definition of groundwater in that it only includes the portion of the subsurface which is saturated and not all water that occurs underground. Colvin et al. (2007) summaries it as follows:

> Undergroundwater may occur:
>
> - In the unsaturated zone as soil water and interflow,
> - In the saturated zone as groundwater in aquifers (extractable) and groundwater in aquitards and aquicludes (not extractable)

Wetlands may rely significantly on water from perched aquifers. Perched aquifers as defined by Colvin et al. (2007) is an aquifer that is separated from an underlying body of groundwater by an unsaturated zone. A perched aquifer is illustrated in Figure 1. The wetland is dependent on surface runoff and rainfall to the perched aquifer which is located in the regional unsaturated zone. Perched aquifers are generally highly localised aquifers and not laterally extensive. The base of the aquifer is typically an aquitard like a clay lens or calcrete formation as shown in the conceptual hydrological model for Langebaan lagoon in Figure 2 where the groundwater in the shallow perched aquifer discharges into the *Phragmites* reed beds. In reality the interface between the ocean and the aquifer is dynamic and is dependent on the elevation of the groundwater table and the groundwater flow. In cases where the groundwater elevation is below the sea elevation (typically as a result of over abstraction), salt water intrusion can occur.

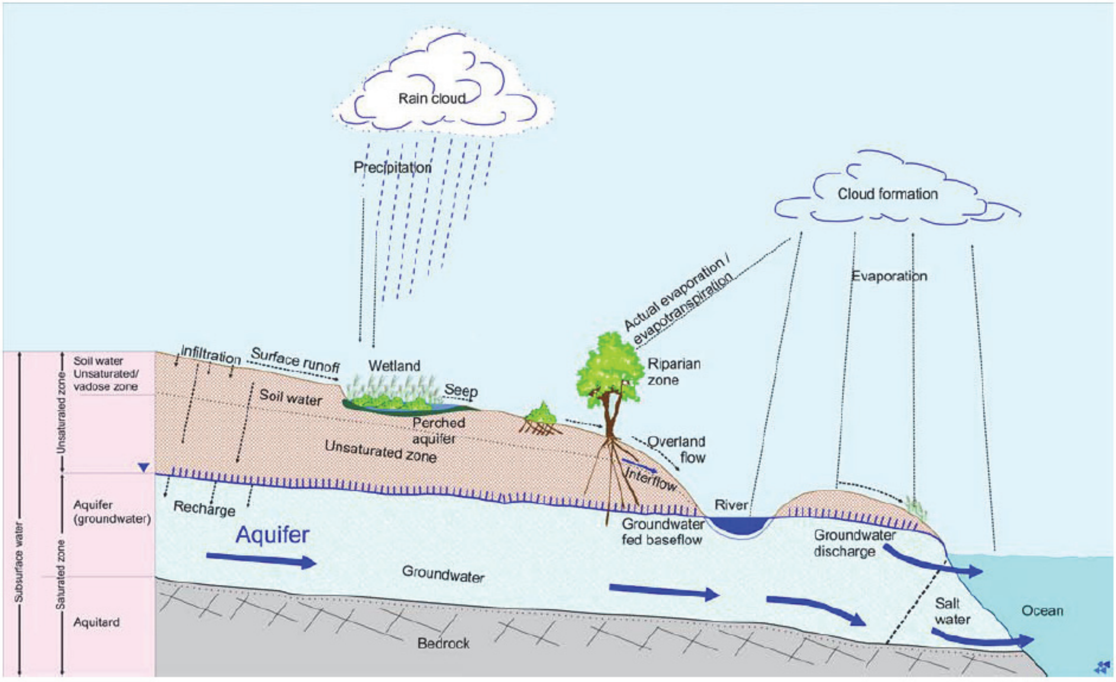


Figure 1 Subsurface and surface flows of water in the environment. From Colvin et al. (2007)

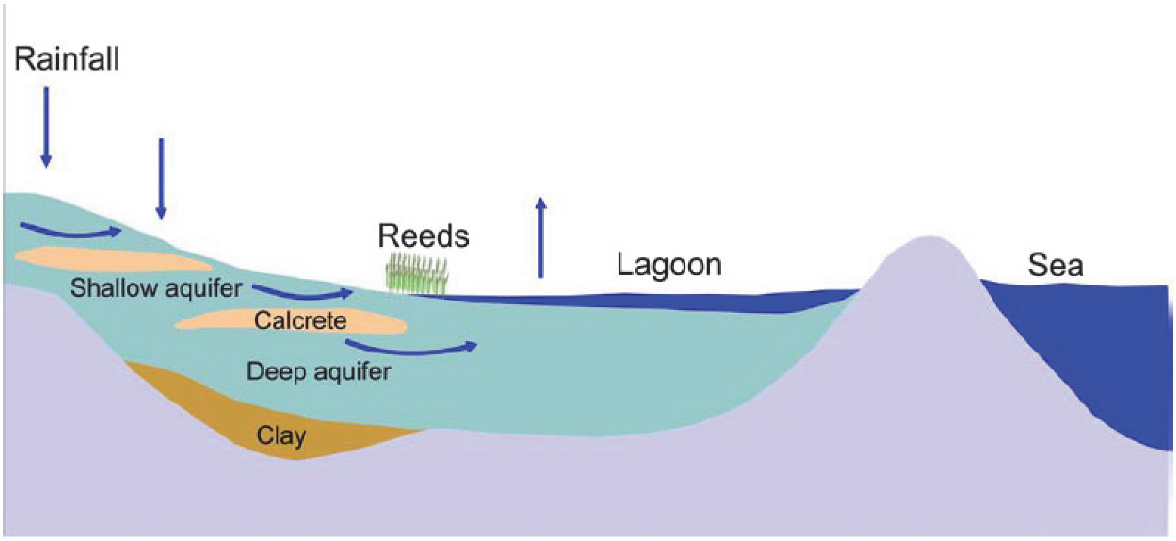


Figure 2 Conceptual hydrological flow model for Langebaan lagoon. Taken from Figure 3.8 from Colvin et al. (2007).

Perched aquifers are difficult to detect in the field. The water table in an aquifer can be determined by drilling a borehole or installing a piezometer to intersect the water table, or it can be interpolated from existing boreholes and surface topography for unconfined aquifers. The perched water table is more difficult to determine and requires field measurements to be taken within the perched aquifer, with care being taken not to puncture the underlying aquitard. The perched water table cannot be interpolated from regional boreholes that only intercept the regional aquifer.

The Classification System is problematic in the definition of aquatic ecosystems in that it only includes ecosystems that are permanently or periodically saturated to within 0.5 m of the soil surface. The Groundwater Resource Assessment II (DWAF 2005) produced an interpolated depth to groundwater layer for South Africa. This was interpolated from groundwater level data from the National Groundwater Database and is shown in Figure 3. Although the interpolated groundwater levels from the GRAII is a very coarse dataset, a desktop examination would erroneously conclude that the only aquatic ecosystems that intersect with a depth to groundwater of within 0-2 m would be wetlands in Maputuland in KwaZulu-Natal, and that groundwater does not play a role in aquatic ecosystems elsewhere in South Africa.

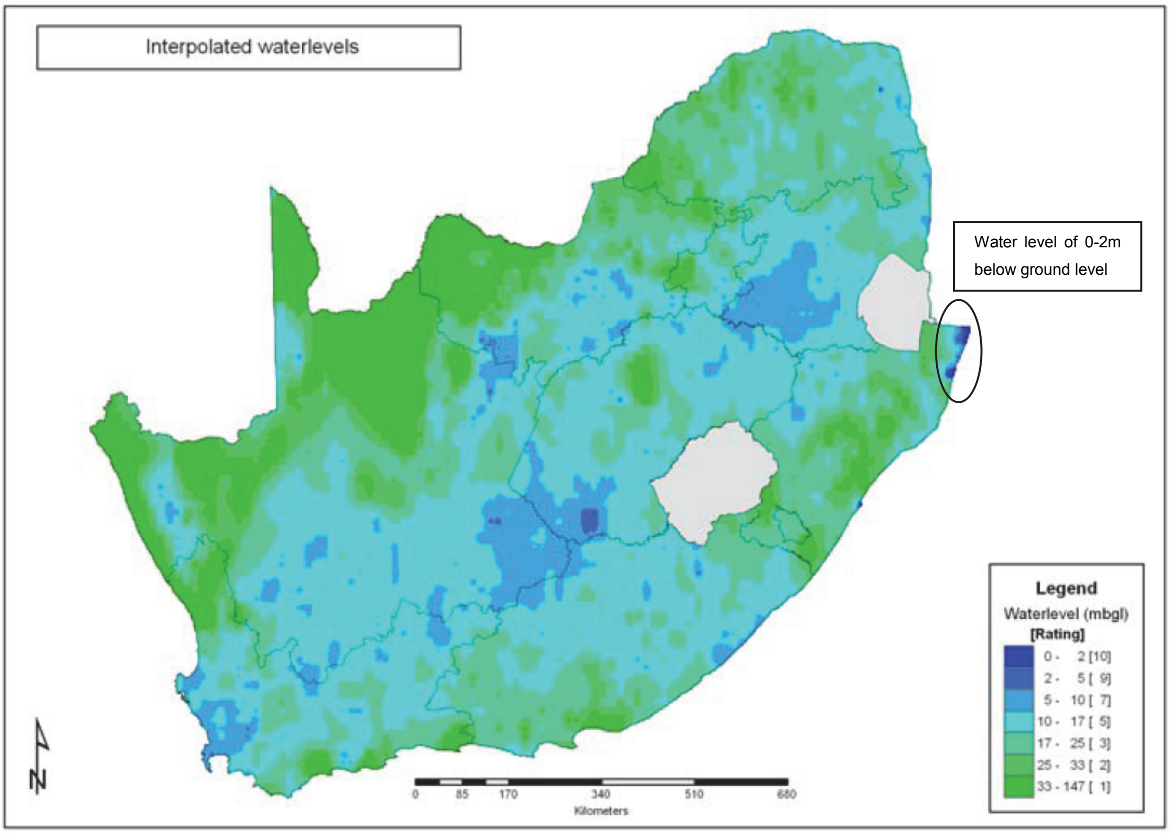


Figure 3 Interpolated groundwater levels for South Africa. Taken from Figure 6.12 of DWAF 2006.

A more recent groundwater level map from the Department of Water and Sanitation website shows the point locations of depth to water levels measured over a 3 month period from January to March 2014 in Figure 4. The dark blue dots indicate where the regional groundwater table is between 0 and 5 m below the surface. This map would identify more aquatic ecosystems that might intercept a shallow water table, but it would be problematic to apply because the shallow water levels are often located next to deeper water levels.

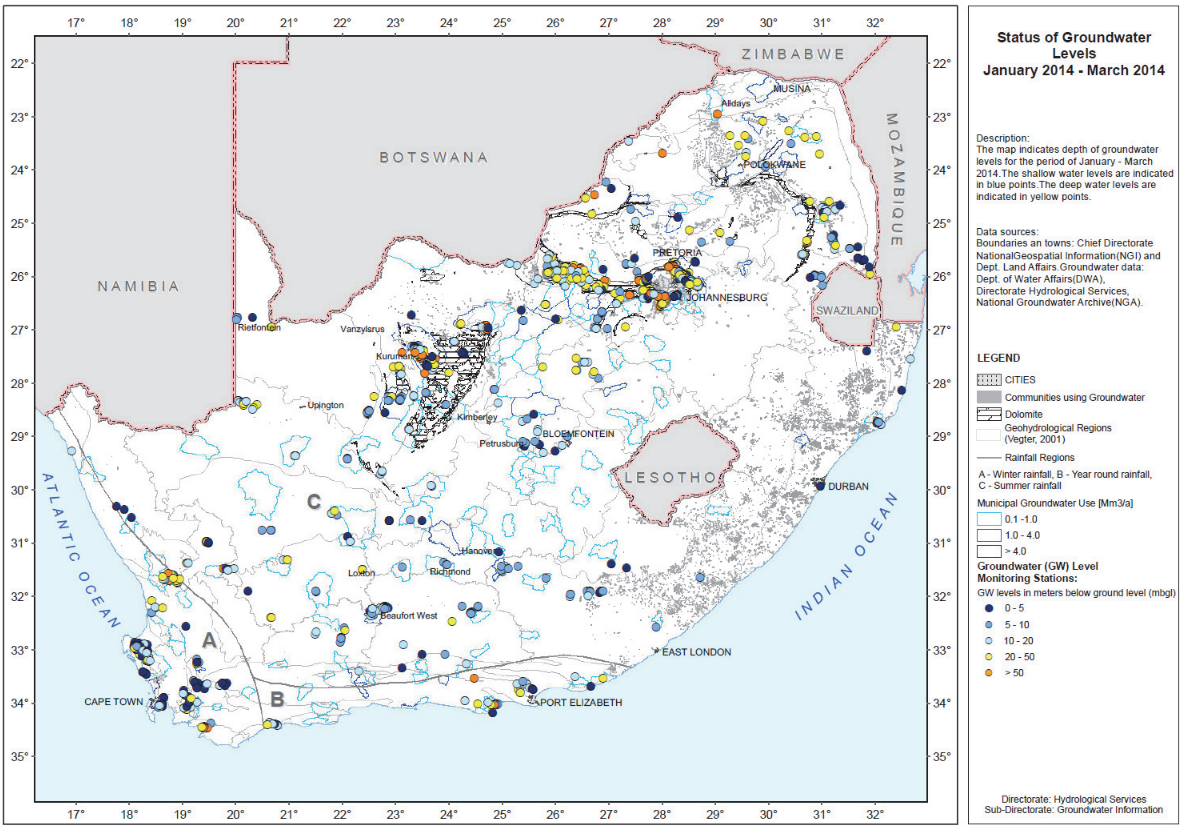


Figure 4 Quarterly groundwater levels from Jan to March 2014 monitored by DWS (https://www.dwaf.gov.za/Groundwater/maps/Quarterly/Status_GWL_Jan_Mar2014.pdf)

Because of the lack of useful depth to water table data on a regional scale, alternative methods to determine groundwater contributions will be discussed in later sections, namely the water balance, chemical characterisation and stable isotopes.

The aim of this project is to improve the understanding of the hydrology of wetlands. In order to do this the project team produced a series of conceptual hydrological flow diagrams for the different hydrogeomorphic wetland types for South Africa. The next step was to assess the current suite of hydrological models used in Integrated Water Resource Determination in South Africa in order to critically review the wetland functions of the different hydrological models. A selection of these models then were tested in catchment case studies in order to assess how the wetland impacts on the catchment as modelled by the stream flow within the river, taking into account wetland area and processes as well as groundwater-surface water interactions characteristic of the wetland/river interface.

2 CONCEPTUAL HYDROLOGICAL FLOW MODELS PER HGM WETLAND TYPES IN SOUTH AFRICA

Why conceptual modelling?

In order to asses which of the current suite of Hydrological models are best suited to the wetland types, we need to first understand and be clear about the different hydrological processes that the different wetlands have. Most wetland functions in hydrological models have not been developed to assess the hydrological role of wetlands in the catchment but rather to fulfil other hydrologic objectives as these models have been developed by hydrologists and not wetland specialists. Only by having clear conceptual flow models for each of our HGM wetland types, can the wetland community approach the hydrologists and say that the current suite of models are not suitable for wetland modelling because the models do not accurately represent the different flow mechanisms of the different wetland types.

A simple water balance for a wetland

A simple conceptual hydrological model is shown in Figure 5. Simplistically, the inflows into a wetland are through rain, surface water and groundwater; the outflows from a wetland are in the form of evapotranspiration, surface water outflow and groundwater discharge. The models can become more complicated and built upon in order to take into account the different wetland types. As a starting point, the Hydrogeomorphic (HGM) wetland types from the National Wetland Classification System (SANBI, 2009) are used because the classification was designed with wetland functionality and processes in mind. The list of level 4: HGM types is shown in Figure 6 along with a schematic diagram showing the landscape position that different HGM types are associated with.

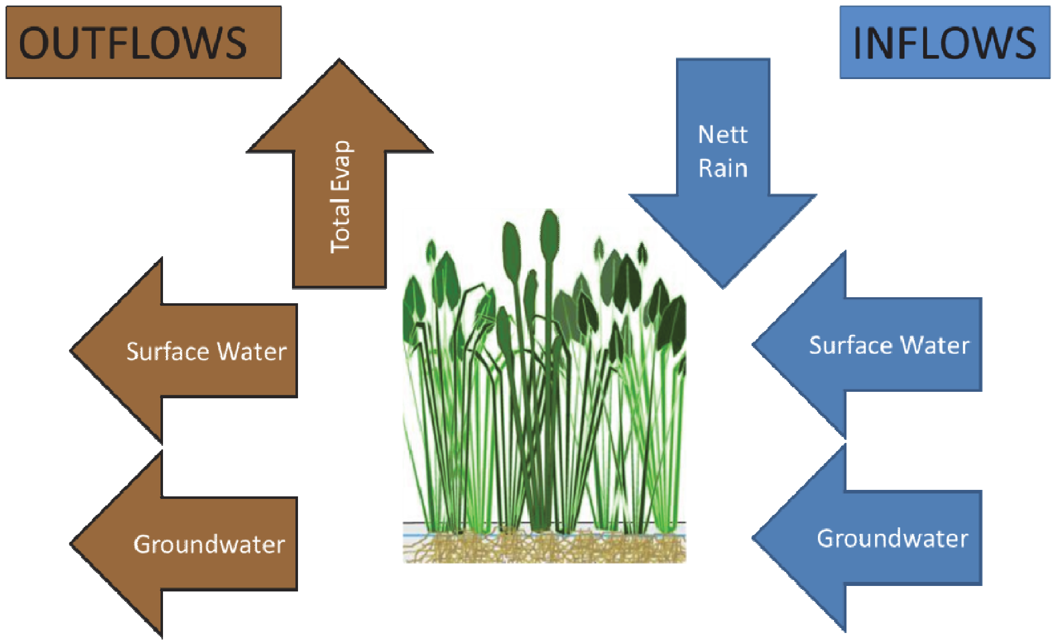


Figure 5 A simple conceptual hydrological flow model for a wetland.

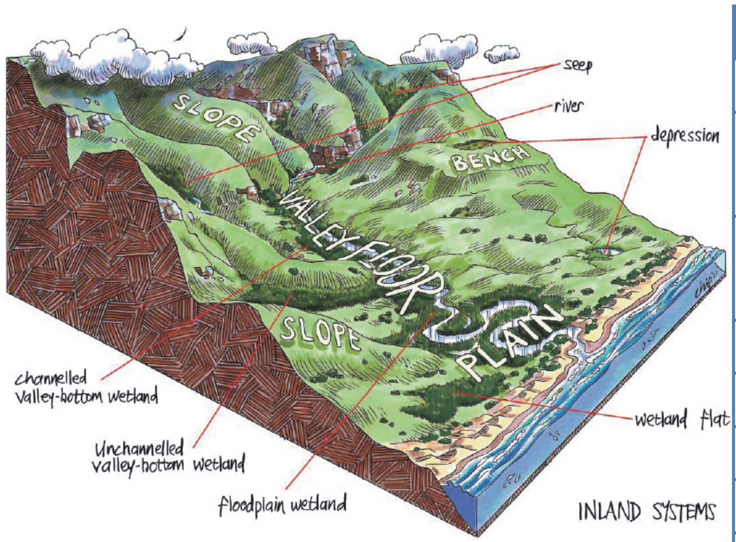


Figure 6 Schematic diagram showing the different HGM types and their position from Figure 14 of the Classification System (Ollis et al., 2013).

Level 4: HGM Unit
Channel (river)
Channelled valley-bottom wetland
Unchannelled valley-bottom wetland
Floodplain wetland
Depression
Flat
Hillslope seep
Valleyhead seep

Demonstration of Models

The conceptual models are grouped into 5 categories:

- Hillslope Seeps (6 conceptual flow models based on different hydrological processes)
- Unchannelled Valley-Bottom Wetlands (2 conceptual flow models)

- Channelled Valley-Bottom Wetlands (1 conceptual flow model)
- Channelled Valley-Bottom Wetlands or Floodplain Wetlands (3 conceptual flow models)
- Pans (5 conceptual flow models)
- Coastal Wetlands (4 conceptual models)

The dominant water inputs for the different HGM types from the Classification System is shown in Figure 7 . The conceptual hydrological flow models presented here expand on the Classification System by expanding the conceptual models to take into account different hydrological processes within the wetlands. The size of the arrows also indicates the relative quantity of the different flow processes.

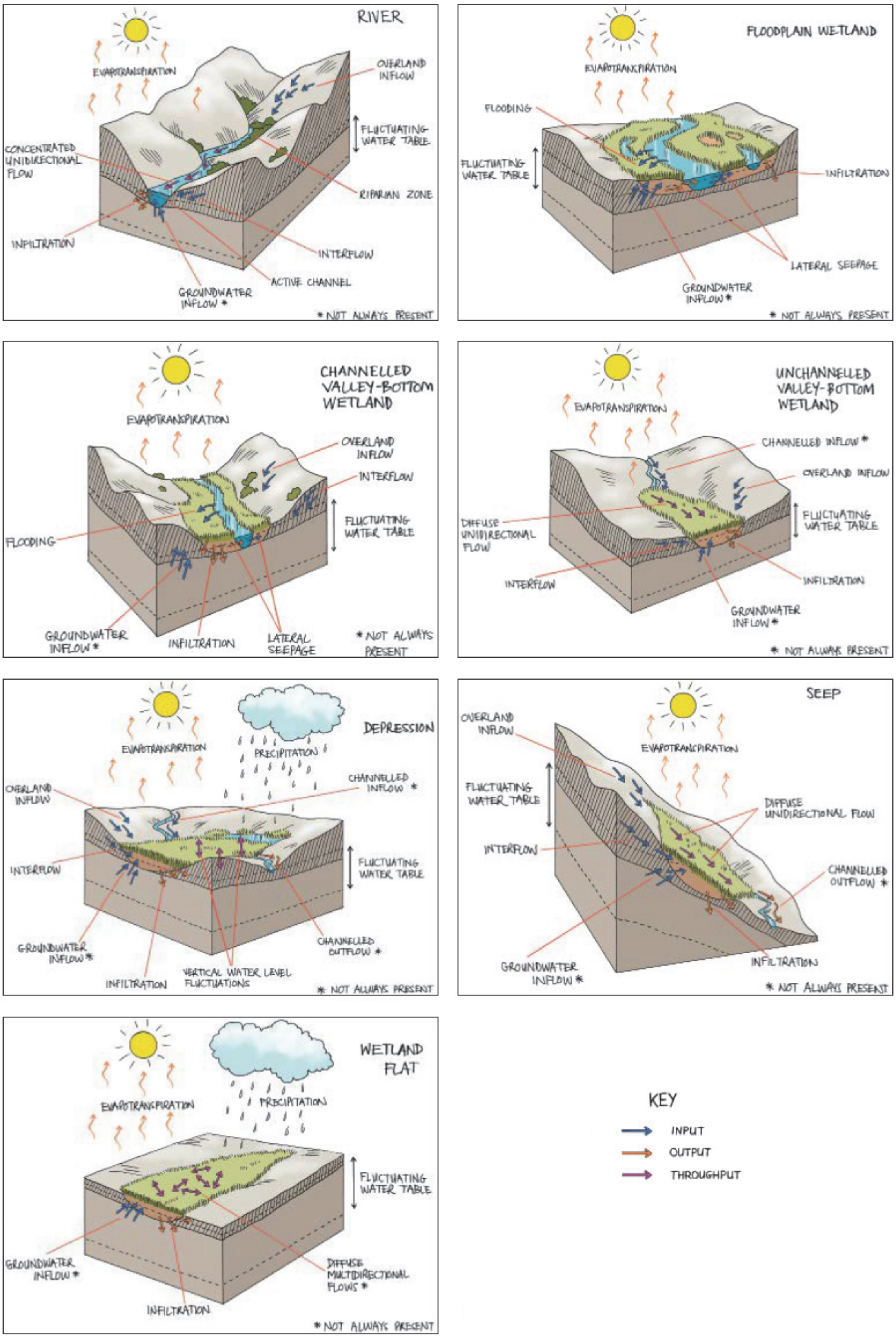


Figure 7 Amalgamated diagram of primary HGM types, highlighting the dominant water inputs, throughputs and outputs taken from Figure 14 of Classification System, (Ollis et al., 2013).

A selection of conceptual hydrological models is shown below. The full suite of 21 models is contained in the Appendix of this report.

LEGEND

GWR – Groundwater recharge

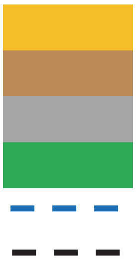
P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow



weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

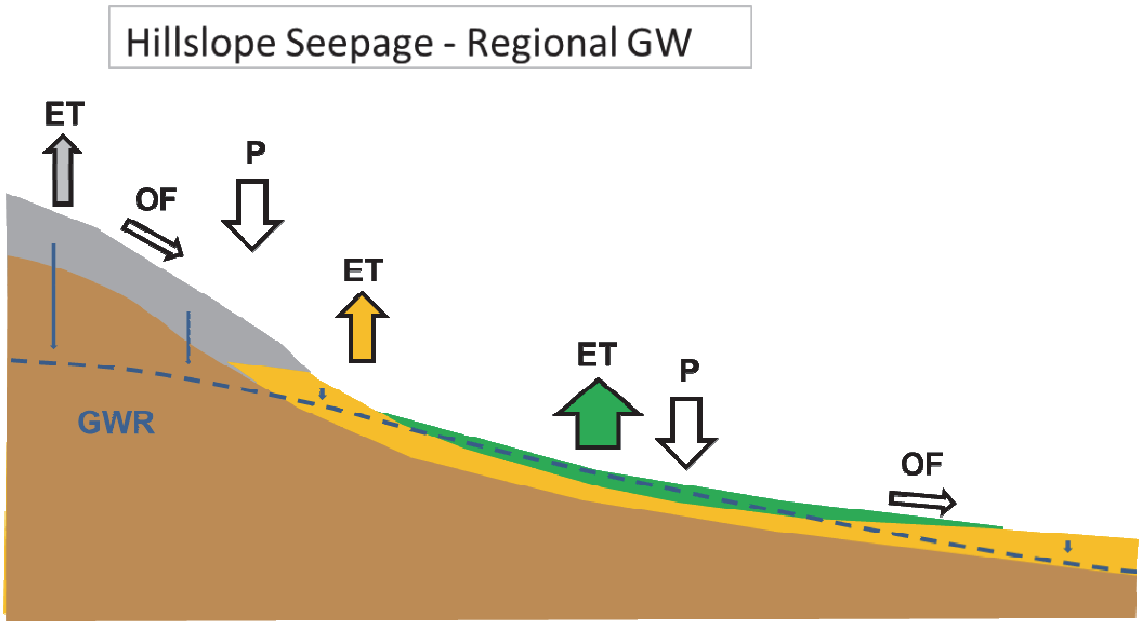


Figure 8 Conceptual flow model for a hillslope seep that is driven by semi-confined groundwater.

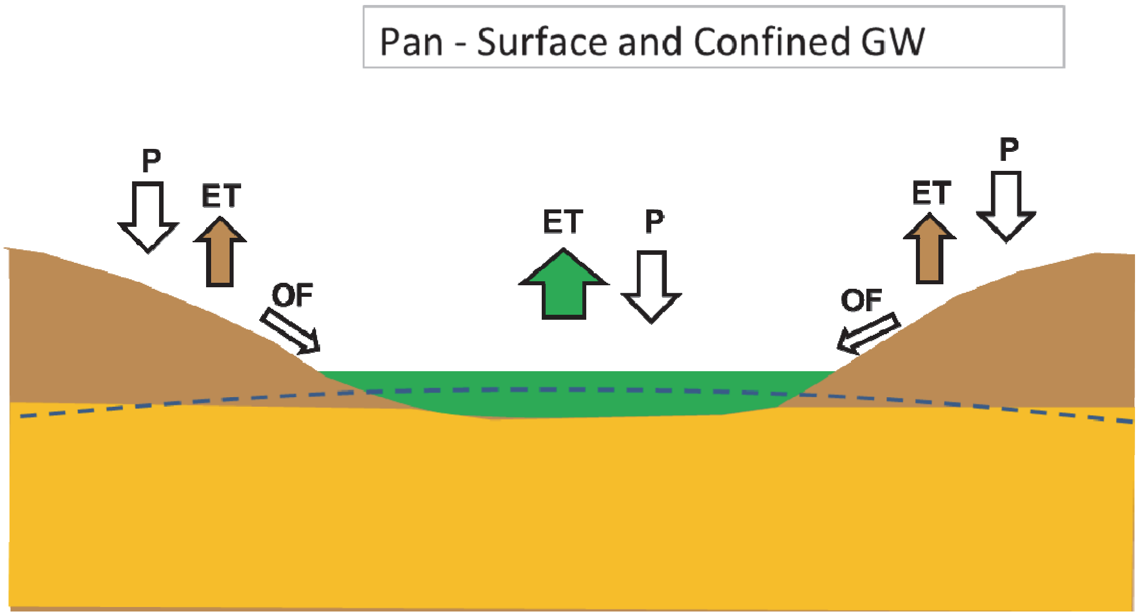


Figure 9 Conceptual flow model for a pan that is driven by surface water and confined groundwater.

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

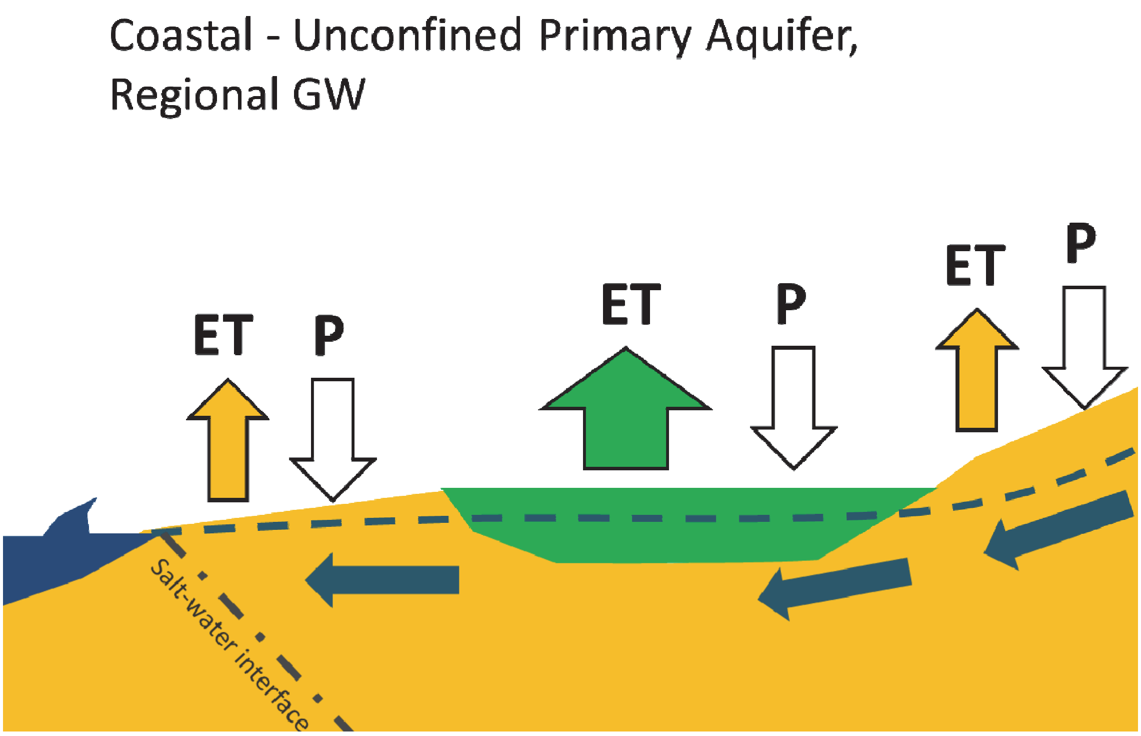


Figure 10 Conceptual flow model for a coastal wetland located on a primary (sandy) aquifer and connected to the regional groundwater table.

3 REVIEW OF MODELS COMMONLY USED TO UNDERSTAND WETLAND PROCESSES

Key processes (that may not be typically explicitly considered to catchment scale hydrological model algorithms) that need to be modelled sufficiently in a hydrological model that incorporates wetland processes should include:

- Overbank flooding
- Subsurface flows
    - Laterally and longitudinally through the floodplain;
    - Into and out of river channels dynamically determined by relative channel and groundwater surface heights;
    - Landscape runoff routing
    - Infiltration of hillslope runoff into floodplain and alluvial fans.

Some of the considerations when evaluating wetland simulation in a hydrological model include the ability of the model to adequately simulate the attenuation that may occur in a sub basin due to the influence of wetlands on flood flows, simulate explicitly the flood storage theoretically available in wetlands under a variety of initial conditions such as empty, partially full, and simulate across spatial scales.

3.1 The Pitman Model

It has been nearly four decades since a model designed for use in climatic conditions prevalent in most southern African countries was developed through the pioneer work of W.V. Pitman in 1973 at the University of the Witwatersrand, South Africa (Hughes, 2004). Through different versions (Pitman, 1973; Hughes et al., 2006; Bailey, 2009), this model has been the most widely used in South Africa and many parts of the region (e.g. Hughes et al., 2006; Mwelwa, 2004; SWECO, 2004; Mazvimavi, 2003; SMEC, 1991; Hughes and Meltzer, 1998; Matji and Gorgens, 2001). In South Africa the Pitman model has been the basis of the national water resource assessment studies of the 1990s (known as WR90, Midgley et al., 1994) and an update thereof in 2005 (WR2005, Middleton and Bailey, 2009), which are used the basis of water resources management in the country.

Until recently, the Pitman model (Pitman, 1973) in its various forms has not had an explicit wetland module (Ndiritu, 2009). Whenever wetlands were encountered a dummy dam was often used as a convenient way round the problem such as in the modelling of the Kafue basin (Mwelwa, 2005). However, current approaches for the WRSM2005 (DWA, 2008) and SPATSIM (Hughes et al., 2006) versions of the model use a basic water balance approach with water draining into and out of the wetland (see DWA, 2008; Hughes et al., 2013). The latest additions to the WRSM 2000 (Pitman) model (Bailey, 2008) include the modelling of wetlands directly connected to the stream but not over land where many wetlands occur (Ndiritu, 2009). Winsemius et al. (2006) modelled wetlands as processes over land and this may be an appropriate approach for the Pitman model.

The approaches to the modelling of wetlands in the two versions considered here are very similar. The following sections outline these approaches.

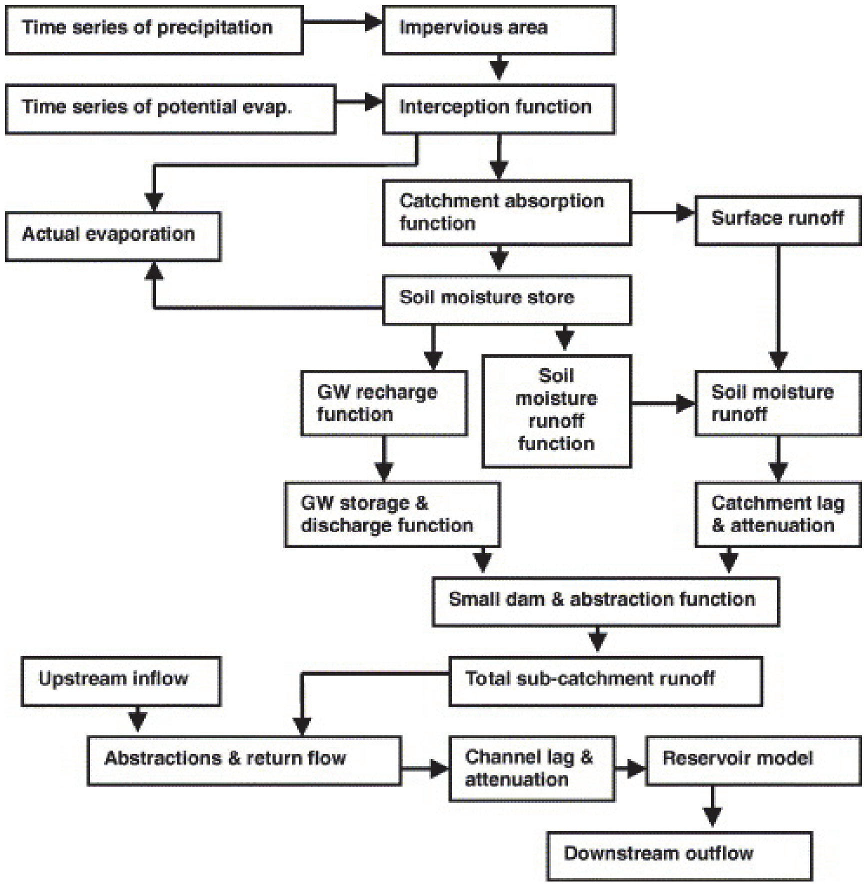


Figure 11 Flow diagram of the main components of the SPATSIM version of the Pitman model (Hughes et al., 2006.)

<u>SPATSIM Pitman</u>

The wetland sub-model that has recently been added to the SPATSIM Pitman model is based on the work of two students working in the Zambezi and Congo basins where huge wetlands (e.g. the Kafue) and natural lakes (e.g. Lakes Tanganyika and Malawi) are important hydrological features with huge impacts on the natural hydrology of their catchment. The application of the wetland sub-model is envisaged to be on “relatively large rivers and wetlands of southern Africa where the downstream impacts of wetland storage are expected to be evident at the monthly time-scale of modelling” (Hughes et al., 2013).

Like the reservoir sub-model, the wetland is an optional component that is only simulated if the input data stream for a specific sub basin includes parameter sets associated with the sub-model.

Table 1 Parameters and algorithms used for the wetlands sub-model in the SPATSIM Pitman model (Hughes et al., 2013). (-) denotes that parameter is dimensionless.

Parameter and Units	Description and use
MaxWA (km^2)	Maximum wetland area
RWV(m^3 * 10^6)	Residual wetland storage volume below which there are no return flows to the river channel.
IWV (m^3 * 10^6)	Initial wetland storage volume at the start of the simulation.
AVC (m^{-1})	Constant in the WA=AVC * WV^{AVP} relationship, where WA (m^2) and WV (m^3) are the current wetland area (limited to MaxWA) and volume, respectively.
AVP	Power in the WA=AVC * WV^{AVP} relationship
QCap (m^3 * 10^6)	Channel capacity below which there is no spill from the channel to the wetland.
QSF (-)	Channel spill factor in SPILL=QSF * (Q–QCAP), where Q is the upstream flow, and SPILL is the volume added to wetland storage.
RFC (-)	Return flow constant in the RFF=RFC * $(WV / RWV)^{RFP}$ relationship. RFF is a fraction limited to a maximum of 0.95 and then adjusted when Q is greater than QCap (RFF=RFF * QCap / Q). The return flow volume is calculated from RFLOW=RFF * (WV–RWV).
RFP (-)	Return flow power in the RFF=RFC * $(WV / RWV)^{RFP}$ relationship.
EVAP (mm)	Annual evaporation from the wetland (distributed into monthly values using a table of calendar month percentages).
ABS (m^3 * 10^6)	Annual water abstractions from the wetland (distributed into monthly values using a table of calendar month percentages).

This wetland sub-model is designed to work over four time steps within a month just as the main model does. This is envisaged to avoid excessively large changes in any single component of the wetland water balance before other components are updated. The following describes the functioning of the wetland sub-routine within the SPATSIM Pitman model;

- The dimensions of the wetland are given by the maxWA which is the maximum local catchment area of the wetland. This includes both the inundated and dry part of the wetland area. The size of the inundated part of the wetland, WA (which increases as the wetland gains water and shrinks as it loses water), is from the area-volume (WV) relationship using parameters AVC and AVP.
- Water is added to the wetland through:
    - Local runoff generated from a part of the wetland catchment area that is not inundated (i.e. maxWA-WA);
    - Local rainfall falling directly on the inundated area;
    - Inflow from the channel. This is calculated as a proportion of the total upstream channel flow.

- Losses from the wetland are via:
  - Evapotranspiration at the potential level (P_{EVAP}) using seasonal (monthly) distributions and is based on the area of the wetland that is inundated;
  - Flow back to the river channel. The size of the flow is determined by a power function between a return flow fraction (RFF, with maximum value of 0.95) and the ration of the current storage of the wetland (WV) to the residual (RWV), where RWV is the volume below which water is unable to flow back to the channel;
  - Any artificial abstractions from the wetland for irrigation, domestic or any other use.

This simplified water balance approach ignores any interactions between the wetland and the groundwater component of the natural hydrology of the catchment, which in some places could be very important and could control the wetland's hydrology.

Hughes et al. (2013) contend that the wetland module has been included in the model specifically to improve the simulations of flows downstream of the wetland, and not "the ecological or water quality dynamics of the wetlands." This is important in evaluating the sub-model. The objective of the model is simulating the natural flows of the catchment and the wetland module is incorporated as a black-box sub-model to assist with the achieving of this objective.

It is possible to estimate some of the parameters (such as MaxWA, RWV, AVC and AVP) of the sub-model from measurable properties of the wetland, while others would have to be calibrated to match the observed or assumed inundation volume or area dynamics of a specific wetland in relation to observed or simulated upstream and/or downstream flows. Such parameters as the channel capacity parameter (QCap), QSF, RFC and RFC will be more difficult to estimate without detailed hydraulic data and will currently be calibrated in most cases.

<u>WRSM 2000 Pitman</u>

The original wetland sub-model worked very much like a reservoir where downstream flow took place only when the wetland storage capacity was exceeded, the new sub-model is designed to simulate a wetland that is either off-channel or in-channel. It can also be employed to simulate the effect of a man-made off-channel storage dam for water supply (DWA, 2008). This implementation of the wetland sub-model includes relatively simple relationships for transfers to and from the wetland and evaporative losses from the wetland. Figure 1 shows the principles of the wetland model implementation in the WRSM2005 Pitman model (DWA, 2008; Bailey and Middleton, 2009).

The following descriptions have been extracted from DWA (2008) which give the detailed theory behind the model.

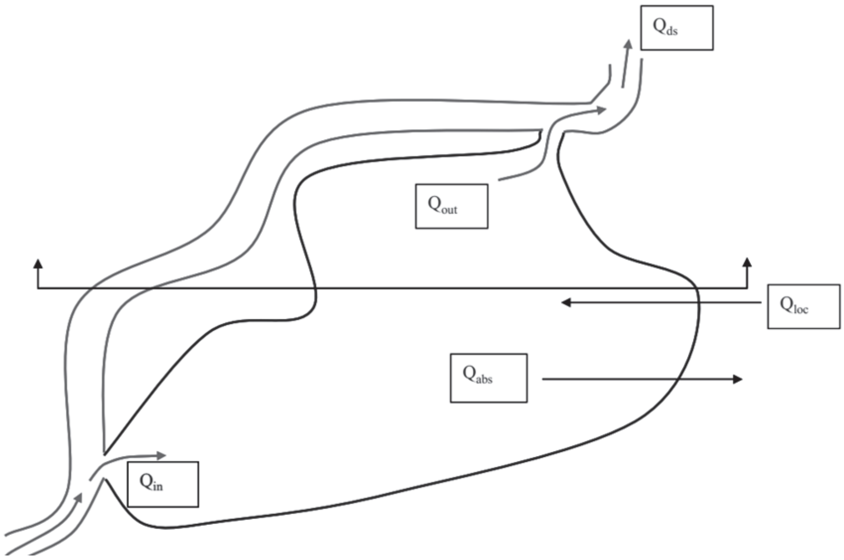


Figure 12 An illustration of the principle implementation of the wetland sub-model in the WRSM2005 Pitman model (DWA, 2008). The diagram shows a single link from river channel to wetland and another single link from wetland back into the channel facilitates visualization of the model. In reality a wetland has many links, where water can flow to/from the channel from/to wetland depending on water levels.

In the new wetland sub-model, the wetland has a nominal storage capacity and surface area, which can be exceeded and the nominal values refer to the wetland storage (and associated area) below which there is no linkage to the river channel. Flow from wetland to channel is governed by the storage state of the wetland and is proportional to the storage volume over and above the nominal capacity. Flow from channel to wetland occurs when channel flow is above a prescribed threshold. The surplus flow is then apportioned between river channel and wetland link. If the model is to be used to simulate off-channel storage an upper limit can be set for the flow in the channel to wetland link, equivalent to the diversion capacity. The model also caters for local runoff entering directly into the wetland. Units of million cubic metres (10^6 m^3) are used throughout for volumes and flow rates are in million cubic metres per month.

Water balance for wetland

$$S_2 = S_1 + Q_{loc} + Q_{in} - Q_{out} - Q_{evap} - Q_{abs} \quad \text{Equation 1}$$

Where: S_2 = Wetland volume at end of month; S_1 = Wetland volume at start of month; Q_{loc} = Local inflow directly into wetland; Q_{in} = Flow into wetland from river channel; Q_{out} = Flow into river channel from wetland; Q_{evap} = Rate of net evaporation loss from wetland; Q_{abs} = Rate of abstraction from wetland/off-channel storage.

Inflow to the wetland is from the river channel, whereas outflow can be a combination of flow back into the channel, net evaporation loss and abstractions from the wetland (or off-channel storage). In times of heavy rain the net evaporation rate can be *negative* and constitute an additional input to the wetland.

Flow into wetland

$$\begin{cases} Q_{in} = MIN[Q_{div}, K_{in} \cdot (Q_{us} - Q_{bf})] \\ 0 \text{ if } Q_{us} < Q_{bf} \end{cases} \qquad \text{Equation 2}$$

Where: Q_{in} = Flow into wetland form river channel; Q_{div} = Diversion capacity into off-channel storage; Kin = Proportion of Q_{us} above Q_{bf} flowing into wetland; Q_{us} = Flow in river channel upstream of wetland; Q_{bf} = Channel capacity above which spillage into wetland occurs.

If flow in the channel is less than the threshold value Q_{bf}, then there is no inflow. Above the threshold the inflow is a proportion of the channel flow above Q_{bf}. If an off-channel scheme is being modelled, Q_{bf} becomes the flow below which no diversion is allowed (say, for the Reserve) and Q_{div} is the maximum rate of transfer to the off-channel dam, viz. the diversion capacity. For a natural wetland Q_{div} is not used, hence an arbitrary large value is assigned in the model. An in-channel wetland can be modelled by setting Q_{bf} equal to zero and K_{in} equal to 1, such that all flow enters the wetland.

Outflow from wetland

$$\begin{cases} Q_{out} = K_{out} \cdot (S_{ave} - S_{nom}) \\ 0 \text{ if } S_{ave} < S_{nom} \end{cases} \qquad \text{Equation 3}$$

Where: Q_{out} = Flow into river channel from wetland; K_{out} = Proportion of wetland storage above S_{nom} returned to channel; S_{ave} = Average wetland volume for month; S_{nom} = Nominal wetland storage volume.

Outflow from the wetland back into the channel occurs only when the wetland volume exceeds the nominal storage. The factor K_{out} determines the rate at which the surplus water drains back to the channel. For some very extensive wetlands a low value of K_{out} would be appropriate, signifying a slow release of water back to the channel. However, if an off-channel scheme is being modelled the value of K_{out} would be close to unity, since the dam would be provided with a spillway.

Evaporation from wetland

$$Q_{evap} = E_{net} \cdot A_{ave} \qquad \text{Equation 4}$$

Where: Q_{evap} = Rate of net evaporation loss from wetland; E_{net} = Net evaporation from wetland for month [m]; A_{ave} = Average wetland area for month [km²].

The net evaporation loss E_{net} is determined in the usual manner by subtracting rainfall from the gross evaporation, which is derived by applying a coefficient to the monthly pan evaporation. The relationship between wetland volume and surface area is given by the equation $A=aS^b$, where a and b are constants defined by the shape of the wetland basin. For most wetlands one has a good estimate of the nominal surface area (A_{nom}) and the nominal volume (S_{nom}) can be estimated by assuming an average water depth. The coefficient b can be derived by assuming a basin shape: a typical value for b is plus/minus 0.5. The value of a is determined by the following equation.

$$a = \begin{cases} \dfrac{A_{nom}}{S_{nom} \cdot b} & \textit{if there is an estimate of b} \\ \dfrac{A_{nom}}{S_{nom} \cdot 0.5} & \text{if no estimate of b} \end{cases} \qquad \text{Equation 5}$$

Where: A_{nom} = Nominal wetland surface area [km²]; S_{nom} = Nominal wetland storage volume; a,b = Constants in wetland area-capacity eqn. $A = aS^b$

The net evaporation can now be calculated from the wetland storage state as follows:

$$Q_{net} = E_{net} \cdot a \cdot S_{ave} \cdot 0.5 = E_{net} \cdot A_{nom} \cdot \left(\frac{S_{ave}}{S_{nom} \cdot 0.5}\right) \qquad \text{Equation 6}$$

Where: E_{net} = Net evaporation from wetland for month [m]; A_{nom} = Nominal wetland surface area [km²]; S_{nom} = Nominal wetland storage volume; a,b = Constants in wetland area.

Flow downstream of wetland

$$Q_{ds} = Q_{us} - Q_{in} +\cdot\, Q_{out} \qquad \text{Equation 7}$$

Where: Q_{ds} = Flow in river channel downstream of wetland; Q_{us} = Flow in river channel upstream of wetland; Q_{in} = Flow into wetland form river channel; Q_{out} = Flow into river channel from wetland.

The flow downstream of the wetland is simply the upstream flow less inflow to the wetland plus outflow back to the river channel. For most months Q_{ds} will be less than Q_{us} (i.e. Q_{in} >

Q_{out}). However, periods immediately after high flow can be followed by a net increase in flow as floodwater drains back into the river channel.

Owing to the coarse time step (one month) it is necessary to perform some kind of iteration to achieve a water balance of sufficient accuracy. The model achieves this by making successive approximations to the average wetland storage (S_{ave}) until the difference between successive estimates is less than a predetermined value.

3.2 The ACRU Model

The ACRU agrohydrological model (Schulze, 1986 and updates) is a daily time-step, conceptual-physical model with a daily water balance that simulates hydrological responses to climatological inputs.

The wetland sub-model for the ACRU model (Schulze, 1986; 1995) was initially developed by Schulze et al. (1987) and used to assess the hydrological impacts of upstream reservoirs on wetlands in East Griqualand. This sub-model was refined and updated in the later work by Smithers (1991) and Smithers and Schulze (1993).

This sub-model includes features such as inflow hydrograph attenuation, evaporation from open surfaces, transpiration from riparian vegetation, rainfall onto the wetland area, and losses to or gains from underlying aquifers and outflows from these features. The morphology of the wetlands and associated effects of increases in ponded surface areas are also accounted for. From a hydraulic perspective, the model development is focused on a single channel rather than a dendritic pattern of channel networks (Helmschrot, 2006). These, impact on the applicability of sub-model in some areas.

The implementation of the wetland module in the ACRU model is a lumped approach based on the hydrological mass balance equation (Schulze, 1995). Hammer and Kadlec (1986), Huff and Young (1980) and Mitsch and Gosselink (2000) contend that this approach is the best for wetland models, and is expressed as follows:

$$dS_W = P_g + I_S + I_{gw} - E - O_S - O_{gw}$$ Equation 8

Where: dS_W = change in storage [mm]; P_g = gross rainfall [mm]; I_S = surface inflow [mm]; I_{gw} = groundwater inflow [mm], E = total evaporation [mm]; O_S = the surface outflow [mm] and O_{gw} = groundwater outflow [mm].

As in the Pitman model, the ACRU model simulates a wetland separately as a reservoir located at the outlet of the sub basin, and the wetland is routed to the channel by applying the Manning's equation (Schulze, 1995).

The conceptualisation of the wetland sub-model within the ACRU model is illustrated in Figure 2 and Figure 3 is a flow diagram of the implementation of the wetlands module.

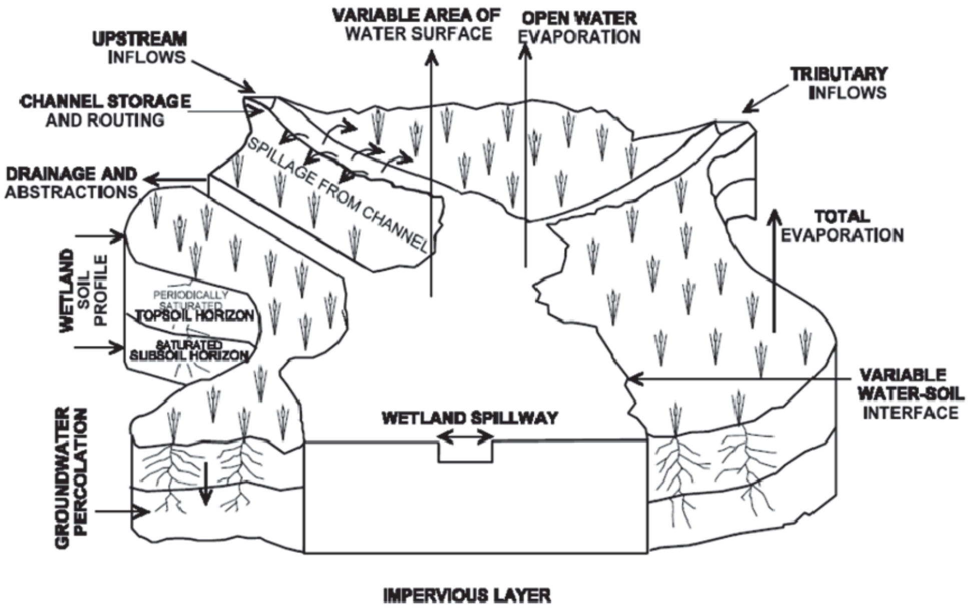


Figure 13 Concepts, processes and assumptions of the ACRU wetlands module (Schulze, 1987; Schulze, 2001).

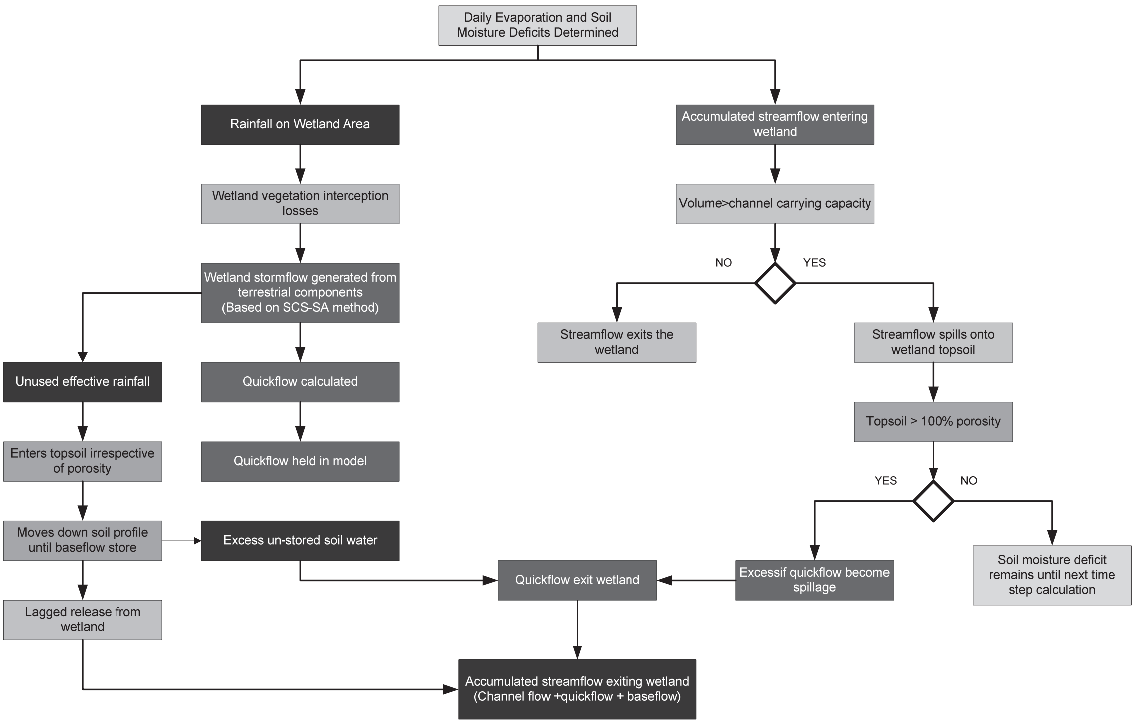


Figure 14 A flow diagram of the implementation of the hydrological processes in the ACRU Wetland Routines (Gray, 2011).

The following is a description of the typical ACRU model configuration to simulate wetlands responses (Gray, 2011). The wetland is modelled as its own sub-catchment, with fixed boundaries. An impervious layer is assumed to underlie the base of the wetland. Spills from the channel onto the wetland's topsoil only occur when the channel capacity is exceeded. Wetland water also derived from releases of water out of the wetland catchment as baseflow. When the wetland's soil is totally saturated, the excess water then exits the wetland as stormflow. When the wetland's topsoil is at, or above, field capacity, percolation of soil water moves water down the soil profile to the subsoil. This process is repeated from the subsoil to the baseflow store. The baseflow store below the subsoil horizon is considered to be unlimited in volume and has an impervious base, therefore only releasing water out of the wetland in the form of baseflow. There is thus no deep percolation or groundwater recharge from the wetland in this model. The water release from the baseflow store is based on a decay function that is dependent on the volume of water contained in the baseflow store, i.e. the greater the volume of water stored in the baseflow store, the higher the rate of baseflow released from the store on a daily basis. Thus, the wetland system losses are made up of total evaporation and outflows in the form of stormflow and baseflow.

3.3 The MIKE SHE model

MIKE SHE is a spatially and temporally explicit, integrated, physically based, distributed model that simulates hydrological and water quality processes on a basin scale. The model consists of a water movement module and several water quality modules that model simulate surface and groundwater movement, the interactions between the surface water and groundwater systems, and the associated point and non-point source water quality problems (Yan and Zhang, 2004).

The Water Movement module has a modular structure comprising six process-oriented components that describe the major physical processes of the land phase of the hydrological cycle (Rahim et al., 2012). These components are unsaturated and saturated groundwater flow, overland flow, channel flow, and evapotranspiration. Each component solves a corresponding equation.

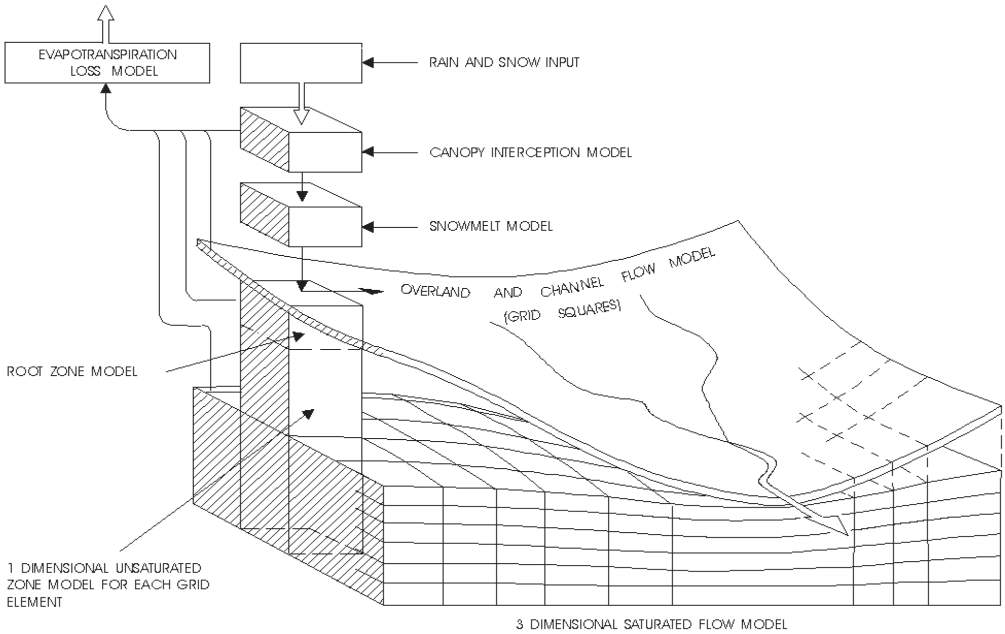


Figure 15 Schematic presentation of the MIKE SHE model structure (Singh et al., 1999).

One- and two-dimensional (2D) diffusive wave approximation Saint Venant equations describe channel and overland flow (Equation 9), respectively.

$$\begin{cases} \frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(uh) + \frac{\partial}{\partial x}(vh) = i \\ S_{fx} = S_{Ox} - \frac{\partial h}{\partial x} - \frac{u}{g}\frac{\partial u}{\partial x} - \frac{1}{g}\frac{\partial u}{\partial t} - \frac{qu}{gh} \\ S_{fy} = S_{Ox} - \frac{\partial h}{\partial y} - \frac{u}{g}\frac{\partial u}{\partial y} - \frac{1}{g}\frac{\partial v}{\partial t} - \frac{qv}{gh} \end{cases} \qquad \text{Equation 9}$$

Where: S_f = the friction slopes in the x- and y-directions and S_O = the slope of the ground surface.

These equations are known as the St. Venant equations and when solved yield a fully dynamic description of shallow, (two-dimensional) free surface flow.

The methods of Kristensen and Jensen (1975) are used for evapotranspiration. This method simply adds the evaporation from canopy storage (Equation10), the transpiration from the plants) and evaporation from soil surface (Equation 11) and updates the soil water balance.

The evaporation from the canopy is given as:

$$E_{can} = \min\left(I_{max}, E_p \Delta t\right) \qquad \text{Equation 10}$$

Where: E_{can} = canopy evaporation [LT-1 /day], I_{max} = maximum interception storage capacity [L], Ep = potential evapotranspiration rate [LT-1] and t = the time step length for the simulation.

The plant transpiration is given as:

$$E_{at} = f_1\,(LAI) \cdot f_2\,(\theta) \cdot RDF \cdot E_p$$ Equation 11

Where: Eat is the actual transpiration [LT^{-1}], f_1 (LAI) is a function based on the leaf area index (dimensionless), $f_2(\theta)$ is a function based on the soil moisture content in the root zone (dimensionless), and RDF is a root distribution function (dimensionless).

The function, $f_1(LAI)$, expresses the dependency of the transpiration on the leaf area of the plant.

$$f_1\,(LAI) = C_2 + C_1\,(LAI)$$ Equation 12

Where: C1 and C2 are empirical parameters that influence the ratio of soil evaporation and transpiration (Kristensen and Jensen, 1975). The estimated value of C1 for agricultural crops and grass is approximately 0.3. C2 has an approximate value between 0 and 0.5.

The second function is given by,

$$f_2\,(\theta) = 1 - \left(\frac{\theta_{fc} - \theta}{\theta_{fc} - \theta_w}\right)^{\frac{C_3}{E_p}}$$ Equation 13

Where: θ_{fc} = volumetric soil moisture at field capacity (dimensionless), θ_w = volumetric soil moisture at wilting point (dimensionless), θ = actual volumetric moisture content (dimensionless), and C_3 is the empirical parameter [LT^{-1}].

The larger the value for C_3, the higher will be the transpiration, assuming all other factors remain constant.

The evaporation from the soil surface is given as:

$$E_s = E_p \cdot f_3(\theta) + \left(E_p - E_{at} - E_p \cdot f_3(\theta) \cdot f_4(\theta) \cdot \left(1 - f_1\,(LAI)\right)\right)$$ Equation 14

Where: E_p = potential evapotranspiration, E_{at} = actual transpiration, and functions $f_3(\theta)$ and $f_4(\theta)$ are given by:

$$f_3(\theta) = \begin{cases} C_2 \text{ for } \theta \leq \theta_W \\ C_2 \dfrac{\theta}{\theta_W} \text{ for } \theta_r \leq \theta \leq \theta_W \\ 0 \text{ for } \theta \leq \theta_r \end{cases}$$ Equation 15

$$f_4(\theta) = \begin{cases} \dfrac{\theta - \dfrac{\theta_W + \theta_{fc}}{2}}{\theta_{fc} - \dfrac{\theta_W + \theta_{fc}}{2}} \text{ for } \theta \geq \dfrac{\theta_W + \theta_F}{2} \\ 0 \text{ for } \theta < \dfrac{\theta_W + \theta_F}{2} \end{cases}$$

The 1D equation of Richards (1931) for unsaturated zone flow (Equation 16) and a 3D equation of Boussinesq (1904) for saturated zone flow (Equation 17).

$$C\frac{\partial \Psi}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial \Psi}{\partial z}\right) + \frac{\partial K(\theta)}{\partial z} - S \qquad \text{Equation 16}$$

Where: $K(\theta)$ = unsaturated hydraulic conductivity [m s^{-1}]; ψ = pressure head; z= elevation head [m] and S=Source/sink.

The dependent variables, θ and ψ are related through the hydraulic conductivity function, $K(\theta)$, and the soil moisture retention curve, $\psi(\theta)$.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - Q = S\frac{\partial h}{\partial t} \qquad \text{Equation 17}$$

Where: K_{xx},K_{yy},K_{zz} = hydraulic conductivity along the x, y and z axes of the model [m s^{-1}], which are assumed to be parallel to the principle axes of hydraulic conductivity tensor; h = the hydraulic head[m]; Q = source/sink terms, and S_s = specific storage coefficient.

These partial differential equations are solved by finite difference methods, while other methods (interception/evapotranspiration) in the model are empirical equations obtained from independent experimental research (DHI 2004).

The coupling of MIKE SHE and the MIKE 11 hydraulic modelling system, allows to simulate the complete terrestrial water cycle (Thompson et al., 2004). In this combined modelling system, the simulation takes place simultaneously in MIKE 11 and MIKE SHE, and data transfer between the two models takes place through shared memory (Refsgaard et al., 1998).

To model wetlands with MIKE SHE requires the use of the Overland, Rivers, Unsaturated Zone and Saturated Zone modules. The type of wetland modelled and the purpose of the modelling dictate the choice of numerical modelling approaches within each module. Hence, the 2-layer unsaturated zone module replaced the original “Wetland module” of the MIKE SHE. The 2-layer Unsaturated module is primarily used for unsaturated groundwater infiltration and root zone processes when the groundwater table is very shallow, which is characteristics of wetlands.

3.4 The Soil Water Assessment Tool model

The Soil and Water Assessment model (SWAT) is a physical based semi distributed model that operates on a daily time step. The model is a continuation of 30 years of modelling experience of the Agricultural Research Service of the United State Department of Agriculture (Gassman, 2007). The model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions (Neitsch et al., 2002). Major model components relevant to this study include weather, hydrology, soil temperature and properties, plant growth and land management. SWAT partitions the watershed into sub basins which are further divided into hydrologic response units that possess unique landuse, management and soil attributes. The hydrological processes are individually simulated in each hydrological response unit (HRU) and aggregated at the sub basin level. The ArcGIS-SWAT (ArcSWAT) interface tool is designed to generate model inputs from ArcGIS data layers and execute SWAT2012.

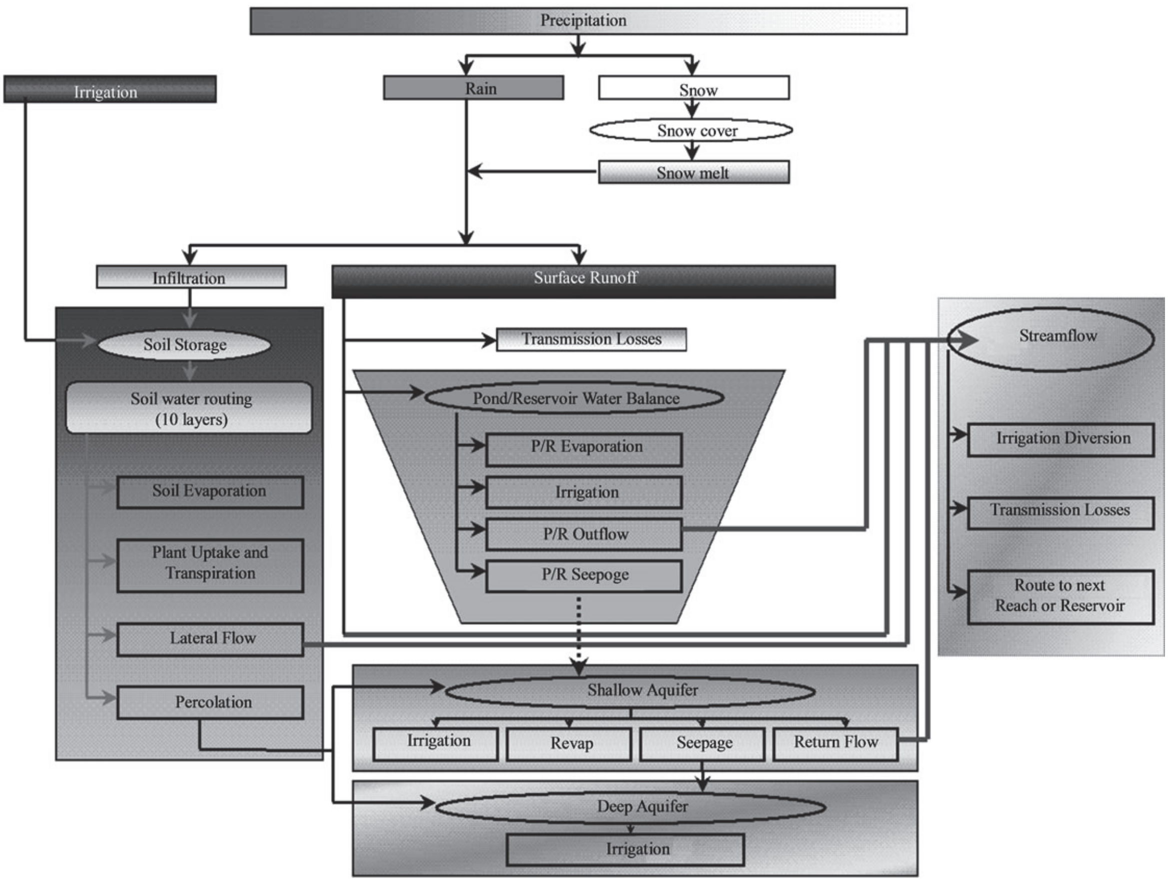


Figure 16 Schematic of pathway available for water movement in SWAT.

Representation of wetland processes in SWAT is not sufficient, and has to be improved (Krysanova and Arnold 2008). SWAT models wetlands as water bodies located within sub basins that received inflow from a fraction of the sub basin area (Neitsch et al., 2011). The model allows only one wetland to be modelled for each sub basin using a water balance equation expresses as:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep}$$ Equation 18

Where: V = volume of water in the wetland at the end of the day [m^3], V_{stored} is the volume of water stored in the water body at the beginning of the day [m^3]; V_{flowin} = volume of water entering the water body during the day [m^3]; $V_{flowout}$ = volume of water flowing out of the water body during the day [m^3], Vpcp is the volume of precipitation falling on the water body during the day [m^3]; V_{evap} = volume of water removed from the water body by evaporation during the day [m^3]; and V_{seep} is the volume of water lost from the water body by seepage [m^3].

Surface area

The surface area of the wetland is needed to calculate the amount of precipitation falling on the water body as well as the amount of evaporation and seepage. Surface area varies with change in the volume of water stored in the impoundment. The surface area is updated daily using the equation:

$$SA = \beta_{sa} \cdot V^{expsa}$$ Equation 19

Where: SA is the surface area of the water body [ha], β_{sa} = coefficient, V = volume of water in the wetland [m^3], and expsa is an exponent.

The coefficient, β_{sa}, and exponent, expsa, are calculated by solving Equation 19 using the surface area and volume information provided for the normal and maximum water levels.

$$expsa = \frac{log_{10}(SA_{mx}) - log_{10}(SA_{nor})}{log_{10}(V_{mx}) - log_{10}(V_{nor})}$$ Equation 20

$$\beta_{sa} = \left(\frac{SA_{mx}}{V_{mx}}\right)^{expsa}$$ Equation 21

Where: SA_{mx} = surface area of the wetland when filled to the maximum water level [ha]; SA_{nor} = surface area of the wetland when filled to the normal water level [ha]; V_{mx} = volume of water held in the wetland when filled to the maximum water level [m]; and V_{nor} = volume of water held in the wetland when filled to the normal water level [m^3].

Precipitation

The volume of precipitation falling on the wetland during a given day is calculated:

$$V_{pcp} = 10 \cdot R_{day} \cdot SA$$ Equation 22

Where: V_{pcp} = volume of water added to the water body by precipitation during the day [m^3], R_{day} = amount of precipitation falling on a given day [mm], and SA = surface area of the water body [ha].

Inflow

The volume of water entering the wetland on a given day is calculated:

$$V_{flowin} = fr_{imp} \cdot 10 \cdot (Q_{surf} + Q_{gw} + Q_{lat}) \cdot (Area - SA)$$ Equation 23

Where: V_{flowin} = volume of water flowing into the water body on a given day [m^3]; fr_{imp} = fraction of the sub basin area draining into the impoundment; Q_{surf} = surface runoff from the sub basin on a given day [mm]; Q_{gw} = groundwater flow generated in a sub basin on a given day [mm]; Q_{lat} = lateral flow generated in a sub basin on a given day [mm]; Area = sub basin area [ha]; and SA = surface area of the water body [ha].

The volume of water entering the wetland is subtracted from the surface runoff, lateral flow and groundwater loadings to the main channel.

Evaporation

The volume of water lost to evaporation on a given day is calculated:

$$V_{evap} = 10 \cdot \eta \cdot E_0 \cdot SA$$ Equation 24

Where: V_{evap} = volume of water removed from the water body by evaporation during the day [m^3]; η is an evaporation coefficient [0.6]; E_0 = potential evapotranspiration for a given day [mm]; and SA = surface area of the water body [ha].

Seepage

The volume of water lost by seepage through the bottom of the wetland on a given day is calculated:

$$V_{seep} = 240 \cdot K_{sat} \cdot SA$$ Equation 25

Where: V_{seep} = volume of water lost from the water body by seepage [m^3]; K_{sat} = effective saturated hydraulic conductivity of the pond or wetland bottom [mm hr^{-1}]; and SA = surface area of the water body [ha].

Outflow

The wetland releases water whenever the water volume exceeds the normal storage volume, V_{nor}. Wetland outflow is calculated:

$$V_{flowout} = \begin{cases} 0, & if\ V < V_{nor} \\ \frac{V - V_{nor}}{10}, & if\ V \leq V_{nor} \leq V_{mx} \\ V - V_{mx}, & if\ V > V_{mx} \end{cases}$$ Equation 26

Where: Vflowout = volume of water flowing out of the water body during the day [m^3]; V = volume of water stored in the wetland [m^3]; Vmx = volume of water held in the wetland when filled to the maximum water level [m^3]; and Vnor = volume of water held in the wetland when filled to the normal water level [m^3].

SWAT requires the following data of the Wetland (Table 2).

Table 2 Data required to model the wetland with SWAT

Variable name		Definition
WET_MXSA	SA_{mx}	Surface area of the wetland when filled to the maximum water level [ha]
WET_NSA	SA_{nor}	Surface area of the wetland when filled to the normal water level [ha]
WET_MXVOL	V_{mx}	Volume of water held in the wetland when filled to the maximum water level [m^3]
WET_NVOL	V_{nor}	Volume of water held in the wetland when filled to the normal water level [m^3]
WET_FR	fr_{imp}	Fraction of the sub basin area draining into the wetland
WET_VOL		Initial volume of water in wetlands [10^4 m^3].
WET_K		Hydraulic conductivity of bottom of wetlands [mm hr^{-1}]

It has been a challenge to appropriately represent wetlands in models, and few SWAT applications reported in the literature have considered wetlands. SWAT does not consider hydrologic processes such as Runoff, infiltration and evapotranspiration for water HRUs (Neitsch et al, 2011). For wetland HRUs, while the hydrological processes are considered, the hydrological functions of conveyance, storage, and retention (Quinton et al., 2003; Hayashi et al., 2004) are not taken into account. This greatly affect model results when water and wetland HRUs make up more than 3 % of a study area size (Wang et al., 2004).

Wang et al. (2004) incorporate wetlands into a SWAT model using a "hydrologic equivalent wetland" (HEW) concept. Because an HEW has a hydrological function identical to its component, it can be substituted to the wetlands without affecting the precipitation-runoff process. As with a regular wetland, an HEW is described by five parameters: the fraction of the sub basin area that drains into the HEW, the surface area at normal water level, the volume of water stored in the HEW when it is filled to its normal water level, the surface area at maximum water level and the volume of water stored in the HEW when it is filled to its maximum water level.

The HEWs are defined in terms of six calibrated parameters: the fraction of the sub basin area that drains into wetlands (WET_FR), the volume of water stored in the wetlands when filled to their normal water level (WET_NVOL), the volume of water stored in the wetlands when filled to their maximum water level (WET_MXVOL), the longest tributary channel length in the sub basin (CH_L), Manning's n value for the tributary channels (CH_N), and Manning's n value for the main channel (CH_N2).

3.5 PyTOPKAPI

The **Py**thon **TOP**ographic **K**inematic **AP**proximation **I**ntegration (PyTOPKAPI) model (Sinclair, Pegram 2013 and Vischel, Pegram, Sinclair, Wagner and Bartsch, 2008) is a fully distributed, physically based hydrological model that was designed to simulate river runoff. PyTOPKAPI had been modified from the original model TOPKAPI (Liu and Todini, 2002) to accommodate South African conditions. Due to the nature of the model it bears the potential to simulate wetland hydrological processes. Supporting arguments for this are:

- PyTOPKAPI is fully distributed and therefore able to represent spatial variability of physiographic conditions such as topography, soil characteristics, evaporation, vegetation and landuse, all of which are necessary to depict different characteristics between terrestrial and wetland soils;
- Many wetlands are an expression of geological and topographic characteristics (Vepraskas, Craft, Richardson and Vepraskas, 2000). PyTOPKAPI uses topography and physical soil characteristics to simulate flows both below and above ground (Liu and Todini, 2002). Topography often determines the accumulation of water in the soil profile to a large extent (Kirkby and Chorley, 1967; Moore et al., 1988) as found in wetlands;
- Surface runoff and interflow, both important drivers for many wetland types in South Africa (le Roux, van Tol, Kunene, Hensley, Lorentz, Everson, van Huyssteen, Kapangaziwiri and Riddell, 2011) are well represented in the model;
- The model is freely available with open source code and has the potential to be extended to cater for additional wetland specific characteristics such as shallow perched groundwater flow. A second soil layer can also be added to be able to represent wetland typical soil types as well as the possibility to calibrate wetland saturation against measured shallow water levels in wetland soils;
- The grid based model structure enables the extraction of water balance components for various wetland units which allows wetlands to be characterised according to their

hydrological types. This supports the differentiation of units based on the HydroGeoMorphic (HGM) classification system currently used in South Africa (modified from Brinson, 1993; and Marneweck and Batchelor, 2002) in Kotze, Marneweck, Batchelor, Lindley and Collins (2007); and

- The use of the model for water balance modelling in individual wetland units has been tested and applied with reasonable success (for the purposes, and at a level of confidence applicable to, the studies in question) in recent intermediate level Wetland Reserve Determinations in South Africa.

The original version of TOPKAPI consists of 5 main modules comprising soil, overland, channel (those three modules take the form of non-linear reservoirs controlling the horizontal flows.), evapotranspiration and snow modules (Vischel et al., 2008). Recent versions now also include a lake/reservoir component, a parabolic routing component and a groundwater component (Figure 17). While the model does not have a wetland module per se, it has a reservoir/lake module that was introduced to improve the models' performance. Lakes and reservoirs are represented by defining the cells within the lake or the reservoir with the land use type of water body (Mazzetti, 2012).

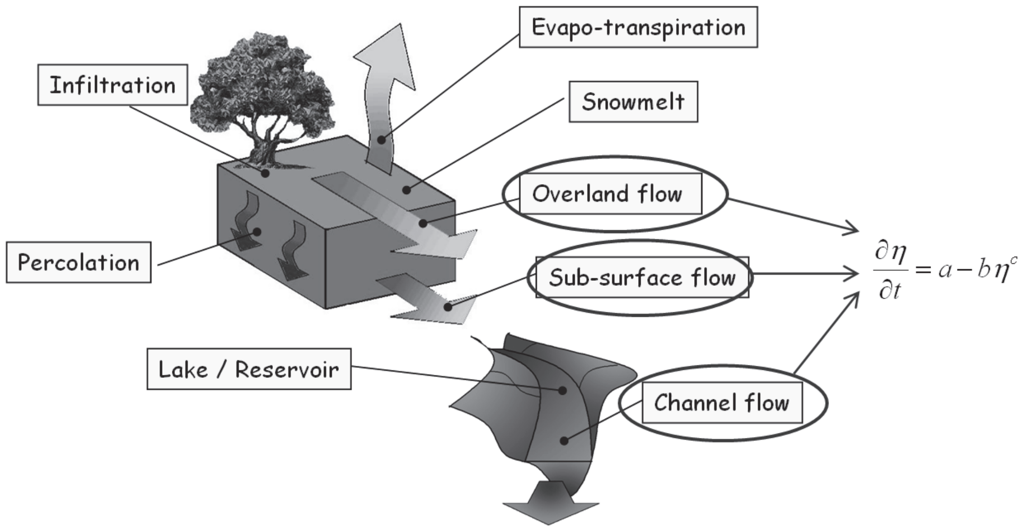


Figure 17 **Schematic presentation of the TOPKAPI model structure (Lastoria 2008).**

The following lake equations were incorporated into the model (Bartholmes and Todini, 2003):

$$Q_{out} = \alpha \cdot h_{start}^{\beta}$$ Equation 27

Where: Q_{out} = volume of water flowing out of the lake [$L^3 T^{-1}$]; h_{start} = initial lake level [L]; α and β = lake coefficients (dimensionless).

$$h_{end} = h_{start} + \frac{(Q_{in} - Q_{out}) \cdot \Delta t}{A}$$ Equation 28

Where: h_{start} = final lake level [L]; h_{start} = initial lake level I [L]; Q_{in} = volume of water flowing into the lake [L^3 T^{-1}]; Q_{out} = volume of water flowing out of the lake [m^3 s^{-1}]; Δt = time period [3600 s]; A= surface area of the lake.

Model drawbacks:

- The substrate/soil profile is currently represented as a single layer only;
- No groundwater flow is currently supported;
- No dam routing module is currently supported;
- The model is data hungry and requires detailed parameters describing soil hydraulic characteristics which are not readily available on a small scale; and
- Calibration requires local reference evapotranspiration, rainfall and river runoff data.

Conclusion and Recommendations

The potential capability of PyTOPKAPI to simulate most hydrological processes necessary to describe the drivers of the different HGM wetland types has been demonstrated as indicated above. Although the model is not designed specifically for wetlands, it can potentially be enhanced to cater for most hydrological processes to describe flows in the different HGM wetland types. The model therefore has the potential to become a tool which can be used for modelling flows related to wetland hydrological processes. This could be expanded to quantitative hydrological impact assessments on wetlands and for determining the water quantity component in Wetland Reserve Determination studies.

It is thus recommended that the application of the model to wetlands be investigated further with specific emphasis on amending modules and routines to enhance its capability in this regard. This should include the testing of the model performance against field data from different HGM wetland types.

3.6 HYDRUS

HYDRUS is a finite element soil physical and hydrological model which calculates unsaturated/saturated water movement in porous media and includes solute transport, root water uptake, soil surface evaporation and other processes (Šimůnek et al., 1999). The model can be set up in 1, 2 or 3 dimensions; however it is not suitable at catchment scale

(Šimůnek et al., 2012). All necessary processes required for wetland hydrology can be simulated. HYDRUS has been applied in numerous scientific applications including wetland hydrology. Additional modules are available to simulate processes within constructed wetlands.

A selection of publications where HYDRUS has been used in relation to wetland or hillslope hydrology is as follows:

- "Modelling water flow and seasonal soil moisture dynamics in an alluvial groundwater-fed wetland" by Joris and Feyen (2003);
- "Water Table Dynamics of a Severely Eroded Wetland System, Prior to Rehabilitation, Sand River Catchment, South Africa" by Riddell, Lorentz, Ellery, Kotze, Pretorius and Nketar (2007);
- "Conditions for lateral downslope unsaturated flow and effects of slope angle on soil moisture movement " by Lv, Hao, Liu, and Yu (2013); and
- "Connectivity at the hillslope scale: Identifying interactions between storm size, bedrock permeability, slope angle and soil depth" by Hopp and McDonnell (2009).

Model drawbacks:

- The model is designed to simulate detailed soil hydraulic processes on a small scale and cannot be applied beyond the hillslope scale;
- The model is data intensive and requires detailed parameters describing soil hydraulic characteristics which are not readily available on a small scale; and
- Most common calibration parameters are soil moisture or surface runoff, both aspects which are difficult to measure in the field.

3.7 SUMMARY

The hydrological processes in wetland ecosystems are not well-understood (Rahim et al., 2012). In fact, there are great concerns and uncertainties about the hydrological response of wetlands to land use and climate change. Hydrological models provide a framework to analyse data and test hydrological hypotheses; however, their performance encountered substantial deficiencies when considering detailed water balance computation such as wetland.

Although all hydrological models presented in the previous section have been used to model wetlands, most of them do not have the integration nature to be capable of modelling wetlands. Moreover, most models, especially the semi distributed connects wetlands directly to the stream but not over land where many wetlands occur.

Although the recent versions of the Pitman model are spatially semi-distributed, based on sub basin divisions with their own climate inputs, the model does not integrate the surface and groundwater systems. The current wetland module mostly accounts for the input-storage-output relationships between the river channel and the wetland.

The ACRU has the added advantage of simulating an interaction between surface and groundwater, though the results at a daily scale were less reliable than monthly totals. Nevertheless, in spite of a relatively detailed representation of the wetland module, the actual equations used in the model are not documented.

The integration nature and the ability to account for both surface and subsurface flow systems, and their interaction make MIKE SHE well suited in establishing a detailed water balance of wetland systems. Compare to the other three hydrological modelling systems, MIKE SHE is a data intensive system (Thompson et al., 2004). South Africa has several basins classified as ungauged because they have inadequate hydrological observations, in terms of both data quantity and quality, to enable a computation of hydrological variables -at appropriate spatial and temporal scales- at a level of accuracy acceptable for practical water resource management. There is therefore a tremendous lack of data for a detailed modelling of existing wetlands. This is a concern, considering the recognised large data requirements of an integrated, distributed hydrological models such as MIKE SHE (Yan and Zhang, 2004; Vázquez and Feyen, 2007; Im et al., 2009; Rahim et al., 2012). The subsequent coupling of a MIKE 11 river model to MIKE SHE imposes further data requirement (Thompson et al., 2004). The use of the MIKE SHE will therefore likely require expensive and extensive field data collections. This is to a certain extent also valid for the SWAT model.

The main limitation of the SWAT model is being a semi distributed, where it divides the watershed into sub basins having homogeneous climate, soil, land cover and management practices. In addition, the surface and groundwater systems are not fully integrated. As a result, the SWAT model fails to represent the surface groundwater interaction. This also applies to the hydrologic equivalent wetland concept (Wang et al., 2004).

Although TOPKAPI is not designed specifically for wetlands, it can potentially be enhanced to cater for most hydrological processes to describe flows in the different HGM wetland types. The model therefore has the potential to become a tool which can be used for modelling flows related to wetland hydrological processes. This could be expanded to quantitative hydrological impact assessments on wetlands and for determining the water quantity component in Wetland Reserve Determination studies.

Hydrus can be set up in 1, 2 or 3 dimensions; however it is not suitable at catchment scale although all necessary processes required for wetland hydrology can be simulated.

Different types of wetlands varying in size and functioning occur in the country. They are controlled by local hydrology, terrain position and geology. We can hypothesise that hydrological impacts on wetlands are strongly associated with the size and type of the specific wetland. However, it is very unclear which model is more appropriate for modelling a certain type of wetlands.

While the hydrological dynamics of smaller wetlands in the region may certainly be dominated by subsurface exchanges of water, they are assumed to have only small impacts on patterns of monthly runoff volume, due to their relatively small storage volumes. However, they may be important at influencing daily flow regions and therefore hydrological regimes at the daily time scale.

It is critical to refine and adapt to local conditions the link between landscape location and water transfer mechanisms in order to build appropriate conceptual and mathematical models.

4 CASE Studies

4.1 GaMampa Wetland – WRSM2000

Modelling wetland processes with the Pitman model

The SPAtial and Time Series Information Modelling (SPATSIM; Hughes, 2004; Hughes and Forsyth, 2006) is an integrated hydrology and water resource information management and modelling system, developed by the institute for water research in Rhodes University that was used for the study. It is a conceptual, semi distributed hydrological model. **Figure 18** indicates the main hydrological processes that are considered by the model.

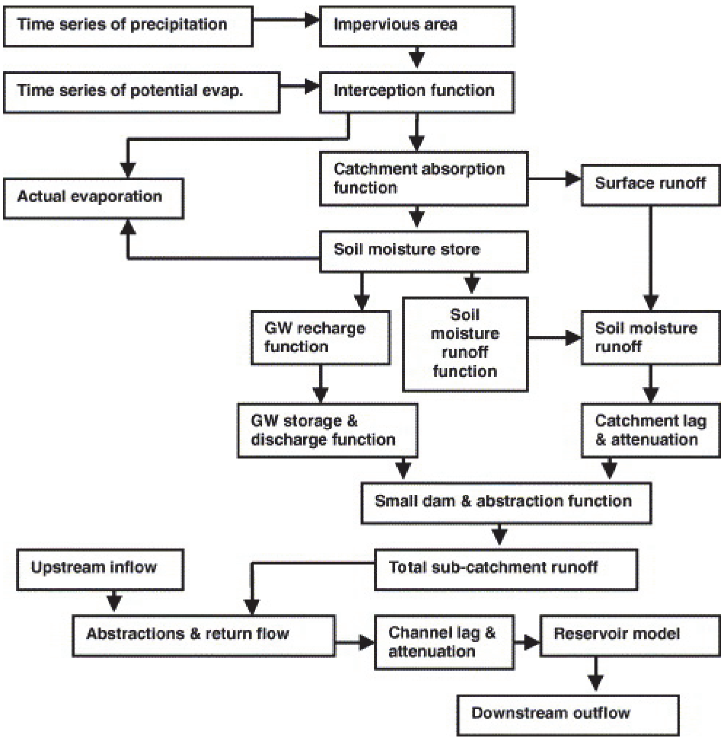


Figure 18 Flow diagram of the main components of the SPATSIM version of the Pitman model (Hughes et al., 2006.)

Table 3 shows the parameters of the Pitman model. This study focuses on those parameters that influence the generation and transition of runoff, soil moisture accounting and surface and groundwater movement and storage.

Table 3 A list of the parameters of the Pitman model including those of the reservoir water balance model (Hughes et al., 2006).

Parameter	Unit	Parameter description
RDF	-	Controls the distribution of total monthly rainfall over four model iterations
AI	Fraction	Impervious fraction of sub-basin
PI1 and PI2	mm	Interception storage for two vegetation types
AFOR	%	% area of sub-basin under vegetation type 2
FF	-	Ratio of potential evaporation rate for Veg2 relative to Veg1
PEVAP	mm	Annual sub-basin evaporation
ZMIN	mm $month^{-1}$	Minimum sub-basin absorption rate
ZAVE	mm $month^{-1}$	Mean sub-basin absorption rate
ZMAX	mm $month^{-1}$	Maximum sub-basin absorption rate
ST	mm	Maximum moisture storage capacity
SL	mm	Minimum moisture storage below which no GW recharge occurs
POW	-	Power of the moisture storage- runoff equation
FT	mm $month^{-1}$	Runoff from moisture storage at full capacity (ST)
GPOW	-	Power of the moisture storage-GW recharge equation
GW	mm $month^{-1}$	Maximum groundwater recharge at full capacity, ST
R	-	Evaporation-moisture storage relationship parameter
TL	months	Lag of surface and soil moisture runoff
CL	months	Channel routing coefficient
DDENS	-	Drainage density
T	m^2 d^{-1}	Groundwater transmissivity
S	-	Groundwater storativity
GWSlope	%	Initial groundwater gradient
AIRR	km^2	Irrigation area
IWR	Fraction	Irrigation water return flow fraction
EffRf	Fraction	Effective rainfall fraction
NIrrDm	Ml yr^{-1}	Non-irrigation demand from the river
MAXDAM	Ml	Small dam storage capacity
DAREA	%	Percentage of sub-basin above dams
A, B	-	Parameters in non-linear dam area-volume relationship
IrrAreaDmd	km^2	Irrigation area from small dams
CAP	Mm^3	Reservoir capacity

Parameter	Unit	Parameter description
DEAD	%	Dead storage
INIT	%	Initial storage
A, B	-	Parameters in non-linear dam area-volume relationship
RES 1-5	%	Reserve supply levels (percentage of full capacity)
ABS	Mm^3	Annual abstraction volume
COMP	Mm^3	Annual compensation flow volume

a. Catchment absorption (infiltration)

Infiltration capacity is the amount of water that can be absorbed by the soils surfaces in response to rain falling in different intensities. This depends mainly on the soil, geology and vegetation type (Kapangaziwiri and Hughes, 2008). The pitman model takes into account catchment absorption capacity through parameters AI, ZMIN, ZAVE and ZMAX. The parameter AI represents the proportion of a sub-basin which is impermeable, while the parameters ZMIN, ZAVE and ZMAX represent the absorption rates of a catchment which is represented by a triangular distribution. Rainfall intensity and infiltration rates have a direct influence to runoff generation. Rain falling at low intensities (greater than ZMIN) allows for all water to be absorbed thus low generation of runoff while high intensity rainfall allows (greater than ZMAX) results in high runoff generation.

b. Soil moisture accounting and runoff generation

Soil moisture refers to the proportion of water withhold by the soil particles. In the Pitman model, soil moisture is accounted for by parameters ST, FT, POW and GW. ST is the maximum soil moisture storage of the soil. The storage depends on infiltration, and water will continue to infiltrate through the soil until the soil moisture storage is at its full capacity (i.e. soil is saturated). Water within soil moisture storage is lost through evaporation, lateral movement contributing to runoff and recharge to groundwater (Kapangaziwiri and Hughes, 2008). FT is the maximum runoff from the soil moisture at saturation. The generation of runoff through soil moisture is usually delayed or lagged (TL), depending on the type of soils and the storage of moisture to the soil. Higher TL values entails that the movement of runoff from upstream to downstream will take longer. The relationship between moisture storage and runoff in a catchment is described by parameter POW, which is the power of the moisture storage-runoff equation. An increase in POW will results in an increase in runoff generation.

Groundwater is recharged through losses from the soil moisture storage through percolation. The parameter GW refers to the maximum amount of groundwater recharge at maximum soil moisture storage (ST).

c. The wetlands sub module

The wetland sub-model that was recently added to the SPATSIM Pitman model is based on work in the Zambezi and Congo basins (Mwelwa, 2004; Tshimanga, 2012; Tirivarombo, 2012)) where vast wetlands (e.g. the Kafue) and natural lakes (e.g. Lakes Tanganyika and Malawi) are important hydrological features that significantly impact the natural hydrology of the catchments. Thus, the application of the wetland sub-model is envisaged to be on "relatively large rivers and wetlands of southern Africa where the downstream impacts of wetland storage are expected to be evident at the monthly time-scale of modelling" (Hughes et al., 2013). The wetland sub-model is an optional component that is only simulated if the input data stream for a specific sub-basin includes parameter sets associated with it. **Error! Reference source not found.** shows the set of parameters required for the simulation of a wetland with the Pitman model (Hughes et al., 2006).

The wetland sub-model is designed to work over four time steps within a month just as the main model does. This avoids excessively large changes in any single component of the wetland water balance before other components are updated. The following describes the functioning of the wetland sub-routine within the SPATSIM Pitman model;

The dimensions of the wetland are given by the maxWA which is the maximum local catchment area of the wetland. This includes both the inundated and dry part of the wetland area. The size of the inundated part of the wetland, WA (which increases as the wetland gains water and shrinks as it loses water), is derived from the area-volume (WV) relationship using parameters AVC and AVP.

Water is added to the wetland through:

- Local runoff generated from a part of the wetland catchment area that is not inundated (i.e. maxWA-WA).
- Local rainfall falling directly on the inundated area
- Inflow from the channel, which is calculated as a proportion of the total upstream channel flow.

Losses from the wetland are via:

- Evapotranspiration at the potential level (PEVAP) using seasonal (monthly) distributions and is based on the area of the wetland that is inundated.
- Flow back to the river channel. The size of the flow is determined by a power function between a return flow fraction (RFF, with maximum value of 0.95) and the ratio of the current storage of the wetland (WV) to the residual (RWV), where RWV is the volume below which water is unable to flow back to the channel.
- Any artificial abstractions from the wetland for irrigation, domestic or any other use.

This simplified water balance approach ignores any interactions between the wetland and the groundwater component of the natural hydrology of the catchment, which in some places could be very important and could control the wetland's hydrology.

Hughes et al. (2013) contend that the wetland module has been included in the model specifically to improve the simulations of flows downstream of the wetland, and not "the ecological or water quality dynamics of the wetlands." This is important in evaluating the sub-model. The objective of the model is simulating the natural flows of the catchment and the wetland module is incorporated as a black-box sub-model to help achieve this objective.

It is possible to estimate some of the parameters (such as MaxWA, RWV, AVC and AVP) of the sub-model from measurable properties of the wetland, while others would have to be calibrated to match the observed or assumed inundation volume or area dynamics of a specific wetland in relation to observed or simulated upstream and/or downstream flows. Such parameters as the channel capacity parameter (QCap), QSF, RFC and RFC are more difficult to estimate without detailed hydraulic data and are therefore calibrated in most cases.

Table 4 The parameters and algorithms used for the wetlands sub-model in the SPATSIM Pitman model. (-) denotes that parameter is dimensionless (Hughes et al., 2013).

Parameter and Units	Description and use
MaxWA (km^2)	Maximum wetland area
RWV(m^3 * 10^6)	Residual wetland storage volume below which there are no return flows to the river channel.
IWV (m^3 * 10^6)	Initial wetland storage volume at the start of the simulation.
AVC (m^{-1})	Constant in the WA=AVC * WVAVP relationship, where WA (m^2) and WV (m^3) are the current wetland area (limited to MaxWA) and volume, respectively.
AVP	Power in the WA=AVC * WVAVP relationship
QCap (m^3 * 10^6)	Channel capacity below which there is no spill from the channel to the wetland.
QSF (-)	Channel spill factor in SPILL=QSF * (Q–QCAP), where Q is the upstream flow, and SPILL is the volume added to wetland storage.
RFC (-)	Return flow constant in the RFF=RFC * (WV / RWV) ^{RFP} relationship. RFF is a fraction limited to a maximum of 0.95 and then adjusted when Q is greater than QCap (RFF=RFF * QCap / Q). The return flow volume is calculated from RFLOW=RFF * (WV–RWV).
RFP (-)	Return flow power in the RFF=RFC * (WV / RWV) ^{RFP} relationship.
EVAP (mm)	Annual evaporation from the wetland (distributed into monthly values using a table of calendar month percentages).
ABS (m^3 * 10^6)	Annual water abstractions from the wetland (distributed into monthly values using a table of calendar month percentages).

Parameters MaxWA, RWV, AVC and AVP can be obtained from topographical data. Detailed information of the channel cross sectional shape throughout the wetland is required to estimate the channel capacity parameter (QCap). The channel spill factor and the return flow parameters require detailed hydrological data for estimation.

The GaMampa wetland

The Mohlapetsi river catchment (quaternary catchment B71C) (Figure 19) is a sub basin of the Olifants basin in the Olifants Water Management Area.

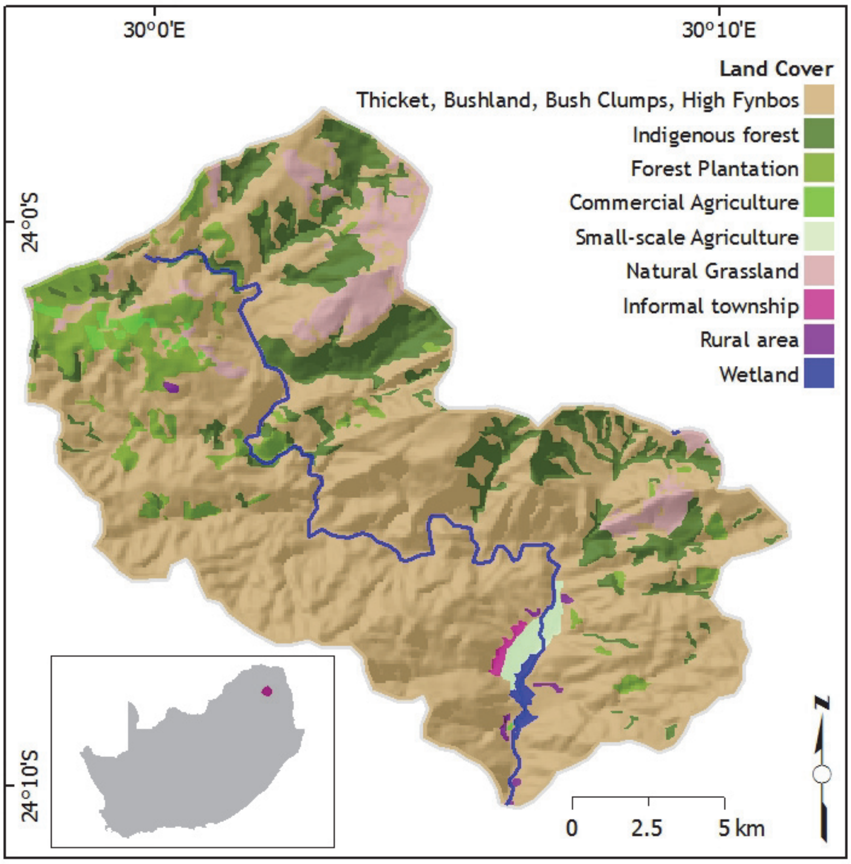


Figure 19 A map showing the land cover classes of quaternary B71C in which the GaMampa wetland is located.

The GaMampa wetland is located at the bottom of a confined steep-sided valley, adjacent to the Mohlapitse River (Figure 19). The wetland is of the riverine type and covers an area of approximately 1 km^2 (SANBI, 2011). The wetland area extends 4 to 5 km on both sides of the river, with the width that ranges from 10 to 100 m (Mai, 2010). The catchment area for the Mohlapetsi River is approximately 263 km^2. The Mohlapetsi River is a perennial river, and is about 50 km long .The area that feed the River at the confluent of the Olifants River is approximately 490 km^2. The catchment upstream of the wetland is mostly characterised by dolomite with high groundwater storage (Kotze, 2005) while the wetland and its local catchment are characterised by banded ironstone and chert (Minayo, 1996). The area upstream of the wetland is characterised by well drained sandy while the area downstream is dominated by poorly drained loamy soil (Morardet, 2010). Soils within the wetland are mostly organic peat soils surrounded by mineral soils which are temporally saturated. The GaMampa wetland has shallow water table, thus the soils have high soil moisture content (Chuma et al., 2009).

Data availability

Hydrological data

The Mohlapetsi river catchment is characterised by seasonal rainfall, mostly occurring in summer between October and April. An annual precipitation of 771 mm per annum has been recorded for the Mohlapetsi catchment, while the area around the wetland is characterised by an annual precipitation that ranges from 500 to 600 mm per annum. The annual precipitation of the catchment of 771 mm is lower than the annual evapotranspiration of 1428 mm derived using Penman-Monteith Equation (McCartney et al., 2006). The WR2005 (Middleton and Bailey, 2009) reports suggest 1450 mm. Daily stream flow data measured at two stations B7H013 and B7H011 (Table 5 and Figure 20), operated by the Department of Water and Sanitation (formerly known as the Department of Water Affairs and Forestry) were used for the study. B7H013 is still functioning while the latter was washed away by rainfall. B7H013 starts recording from 1970, while B7H011 has a record that starts in 1963 and ends in 1988. The mean annual flow for the stream is approximately 38 Mm^3.

Table 5 Stream gauges within the Mohlapetsi river catchment

Station no	Latitude	Longitude	Area (km2)	Length of record
B7H013	24 10 24.5 S	30 06 09.9 E	263	1970-present
B7H011	24 09 51.5 S	30 06 20.1 E	262	1963-1988

Assessment of flow gauge data

To understand stream flow dynamics in the sub-basin better, daily and monthly flow data were used for the analysis. This was done from 1970 to 1988, when both flow gauges were operational. The daily time series for the two gauging stations on the Mohlapetsi River are represented by Figure 20. The two gauges show a similar daily and seasonal pattern. However, it is interesting to note that in majority of the low flow months the downstream gauge B7H013 records lower flows B7H011, which is counter-intuitive. The mean monthly flows for the wet season for B7H011 and B7H013 are 2.700 Mm^3 and 2.924 Mm^3, while the low flow season means are 0.842 Mm^3 and 0.679 Mm^3, respectively. Given that there are no known abstractions between the gauges, it is difficult to explain this apparent anomaly. Could it be that water is lost to the groundwater aquifer, or is absorbed by the lower extension of the wetland? Mekiso (2011) associates the stream flow variation at B7H013 with groundwater level fluctuations, which has been said to reflect rapid lateral flow.

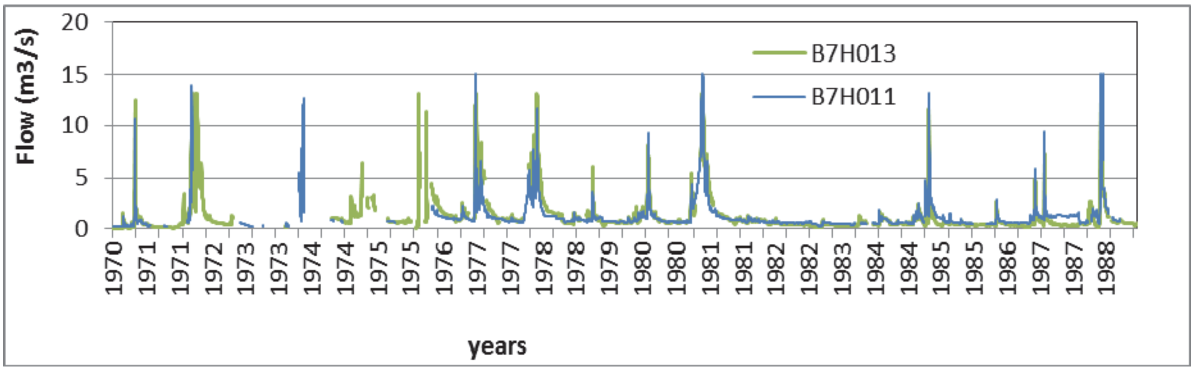


Figure 20 Time series comparison for flow gauges B7H013 and B7H011.

There is no contribution from the wetlands to stream flow, especially in the dry seasons McCartney et al. (2006). This may imply that at this time the water level in the wetland (or the surrounding area) is lower that the stream flow which would create a gradient between the stream and the wetland, resulting in water loss to the wetland. Models (especially the Pitman model) simulate this process as transmission losses from the stream.

GaMampa wetland conceptual model

It is important to construct a conceptual model before attempting to model. The conceptualisation so developed would guide the determination of the hydrological processes taking place in an area and more importantly how these would be represented in the model. This conceptualisation also helps to identify the limitations of a model with respect to the area or processes being studied. Important in the conceptual model are the flow fluxes, in terms of source of water, magnitude and direction. The hydrological processes of the GaMampa wetland have been studied by several scholars (Mekiso, 2001; Sarron, 2005; Kotze, 2005; Masiyandima *et al*, 2006; McCartney et al., 2011). Mekiso (2001) used environmental isotopes (oxygen and hydrogen isotopes) to determine sources of water in the wetland and the flow patterns and generated a conceptual model of the wetland (Figure 21).
The wetland is sustained by water from surface water (upstream inflows) groundwater flow from the surrounding catchment Groundwater flow is laterally transferred between the catchment, the wetland and the river. Spills from/to wetlands were assumed to be zero because they rarely occur (during major floods events).

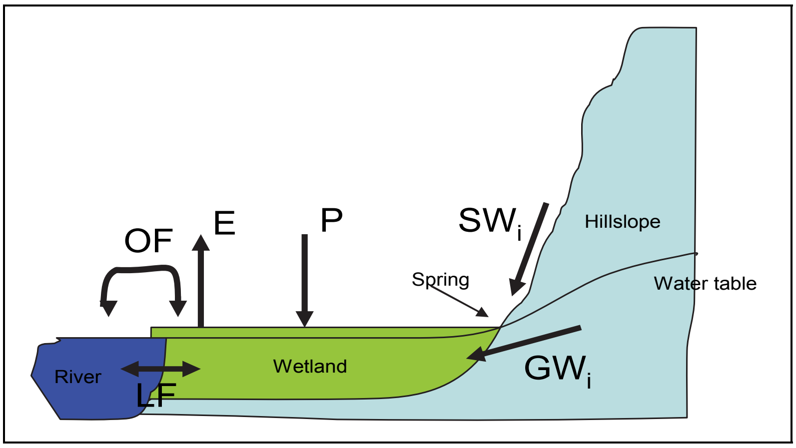


Figure 21 A conceptual model of the GaMampa wetland (McCartney et al., 2011). With P = Precipitation; E = Evapotranspiration; LF = Subsurface lateral flow to/from the river; OF = Surface water moving to/from the river. SWi= Surface water moving into the wetland and GWi = Groundwater moving into the wetland.

Model setup

The SPATSIM (Hughes and Forsyth, 2006) version of the Pitman monthly rainfall-runoff model (Hughes et al., 2006) was used to simulate stream flows of the Mohlapetsi River including the GaMampa wetland. The aim of the exercise is to determine the effect of including or excluding the wetland in the general simulation of the water resources of the sub-basin. The starting point is the national water resources assessments that have been carried out since 1981 (Middleton et al., 1981), the current one being the 2005 assessment, commonly known as WR2005 (Middleton and Bailey, 2009). Figure 22 is the WRSM2000 network diagram for the configuration and modelling of the Mohlapetsi river catchment. There are no dams or active irrigation within the catchment, and there is no evidence that the GaMampa wetland was included in the WRSM2000 setup for the Mohlapetsi River which was used for water resources assessment of the sub-basin.

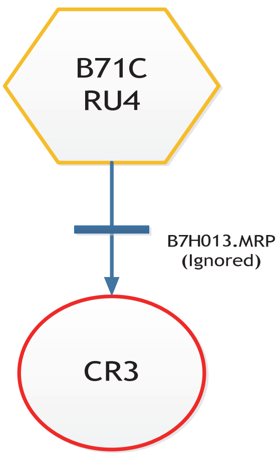


Figure 22 The WRSM2000 system diagram for the Mohlapitse river sub-basin used for setting up the model for the WR2005 simulations.

To investigate the representation of wetlands in hydrological models and to determine the impacts of wetlands on downstream flow and process hydrology, the pitman model was setup as in WR2005 (without wetland) as it is currently used and then the wetland was incorporated. The results were then compared. It is prudent to indicate at this point that the aim is to 'more accurately' represent the processes operating in the sub-basin for purposes of integrated management of the water resources of the area. Rainfall data and catchment model parameters from the WR2005 database (Middleton and Bailey, 2009) were used to set up the initial model. This setup reproduced the stream flow time series used in the WR2005 assessment. The GaMampa wetland is at the outlet of the catchment and this worked well for the model based on the conceptualisation used in the model for the wetland module. Keeping the parameters and all other model inputs constant, the wetland module was added to the model, on the assumption that if the wetland was insignificant and had no effect on the downstream outflow, the simulated flow would not be significantly changed – significant changes would indicate that ignoring the wetland processes in the model setup is a misdirection of the interpretation of the hydrological processes of the sub-basin.

The final set of parameters used for simulating the GaMampa wetland is given in Table 6.
The maximum area of the wetland (MaxWA) was estimated from the wetland coverage prepared by SANBI (2011). In the absence of data for the direct quantification of the parameters of the wetland, the volume of the wetland (RWV) was estimated based on the maximum soil depth and porosity from the land type data (AGIS, 2006). Parameters AVP and AVC for the area-capacity relationship and RFC and RFP for return flow were estimated from a comparison with small dams of similar size in the sub-basins closer to the wetland – the Ohrigstad dam with a total surface area of 0.9916 km^2 was used. This was the only way to get reasonable estimates of these parameters. Abstractions from the wetland were assumed to be zero, while data for evapotranspiration demand data was obtained from WR2005 database (Middleton and Bailey, 2009). The parameters used are reasonably plausible to describe the physical properties of the GaMampa wetland.

Table 6 Parameters used for modelling the GaMampa and Mokolo wetlands.

Parameters	GaMampa wetland B71C	Mokolo Catchment A42A	A42B	A42C
Local Catchment Area (KM^2)	1.000	7.739	8.003	5.960
Residual Wetland Storage (MCM)	0.050	8.000	8.000	8.000
Initial storage (MCM)	0.300	4.000	4.000	4.000
A in Area(m2) = A * Volume$(m^3)^B$	0.600	15.000	15.000	15.000
B in Area(m2) = A * Volume$(m^3)^B$	0.200	0.600	0.600	0.600
Channel capacity for spillage (MCM)	0.080	3.000	3.000	3.000
Channel Spill Factor (Fraction)	0.800	0.200	0.200	0.200
AA in (Ret.Flow = AA*$(Vol/RWS)^{BB}$)	0.950	10.000	10.000	10.000
BB in (Ret.Flow = AA*$(Vol/RWS)^{BB}$)	0.600	0.800	0.800	0.800
Annual Evaporation (mm)	1450.000	1701.000	1701.000	1701.000
Annual Abstraction (MCM)	0.000	0.000	0.000	0.000
AA scaling factor	0.000	0.000	0.000	0.000

Results

<u>Conceptualisation Results</u>

The conceptual model for GaMampa wetland derived by Mekiso (2011) was compared to the conceptual models for wetlands developed by the Ramsar convention and conceptual model that has been reviewed by the wetland consulting services. The GaMampa wetland, a valley bottom flood plain that has direct contact with groundwater, was compared with the valley bottom wetland that has a direct contact with the underlying aquifer (Figure 23). The GaMampa wetland conceptual model has contributions from a number of springs (Mekiso, 2001; Masiyandima *et al*, 2006). The springs indicate the presence of regional groundwater contributing to inflow to the wetland. Interesting also to note is that groundwater from around the catchment is discharged to the wetland, while for the conceptual models developed by the Ramsar convention, there is both output and in puts to/from groundwater. This implies that the conceptual model developed by Mekiso (2011) based on isotope hydrology for the GaMampa wetland is comparable to the Ramsar conceptualisation and can therefore be deemed appropriate and valid.

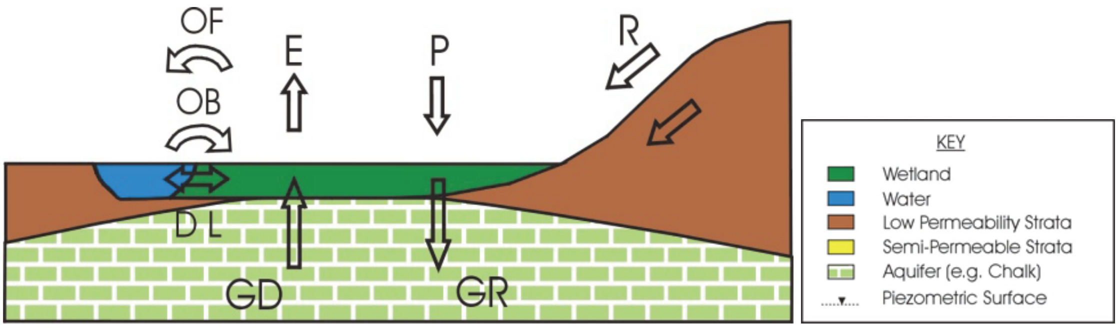


Figure 23 The Ramsar conceptual model of a valley bottom (Ramsar, 2010). With: P = precipitation; R = runoff; E = evaporation; D = drainage; L = lateral inflow; GR = groundwater recharge; GD = groundwater discharge; OF = out flow and OB = over-bank flow.

The wetland is in direct contact with underlying aquifer. Input dominated by over-bank flow and groundwater discharge, when groundwater table is high, supplemented by runoff and precipitation. Output is by groundwater recharge when water table is low, drainage, surface outflow and evaporation

Hydrological modelling results

a. WR2005 simulation results

The simulation based on the WR2005 setup was compared to the historical observed record at B7H013 (Figure 24). The simulation managed to reproduce the observed record with acceptable efficiency. In this case, we accept the results as good if the coefficients of efficiency (CE, the Nash-Sutcliffe (1970) efficiency) and determination (R^2) for both natural flow and log transformed values were at least 0.6 and the bias of the mean flows is less than +/- 5%. This rather relaxed test for model performance is premised on the uncertainty related to the observations. The WR2005 simulations had CE and R^2 values of 0.76 and 0.67 respectively for the normal values and 0.58 and 0.662 respectively for natural logarithm transformed values. The percentage difference between the means of the simulated and observed (a measure of bias and also how well the model reproduces the water balance of the simulated sub-basin) for both normal values and natural logarithm transformed values were 1.684% and 15.984% respectively. The low flows (measured by the natural log transformed values) were overstimulated by this setup. Groundwater outflow was found to be 0.028 Mm^3 per month, while routed base flow was found to be 0,008 Mm^3 per month. Actual evapotranspiration was found to be 57.67 mm per month. There were marginal transmission losses after the inclusion of the wetland module.

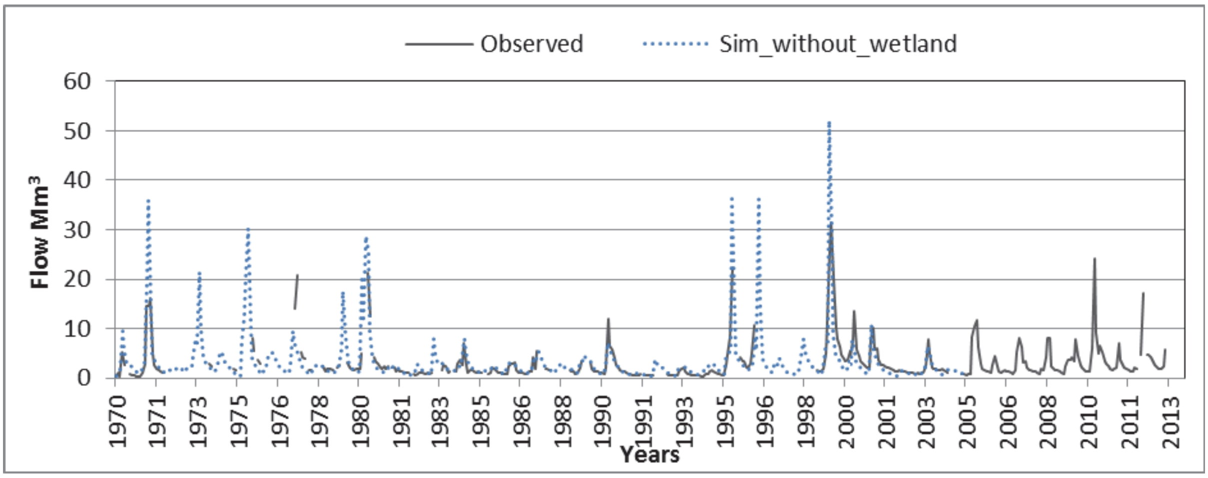


Figure 24 Observed and simulated results before the inclusion of the wetland module.

Incorporating the wetland module

After the inclusion of the wetland module, parameters were re-quantified to fit the simulated stream flow to the historical observed stream flow, this time based on the physical attributes of the sub-basin (Kapangaziwiri and Hughes, 2008). Thereafter, several attempts using both manual (based on the experience of the research team) and automatic calibration were undertaken. The model managed to reproduce the overall water balance of the sub-basin (Figure 9 and Table 6) but failed to reproduce the timing of the observed stream flow as shown by a screenshot of the seasonal distribution of flows simulated with the wetland sub-model (Figure 10). These results seem to indicate that the wetland sub-model within the Pitman model is not well conceptualised, at least for the wetland that in the B71C sub-basin.

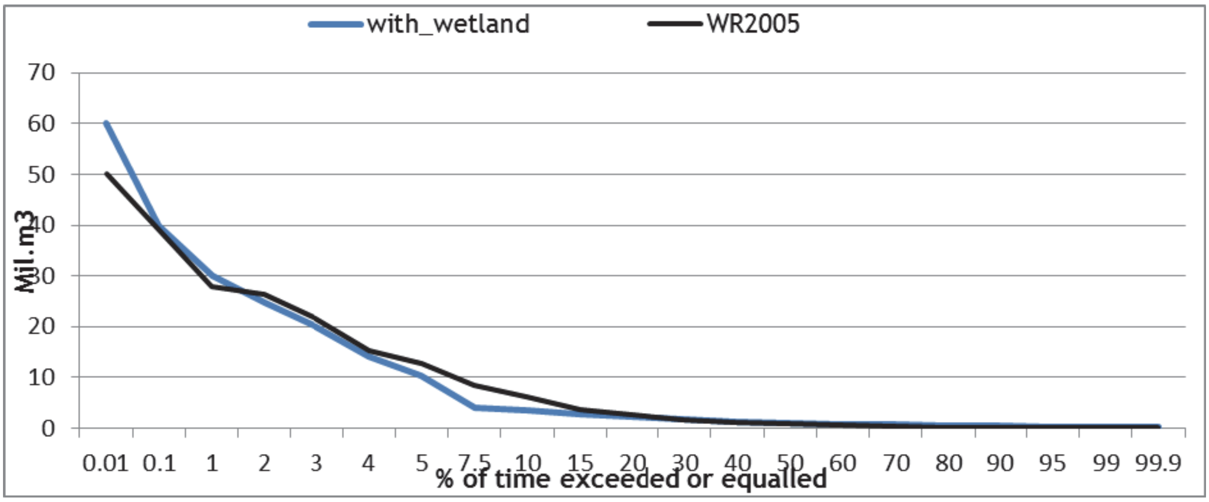


Figure 25 Flow duration curve for simulated and observed stream flow.

Even though the model does not handle wetlands well, a number of points need to be raised based on the final model parameters used in this setup. One of the more significant observations is the increase in the transmission losses simulated by the model in this area.

Transmission losses slightly rose from zero in the initial model to about 0.017 Mm^3 per month during the low flow season. The significance of this is that in general the model simulates losses from the river into the underlying aquifer when the water table in the surrounding aquifer is lower that the stream flow.

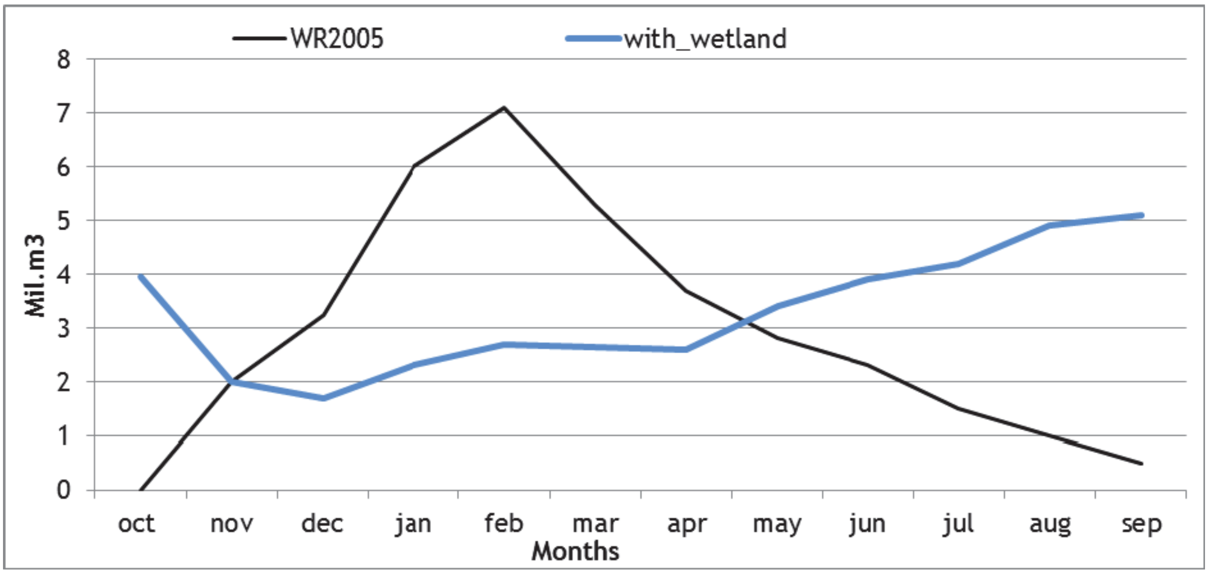


Figure 26 Seasonal distribution of flow in the Gamampa sub-basin after the inclusion of the wetland sub-model.

This suggests that during the dry season, the stream loses water to the wetland. Notable from the table are the changes in some parameters such as evaporation storage coefficient (R), surface runoff time lag (TL) and Riparian strip factor (RSF):

- Change in the riparian strip factor (RSF) to a value of about 0.55% indicates a larger riparian area, which could relate to the presence of a wetland near the stream. This alone would indicate that there would be more water lost from the sub-basin by evapotranspiration, which would be associated with an increase in the value of the evapotranspiration parameter, R.
- In contrast to that, the value of evapotranspiration R, which determines the linear relationship between actual and potential losses at different moisture storage levels indicated a slightly decrease with the addition of the wetland module, which we would have expected to increase as a result of the increase in the riparian strip factor.
- Change in TL (the routing or lag parameter) to a value of 0.37 from 0.25 indicates the longer delay of the water movement in the sub-basin. In the initial setup a TL value of 0.25 indicates that it would take about a week (0.25*30 days (a month)) for flow to be delivered at the sub-basin outlet, while the new value of 0.37 indicates that about 2 weeks is now required to deliver flow at the sub-basin outlet at B7H013. One of the effects of a wetland is flood attenuation; it is therefore reasonable to assume that the incorporation of the wetland into the model changed the flow routing.

Table 7 The parameters used for simulation before and after incorporation of the wetland module.

	WR2005 setup	Setup with wetland module after calibration
Parameter		
ZMIN	998.000	4.957
ZAVE	999.000	323.521
ZMAX	1000.000	480.09
ST	375.000	481.977
POW	2.000	4.194
FT	30.000	4.746
GW	11.200	20.01
R	0.500	0.209
TL	0.250	0.377
GPOW	3.000	3.504
RSF	0.200	0.554
Model Performance measures		
R^2	0.643	0.027
R^2 (ln)	0.558	0.175
CE	0.644	-0.288
CE (ln)	0.653	-0.736
%M	1.684	3.936
%M (ln)	15.984	1.578

N.B. a) The catchment absorption parameters (ZMIN & ZMAX) were switched off in the WR2005 setup. b) The bracketed ln in the performance measures relate to the fact that the statistic measure was taken for natural logarithm-transformed values.

4.2 MOKOLO RIVER CATCHMENT (WATERBERG) – PITMAN and MikeSHE

Background

A review of the groundwater studies, focussing on groundwater and surface water interaction, in the Waterberg catchment indicates a bias towards the Karoo Supergroup sediments (approximately 10% of the Waterberg catchment) in the northern part of the catchment, near Lephalale, as a result of the coal seams located in it. This is shown in Figure 27 (a) and the coal fields are shown in Figure 27 (b). The Waterberg Group lithology, comprising about 75% of the Mokolo catchment, is not well studied and the groundwater surface water interaction is not well documented.

Understanding the groundwater in the Waterberg sandstone is necessary as the groundwater contribution to baseflow in the tributaries is essential in supplying good quality surface water, in particular during the low flow winter months, in the main stem Mokolo to supply sufficient water for farmers for irrigation and meeting environmental flow requirements, as well as diluting the impact of the irrigation return flow and Vaalwater Wastewater Treatment Works. Figure 27 (c) shows that the excepted borehole yields from the Waterberg sandstone are typically in the order of 0.5 to 2 litres per second in comparison to the Karoo group which has borehole yields of 0.1 to 0.5 L/s.

The dominant rock type in the Waterberg Group is arenite, as shown in Figure 27 (d). Arenite is a sedimentary clastic rock with a sand size grain between 0.0625 mm and 2 mm and contains less than 15% matrix. The classification is based on grain size rather than chemical composition. A rudite band runs south of Alma and is made up of rocks with a larger grainsize than sandstone grains, ranging of granules, pebbles and cobbles to boulders. The contact between the Waterberg Group and the Karoo Supergroup lies just north of Lephalale. A large fault contact separates the younger Karoo rocks from the older Waterberg rocks. The Karoo Supergroup in the study area comprises shale and arenite. The shale results in the lower yielding boreholes discussed previously. North of the Karoo Supergroup is the exposed gneiss and quartzite of the Kaapvaal Craton. The Kaapvaal Craton forms the basement rocks and was deposited between 3.6 and 2.5 billion years ago.
Coal mining is restricted to the Ecca Group of the Karoo Supergroup. The same geological formation is currently being targeted using “fracking” in the Karoo. The Waterberg Coalfield is considered to be the fourth largest in the world, with coal reserve estimates at approximately 75 billion tons, comprising 40%-50% of South Africa’s remaining coal reserves (Theunissen 2012, Mgojo 2012). The Waterberg coalfields consists of the Grootegeluk Formation, which is roughly 60 m of alternating mudstone and coal bands, underlain by the Goedgedacht Formation which is 55 m thick contains thinner coal band seams (Theunissen 2012). In total the stratigraphic thickness is 115 m with 11 coal bearing zones (Mgojo 2012). The mining of the coal is complicated because of the intermittent coal and mudstone layers, and in the case of open cast mining, both coal and mudstone are removed during mining operations.

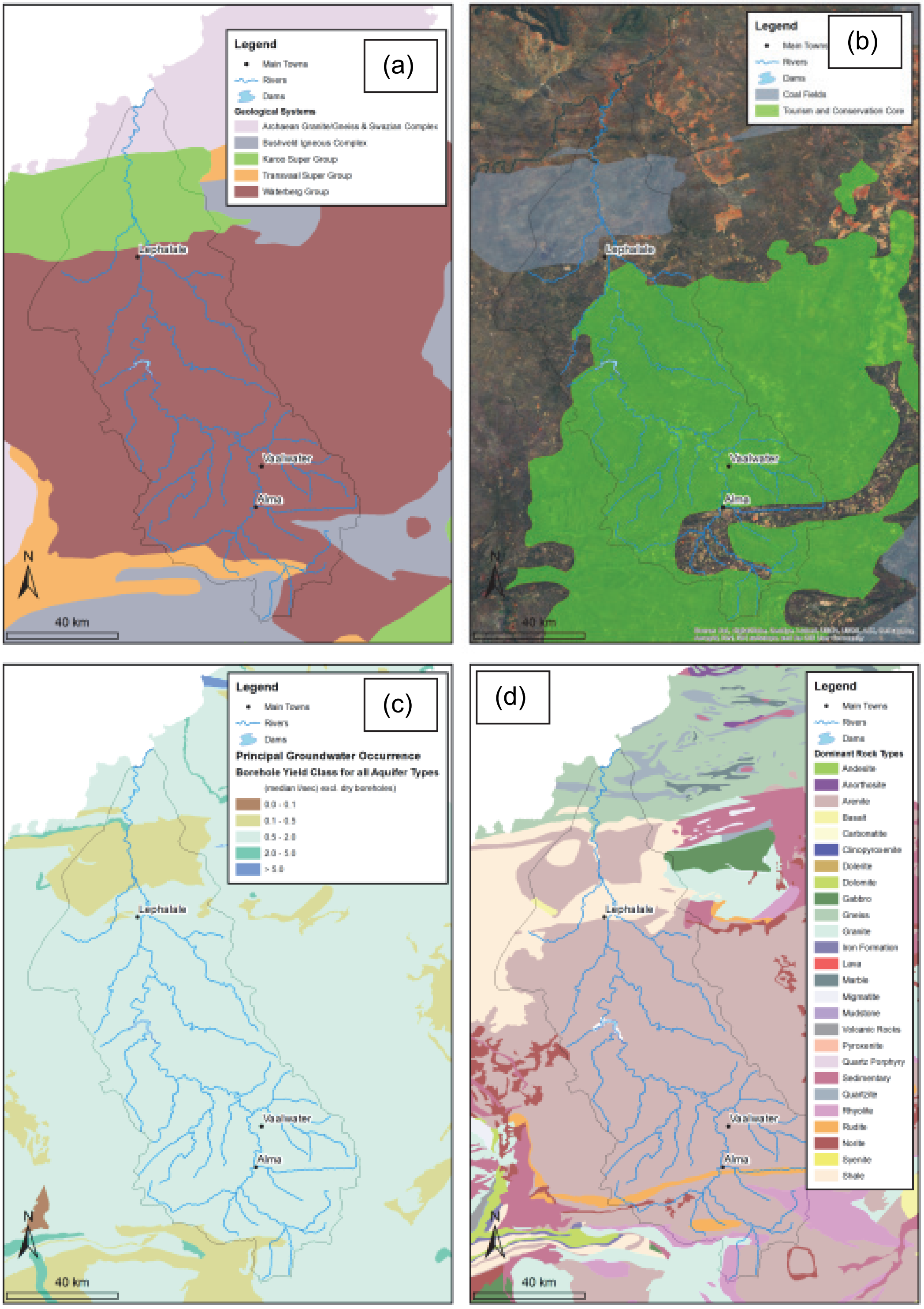


Figure 27 Figure (a) shows the main geological systems for the Waterberg. Figure (b) shows the Coal Fields for the Waterberg and the Tourism and Conservation core from the Waterberg District EMF. Figure (c) shows the principal groundwater occurrence for the Waterberg and Figure (d) shows the dominant rock types (based on geology). The data is taken from the Environmental Management Framework for the Waterberg District Municipality.

There is a lack of available water for the coal mining as well as power stations demands in the Waterberg. DWAF concluded a feasibility study in 2009 to look at various options for the Mokolo and Crocodile (West) Water Augmentation Project (MCWAP) (DWAF 2009). Exarro (Mgojo) presents the updated MCWAP phases, with phase 1 consists of a 42km pipeline from Mokolo dam as shown in Figure 28. Phase 2 is the Crocodile augmentation and consists of a new pipeline from Vlieëpoort weir at Thabazimbi, followed by a pipeline from Klipvoor dam, with later phases incorporating the transport and use of Gauteng's sewage water.

Construction of the pipeline began in September 2011 (TCTA, 2013) and is due to be completed in the middle of 2014. The project consists of a pumpstation and a 46km pipeline transferring water from the Mokolo dam to EXXARO's Grootegeluk mine, Eskom's Matimba Power Station and Lephalale Municipality with a budget of R2.1 billion.

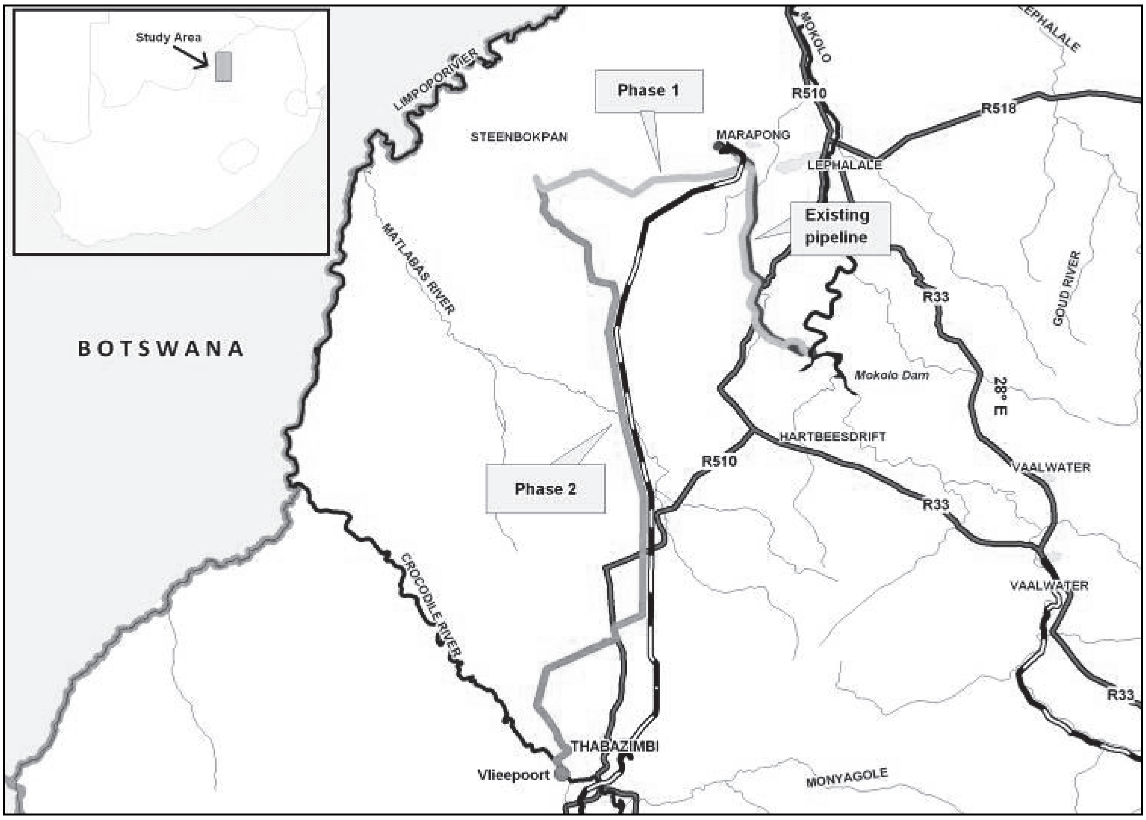


Figure 28 MCWAP phase 1 and phase 2 showing the existing pipeline and the currently constructed pipeline from the Mokolo Dam (van den Berg, 2010).

The projected water requirements for the Waterberg are shown in Figure 29 (van den Berg, 2010). Demands will increase significantly in 2014 as Medupi starts become operational. Eskom's long term plan is to build more coal fired stations in the area and this is shown as CF3 and CF4. Coal 3 and Coal 4 are estimated at (5,400 MW each). Sasol plans to build a coal to liquids plant called Mafuta which significantly adds to the water demands. EXXARO plants to build the IPP power station and there are additional demands from future coal mining planned in the Waterberg. It is also interesting to note the projected increase in water demand for Lephalale as a result of urban growth due to the availability of jobs during the construction phases of the power stations. Figure 30 shows how the MCWAP phase 1 and 2 will meet the projected water demand. MCWAP 1 involves the completion of the pipeline from Mokolo Dam which is expected to become operational during mid-2014. This will temporarily meet the expected water demands. The larger MCWAP 2 involves the interbasin transfer from the Crocodile West and potentially Hartbeespoort dam in order to meet the projected future water demands.

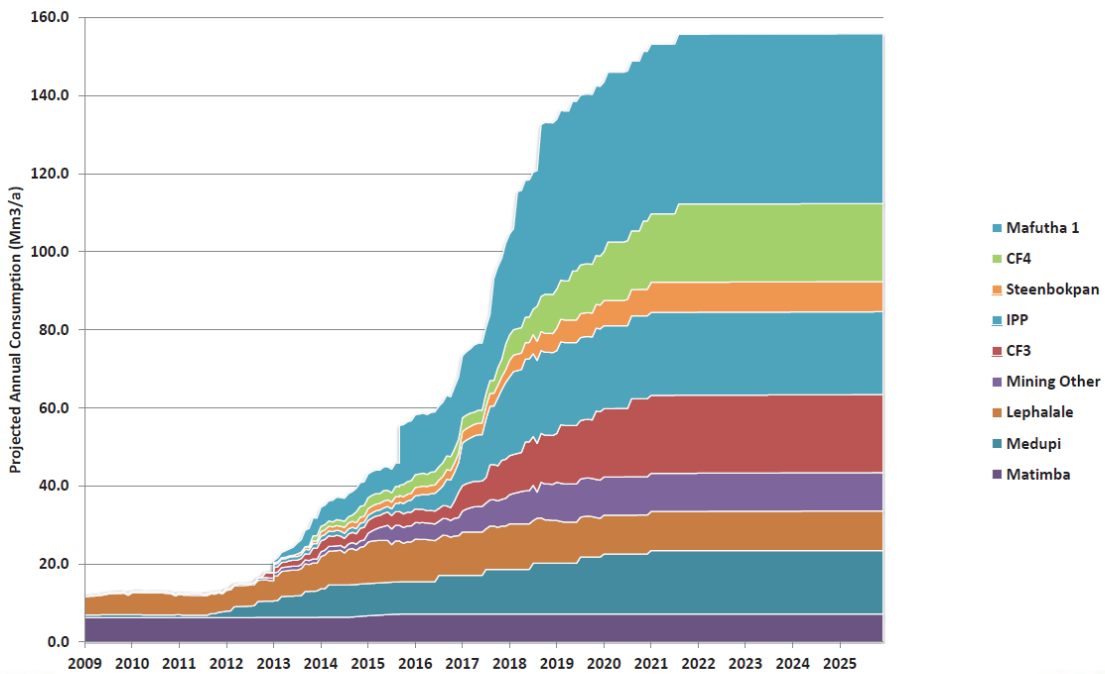


Figure 29 Projected water requirements for the Waterberg (van den Berg, 2010)

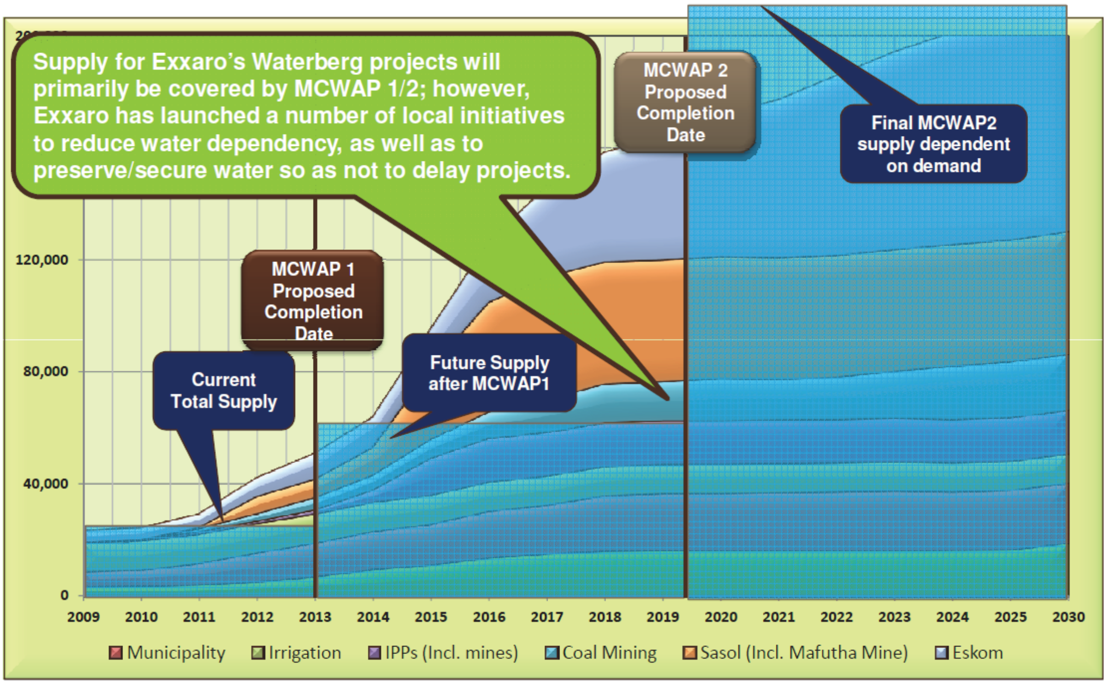


Figure 30 Water demand scenarios for the Waterberg showing how the water demands will be met by MCWAP 1 and MCWAP 2 (Mgojo, 2012).

The MCWAP Steering Committee (van den Berg 2010) also noted that the switch from irrigated agriculture to game and cattle farming in the Mokolo catchment has resulted in a significant increase in the available yield from the dam. They further note that the available water in the Crocodile catchment is not able to meet the demands under certain scenarios and stated that return flows in the Klip River (of the Vaal River system) currently exceed the projected demand in Lephalale in 2025. Figure 31 shows the Lephalale water supply requirements for scenario 11.2 (DWA 2012) which shows how the water demand can be met by Mokolo Dam, surplus from the Crocodile and surplus from the Vaal from 2018 onwards.

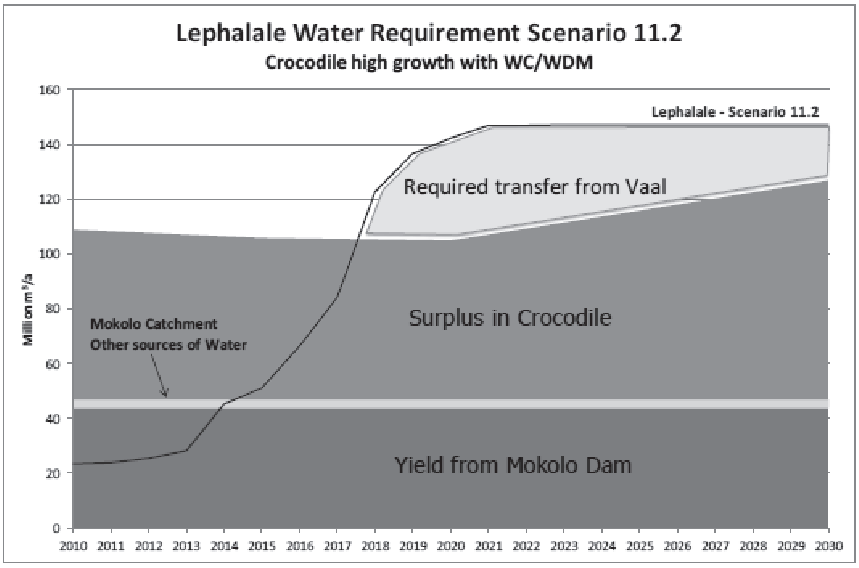


Figure 31 Lephalale Water Requirements scenario 11.2 taken from Figure 4.2 from DWA 2012

Groundwater was identified as a potential source of water however it is available in limited supply around Lephalale and is not able to meet the water demands. Groundwater availability in the area is also limited because of the lower rainfall that occurs north of Lephalale resulting in limited recharge taking place in the aquifers. A sustainable yield or safe yield from an aquifer is defined in the DWA groundwater dictionary as “the maximum rate of withdrawal that be sustained by an aquifer without causing an unacceptable decline in the hydraulic head or deterioration in water quality in the aquifer” or the ecosystem. This concept is shown in Figure 32. Abstracting groundwater from the aquifer results in a draw down in the water table and a cone of depression around the borehole. Safe yield is generally expressed as a percentage of recharge and as stated previously the recharge is limited in the Karoo aquifers in the Waterberg because of the lower rainfall.

Figure 32 also shows what will happen to the water table when mining occurs. In order for mining to occur, the mine needs to be dewatered to below the depth of mining by abstracting the groundwater by pumping. The abstracted groundwater is generally used for mining operations. The drawdown in the water table results in a cone of depression around the mine where the water table is lower than the original water table level, which is monitored by the mines. When mining ceases and the abstraction of groundwater stops, the water level will return to the original water level before mining took place. In some cases groundwater will decant near or on the surface because of a change in the aquifer characteristics (porosity and transmissivity) that result from mining. If the host rock contains sulphide minerals, the oxidation of the minerals with the exposure to air and water results in acid mine water.

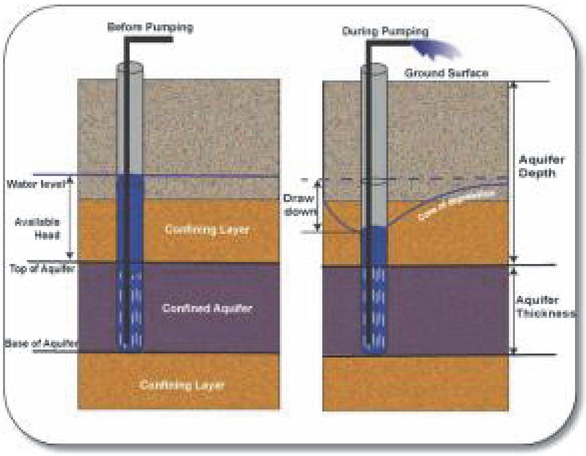


Figure 32 shows the effect on the water table as a result of extracting water from the borehole results in a cone of depression in the water table. The drawdown is the change in water level as a result of the quantity of water abstracted (DWAF unknown)

Groundwater Surface Water Interaction

<u>Background</u>

Four main aquifer types exist in the Mokolo catchment: Basement aquifer, Waterberg aquifer, Karoo aquifers and Alluvial aquifers. This is based on the geological map in Figure 27 (a). The figure does omit the large alluvial aquifer located north of Lephalale. This is more clearly shown in the fine scale (1:250 000) geological map in Figure 33 from DWA (2010), which separates the alluvial aquifer (shown in bright yellow) from the quaternary deposits on the geological map (shown in yellow).

<u>Aquifer types</u>

The aquifer types and descriptions are taken from DWA 2010.

Basement Aquifer (located underneath D)

The northern part of the Mokolo catchments is characterised by flat relief covered in Quaternary sediments mainly consisting of Kalahari sands, alluvial sands and gravel. The Basement aquifers comprise deeply fractured (secondary) aquifers that are overlain by a weathered zone of varying thickness. Thick, weathered zones can be expected where the basement gneiss has undergone intense fracturing. The most notable aquifer are ENE treading zones of shearing, faulting and brecciation and are usually covered by Quaternary sands which add to the aquifers storage potential.

Waterberg Aquifer (A and B)

The Waterberg aquifer (located as B and D) consists of fractured and weathered sandstone, and is potentially connected to the alluvial deposits of the Mokolo River. The main groundwater targets are associated with fault zones and fractured dyke contacts that result in higher yielding boreholes. The Waterberg is typically associated with steep topography (A) and is generally incapable of producing huge amounts of groundwater unless boreholes interested NE or SE trending faults of fault zones (Sami, 2006 in DWA 2010). Recharge to the aquifer is often discharged on steep slopes and provides baseflow to the rivers in the Mokolo catchment. This is particularly noted during the dry season when baseflow comprises the majority of the flow in the river.

Karoo Aquifer (C)

The Karoo aquifer shows similar properties to the Waterberg aquifer and mainly comprises fractured shale rocks, resulting in higher salinity groundwater. The potential of the Karoo aquifer is very low due to the limited recharge that takes place as a result of the low rainfall.

Alluvial Aquifer (D and yellow alluvial)

The alluvial aquifer is recharged during the rainfall season and periods of high-stream flows and discharge events from the Mokolo dam occurs. It is an important local, major aquifer and exists in equilibrium with surface water, adjacent groundwater systems and freshwater ecosystems along the river.

Based on the groundwater Reserve determination study for the Mokolo the following conceptual aquifer model was proposed (DWA 2010)

- The alluvial aquifer associated with the Mokolo River is in direct contact with the river (i.e. no significant colmation layer is present in the river bed itself – colmation is the process which occurs when fine particles, transported by groundwater are damned in gaps in the sediment matrix resulting in a reduction in porosity and permeability)
- The alluvial aquifer is generally unconfined with no confining beds present between the water table and the surface.
- The regional fractured aquifers (Waterberg, Karoo and Basement aquifers) of moderate hydraulic diffusivity (ration of transmissivity and storativity) are in limited interaction with the alluvial (valley train) aquifer.

- The regional aquifers show marginal gradients towards the Mokolo River course and exchange water with the river only indirectly via the alluvial deposits.
- The surface-groundwater exchange between the alluvium and the Mokolo River course occurs on a far shorter time scale in comparison to the interaction between the regional and alluvial aquifers.

Based on the conceptual aquifer model, DWA 2010 separated the alluvial aquifer in four sections shown in Figure 33. The alluvial aquifer was studied in depth in the groundwater Reserve determination and as a result the field work focussed on looking at the groundwater in the Waterberg Sandstone in order to determine the groundwater quality in the Waterberg aquifer and the contribution to baseflow during the year.

Table 8 Physical and hydraulic properties of the Mokolo river alluvial aquifer (taken from Table 2.2 of DWA 2010)

- Section	- Underlying Geology	- Average Depth	- Average Hydraulic Conductivity	- Average Transmissivity	- Hydraulic Gradient (i)
- A	- Waterberg (mountainous)	- 12.4 m	- 175 m/d	- 1489 m^2/d	- 0.00073
- B	- Waterberg (flat)	- 8.5 m	- 175 m/d	- 1489 m^2/d	- 0.00043
- C	- Karoo Supergroup	- 7.5 m	- 132 m/d	- 992 m^2/d	- 0.00045
- D	- Basement	- 6.5 m	- 117 m/d	- 810 m^2/d	- 0.00043

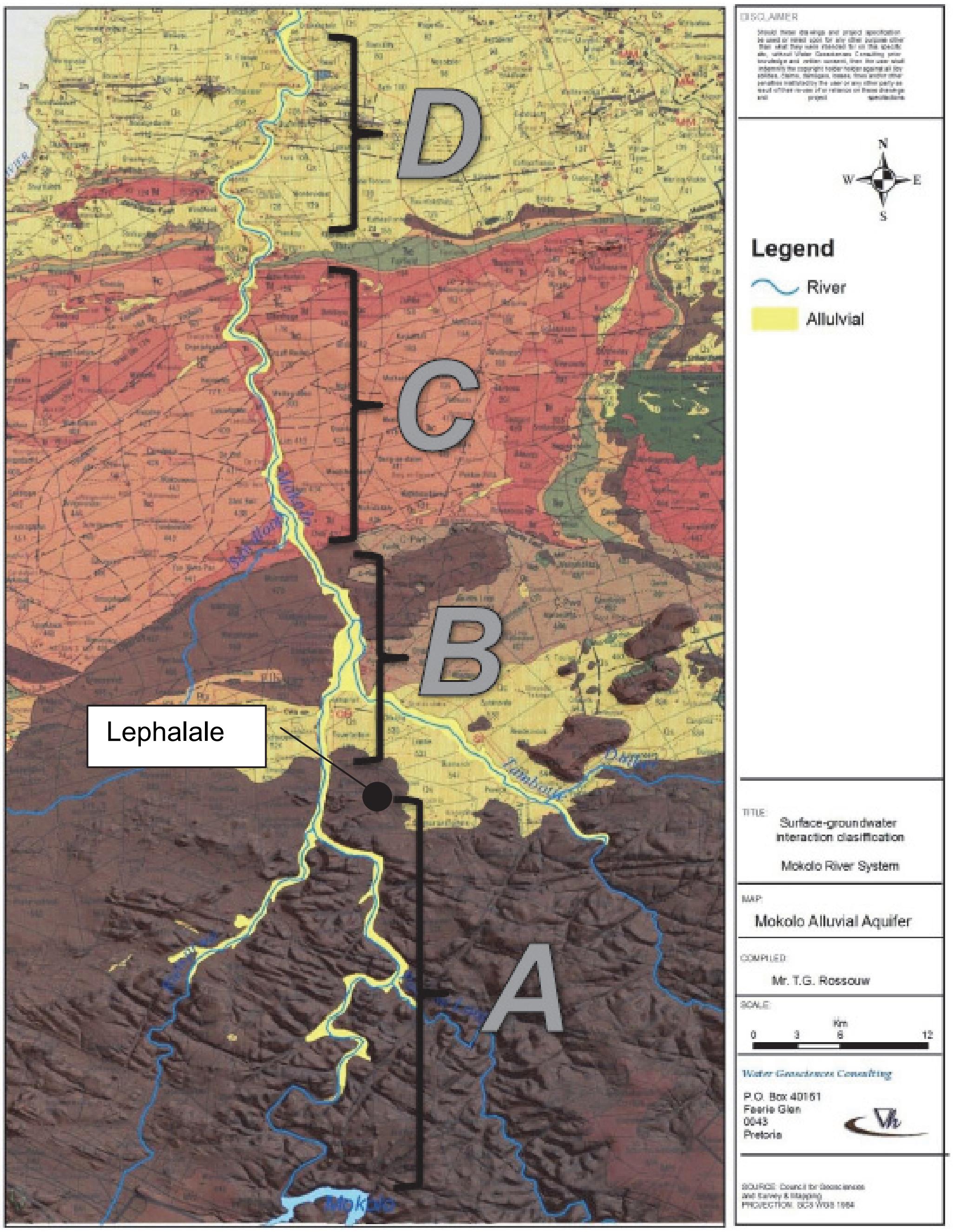


Figure 33 Simplified geological map in the vicinity of the Mokolo River, taken from Figure 2.3, DWA 2010

Summary of Field Work from the CSIR Parliamentary Grant project in the Waterberg

Three major fieldwork campaigns took place as part of the CSIR Parliamentary Grant project in the Waterberg in June 2012, November 2012 and March 2013 and a variety of surface and groundwater samples were taken for chemistry and isotope analysis. A total of 86 sites were visited during the sampling trip, including dams, boreholes, rivers, seepage, springs and rainfall and is shown in Figure 35. All sampling was done according to Weaver et al. (2007).

The June 2012 was a short sampling trip and selected samples were taken and sites identified for future sampling. November 2012 was a more comprehensive sampling exercise followed by an additional comprehensive exercise in March 2013. Emphasis was placed on the Waterberg sandstone in order to characterise the groundwater quality in the Waterberg Group. Limited sampling was done on the Karoo Supergroup as this area has been studied in detail by the mines and consultants focussing on the effect of coal mining on groundwater.

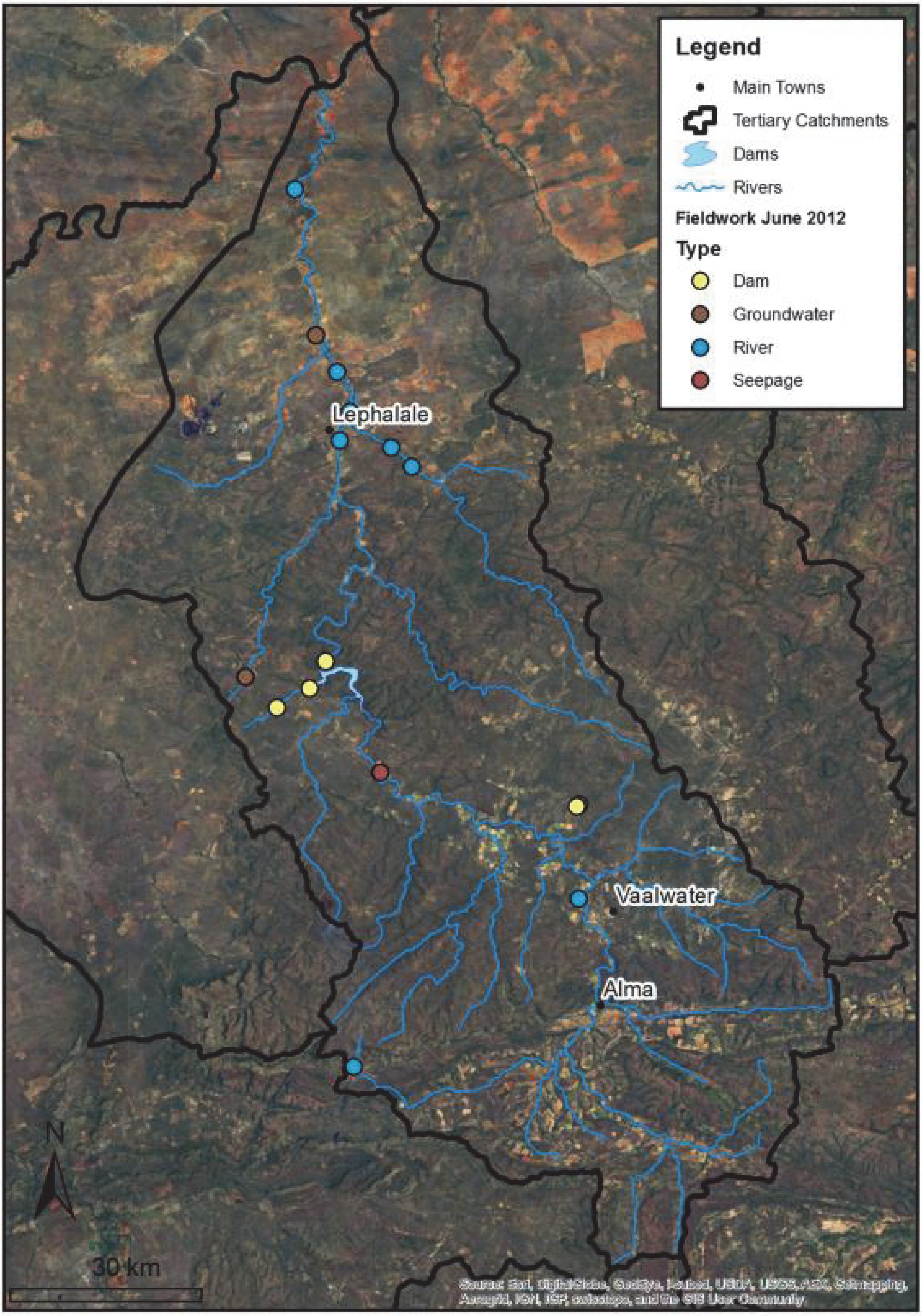


Figure 34 Locality map showing the sites sampled in June 2012

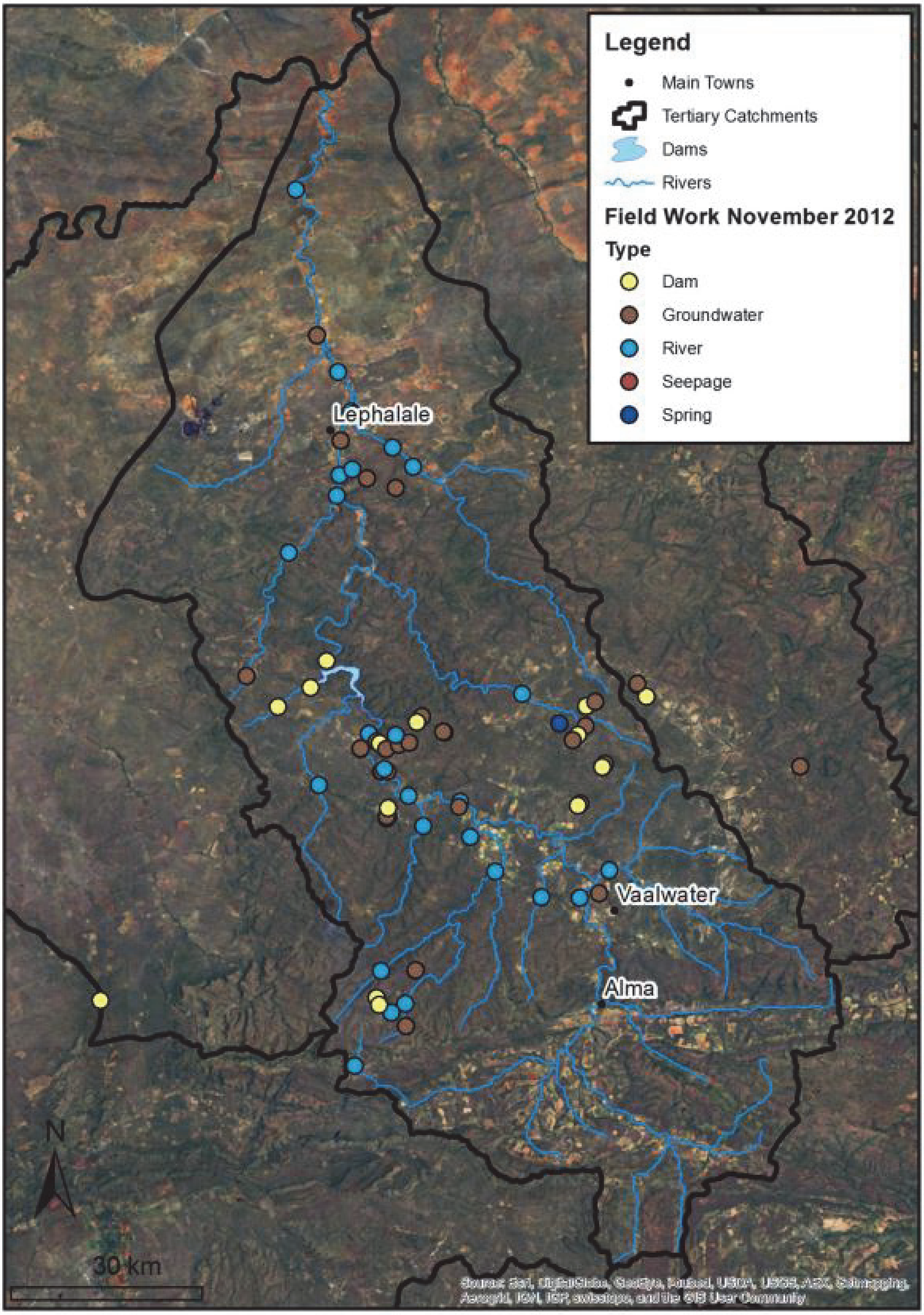


Figure 35 Map showing the locality of the chemistry samples that were taken in November 2012 in the Waterberg.

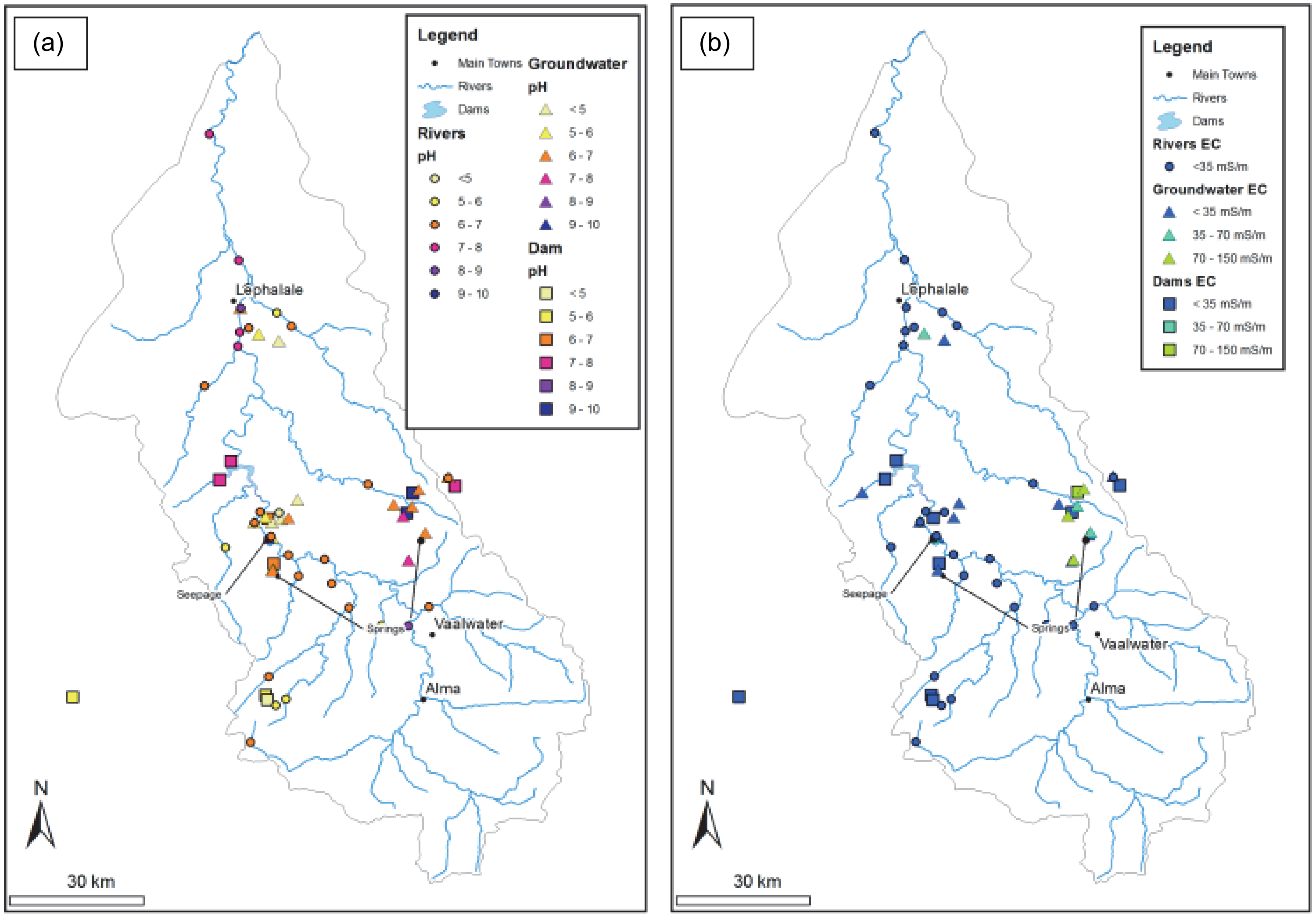


Figure 36 (a) shows the pH of the surface and groundwater and (b) shows the electrical conductivity in mS/m. The drinking water guidelines for South Africa (an EC of less than 70 mS/m is considered ideal, while an EC of less than 150 mS/m is likely to have no health affects (DWAF 1996).

The pH of surface water and groundwater varies across the study area. Generally the groundwater of the Waterberg Sandstone is acidic in nature with a pH of less than 7. The electrical conductivity/salinity of the groundwater is very low in the Waterberg Sandstone with values generally less than 35 mS/m, which is very low for groundwater. The exception is the groundwater seepage zone located adjacent to an agricultural field that has a pH of 0.6 and an EC of 65 mS/m as well elevated nitrate levels.

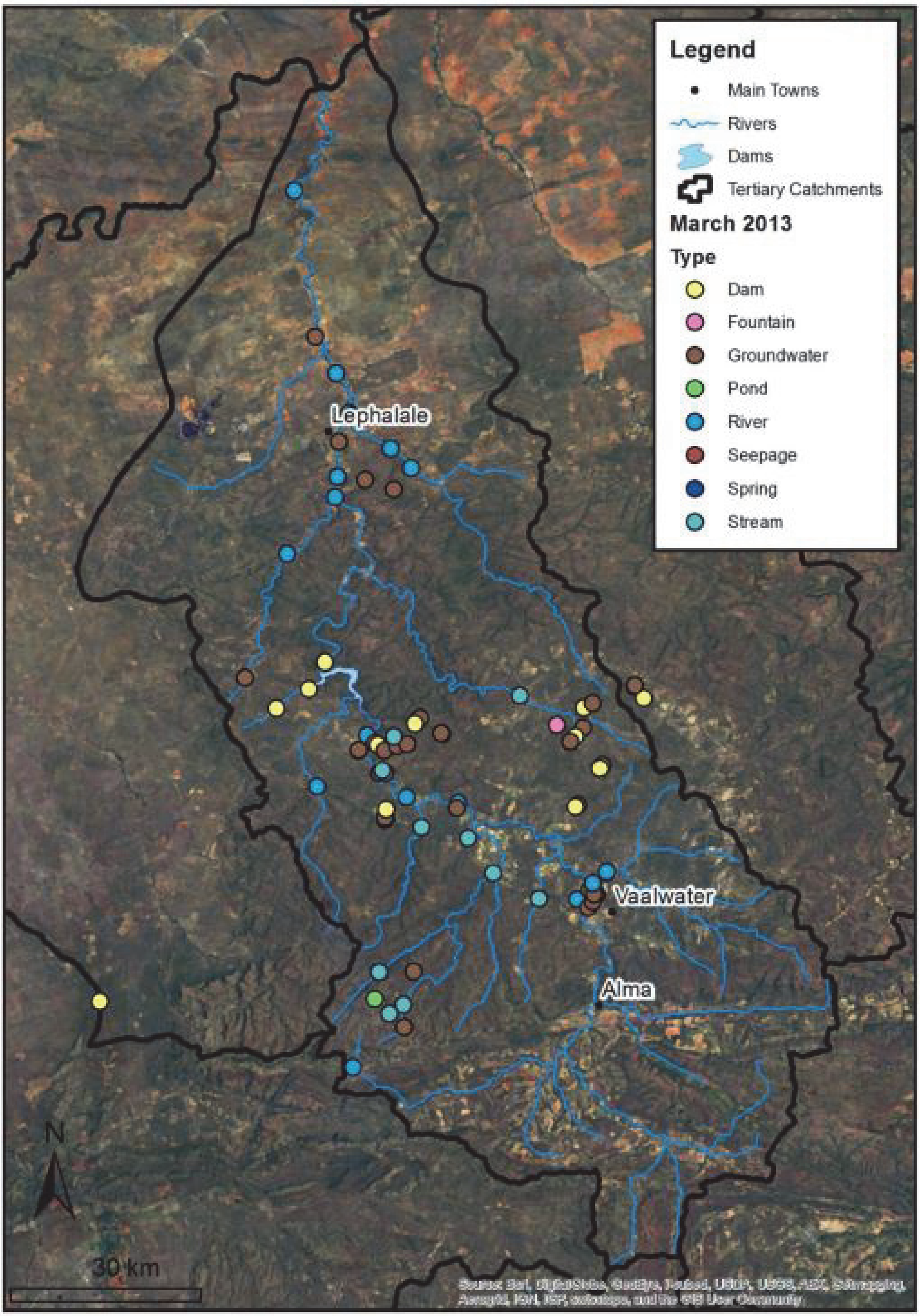


Figure 37 Map showing the sample types and locations taken in March 2013.

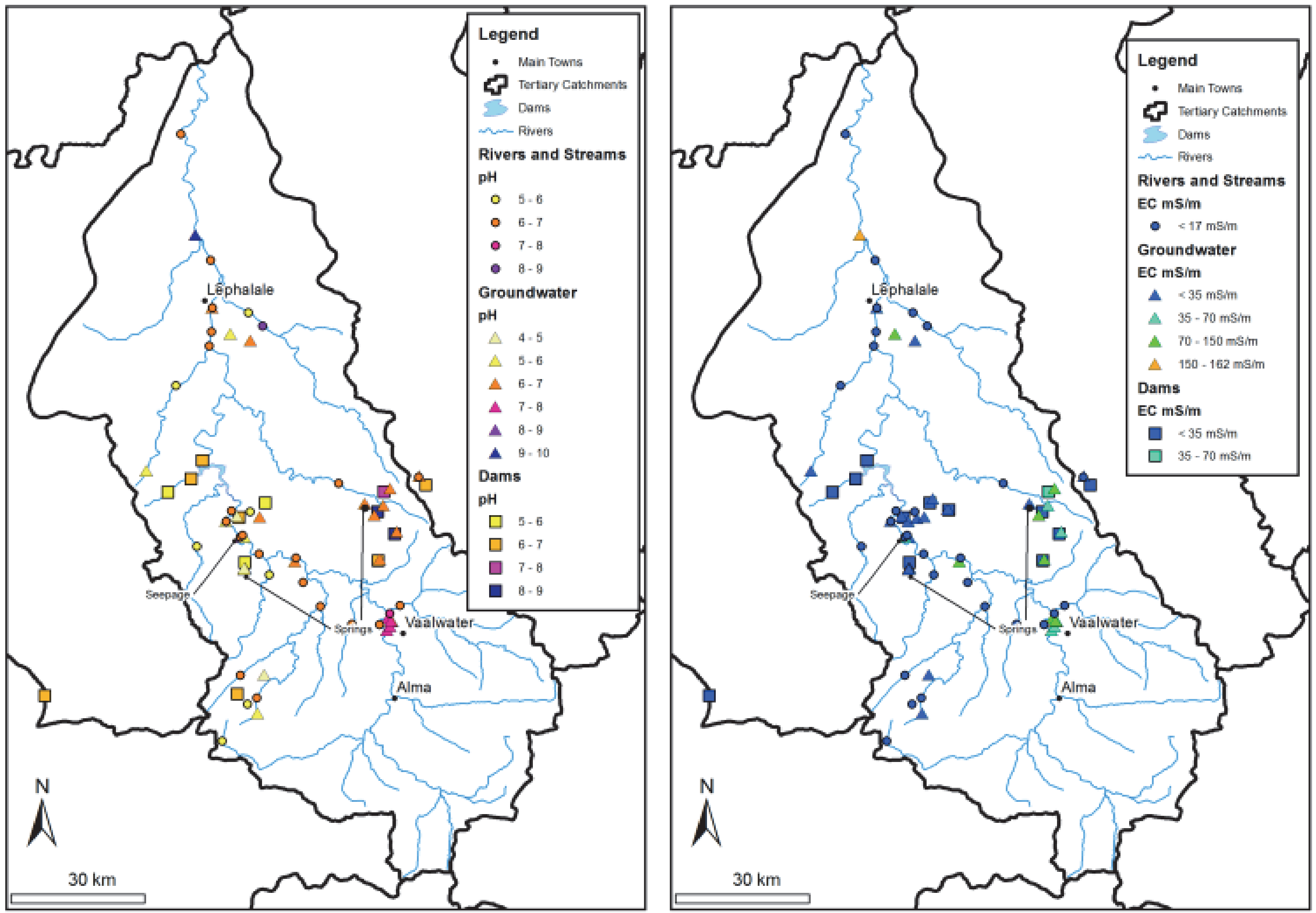


Figure 38 (a) shows the pH values taken in the field in March 2013 and (b) shows the electrical conductivity values in mS/m.

Stable Isotopes

The stable isotope signature matches that of the recharge source. If recharge is primarily through direct infiltration then the groundwater will reflect the isotopic signature of the rainfall. If recharge is by surface water (lakes, rivers), then the groundwater will reflect the isotopic signature of the lake or dams. As water undergoes evaporation, the heavier isotopes (deuterium and oxygen16) become enriched in the water as the lighter isotopes are evaporated more easily. This technique is very useful to determine if evaporation has taken place in the water, or if the surface water more closely reflects the groundwater this would indicated that the groundwater is discharging into the streams in the form of baseflow, especially during the dry months.

The stable isotope plot is shown in Figure 39 and the locations of the samples are shown in Figure 40. The signature of the groundwater reflects the global meteoric water line, indicating recharge is primarily through direct infiltration. The smaller streams and some rivers reflect the groundwater signature. The samples were taken in November during the wet season and when evaporation is very high due to the warm summer temperatures. The evaporation trend can be seen in the dams which are stagnant bodies of water with very little fresh water to replenish the stable isotope ratios.

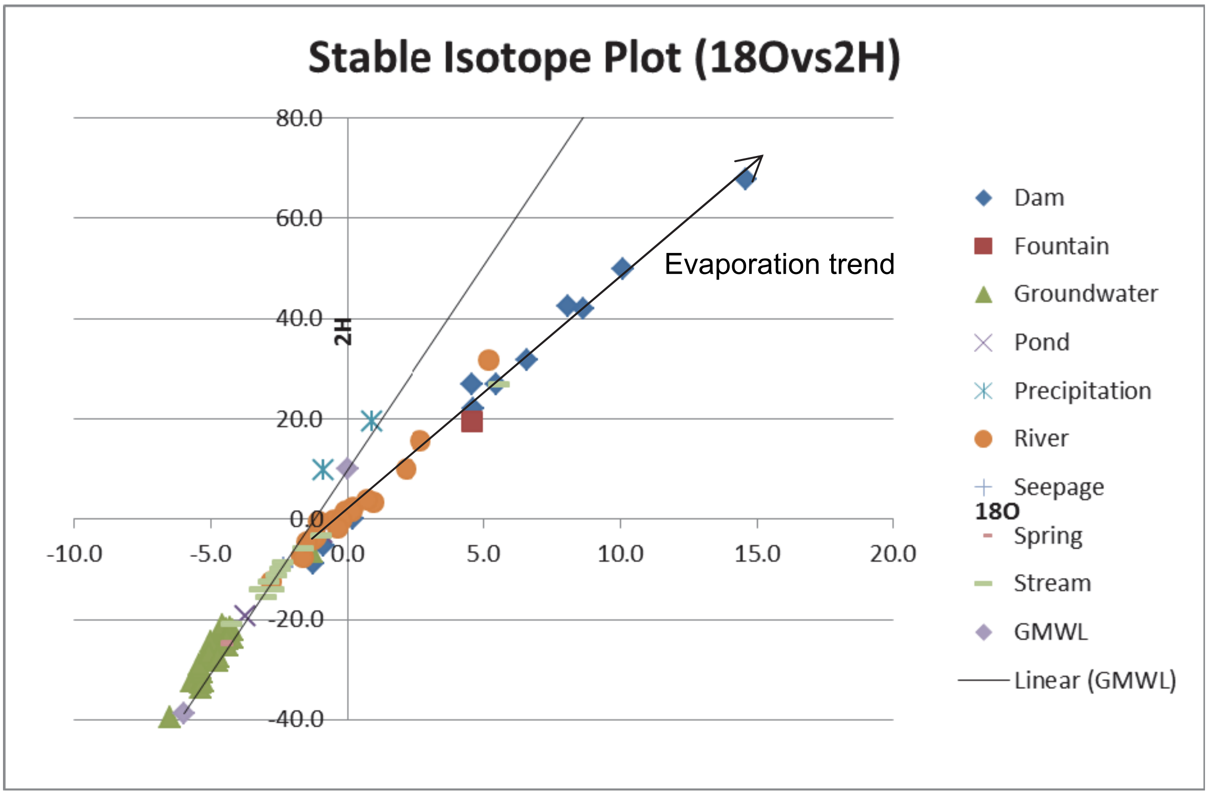


Figure 39 Stable Isotope Plot for the Waterberg, 18O vs 2H. The line represents the Global Mean Water Line for rainwater.

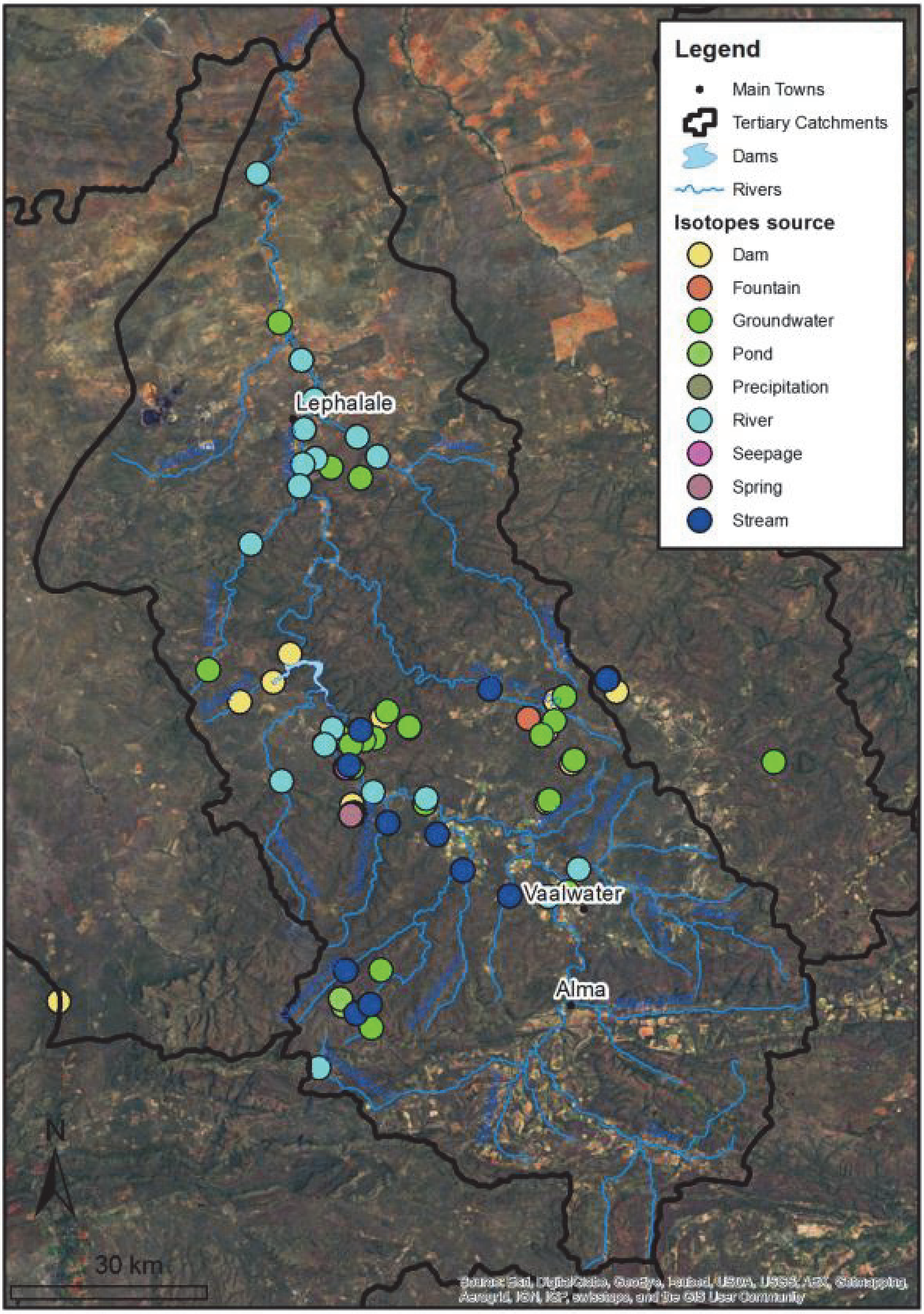


Figure 40 Stable Isotope sampling locations and the type of sample in the Waterberg.

Evapotranspiration Characteristics

MODIS

The MODIS derived MOD16 global terrestrial evapotranspiration (ET) data was used to determine the evapotranspiration characteristics of the wetlands in the catchment. The ET data is freely available from the following ftp site (ftp://ftp.ntsg.umt.edu/pub/MODIS/Mirror/MOD16/) and is distributed in 8-day, monthly and annual ET composite formats. The MOD16 is distributed in hdf 5 format and contains 4 data sets; evapotranspiration (ET), latent heat flux (LE), potential ET (PET) and potential LE (PLE). These data sets are distributed as grids with a 1 km^2 spatial resolution making use of a sinusoidal projection. The MODIS product is ACTUAL Evapotranspiration as and not POTENTIONAL Evapotranspiration. The MODIS algorithm runs on a daily basis and the daily ET is the sum of the day and the night. Figure 41 shows the conceptual water balance for the wetland. The inflows into a wetland are net precipitation, surface water and groundwater. The outflows from the wetland are groundwater, surface water and Total Evaporation and plant transpiration (Evapotranspiration). The MODIS data is used to provide actual ET values over a catchment scale. Obtaining actual ET measurements is often a very costly and time consuming process, while the MODIS products provide a free and desktop assessment of the evapotranspiration characteristics in the catchment. ET is the sum of water vapour fluxes from soil evaporation, wet canopy evaporation and plant transpiration at dry canopy surface (Mu et al., 2013).

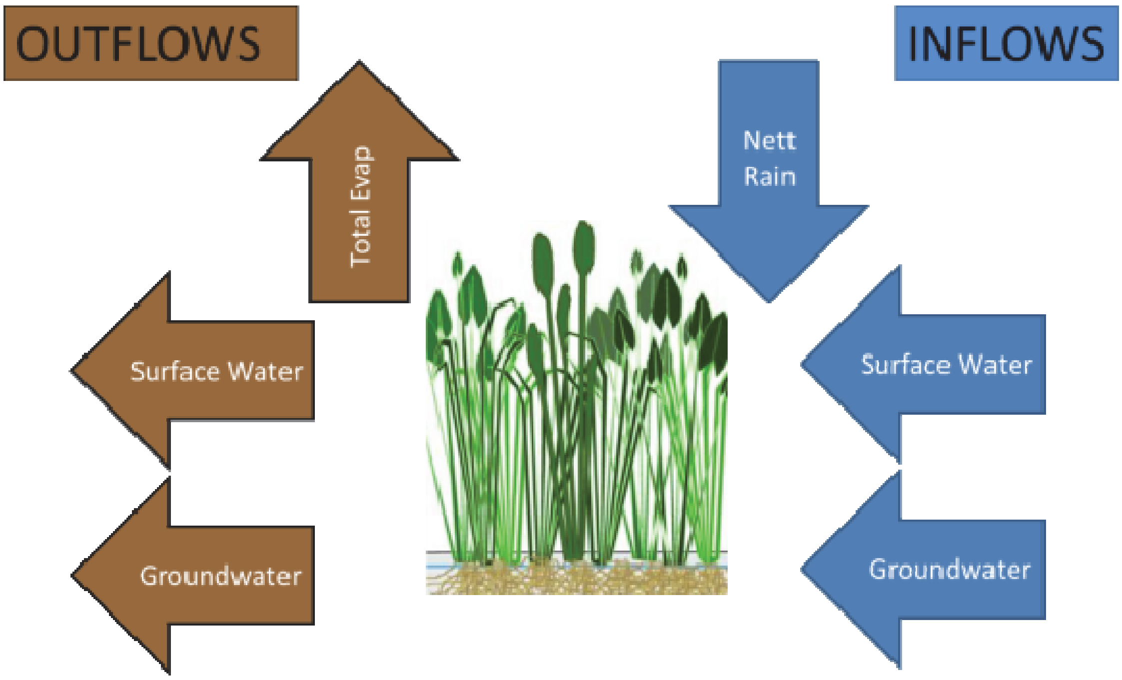


Figure 41 Conceptual water balance for a wetland. The MODIS satellite data is used to quantify Total Evapotranspiration as shown in the figure.

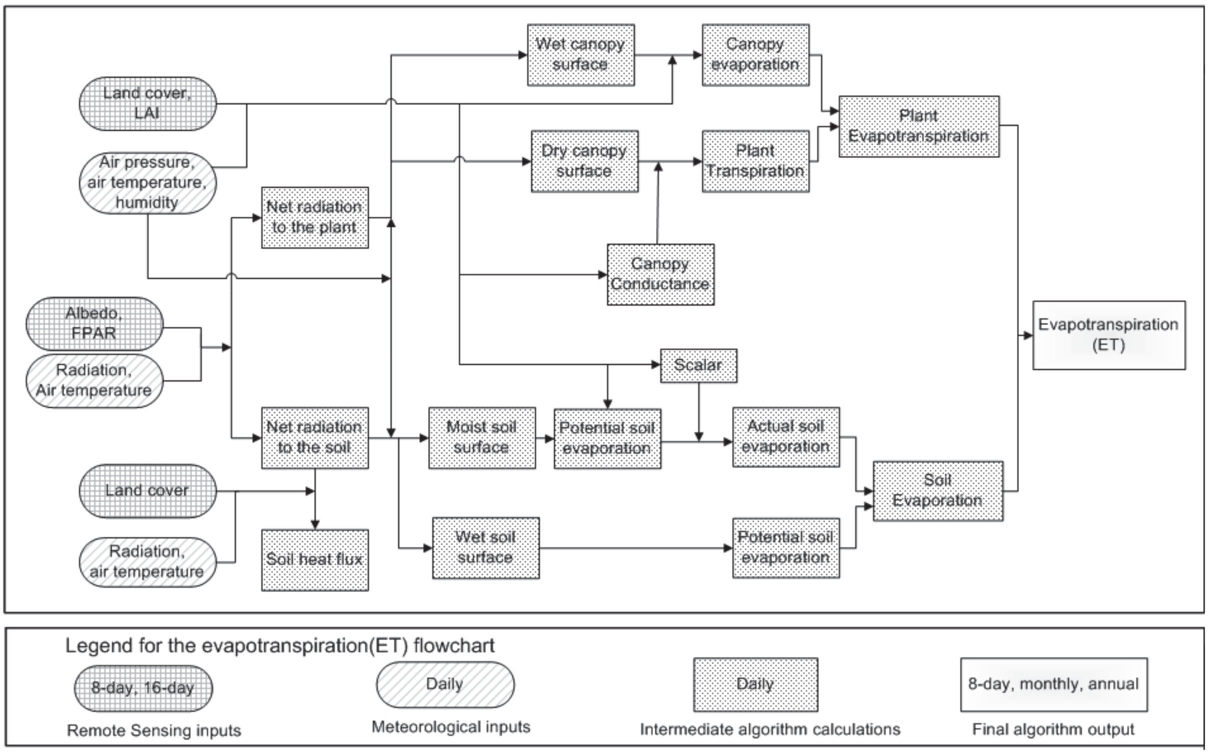


Figure 42 Flow chart showing the MOD16 ET calculations, taken from Figure 2 Mu et al. (2013)

The MOD16 ET algorithm is based on the Penman-Monteith equation (Monteith, 1965) and the flow chart for the calculations is shown in Figure 42. The process involves using daily meteorological inputs as well as 8day or 16day remote sensing inputs from satellites. The MODIS ET product is from 2000 until 2010, with ET rasters available in 8-day format, monthly format as we all annual ET composite images.

Methodology

The Waterberg is located on the h20v11 MOD16 tile. The tile covers the north eastern portion of South Africa as well as parts of Botswana, as shown in Figure 43. The MODIS Sinusoidal Projection was applied to all of the data.

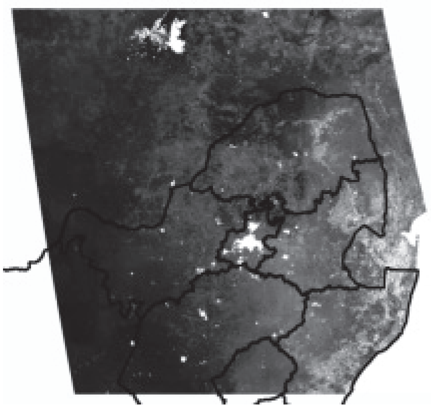


Figure 43 the MODIS h20v11 tile with the outline of the provinces.

The integer values of the raster were multiplied by a factor of 0.1 in order to convert the values to ET values in mm/8day, mm/month or mm/year (Mu et al., 2013). The reason behind this is that integer values require less storage space and result in smaller files compared to double values that have decimal points. For the 8-day and monthly ET the valid range of values are from -32767 to 32700. The range value for the annual ET is from 0-65500. The classes and the values are shown in Table 9.

Table 9 Range values for the MODIS ET datasets from Mu et al. (2013)

Class	Value
8 day or monthly ET	
Fill value, out of the earth	32767
Barren or sparsely vegetated	32765
Permanent snow and ice	32765
Permanent wetland	32763
Urban or Built-up	32762
Unclassified	32761
Annual ET	
Fill value, out of the earth	65535
Waterbody	65534
Barren or sparsely vegetated	65533
Permanent snow and ice	65532
Permanent wetland	65531
Urban or Built-up	65530
Unclassified	65529

Using spatial analyst in ESRI ArcMAP 10.1, the mean annual ET from 2000 to 2010 was calculated for the MODIS tile. The results are shown in Figure 44. The mean annual ET shows a distinct gradient from west to east, with Karoo having very low ET values because of the lack of water available for plants to use. A plant is only able to transpire as long as there is water available for it to use. Similarly, evaporation can only happen if there is water to evaporate. KwaZulu-Natal has higher ET values because there is more water available for plants to use. The actual ET values differ significantly from the potential ET values which are more commonly used.

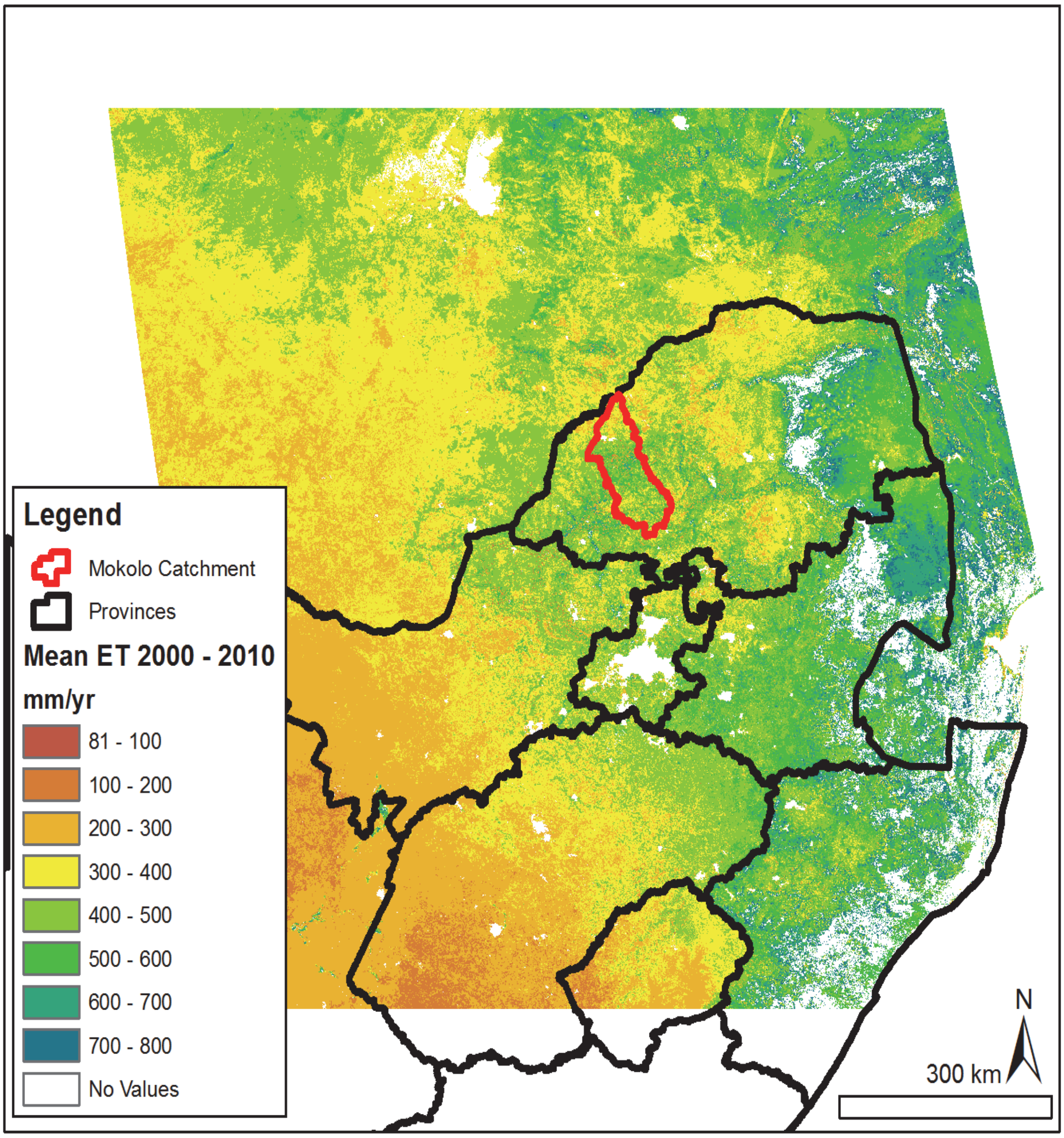


Figure 44 Mean Annual ET from 2000 to 2010. Values are in mm/yr.

There are 503 8day ET images from 2000 to 2010. The values (after being multiplied by a factor of 0.1) are mm/8day (the sum of the ET over the 8 day period). These values we divided by 8 in order to obtain ET for a single day (mm/day) which is more commonly used. The date of the image is shown in the file name and is in Julian format (days from the start of the year) and not calendar format. The Julian dates were converted to calendar dates in EXCEL. In order to obtain ET values for wetlands, point locations were digitised in wetlands in the Waterberg. Because MODIS calculates the ET value per grid cell, points were selected where there was no irrigated agriculture as the agriculture ET characteristics would dominate the pixel so that the pixel value would be representative of the agriculture and not of the wetland. The points were located near the centre of the ET pixel in order to simplify the analysis. This is shown in Figure 45.

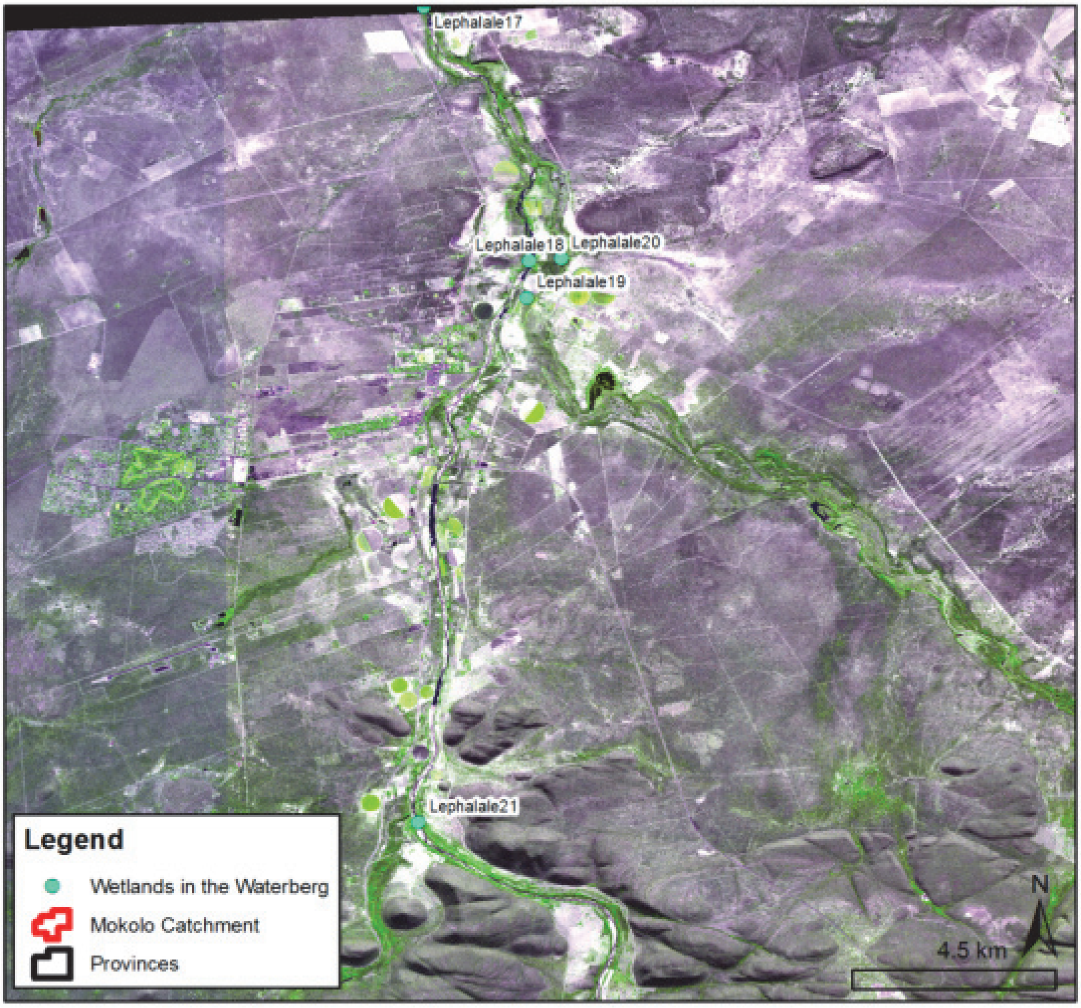


Figure 45 Map showing the location of the digitised point locations. The point locations are in the centre of a MODIS tile as well as located in a wetland. Areas under irrigation that overlapped with a wetland pixel were avoided. The background image is a RapidEYE image with the vegetation greenness exaggerated.

<u>Evapotranspiration Values – Annual ET</u>

A total of 22 points were digitised in the riparian wetland of the Mokolo near Lephalale. This riparian wetland is also a NFEPA wetland and is currently under stress due to sand mining near Lephalale as well as a reliance on the Mokolo Dam water releases, especially during the dry season. Sites Lephalale0 to Lephalale10 are located in the alluvium on basement granite and sites Lephalale11 and higher are located on alluvium overlying the Karoo Supergroup. A total of 12 points were identified in the Alma region in the upper catchment resulting in a total of 34 points for the Waterberg study area as shown in Figure 46. Using the Extract Multi Values to Points in Spatial Analyst in ArcMAP, the points were intersected with the 8 day ET dataset and the annual ET dataset. The data was exported to EXCEL and is summarised in Table 10 .

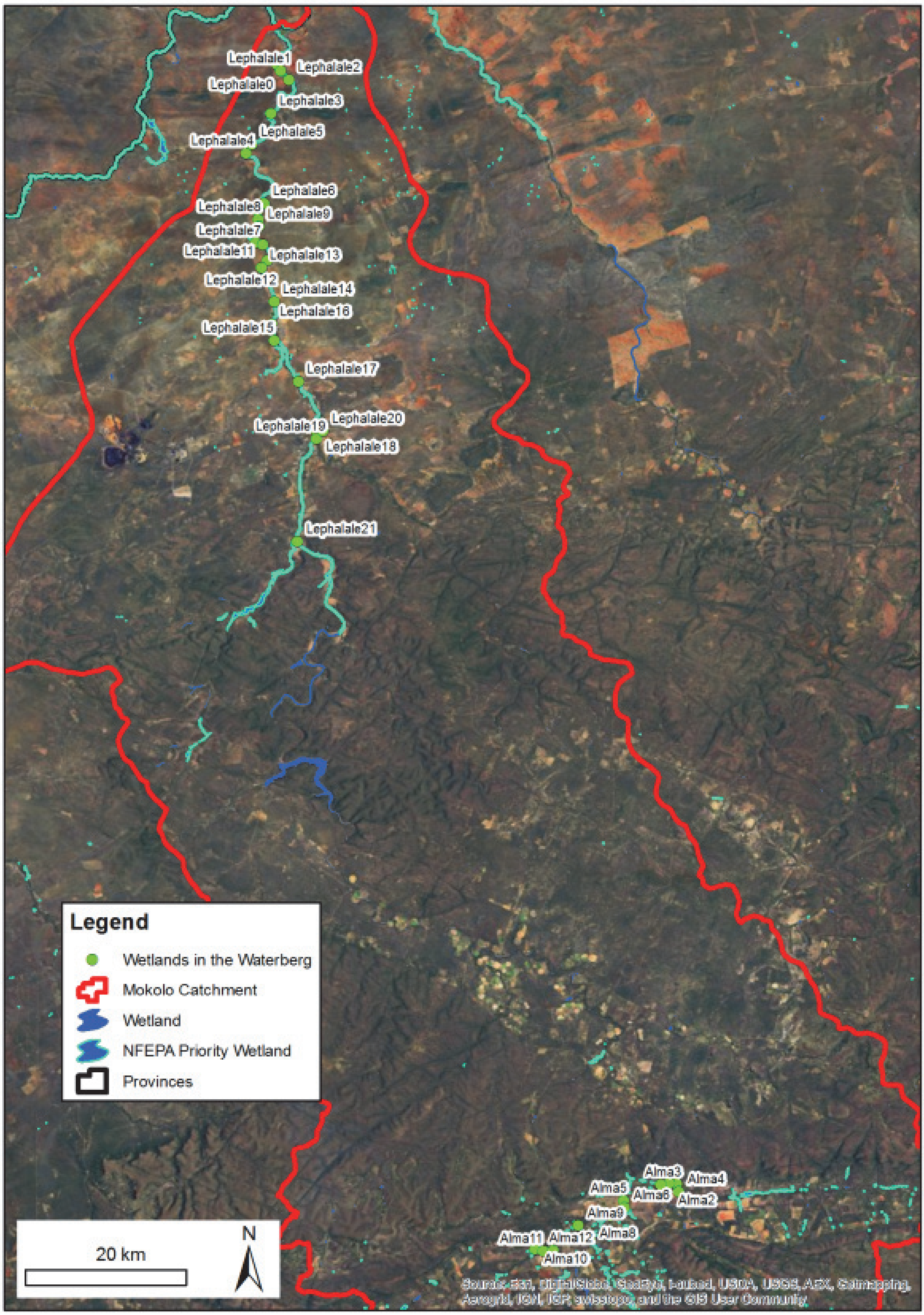


Figure 46 Locality map showing the point locations of the wetland points used in the MODIS ET analysis as well as the NFEPA Priority Wetlands.

Table 10 Annual ET values for points located in wetlands in the Mokolo. Values are in mm/yr and are from 2000 to 2010.

Description	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Avg	Median	STD Dev	CoV
Lephalale0	261	341	265	282	365	281	325	307	270	335	251	298	282	36	12%
Lephalale1	403	395	348	336	451	323	379	428	366	413	335	380	379	40	11%
Lephalale2	384	404	331	354	439	348	368	439	384	430	345	384	384	37	10%
Lephalale3	269	343	287	273	324	249	361	313	281	328	244	297	287	37	12%
Lephalale4	434	444	334	346	436	332	452	422	345	439	347	394	422	49	12%
Lephalale5	304	347	306	264	280	250	316	273	276	344	247	292	280	33	11%
Lephalale6	277	325	245	256	276	287	316	304	273	326	269	287	277	26	9%
Lephalale7	260	307	242	256	241	273	258	268	267	291	256	265	260	19	7%
Lephalale8	314	372	297	318	281	314	311	295	334	386	333	323	314	30	9%
Lephalale9	327	416	339	312	311	344	310	305	315	375	369	338	327	33	10%
Lephalale10	306	401	335	319	331	328	302	380	352	375	414	349	335	36	10%
Lephalale11	369	371	296	274	286	308	293	321	309	384	350	324	309	37	11%
Lephalale12	298	393	349	311	289	293	344	288	320	410	403	336	320	45	13%
Lephalale13	326	386	312	334	312	304	374	291	331	390	416	343	331	39	11%
Lephalale14	375	397	341	349	402	362	388	415	351	436	424	385	388	31	8%
Lephalale15	442	466	363	372	435	394	466	418	433	487	395	425	433	38	9%
Lephalale16	404	404	349	328	394	357	416	417	416	444	382	392	404	33	8%
Lephalale17	417	402	352	361	398	355	420	448	400	445	415	401	402	32	8%
Lephalale18	490	481	390	327	500	371	429	422	419	504	407	431	422	55	13%

Description	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Avg	Median	STD Dev	CoV
Lephalale19	464	416	375	327	453	399	417	423	438	469	350	412	417	44	11%
Lephalale20	460	503	402	352	513	435	466	463	453	514	427	453	460	47	10%
Lephalale21	497	468	367	338	472	383	474	374	447	558	439	438	447	63	14%
Alma1	584	543	446	415	483	460	523	427	513	600	522	502	513	58	12%
Alma2	282	246	178	162	232	207	270	192	243	263	220	227	232	37	16%
Alma3	557	512	408	438	471	484	576	477	532	573	481	501	484	52	10%
Alma4	389	362	339	320	347	338	394	329	393	453	416	371	362	40	11%
Alma5	520	496	411	434	472	469	482	466	503	530	498	480	482	34	7%
Alma6	520	493	424	381	456	457	486	449	465	500	502	467	465	38	8%
Alma7	487	493	412	375	428	411	457	406	435	492	454	441	435	37	8%
Alma8	493	518	412	389	450	436	507	427	496	499	467	463	467	41	9%
Alma9	523	519	404	411	494	449	512	437	483	553	496	480	494	46	10%
Alma10	625	581	474	453	502	490	521	437	529	564	564	522	521	55	11%
Alma11	515	495	413	417	433	424	475	379	420	486	491	450	433	42	9%
Alma12	552	495	432	424	456	436	491	387	470	550	500	472	470	49	10%

The average annual ET as well as the median and the standard deviation were calculated for each point location. The Coefficient of Variation (CoV) is the ratio between the standard deviation and the mean, expressed as a percentage, and is an indicator of the variability of the ET between years. Generally the ET values are consistent, with ET values in 2004 being the highest. The annual ET is shown graphically in Figure 47 and Figure 48.

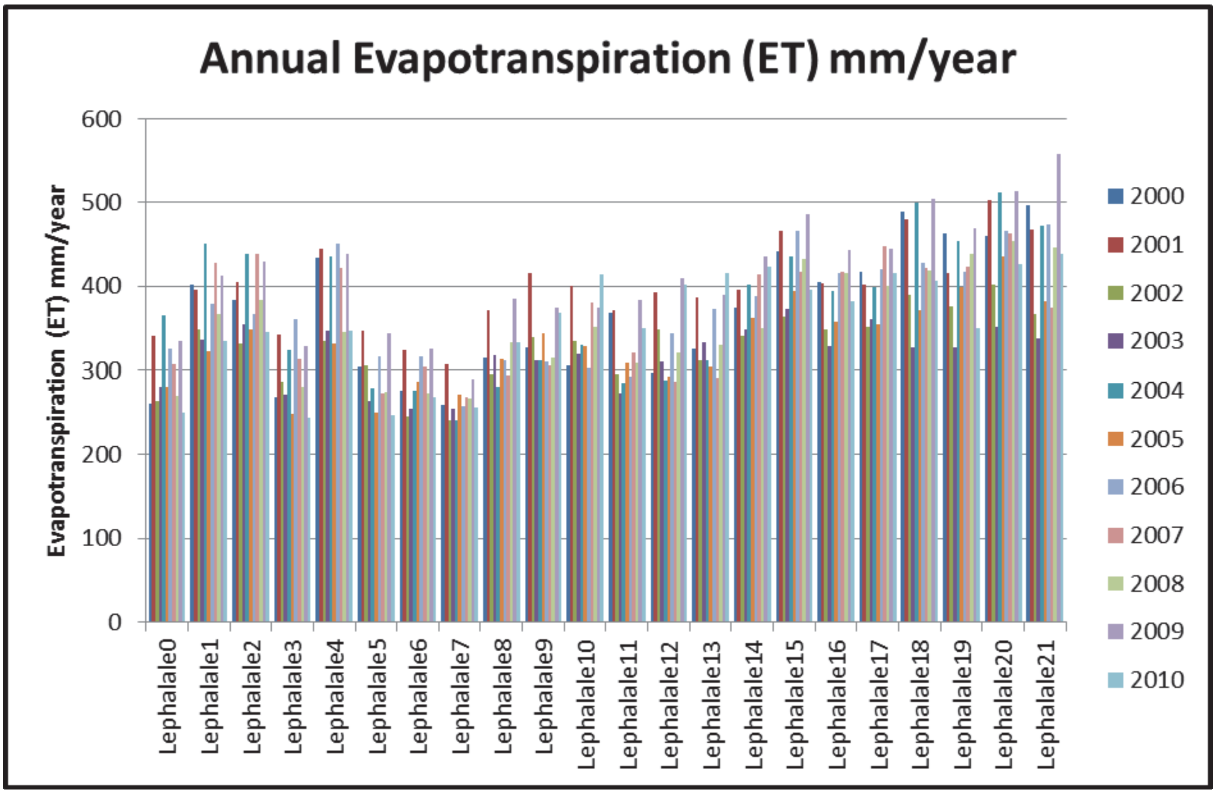


Figure 47 Annual Evapotranspiration (ET) in mm/year for the points in the riparian wetland near Lephalale

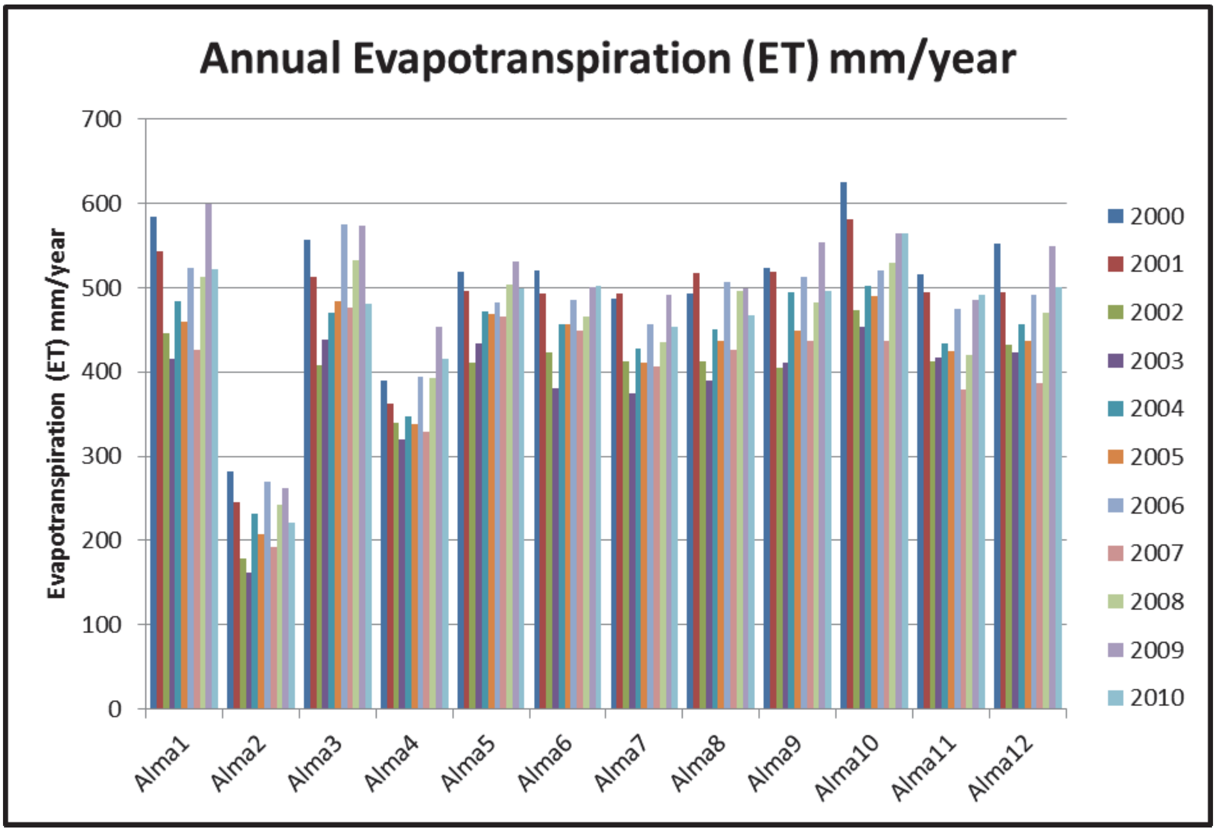


Figure 48 Annual Evapotranspiration (ET) in mm/year for the points in the wetlands near Alma in the Waterberg.

<u>Evapotranspiration Values – 8day</u>

The variation in ET for the different points located in riparian vegetation and wetlands are shown in the Appendix A. ET values are in mm/day and based on the MODIS 8day ET dataset. The samples were split into 3 groups. The first group is Lephalale0 to Lephalale10 which are located in the alluvium on basement rocks to the north of the catchment. The second group is Lephalale11 to Lephalale21 and the third group is the wetlands in the Alma region. The graphs are located in Appendix A.

Recharge and Discharge Processes

The water balance approach is a simple method which uses total rainfall and precipitation for a specific area to construct a water balance between rainfall and ET. In areas where rainfall is lower than ET the hypothesis is that vegetation within these zones is receiving water from sources other than rainfall and inflow. As such the vegetation is deemed to be making use of groundwater resources and could possibly be labelled as zones of potential groundwater dependant ecosystems. The water balance approach relies heavily on an accurate rainfall data set. The Lynch (2004) rainfall dataset was used for the water balance as it represents the best available gridded rainfall coverage for South Africa. The original cells were resampled to match the annual average ET calculated previously.

The results of the water balance for the MODIS tile is shown in Figure 49. The map shows areas in the country where ET exceeds rainfall. Figure 50 shows the water balance for the Mokolo Catchment. The area where ET exceeds rainfall is generally located in the middle part of the catchment, south of Lephalale. Figure 51 shows a zoomed in version of the middle part of the catchment. The NFEPA priority wetland located on the Rietspruit has a very high probability of having groundwater as its source of water because the ET exceeds rainfall. The terrestrial vegetation is the catchment also has a very high probability of being groundwater dependent because the ET exceeds rainfall, and in some places significantly exceeds rainfall. The water balance is useful in that it applies to all vegetation types, and not just restricted to wetland species.

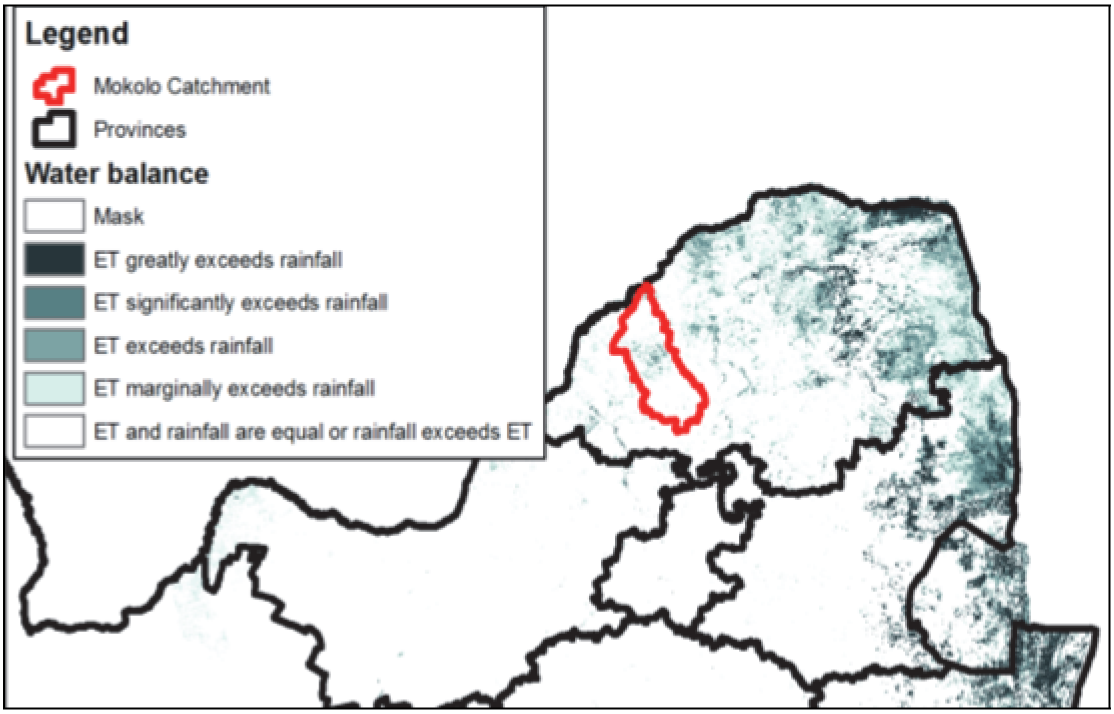


Figure 49 Water balance for MODIS tile. The map shows where evapotranspiration exceeds rainfall, which implies an additional source of water other than rainfall and inflow.

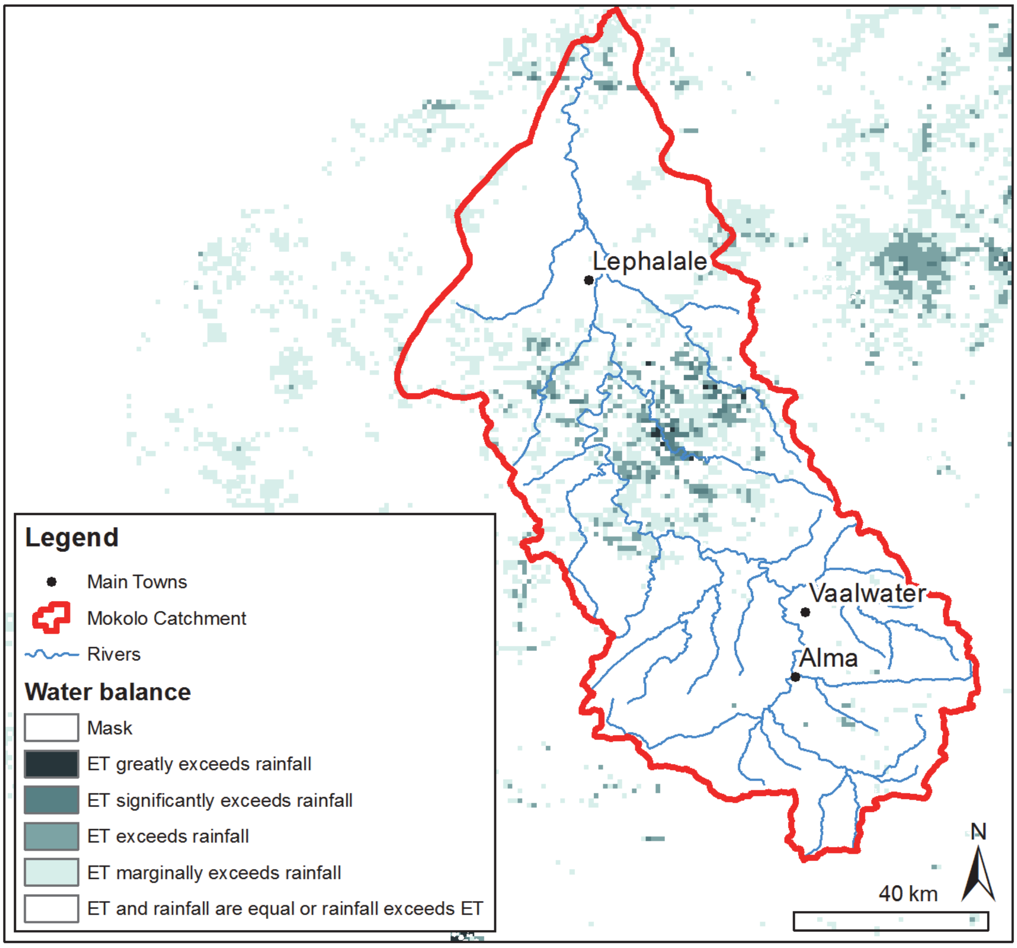


Figure 50 Water balance for the Mokolo Catchment showing areas where ET exceeds rainfall.

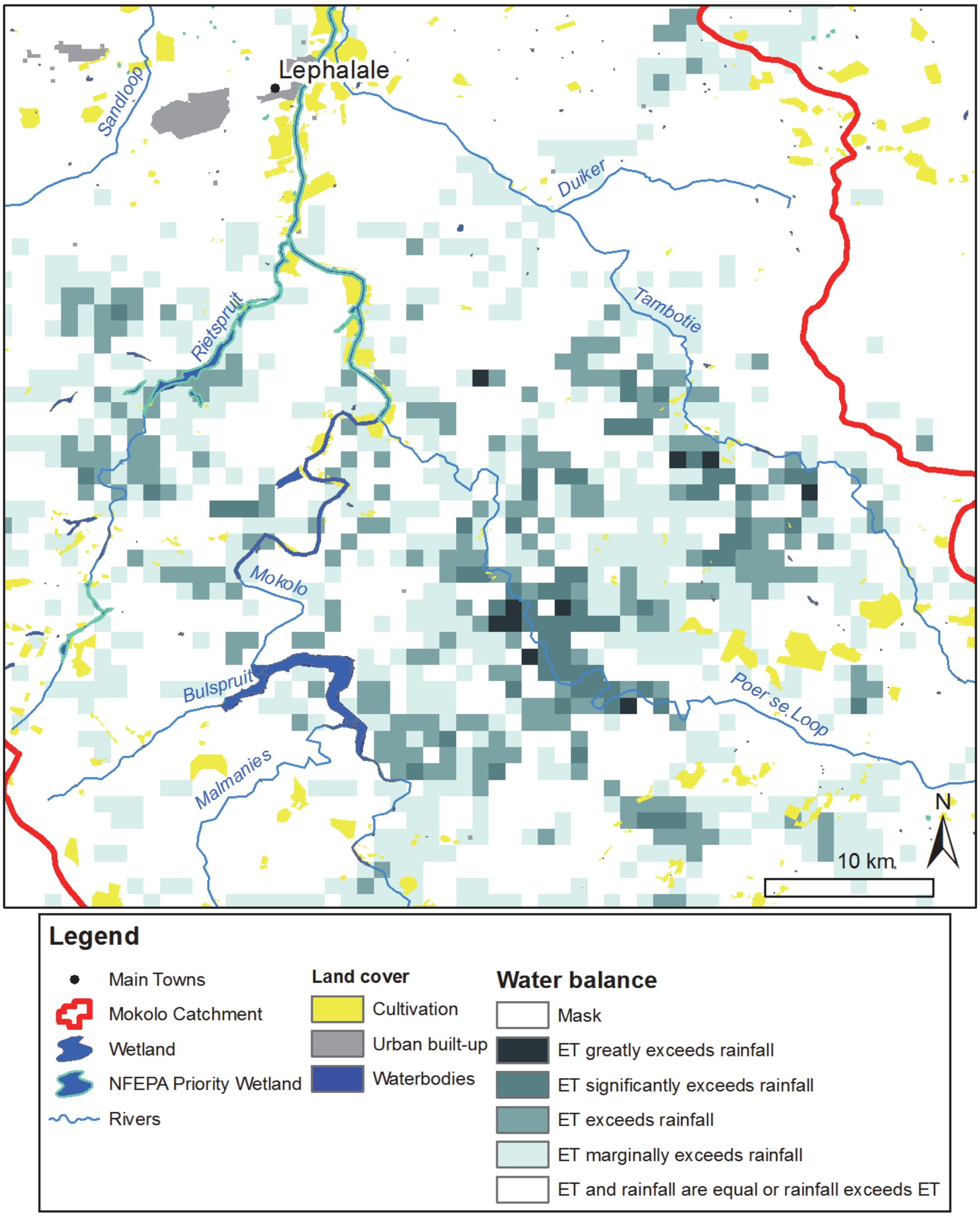


Figure 51 Zoomed in map showing the water balance for the Waterberg. Areas where ET exceeds rainfall are shown, in particular the NFEPA priority wetland located on the Rietspruit. The terrestrial vegetation in the middle part of the catchment has a strong dependence on groundwater in the Waterberg sandstone.

Hydrological Modelling of the Mokolo River Catchment

The Mokolo River originates from the Waterberg Mountains through the upper reaches of the sand river, and flows until its confluence with the Limpopo River. The 8,387 km^2 catchment is made up of a number of tributaries that join the Mokolo River. The catchment is characterised by seeps and valley floor channelled valley-bottom wetlands in the headwaters, and a large alluvial flood plain wetland from Lephalale to the confluence of the Limpopo River.

The geology of the upper and middle catchment is characterised by conglomerates of the Waterberg group and glenting formation while the lower part the catchment is characterised by sandstones of the Karoo sequence and migmatites of the Limpopo mobile belt. Soil for the catchment has been classified as: moderate to deep sandy loam soil, shallow to moderately deep sandy soil and moderately deep sandy loam soil. The elevation of the catchment ranges from 1200 m to 1600 m above mean sea level. The catchment is characterised as a mountainous area (Water berg mountain range) with a changing geology towards the north into more flat-lying areas (Barnard, 2000).

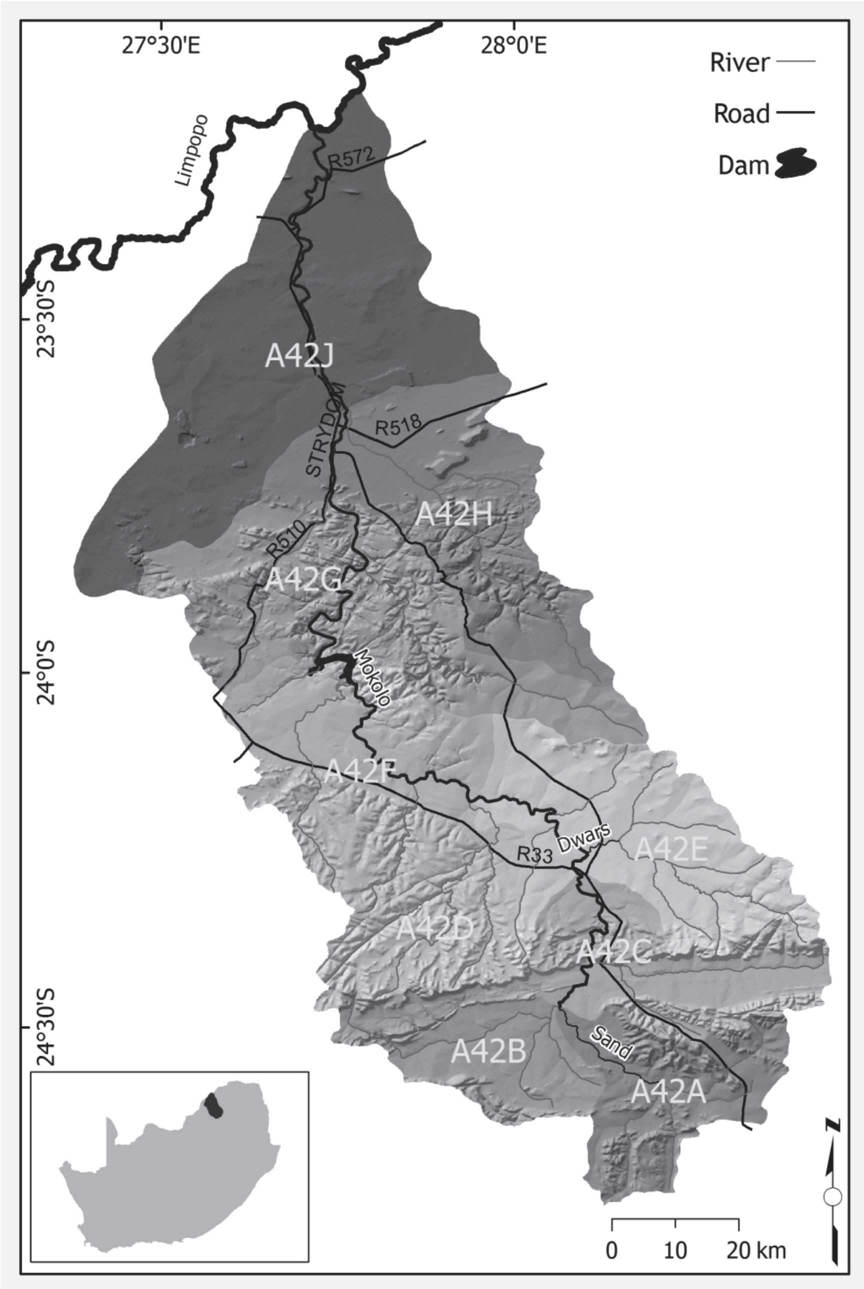


Figure 52 The Mokolo river catchment and its quaternary catchments.

Data availability

Hydrological data

Rainfall in the Mokolo catchment ranges from 700 mm in the Waterberg region to 400 mm in the Limpopo plain. It is characterised by summer rainfall with an annual average rainfall of 558 mm. Temperature increases in gradient from 14°C to 22°C, from south to north. The catchment is characterised by an annual potential evaporation of 1783 mm (McCartney, 2004). Monthly rainfall data obtained from WR2005 (Middleton and Bailey, 2009) database was used to drive the model. Stream flow is monitored in the catchment at B4H002 which is at the outlet of B42C and observed record covers the period from 1948 to 2014. The historical flow records at B4H002 are uncertain and therefore WR2005 simulated flows (Middleton and Bailey, 2009) were used in this exercise as a surrogate to compare with the simulated time series. The idea in this case is therefore to reproduce the WR2005 simulated flows both without and with wetlands.

<u>Hydrological processes of the Mokolo wetlands</u>

The hydrological processes of the Mokolo wetlands have been investigated by the Department of Water and Sanitation (DWA, 2010) and the section below states the current understanding of the Mokolo catchment wetlands in the Alma region. The Alma region falls within the Western bankenveld wetlands resources unit (DWA, 2010). The region is characterised by unchannelled, channelled and seepage valley bottom type of wetlands. The wetlands are formed in gentle valleys and associated slopes of the upper catchment. Slow interflow from precipitation is the main source sustaining the wetlands (DWA, 2010). In addition, the wetlands are also maintained by flows from drainage networks.

Model setup

There are a number of different sizes and types of wetlands in the Mokolo basin. The main idea in using the Mokolo in this exercise is twofold: The first is to use a sub-basin where wetlands exist but there is no data related to the wetlands; and secondly, the wetlands in the sub-basin are small and quite numerous and are not at the outlet of the sub-basins. We therefore wanted to test the models handling of this by amalgamating the wetlands into one large one that was located at the catchment outlet. The Pitman model was setup for the A42A to A42C sub-basins of the Mokolo. Figure 53 indicates the WRSM 2000 flow network diagram for the Mokolo river catchment A42A to A42C. The catchments are all characterised with active irrigation, and reservoirs. Apparent also from the WRSM 2000 flow network of Mokolo catchment, is that there is no evidence of wetlands. Rainfall data and catchment model parameters from the WR2005 database (Middleton and Bailey, 2009) were used to set up the model. The model parameters were calibrated until a best fit was obtained.

In this instance, the wetlands in a sub-basin were clustered into one wetland at the outlet of each sub basin. This is based on the conceptualisation of the Pitman model (Hughes et al., 2006; Hughes et al., 2013) where wetlands are treated as reservoirs at the outlet of the sub-basin. Without changing the parameters, the wetland module was added to the model, on the assumption that if the wetland was insignificant and had no effect on the downstream outflow, the simulated flow would not change – any changes would indicate that ignoring the wetland processes in the model setup is a misdirection of the interpretation of the hydrological processes of the sub-basin. The maximum wetland area for each wetland within the different sub basins (MaxWA) were estimated from wetland coverage prepared by SANBI (2011). A hypothetical wetland module was used for the other parameters for the Mokolo catchment since there is no data available within the catchment. Abstractions were assumed to be zero while data for evaporation was obtained from WR2005 database (Middleton and Bailey, 2009). The parameters that were used for the Mokolo catchment are presented in Table 6.

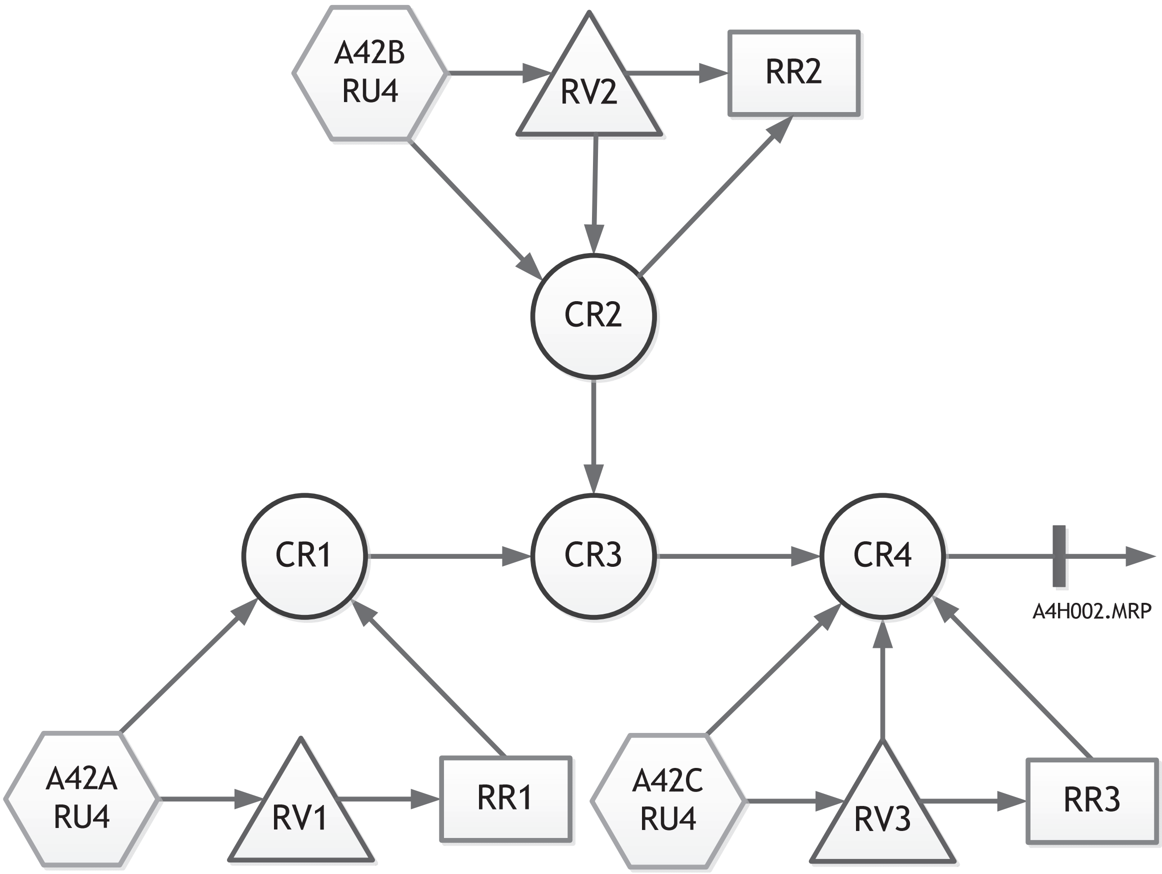


Figure 53 The WRSM 2000 system diagram for the Mokolo river catchment used for setting up the model for the WR2005 simulations

Results

Hydrological modelling results

The only existing gauge in the Alma region is at A4H002 on the Mokolo River at the outlet of A42C. However, the existence of unquantified water uses and some reservoirs in the sub-basin imply that the historical observation at A4H002 are impacted, the extent of which we cannot ascertain. Consequently, simulated results at the outlet at A42C were compared with cumulative flows from the WR2005 (Middleton and Bailey, 2009) simulations. This part of the study therefore aimed to reproduce the stream flow simulated by the WR2005 study, in the absence of reasonable observed data within the catchment. Simulation results from SPATSIM Pitman before the inclusion of the wetland module were able to reproduced WR2005 flows. The model performance measures for the three sub basins is summarised in Table 7.

Table 11 Results of Pitman monthly stream flow model output in the Mokolo Catchment.

Model performance measures	A42A	A42B	A42C
R2	0.861	0.754	0.775
R2 (In)	0.479	0.417	0.456
CE	0.810	0.736	0.777
CE (In)	0.027	0.146	-2.578
%M	0.099	2.909	1.751
%M (In)	3.95	8.267	-400.000
Performance	U	U	U

V = Very Good; G = Good; S = Satisfactory; U = Unsatisfactory

Figure 54 shows the monthly distribution for A42A after inclusion of the wetland sub-model (after recalibration). From the graph, it is apparent that with the wetland sub-model included, the Pitman model fails to reproduce the seasonal distribution of the WR2005 flows though the overall water balance seems to be attained (Figure 55).

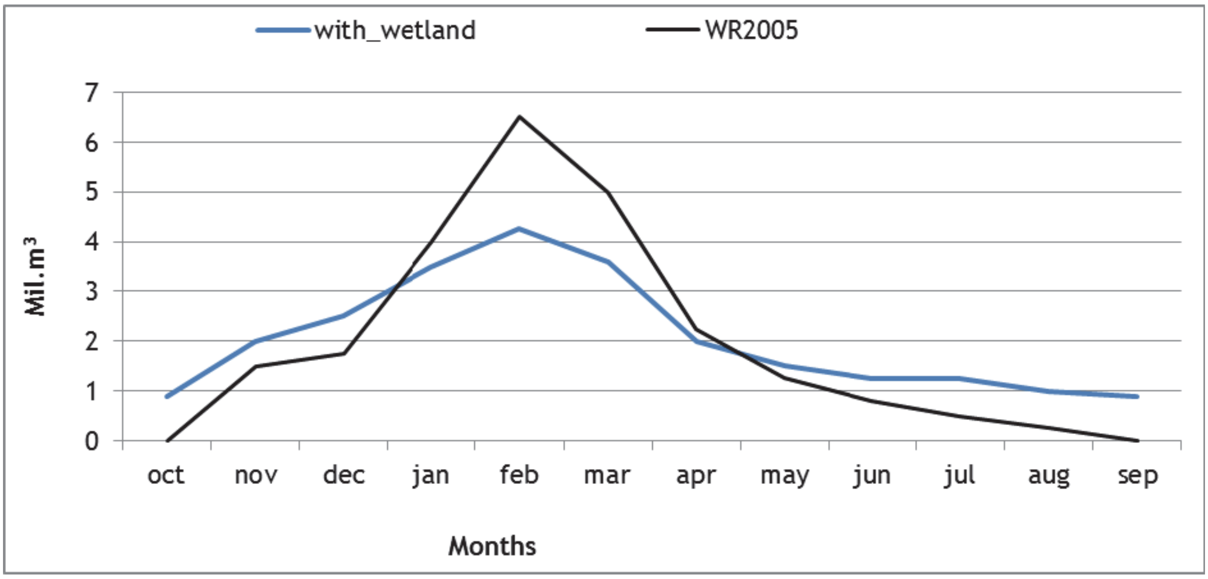


Figure 54 A42A monthly distribution graph after the inclusion of the wetland sub-model.

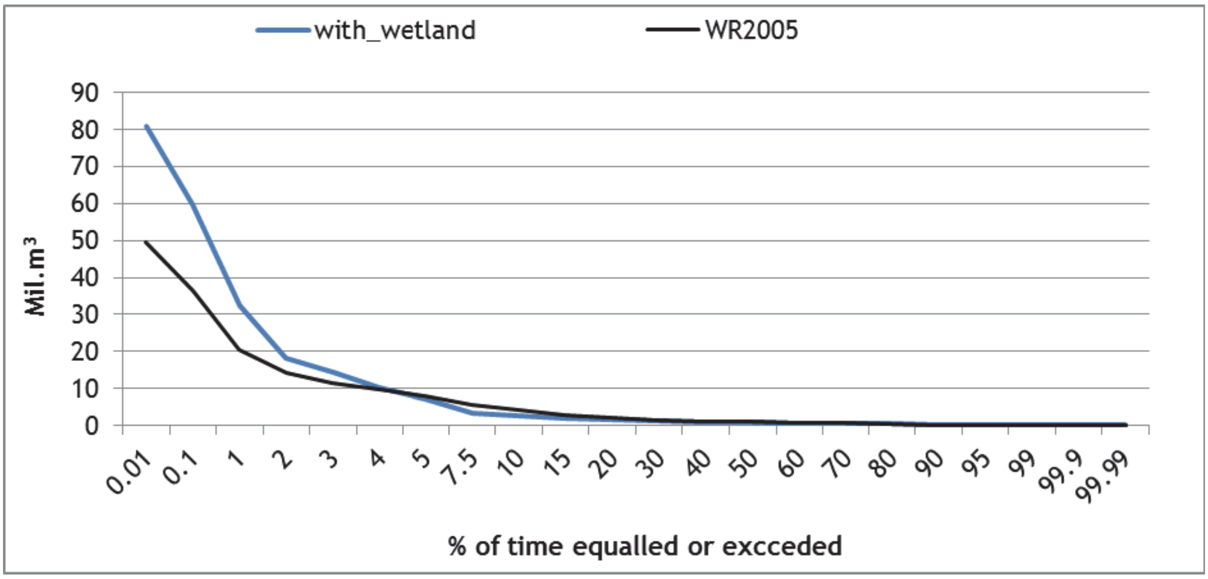


Figure 55 A42A flow duration curve after the inclusion of the wetland sub-model.

A similar behaviour with that of A42A is noted in A42B. Figure 56 shows the monthly distribution simulation results for A42B after inclusion of the wetland-sub-model (after recalibration). The flows in A42B are also not well distributed with the WR2005 simulated flows. Figure 57 indicates the flow duration curve for A42A after the inclusion of the wetlands.

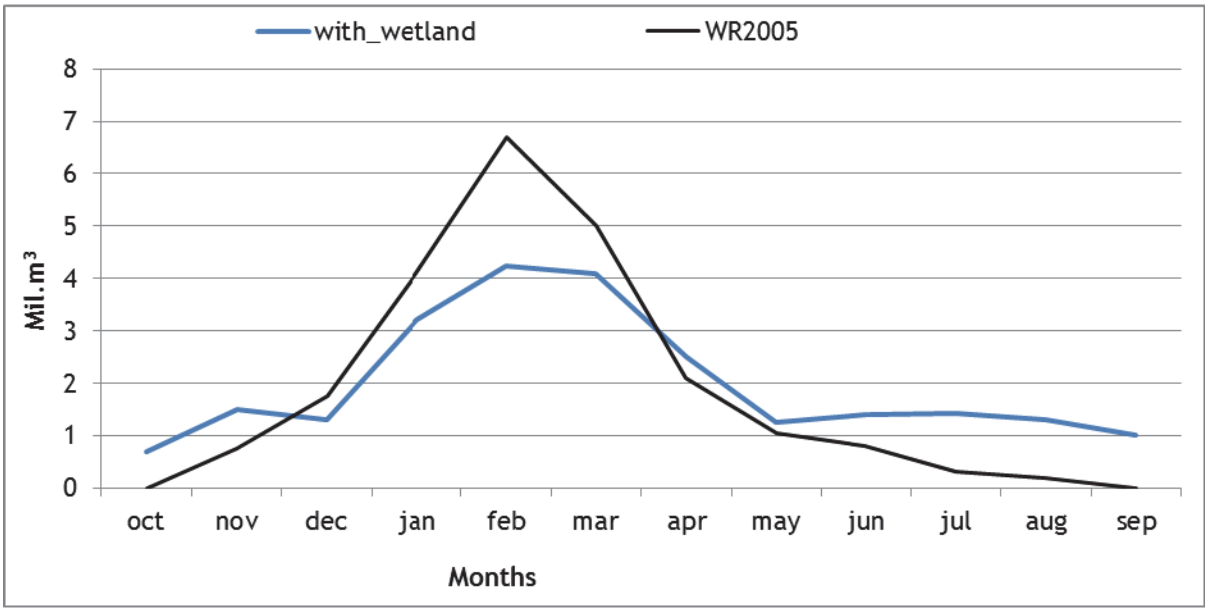


Figure 56 A42B monthly distribution curve after the inclusion of the wetland sub-model (after recalibration).

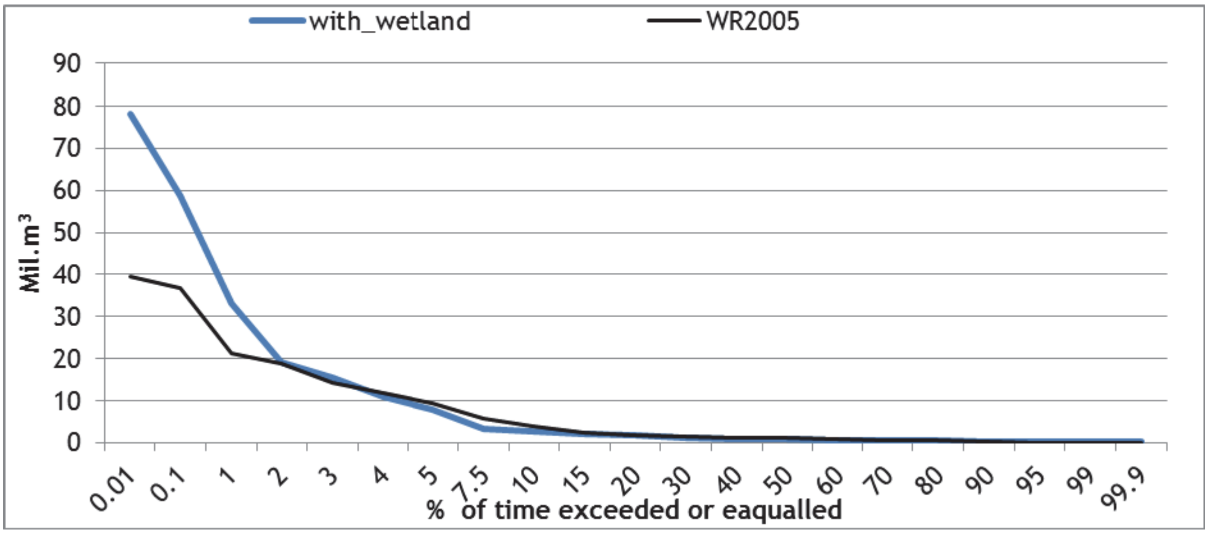


Figure 57 A42B flow duration curve after the inclusion of the wetland sub-model (after recalibration).

A42C is also not well distributed with the WR2005 flows but with a good overall water balance.

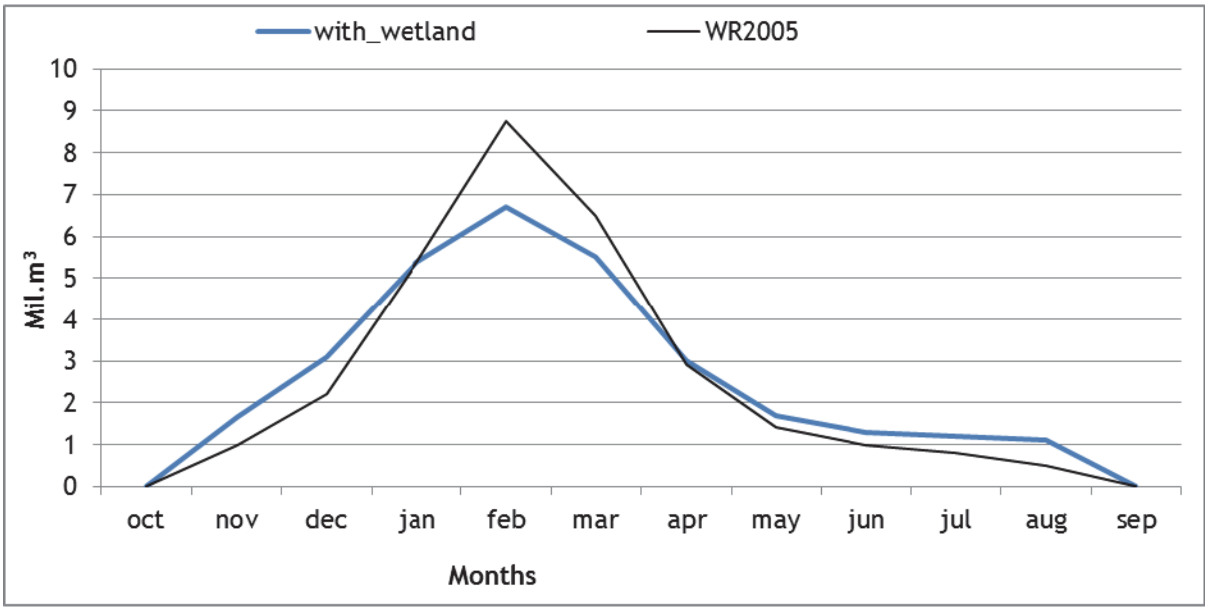


Figure 58 A42C monthly distribution curve after the inclusion of the wetland sub-model (after recalibration).

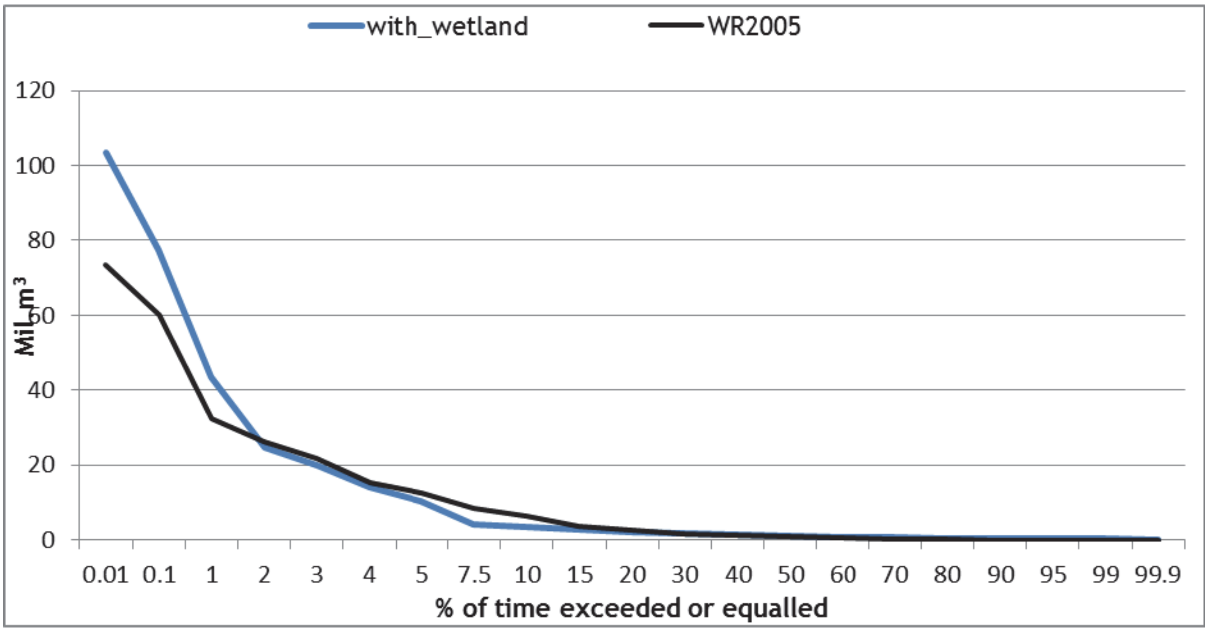


Figure 59 A42C flow duration curve after the inclusion of the wetland sub-model (after recalibration).

The poor distribution of flows within the three sub-catchments seems to indicate that the wetland sub-model of the Pitman model is not well conceptualised and thus fails to adequately represent the wetlands in the sub-basins. Even though a hypothetical wetland was used for the sub-basins with all the wetland types amalgamated and treated as a single one at the outlets of the sub-basins, a similar behaviour with that of the GaMampa has been noted with the addition of the wetland sub-model.

4.3 WILDERNESS ESTUARIES (WATERBALANCE)

Background

The Wilderness estuaries are located near the town of Wilderness in the Western Cape. The quaternary catchment K30D forms part of a CSIR Parliamentary Grant project entitled: Catchment level management of water quality in the Gouritz coastal sub-Water Management Area. The key challenge in the Gouritz Water Management Area is balancing water supply and demand while ensuring adequate water quality in the catchment and estuaries (Petersen et al., 2014).

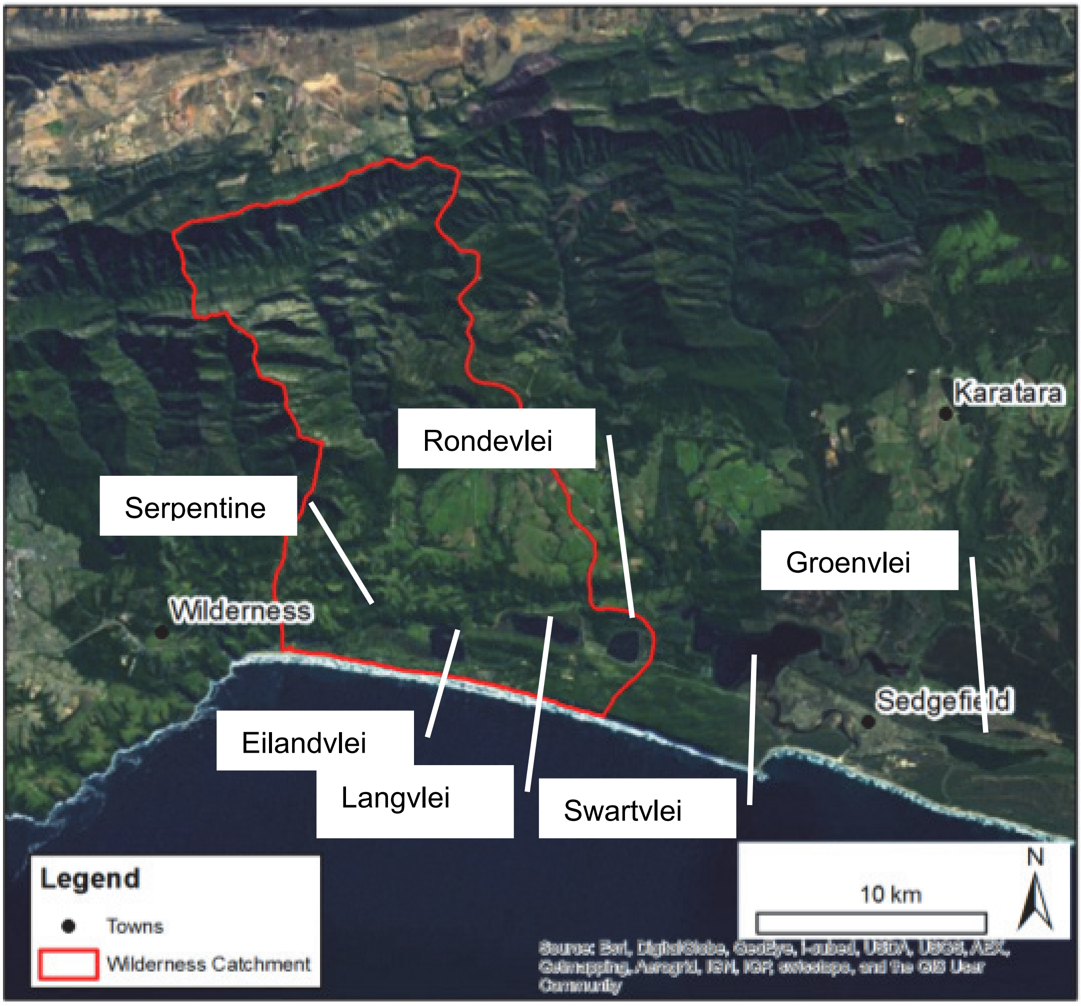


Figure 60 Locality map showing the quaternary catchment K30D and the location of the estuarine lakes.

Groundwater Surface Water Interaction

<u>Aquifer Types</u>

There are three main aquifer types in the study area based on the geology in Figure 61. The Table Mountain Group comprises on the Peninsula Group and the Skurweberg Formation. In the study area the fynbos has predominantly been replaced by pine plantations, although these are now being rehabilitated. The cross section in Figure 62 shows that the Table Mountain Group is northward dipping and as a result any recharge that takes place in the Outeniqua Mountains (the Peninsula Formation in the geological map) will travel northwards and not towards the coast. This aquifer is what is currently being targeted by the deep boreholes being drilled in Oudsthoorn.

The Woodville and George Batholiths are granitic plumes which intruded into the Kaaimans Group. Generally granitic rocks are very poor aquifers because of the very low primary porosity, except where there is extensive weathering and faulting. The Kaaimans Group are the oldest rocks and form the basement rocks in the study area. They are similar in age to the Malmesbury Group in the Western Cape. Generally the Kaaiman aquifer is a poor quality aquifer (similar to the Malmesbury aquifer), resulting in low yielding boreholes with brackish water. The farms who farm predominantly on the granite and Kaaimans Group do not use borehole for irrigation purposes but rely on surface water for the crops.

The third aquifer is the Bredasdorp Aquifer. This is an alluvial aquifer consisting primarily of aeolianite sand and is Quaternary in age. The Bredasdorp aquifer is underlain by the low permeability Kaaimans Group and granitic plumes. Towards the east (K40E) the aquifer is underlain by Table Mountain Group sandstone. The Wilderness estuaries (Eilandvlei, Langevlei and Rondevlei) as well as Swartvlei and Groenvlei are situated on this primary aquifer. Recent work, mainly by Roger Parsons (2008), has looked at the groundwater contributions to Swartvlei (which does not have a river flowing into) as well as work around Sedgefield and the boreholes which have been drilled as a water source for the municipality.

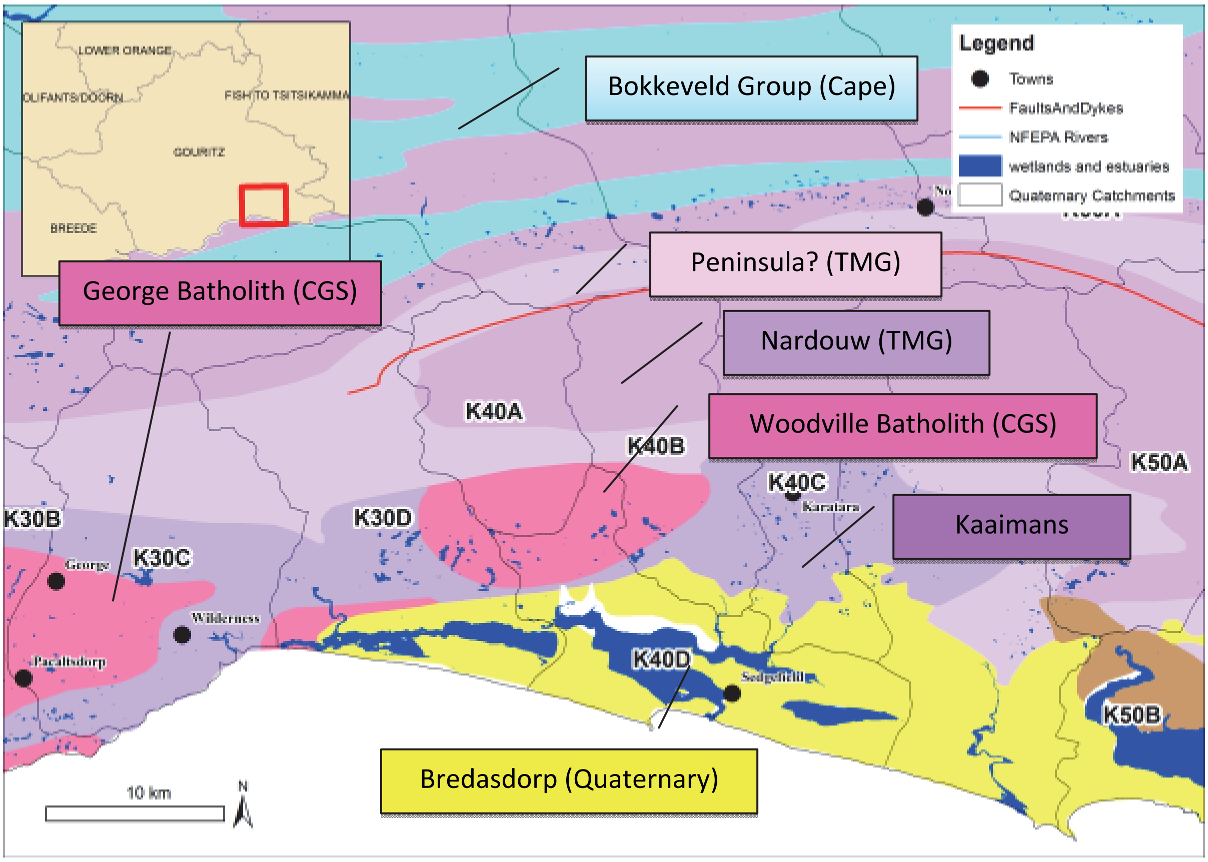


Figure 61 Geological Map for the Wilderness study area showing the main geological units

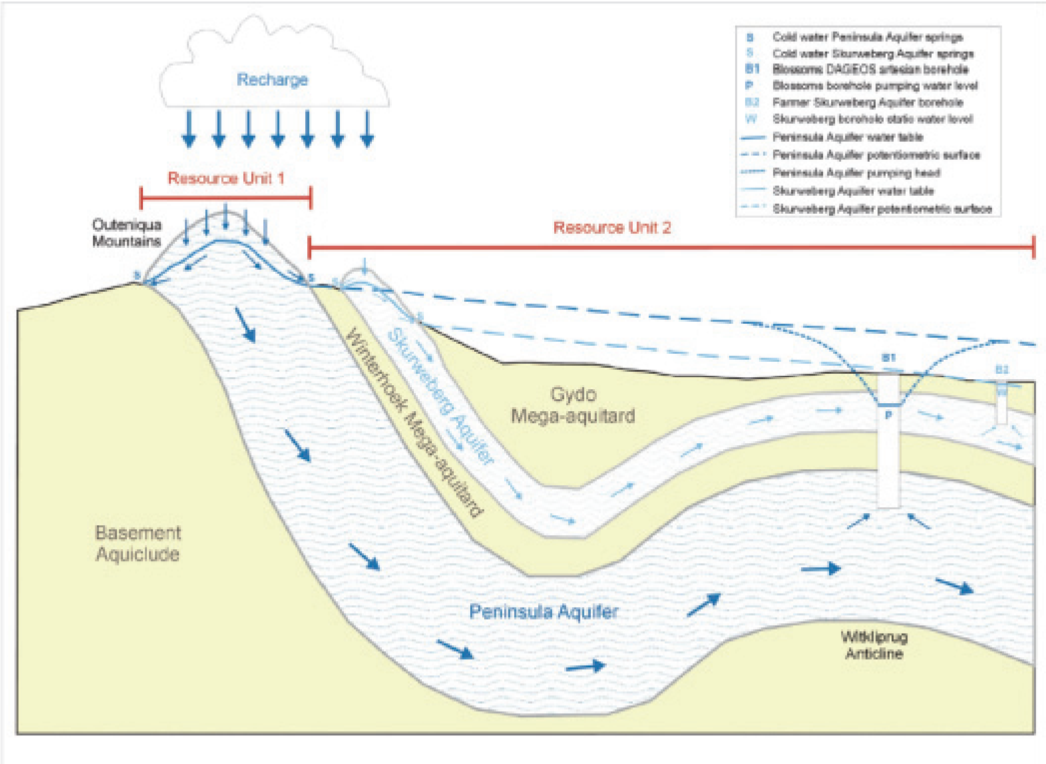
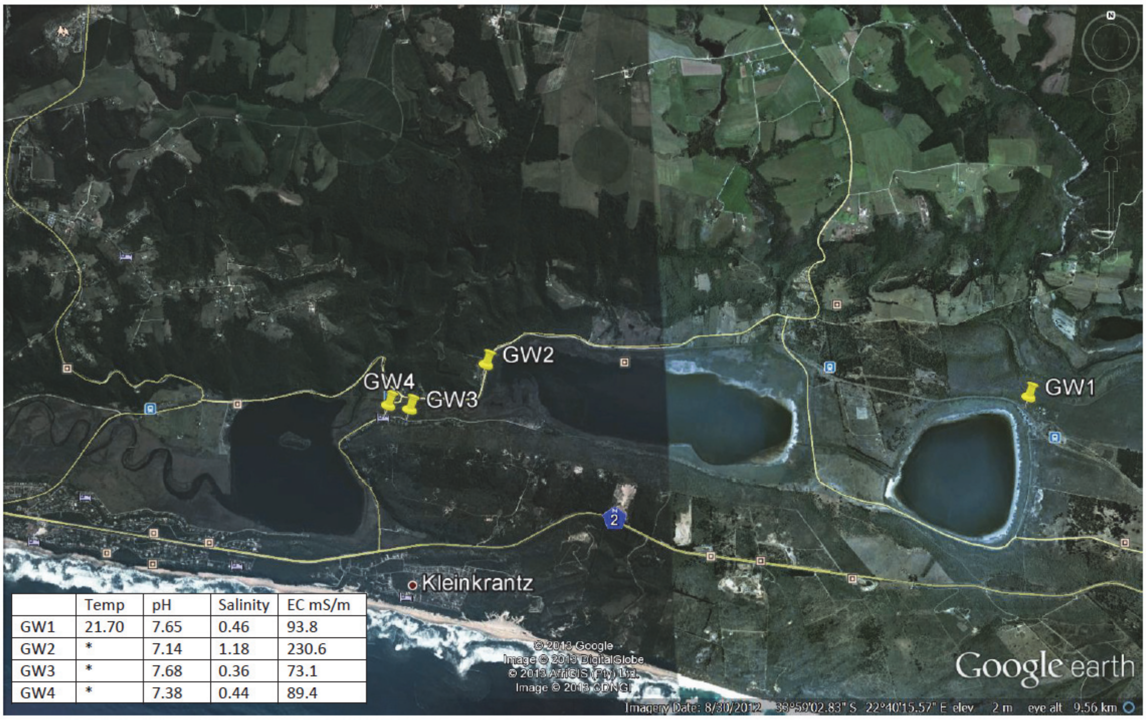


Figure 62 Cross-section showing the Table Mountain Group sandstone dipping northwards towards Oudsthoorn

<u>Fieldwork</u>

Limited fieldwork has been done trying to characterise the groundwater component in the study area. The reason for this is that because of the abundance of surface water, as well as good quality shallow groundwater, most residents do not have proper boreholes but rather rely on spikes as a water supply. The spikes are typically between 1 and 3 metres deep and are equipped with pumps which make water level sampling problematic. Water levels would indicate the flow direction of groundwater in the study area. The location and water chemistry of the limited groundwater samples are shown in Figure 63. GW1, GW3 and GW4 are probably representative of the groundwater in the aquifer, while GW2 represents a spike which is located closer to the saline estuary interface.



	Temp	pH	Salinity	EC mS/m
GW1	21.70	7.65	0.46	93.8
GW2	*	7.14	1.18	230.6
GW3	*	7.68	0.36	73.1
GW4	*	7.38	0.44	89.4

Figure 63 Limited groundwater samples based on available spikes and boreholes.

Stable Isotopes

Five samples were taken from groundwater and surface water in order to begin characterising the isotopic signatures and to determine how successful stable isotopes are in characterising water in the estuarine/coastal environment. The sixth sample was from Rondevlei itself but broke during transfer to UCT laboratories. The location of the five samples is shown in Figure 64 and the results are shown in Table 12.

Figure 64 Location map from Google Earth showing the position of the stable isotope samples.

Table 12 Stable isotope analysis for the Wilderness estuaries

Sample	dD	$d^{18}O$
Touws Estuary Headwater – Stepping stones	-5.1	-1.38
Touws Mouth – Ebb and Flow	0.6	-0.09
LV1 Langvlei – Surface Water	26.8	4.84
Sprite Rondevlei – Groundwater	-22.1	-4.68
Touws Estuary Mouth	-5.7	-1.63

Figure 65 shows where the samples plot according to the Global Meteoritic Water Line. The groundwater from the Rondevlei spike has a signature very similar to the rainfall, indicating that recharge is through direct recharge. The Langvlei sample showed a very high degree of evaporation which is indicative of surface water as a result of the evaporation taking place from the lake. The Rondevlei spike showed a typical groundwater signature despite the spike depth only being two metres. The sample at the Touws estuary headwater – stepping stones, which is just beyond the maximum extent of the Wilderness estuary influence, reflects the rainfall signature, which is not surprising as it had rained the day before sampling. Further analysis is needed for Rondevlei in order to identify the groundwater contribution to the system. The estuarine lakes are very well mixed as a result of wind mixing and tidal influence (Petersen 2014). The chemistry depth profiles done by the CSIR showed consistent chemistry and temperature with the conclusion that one chemistry sample from the lake is representative of the entire body of water. The Touws Mouth – Ebb and Flow taken at the SANParks Ebb and Flow guest camp is on the local evaporation line, indicating evaporation taking place as well as mixing of the evaporated water from Langevlei and the fresh rainwater from the Touw River as it is located downstream of the confluence. It is interesting to note that the Touws Estuary Mouth sample (taken right at the outlet or the estuary mouth) is closer in character to the rainfall and the inflow from the Touws Estuary Headwater – stepping stones rather than the upstream Ebb and Flow sample and the connected Langevlei. This could imply either direct runoff from rainwater along the serpentine, or possibly a greater contribution from the stable isotope enriched groundwater along the meandering stretch of river.

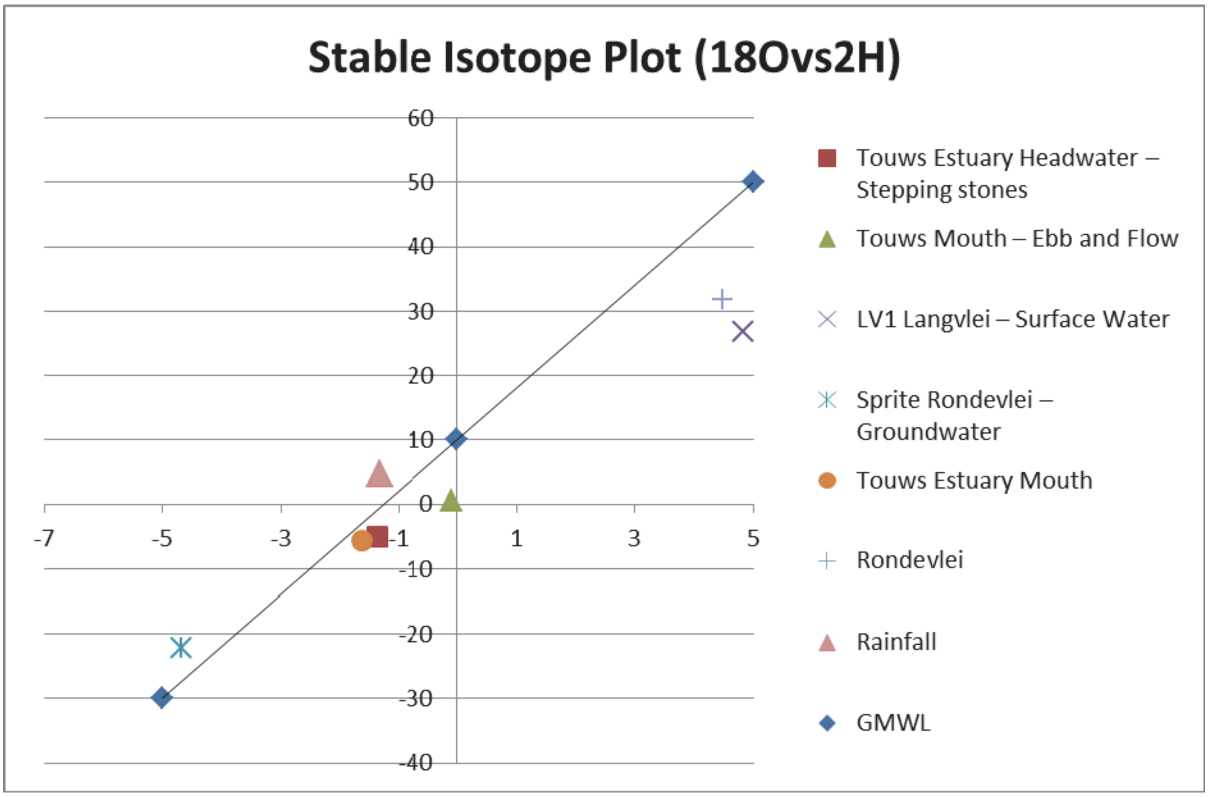


Figure 65 Stable Isotope Plot for the Wilderness case study

Evapotranspiration Characteristics

Methodology

Wilderness is located on the h19v12 MOD16 tile. The tile covers the Western Cape as shown in Figure 66. The MODIS Sinusoidal Projection was applied to all of the data.

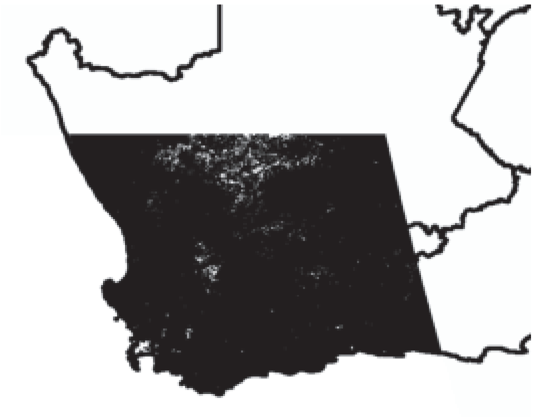


Figure 66 The MODIS ET h19v12 tile for the Western Cape.

The methodology applied was the same procedure as the Waterberg case study as discussed in 0 Methodology.

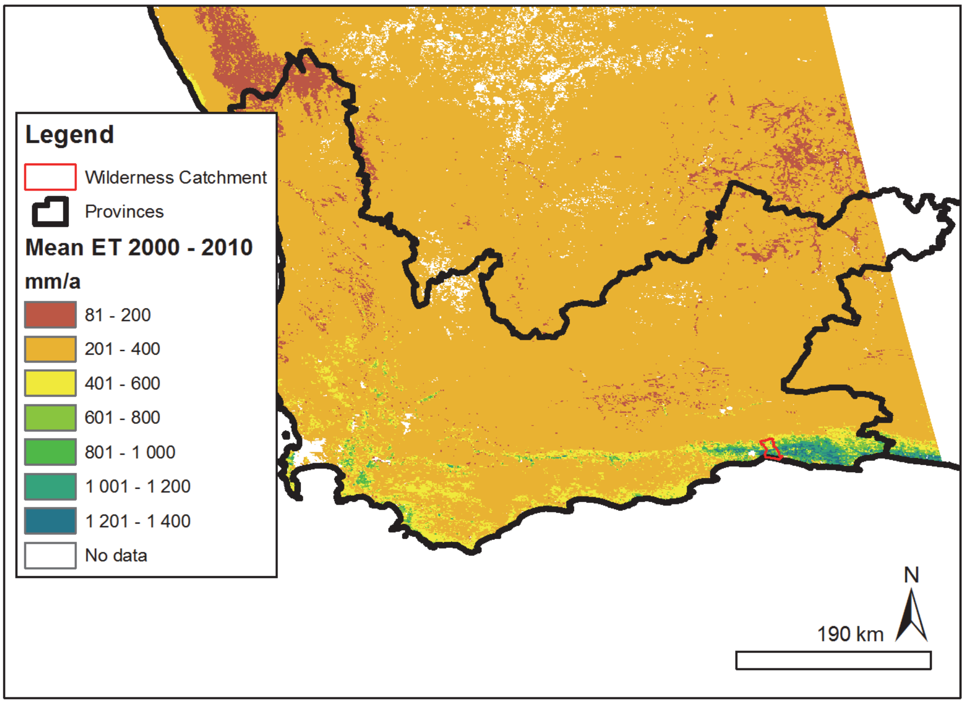


Figure 67 Mean Annual ET (mm/yr) for the Western Cape for 2000 to 2010.

Evapotranspiration Values – Annual ET

A total of 26 point locations were digitised based on the position of the ET pixel and the wetland. The identification of wetlands located within tiles that did not overlap with irrigated agriculture was problematic. The location of the Wilderness points are shown in Figure 68 Although Groenvlei is not part of the study area; an analysis was also done in order to compare the results with the methodology used by Parsons (2008). The locations of the Groenvlei points are shown in Figure 69.

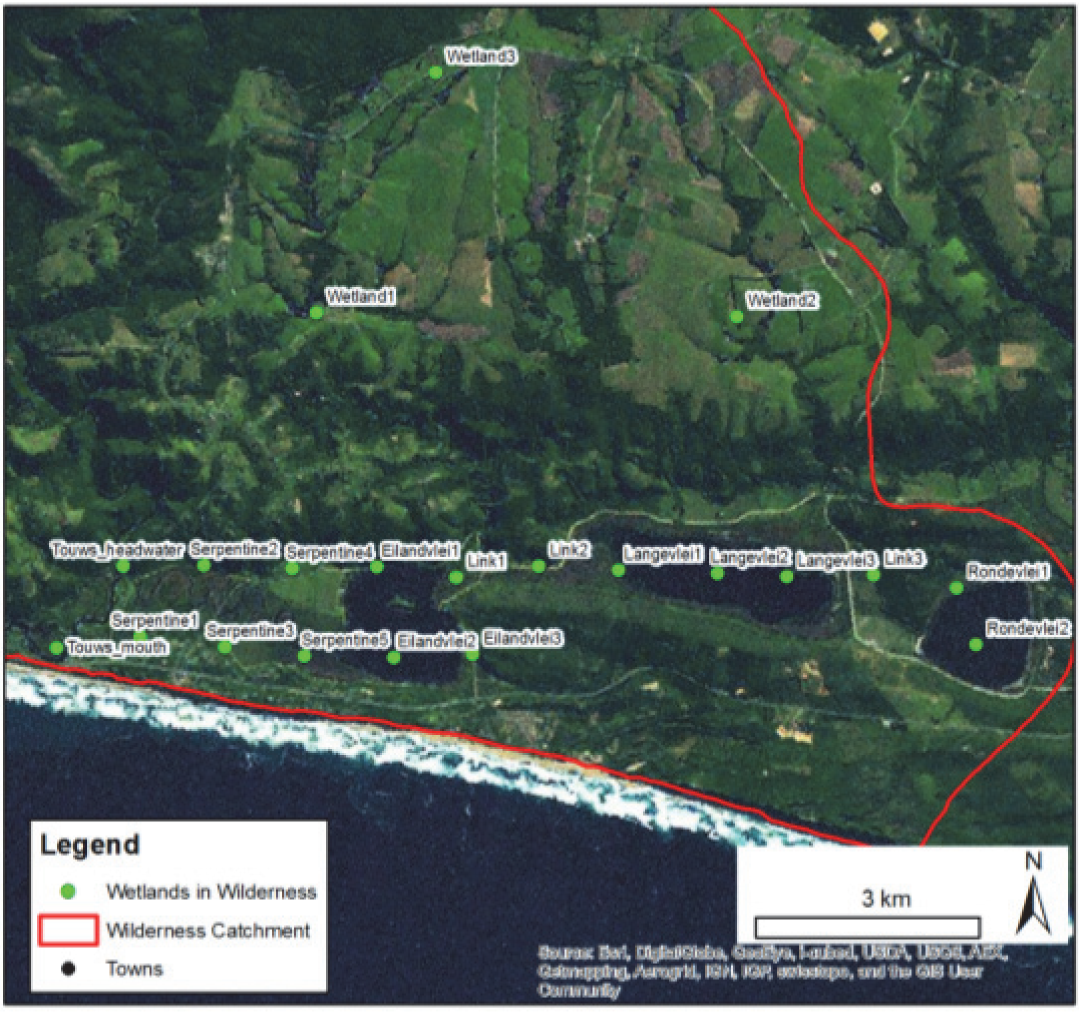


Figure 68 Location of the wetland points in Wilderness for the ET measurements.

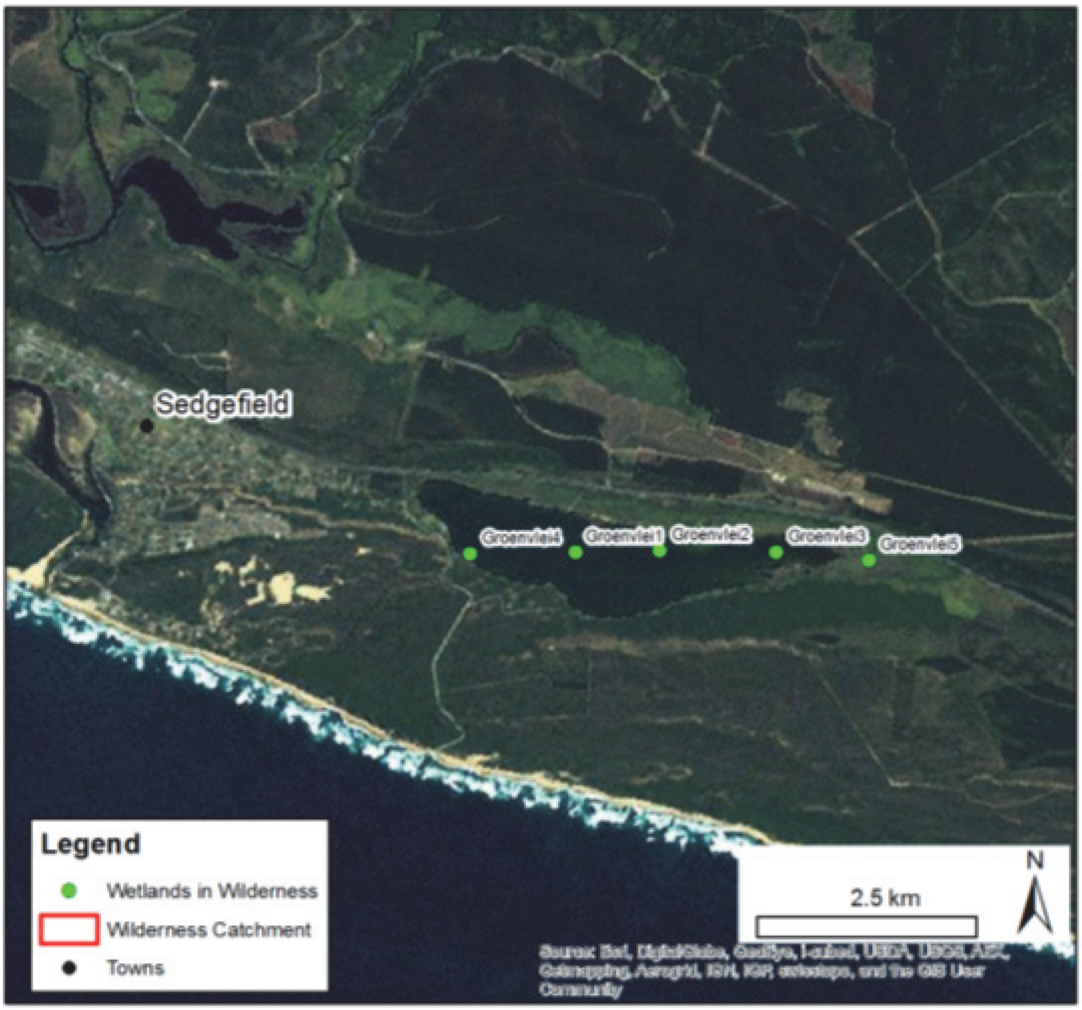


Figure 69 Location of the wetland points in Groenvlei for the ET measurements.

The annual ET (mm/yr) was extracted for all of the points and exported to EXCEL. The average, median, standard deviation and the coefficient of variation (CoV) was calculated for each of the points and is shown in Table 13. Generally the inter annual variations are within acceptable limits, except for higher variations in Wetland1 and Wetland2, possibly as a result of the influence of irrigated agriculture and harvesting on the overlapping pixels.

The annual ET values from 2000 to 2010 are shown for all of the points in Figure 70. It is surprising that the ET values for most of the estuarine lakes are below 400 mm/year, especially considering the availability of rainwater, groundwater and surface water for the plants. The values might be a result of the ET algorithm and the coarse scale landcover applied in the algorithm as shown in Figure 42. The MODIS ET products do not include ET estimates for open bodies of water, which is what occurs with the large open water bodies of the estuarine lakes. Further research is needed to explain this.

Table 13 Annual ET (mm/yr) for the Wilderness study area.

Description	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	AVG	MED	STD DEV	CoV
Touws_mouth	206	222	202	191	214	214	239	214	209	154	190	205	209	21	10%
Serpentine1	787	1019	901	858	901	904	901	899	904	695	593	851	901	112	13%
Touws headwater	1133	1185	1166	1186	1227	1198	1132	1208	1192	1116	1040	1162	1185	51	4%
Serpentine2	604	708	685	668	707	673	689	693	686	568	575	660	685	49	7%
Serpentine3	652	732	667	705	727	744	711	689	618	528	433	655	689	92	14%
Serpentine4	736	847	823	857	905	938	831	760	865	605	606	797	831	105	13%
Serpentine5	511	512	496	479	494	509	540	509	494	458	426	494	496	29	6%
Eilandvlei1	328	352	320	370	353	377	466	387	510	255	294	365	353	69	19%
Eilandvlei2	154	166	132	150	145	147	220	162	145	133	176	157	150	24	15%
Link1	709	752	683	741	765	836	720	699	702	565	575	704	709	75	11%
Link2	1078	1080	1072	1036	1129	1113	1013	1110	1073	938	891	1048	1073	71	7%
Eilandvlei3	573	606	515	523	536	666	587	575	515	451	429	543	536	65	12%
Langevlei1	370	379	310	326	332	337	402	381	350	335	396	356	350	29	8%
Langelvie2	444	442	372	413	413	409	481	447	412	416	486	430	416	32	7%
Langevlei3	214	222	214	210	169	211	255	220	191	191	185	207	211	22	11%
Link3	587	669	611	641	692	710	604	595	562	502	488	606	604	68	11%
Rondevlei2	427	424	354	384	384	382	465	439	390	398	466	410	398	35	8%
Rondevlei1	373	396	334	358	410	378	406	409	408	313	324	374	378	35	9%
Groenvlei1	483	483	424	436	428	439	507	470	431	433	518	459	439	32	7%
Groenvlei2	422	427	385	377	373	373	449	398	368	382	474	403	385	34	8%
Groenvlei3	396	405	345	397	413	417	459	473	477	322	368	407	405	48	12%
Groenvlei4	381	392	329	380	358	340	432	434	385	337	408	380	381	35	9%
Groenvlei5	697	784	666	805	812	845	819	845	782	692	672	765	784	67	9%
Wetland1	1328	1519	1250	1341	1404	1369	1396	1260	1301	960	964	1281	1328	166	13%
Wetland2	499	682	489	636	708	750	707	613	643	419	487	603	636	106	18%
Wetland3	1005	1045	1009	1025	1066	1050	1032	1069	1079	907	898	1017	1032	59	6%

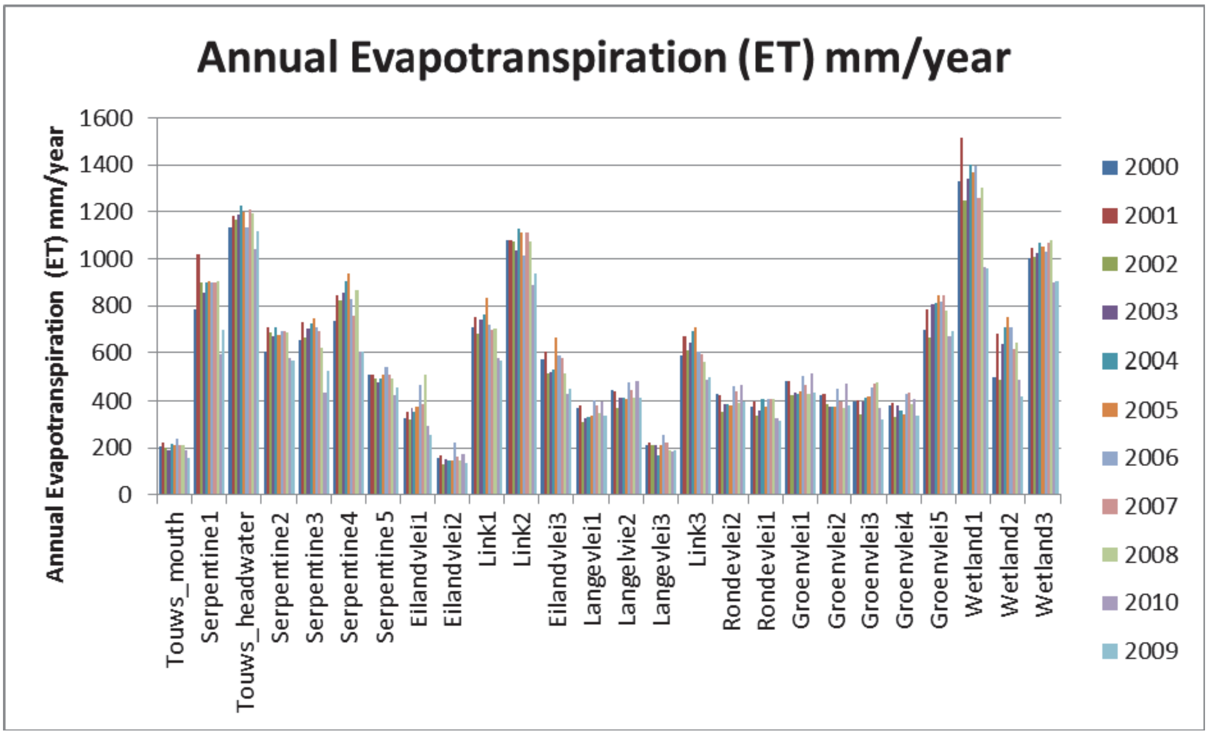


Figure 70 Annual ET for the Wilderness study area from 2000 to 2010.

Evapotranspiration Values – 8day

The variation in ET for the different points located in riparian vegetation and wetlands are shown in Appendix A. ET values are in mm/day and based on the MODIS 8day ET dataset. The samples were split into 4 groups. The first group is from the mouth of the Touws estuary to the end of the Serpentine. The second group is from the start of Eilandvlei through to the end of Langevlei, including the links between the lakes. The third group is Rondevlei and Groenvlei. Groenvlei is dependent on groundwater, with no surface water rivers flowing into it compared to Rondevlei which has no surface water river flowing into it, but is connected to Eilandvlei. The last group are the wetland points located in the agricultural part of the catchment.

Recharge and Discharge Processes

The water balance approach is a simple method which uses total rainfall and precipitation for a specific area to construct a water balance between rainfall and ET. In areas where rainfall is lower than ET the hypothesis is that vegetation within these zones is receiving water from sources other than rainfall and inflow. As such the vegetation is deemed to be making use of groundwater resources and could possibly be labelled as zones of potential groundwater dependant ecosystems. The water balance approach relies heavily on an accurate rainfall data set. The Lynch (2004) rainfall dataset was used for the water balance as it represents the best available gridded rainfall coverage for South Africa. The original cells were resampled to match the annual average ET calculated previously. The water balance for the Western Cape is shown in Figure 71.

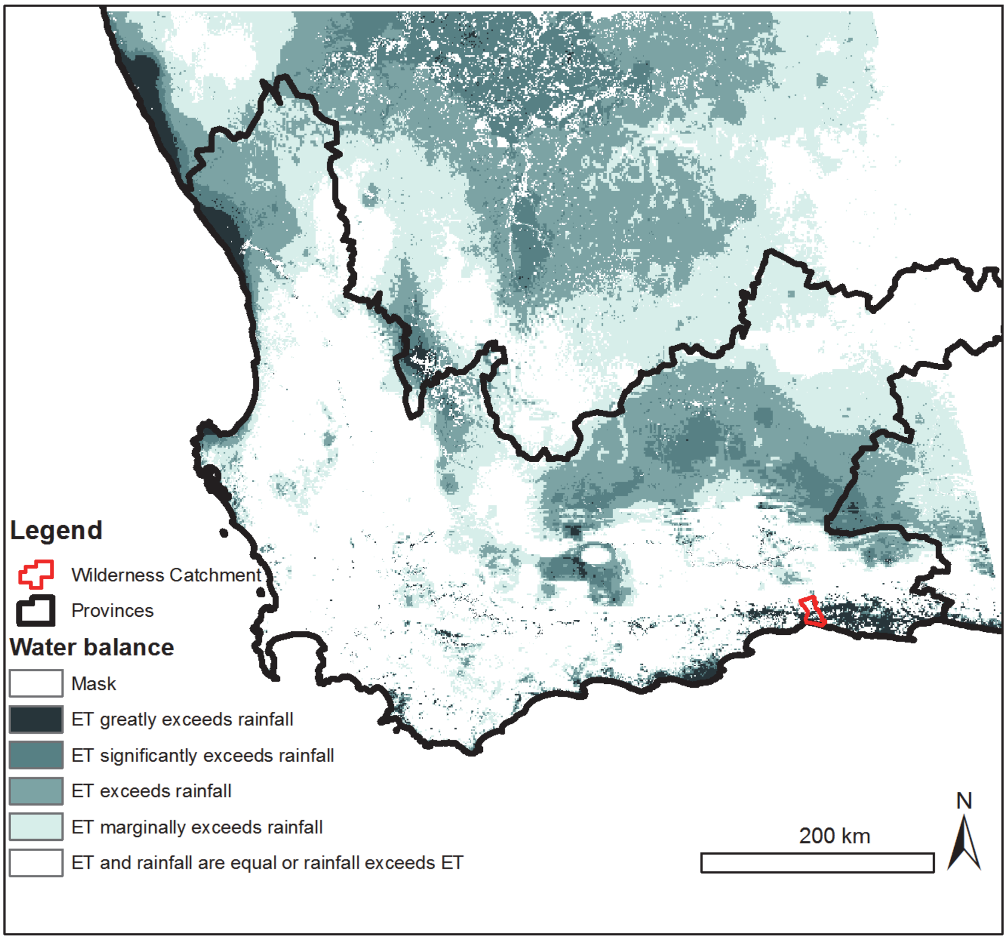


Figure 71 Water balance for MODIS tile. The map shows where evapotranspiration exceeds rainfall, which implies an additional source of water other than rainfall and inflow.

The areas in the province which stand out as ET greatly exceeding rainfall are around Stilbaai, George through to Knysna (including Wilderness), and the Quaternary (alluvial) sediments on the west coast near Velddrift and from Lamberts Bay northwards to Hondeklipbaai. Typically in quaternary sediments, the unconfined primary aquifer supplies an additional source of water to the vegetation, especially on the west coast where rainfall is limited.

Additional areas where ET exceeds rainfall are in the Karoo in the Northern Cape, the Tankwa Karoo northwards towards Calvinia, and the Beaufort Group sediments of the Karoo, from Laingsburg on the N1 through to Beaufort West in the north and Willowmore in the east, suggesting a dependency on groundwater for the terrestrial vegetation and the few wetlands identified in these areas.

The water balance for the study area is shown in Figure 72. The cultivated areas are shown in yellow based on the updated national land cover mosaic from SANBI, compiled in 2009. Cultivated areas, especially under irrigation, have an additional water source from irrigated water so they are masked out in the map. The area which stands out at ET significantly exceeding rainfall is the Southern Afrotemperate Forest (aka the Southern Cape Forests) vegetation type. These natural, indigenous forests (which include the Outeniqua Yellowwood, Real Yellowwood (South Africa's national tree), white stinkwood, black stinkwood, just to name a few. These are tall deep rooted trees which are able to tap into deeper groundwater levels more easily than ordinary shallow rooted vegetation.

Neither the Serpentine nor any of the estuarine lakes, including Groenvlei have an ET that exceeds the rainfall. As stated previously the annual MODIS ET calculated for these lakes are relatively low (possibly as a result of a coarse landcover classification that does not identify the waterbody). However, the surrounding vegetated pixels also do not have an ET that exceeds rainfall. A further possible explanation is that based of the vegetation species present, the species can only transpire a certain amount of water despite abundant water being available, or alternatively the vegetation is stressed because of other causes (not because of water) and thus is unable to use all the available water.

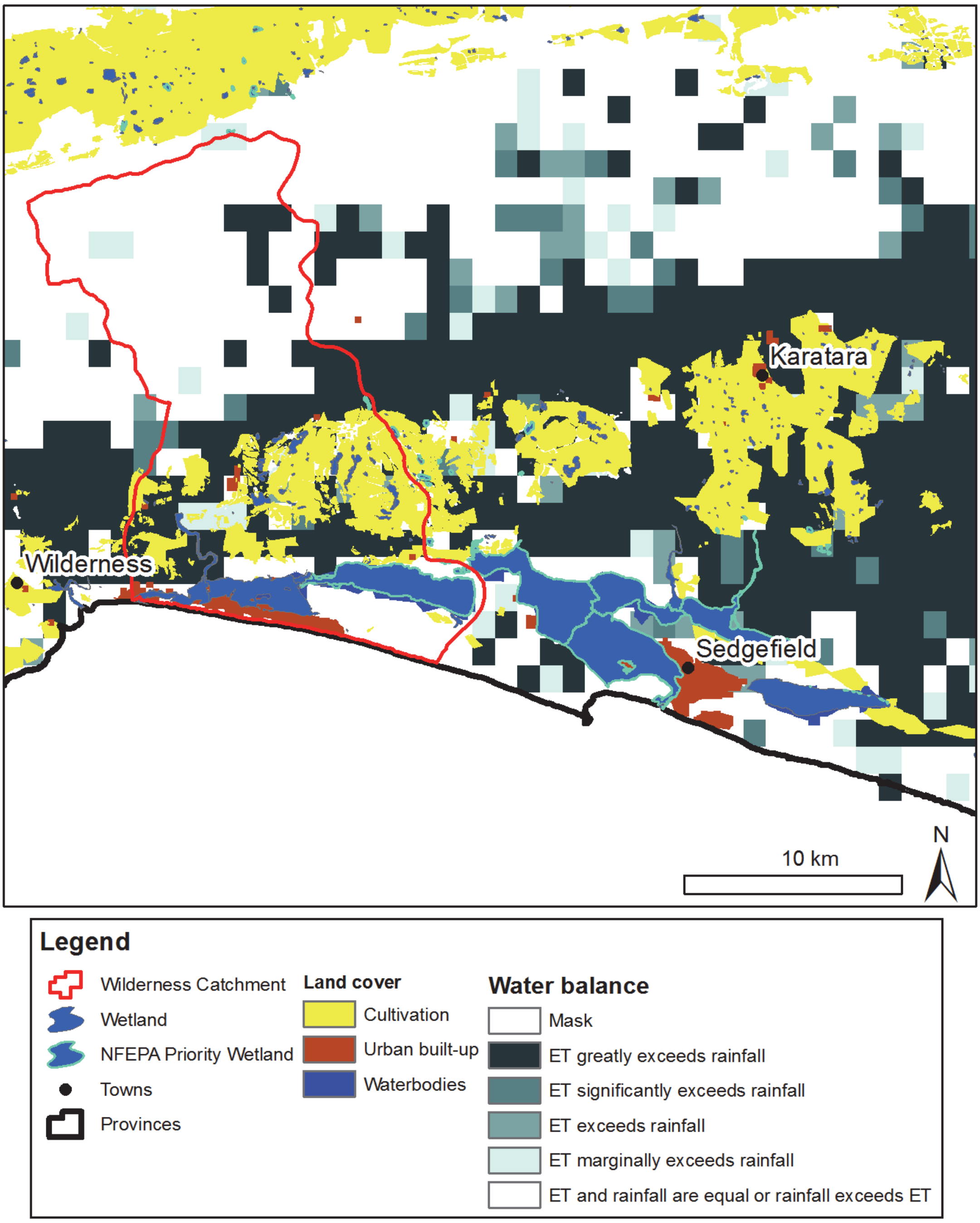


Figure 72 Water balance for the Wilderness case study site, showing where ET exceeds rainfall. The cultivated areas are shown in yellow.

Conclusions

Stable Isotopes provides an accurate tracer for groundwater in freshwater ecosystems. Stable isotopes proved the most useful in the Waterberg case study in order to identify groundwater discharge in the form of baseflow in the streams. Stable isotopes did not perform as successfully in the Wilderness case study as a result of the high evaporative signature of the lakes, although it was successful in identifying the groundwater within the aquifer.

The MODIS ET algorithm produced dubious results for the Wilderness case study with the annual ET estimates being far lower than what was expected. This is likely due to the MODIS algorithm and an incorrect landcover classification for the pixels in which the lakes are located. MODIS proved useful in detecting seasonal trends in evapotranspiration and where this is a lack of field collected data, can be used in water balance equations and hydrological models. Further research is being carried out by the CSIR to refine the MODIS algorithm for South Africa.

5 CONCLUSIONS

Management of water resources in a catchment scale depends on suitable catchment management strategies and tools which can explicitly handle all the hydrological processes within a catchment. Hydrological models have been used as tools in water resources management to inform decision making. The Pitman Model was applied in two different catchments, the GaMampa wetland (B71C) and the wetlands in the Alma region within the Mokolo river catchment.

The Hydrological modelling in the B71C sub-basin before the inclusion of the wetland sub-model yielded satisfactory results. The model simulated all the low flows well while most of the high flows were not well simulated, probably as a result of the limitations of the flow gauging structure. The inclusion of the wetland sub-model gave poor results, and the observed stream flow, especially the timing of the flows, could not be reproduced. The study thus concludes that the wetland sub-model of the Pitman model in its current form is inadequate for simulations in sub-basins were wetlands are an important part of the hydrology in those basins. The reservoir type conceptualisation of the wetland sub-model in the Pitman model may be adequate for large scale wetlands (Hughes et al., 2013) but is not sufficient for smaller scale wetlands type that are prevalent in the country. Attempts by Rhodes University to model some wetlands in the KwaZulu-Natal and Mpumalanga provinces using the same approach have also not been successful (Hughes, 2014, *pers comm*). The reservoir type approach allows for most of the water exchange between the stream and the wetland to occur through 'spillages' which are not necessarily the case in most wetlands where 'seepage' is the dominant process. This difference is significant in the way wetlands are represented in the model and the Pitman model does not currently represent this process properly. Hence, the failures observed in this simple exercise. The GaMampa wetland is a floodplain valley bottom and most of the water is held within the soil as opposed to being a reservoir that gets water and spills it after a particular threshold capacity has been reached. This then creates a challenge for the Pitman to model this type of wetland since their dominant physical processes are not properly represented in the model. This type of wetlands would require more explicit interaction between the soil store and the river, rather than the current filling and emptying sequence currently used. It is thus pleasant to note that the Institute for Water Research at Rhodes University has started a programme on understanding wetland processes and developing a better sub-model to represent them in the model (Hughes, 2014 *pers comm*).

Hydrological simulation in the Mokolo catchment before and after the inclusion of the wetland sub-model also yielded poor results. However, it is important to state that in the absence of hydrological data in the Mokolo catchment, it was difficult to estimate the wetland parameters (except for WA obtained in topographical maps), hence the use of a hypothetical wetland sub-model.

The interaction between the wetland and the groundwater store is also an area that still needs to be fully investigated and understood. The Pitman model clearly does not simulate this interaction well (Hughes et al., 2013).

The direction taken by this study to assess the incorporation of wetland process is a step in the right direction, especially in areas of the country where wetlands are an important hydrological process, not only in understanding but also managing the water resources of the relevant basins. Thus, a key finding of this study is that there is an insufficient representation of the underlying hydrological processes of wetlands in the previous of current water resources assessments. For a number of sub-basins, the right results are therefore generated for the wrong reasons.

While we could simulate the flows in a given sub-basin with reasonable accuracy, if we do not simulate the correct processes then the results are not good for decision making and management of the water resources. Some of changes in the parameters of the model when wetlands were incorporated are very informative, especially for the way models are used. The current trend in the country's water resources assessments is to ignore wetlands and use parameters to compensate for the inadequacy of the models to properly account for these important physical processes. This is not ideal and implies that using the results of the modelling would be difficult given that not all processes would have been adequately represented. The most significant effect is therefore that the management and conservation of wetlands and their incorporation into river basin and natural resources management strategies is less than optimal.

The adequacy of the Pitman model with respect to the simulation of wetlands needs to be evaluated. It is not clear at the moment whether modelling at a finer temporal scale (say on a daily time scale) would be more appropriate. One of the most overriding factors in answering this question would be to assess the purpose of the modelling exercise. If the purpose is for long term water resources assessment and management purposes at the basin scale, then the model would be appropriate. However, for the purposes of research and improving understanding of the functionality and place of wetlands in the catchment, a finer time scale would be preferable. The next logical step for this study would be to set up a model with a finer time step such as the ACRU and evaluate the results. With results from both models a more informed way forward can then be developed.

Hydrological models are an approximation of nature, thus accurate results depends on long term hydrological data with minimal missing data. Initial modelling in the Mokolo catchment was done with minimal data and knowledge of the hydrological processes of the wetlands. The findings can be improved by further studies which will investigate and conceptualise the key dominant hydrological processes of the wetlands, prior to modelling, in order to improve the accuracy of the results.

Stable Isotopes provides an accurate tracer for groundwater in freshwater ecosystems. Stable isotopes proved the most useful in the Waterberg case study in order to identify groundwater discharge in the form of baseflow in the streams. Stable isotopes did not perform as successfully in the Wilderness case study as a result of the high evaporative signature of the lakes, although it was successful in identifying the groundwater within the aquifer.

The MODIS ET algorithm produced dubious results for the Wilderness case study with the annual ET estimates being far lower than what was expected. This is likely due to the MODIS algorithm and an incorrect landcover classification for the pixels in which the lakes are located. MODIS proved useful in detecting seasonal trends in evapotranspiration and where this is a lack of field collected data, can be used in water balance equations and hydrological models. Further research is being carried out by the CSIR to refine the MODIS algorithm for South Africa.

6 RECOMMENDATIONS

A key finding of this study is that there is an insufficient representation of the underlying hydrological processes of wetlands in the previous of current water resources assessments. For a number of sub-basins, the right results are therefore generated for the wrong reasons.

The key recommendations are summarised in bullet form and discussed in detail below.

- Daily water flow measurements upstream and downstream of each (21 in total) conceptual hydrological flow model produced in this report
- Improved Evapotranspiration measurement results from Remote Sensing
- Plant water use measurements for wetland plant species
- Further collaboration with Rhodes University to refine the wetland component of the Pittman model based on field data for different wetland types
- Further research into the application of PyTOPKAPI and HYDRAS to model wetland processes
- Assessment of groundwater numerical models to model the processes of wetlands linked to regional groundwater
- Refinement of the definition of aquatic ecosystems in the Classification System
- Field Guidelines for the identification of the hydrological processes for wetlands in South Africa

The conceptual hydrological flow models are a step in the right direction and an improvement of previous attempts. The 21 conceptual hydrological flow models need to be validated against field data. Conceptual models are a simplification of reality but are only useful as long as what is happening in reality is being monitored. In order to do this, intensive monitoring projects need to take place that includes surface water, soil water and groundwater monitoring within a catchment, with sampling nodes upstream, downstream and within the wetlands. This should include water quantity and quality information, as well as rainfall and evapotranspiration measurements within the wetland. This monitoring can be linked the Present Ecological State (PES) and Ecological Importance Sensitivity (EIS) monitoring for Priority Wetlands, in particular in the Inkomati catchment.

The conceptual hydrological flow models could be expanded to include the soil moisture component, but this might add an unnecessarily complexity to the diagrams without sufficient science and monitoring to validate it. It is recommend that the conceptual flow models remain as they are and that emphasis be placed on the monitoring required to validate them.

Improved evapotranspiration measurements from Remote Sensing is needed. Research is currently being undertaken by the WRC and CSIR to downscale the MODIS ET data. MODIS has a resolution of 250 m by 250 m which is typically too large to measure wetland ET. Landsat 8 has a resolution of 30 m by 30 m would provide a suitable resolution for ET measurements based on the MODIS algorithm. This would need to be validated against field collected ET data. A key component of the water balance is the wetland plant species water use, in particular in the grasslands area. It is recommended that data on wetland species water use be collected in order to inform the hydrological modelling.

Further collaboration with Rhodes University is needed to update the wetland module for the Pittman model. It is recommended that the wetland component of the ACRU and SWAT models also be updated to accurately model wetland processes in the catchment, with an emphasis of application in integrated water resource management. This project is a step in the right direction by more research is needed to improve the wetland modules.

The potential capability of PyTOPKAPI to simulate most hydrological processes necessary to describe the drivers of the different HGM wetland types has been demonstrated as indicated above. Although the model is not designed specifically for wetlands, it can potentially be enhanced to cater for most hydrological processes to describe flows in the different HGM wetland types. The model therefore has the potential to become a tool which can be used for modelling flows related to wetland hydrological processes. This could be expanded to quantitative hydrological impact assessments on wetlands and for determining the water quantity component in Wetland Reserve Determination studies.

It is thus recommended that the application of the model to wetlands be investigated further with specific emphasis on amending modules and routines to enhance its capability in this regard. This should include the testing of the model performance against field data from different HGM wetland types.

Groundwater numerical models did not form part of the scope of this project. It is recommended that further work is done on how wetland processes are represented in groundwater models and how accurately the groundwater surface water interface is represented.

The definition of aquatic ecosystems in the Classification System is contentious in that it specifies a maximum depth of 0.5 m, which although might be suitable in high rainfall areas (with an elevated groundwater table) is problematic in semi-arid and arid areas. The definition needs to be looked at in order to avoid confusion and to include arid areas, in particular pans located in arid areas.

A key recommendation is the development of a field guideline manual to identify the 21 conceptual hydrological flow models. The guideline should focus on field examples of the 21 conceptual hydrological flow models as well as methods (vegetation, soil, invertebrates, isotopes) on how to determine the hydrological processes (rain fed, groundwater fed, interflow fed, perched groundwater fed, and surface water fed). This would be useful to the mining industry to assist EIA practitioners to identify the hydrological characteristics of the wetland and prevent the mines from having to rehabilitate the wetlands post mining because the hydrology was disrupted and altered during the mining process.

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APPENDIX:

CONCEPTUAL HYDROLOGICAL FLOW MODELS PER HYDROGEOMORPHIC WETLAND TYPE IN SOUTH AFRICA

Hillslope Seeps

<u>Hillslope Seepage – Perched Groundwater/Interflow</u>

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

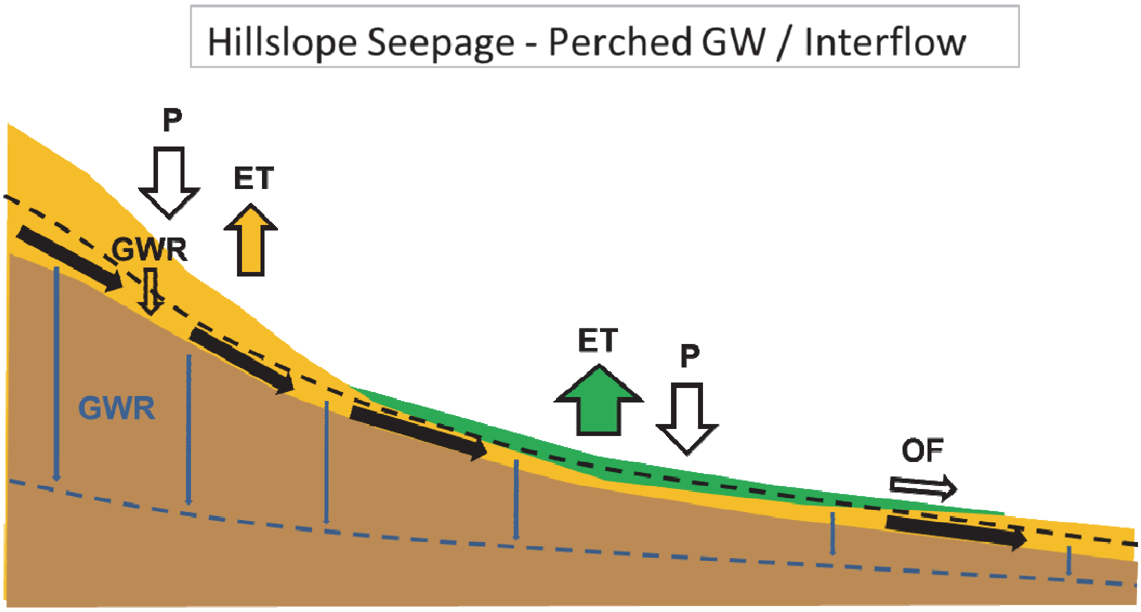


Figure 73 Conceptual flow model for the hillslope seep that this driven by perched groundwater or interflow.

The Hydrogeomorphic (HGM) type is a hillslope seepage wetland as shown in Figure 73. Perched groundwater (GW) which is typically situated in weathered rock or sand reaches the rooting zone (wetland soils) due to topographical drivers and changes in thickness of the aquifer along the hillslope. This thinning of the aquifer is typically found in midslopes. The regional GW level is not in contact with the wetland. Water inputs are mainly from rainfall and subsurface flow. Water losses occur in form of overland flow (sometimes linked to a drainage channel), Evapotranspiration (ET) and subsurface flow.

Hillslope Seepage – Regional Groundwater

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

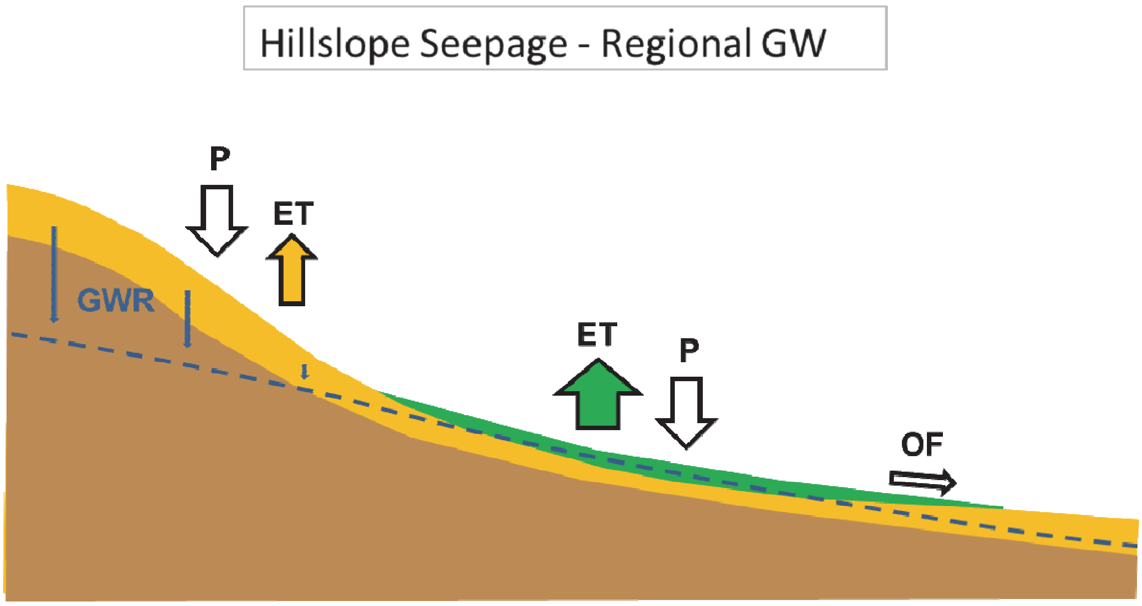


Figure 74 Conceptual flow model for a hillslope seep that is driven by the regional groundwater.

The HGM type is a hillslope seepage wetland shown in Figure 74. Water inputs are mainly from rainfall and groundwater. Water losses occur in form of overland flow, ET and subsurface flow. The regional groundwater is recharged by deep soils on the upslopes. Lower permeability conditions in the bedrock cause water to reach the wetland soils. This scenario usually results in wetter conditions in the wetland, often resulting in a permanently saturation wetting regime.

Hillslope Seepage – Rainfed

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

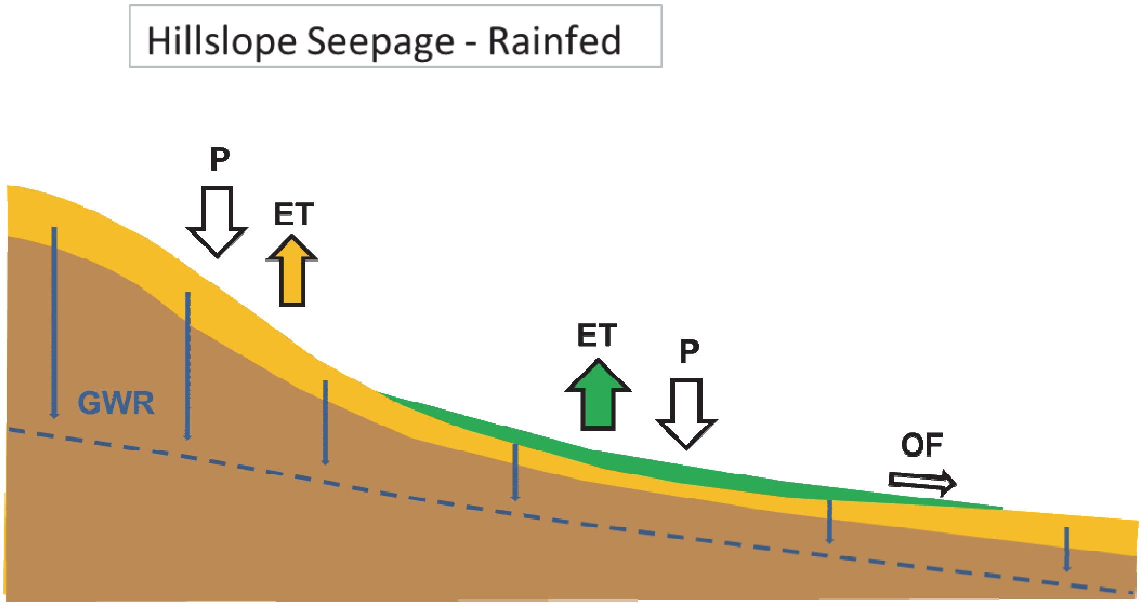


Figure 75 Conceptual flow model for a hillslope seep that is rainfall driven.

The example in Figure 75 does not fit into the standard HGM type classification. For the purpose of this study however we have called it a hillslope seepage wetland, although it is essentially not driven by seepage. Water inputs are from rainfall only. Water losses occur in form of overland flow, ET and drainage. Permeability of the weathered and unweathered materials does not allow water to reach the wetland soils. The wetland is only supplied by rainfall which results in an intermittent wetting regime or temporary system typically consisting of poor draining soils.

Hillslope Seep – Regional Groundwater (semi-confined)

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

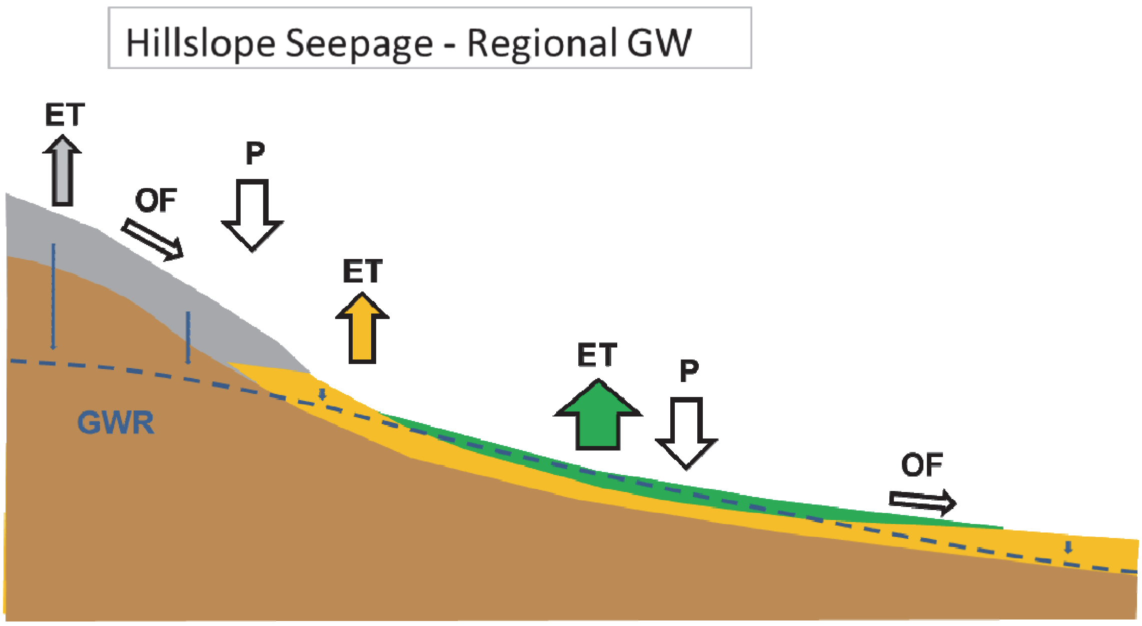


Figure 76 Conceptual flow model for a hillslope seep that is driven by semi-confined groundwater.

The HGM type is a hillslope seepage wetland shown in Figure 76. Water inputs are mainly from rainfall, groundwater and overland flow. Water losses occur in the form of overland flow, ET and subsurface flow. The wetland is supplied by regional GW which has a semi confined nature due to the low permeability of the material on the upslopes and crest. Recharge of the aquifer is low upslope and occurs on the crest.

<u>Hillslope Seep – Perched Groundwater/Interflow down gradient of low permeability material</u>

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

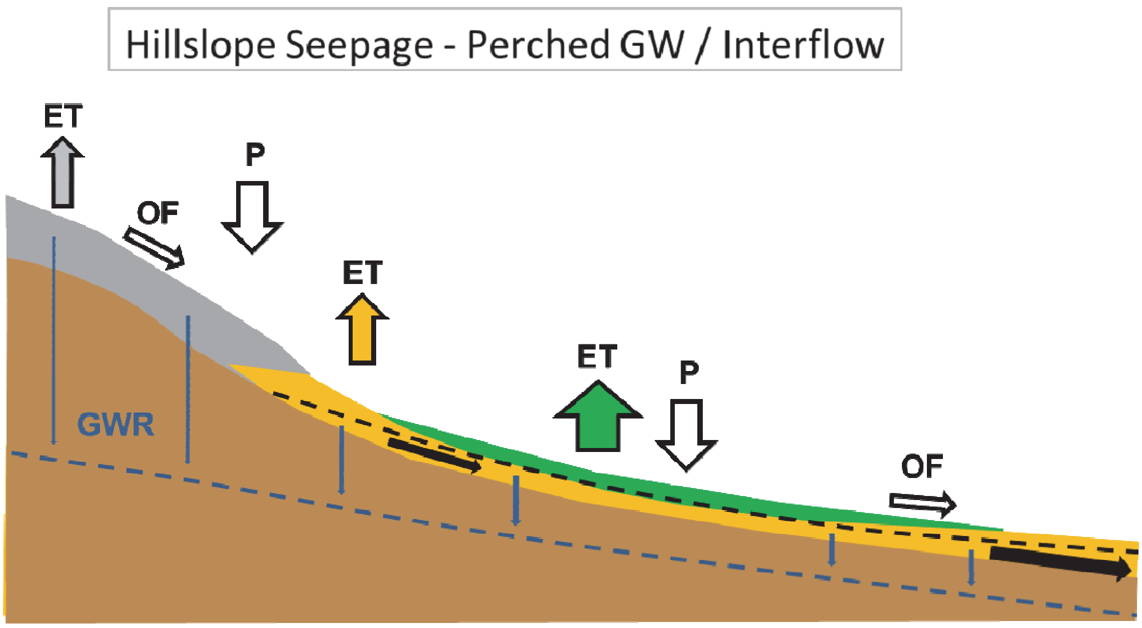


Figure 77 Conceptual flow model of a hillslope seep that is primarily driven by perched groundwater or interflow, and located down gradient of low permeability material.

The HGM type is a hillslope seepage wetland shown in Figure 77. Water inputs are mainly from rainfall, subsurface flow and overland flow. Water losses occur in the form of overland flow, ET and subsurface flow. The regional GW is not in contact with the wetland.

Hillslope Seep – Perched Groundwater/Spring

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

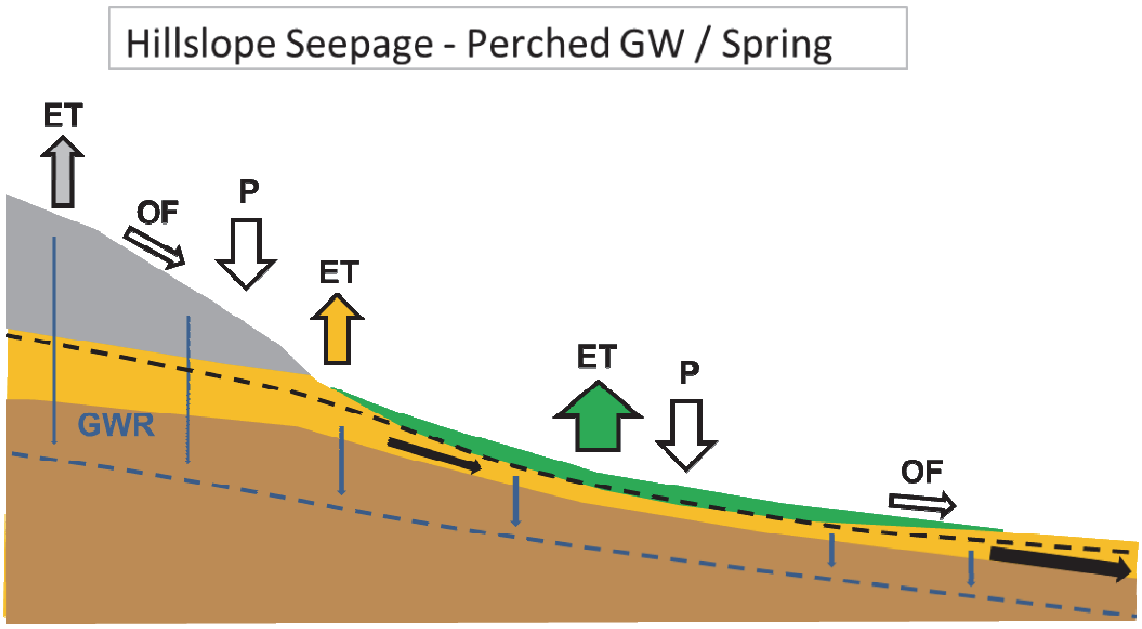


Figure 78 Conceptual flow model of hillslope seep driven by perched groundwater or a spring. The groundwater is confined beneath the confining low permeable material and discharges in the wetland soils.

The HGM type is a hillslope seepage wetland shown in Figure 78. Water inputs are mainly from rainfall, overland flow, subsurface flow and surface water from a spring. The groundwater travels beneath the confining low permeable material and discharges in the wetland soils. Water losses occur in form of overland flow, ET and subsurface flow. The perched aquifer shows confined characteristics below the lower more permeable material and becomes phreatic towards the wetland where it emerges in the form of a spring. The regional GW is not in contact with the wetland.

Unchannelled Valley-Bottom Wetland

Unchannelled Valley-Bottom Wetland – Perched and Regional Groundwater

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

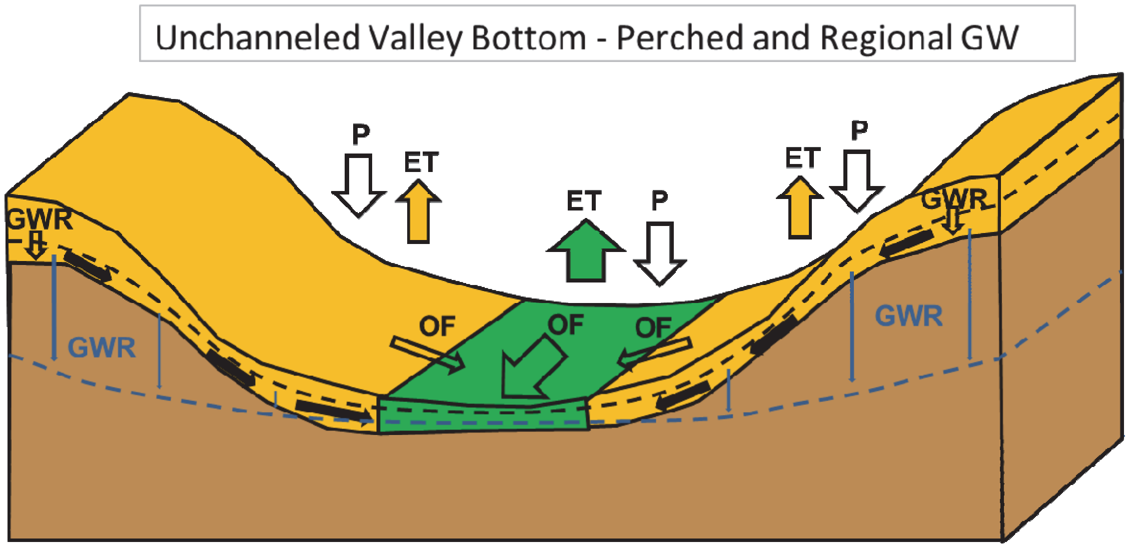


Figure 79 Conceptual flow model of a unchannelled valley-bottom wetland driven by perched groundwater and regional groundwater.

The HGM type is an unchannelled valley bottom wetland shown in Figure 79. Water inputs are mainly from overland flow, rainfall, subsurface flow and regional GW. Outflows are primary overland flow and ET. The lowest part of the wetland typically generates lateral overland flow while the higher lying parts generate flows parallel to the hillslopes.

Unchannelled Valley-Bottom – Regional Groundwater

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

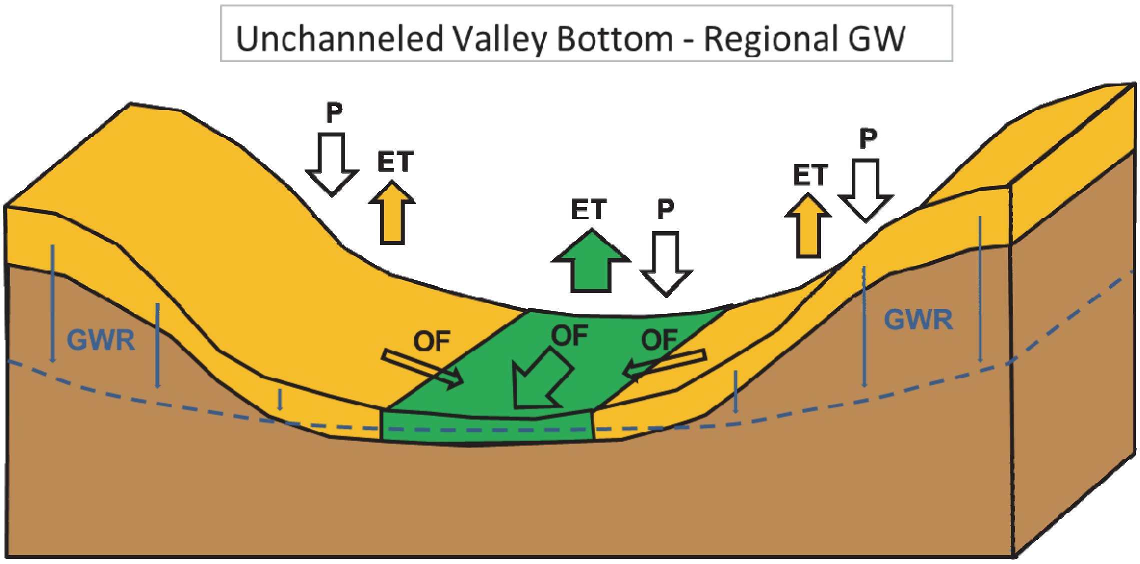


Figure 80 Conceptual flow model for an unchannelled valley-bottom wetland driven by regional groundwater.

The HGM type is an unchannelled valley bottom wetland shown in Figure 80. Water inputs are mainly from overland flow, rainfall and regional groundwater. Outflows are primarily overland flow and ET. The lowest part of the wetland typically generates lateral overland flow while the higher lying areas generate flows parallel to the hillslopes. The regional groundwater is in contact with the wetland.

Channelled Valley-Bottom

<u>Channelled Valley-Bottom – Regional Groundwater</u>

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

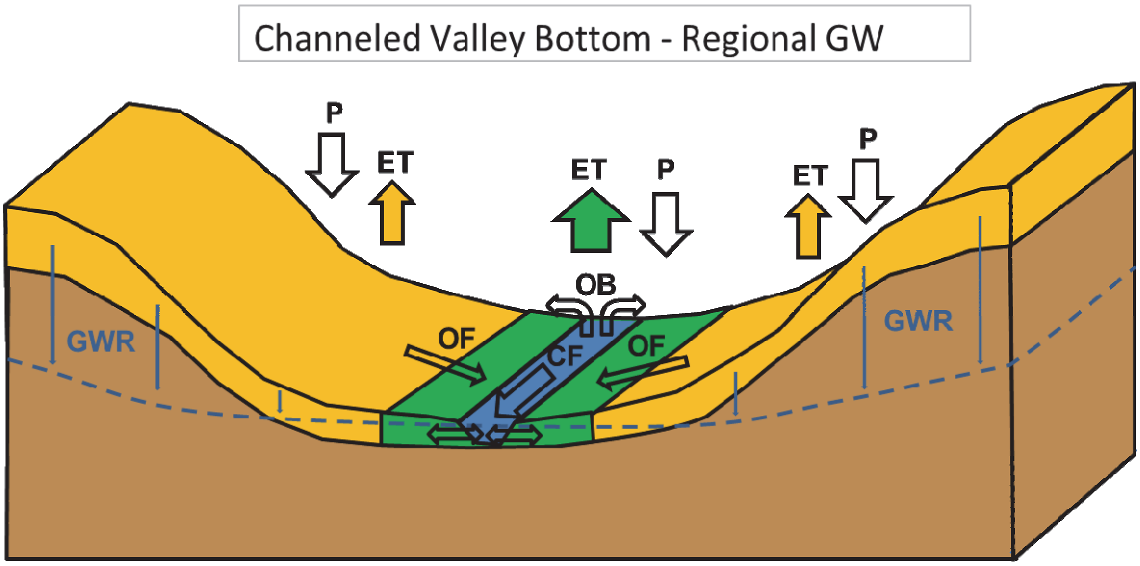


Figure 81 Conceptual flow model for a channelled valley-bottom wetland driven by regional groundwater.

The HGM type is a channelled valley bottom wetland shown in Figure 81. Water inputs are mainly from overland flow, rainfall, regional GW and overbank topping of the channel. Outflows are mainly overland flow, subsurface flows (towards the river) and ET. The regional GW is in contact with the wetland.

Channelled Valley-Bottom or Floodplain

<u>Channelled Valley-Bottom or Floodplain wetland – Regional Groundwater I</u>

LEGEND

GWR – Groundwater recharge
P – Precipitation
ET – Evapotranspiration
GWL – Groundwater level
OF – Overland flow
CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)
Bedrock with regional groundwater (relative low permeability)
Very low permeable material such as clay or low permeable rock
Wetland soils
Piezometric head of regional / deep groundwater
Piezometric head of perched / shallow groundwater

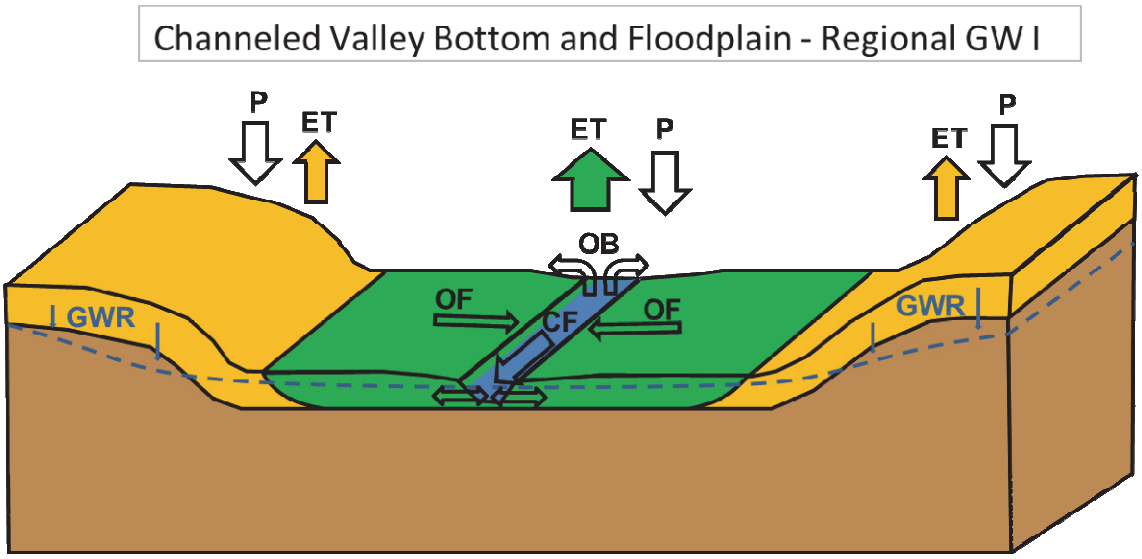


Figure 82 Conceptual flow model for channelled valley-bottom or floodplain wetland driven by regional groundwater with no fractured rock material present beneath the wetland.

The HGM type is a channelled valley bottom wetland or floodplain shown in Figure 82. Water inputs are mainly from overland flow, rainfall, regional GW and overbank topping of the channel. Outflows are mainly ET, overland flow and subsurface flows (towards the rivers). The regional groundwater is in contact with the wetland, however no fractured aquifer material is present below the wetland.

Channelled Valley-Bottom or Floodplain – Regional Groundwater II

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

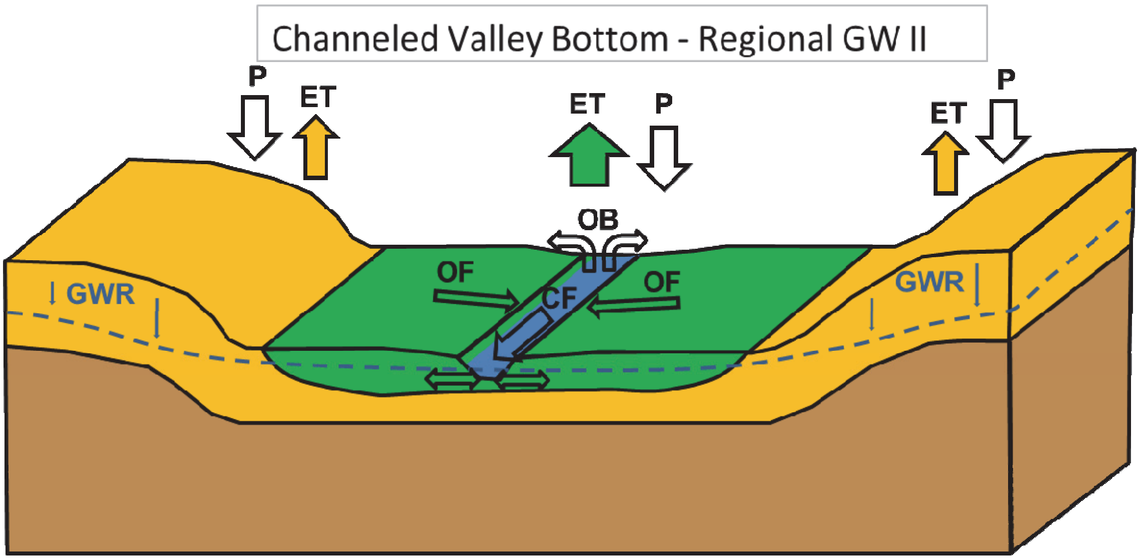


Figure 83 Conceptual flow model for a channelled valley-bottom or floodplain wetland characterised by regional groundwater and higher permeable material beneath the wetland soils.

The HGM type is a channelled valley bottom wetland or floodplain shown in Figure 83. Water inputs are mainly from overland flow, rainfall, regional and perched GW and overbank topping of the channel. Outflows are mainly ET, overland flow and subsurface flows (towards the rivers). The regional groundwater is in contact with the wetland and the wetland is underlain by higher permeability material.

Channelled Valley-Bottom or Floodplain – No Groundwater

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

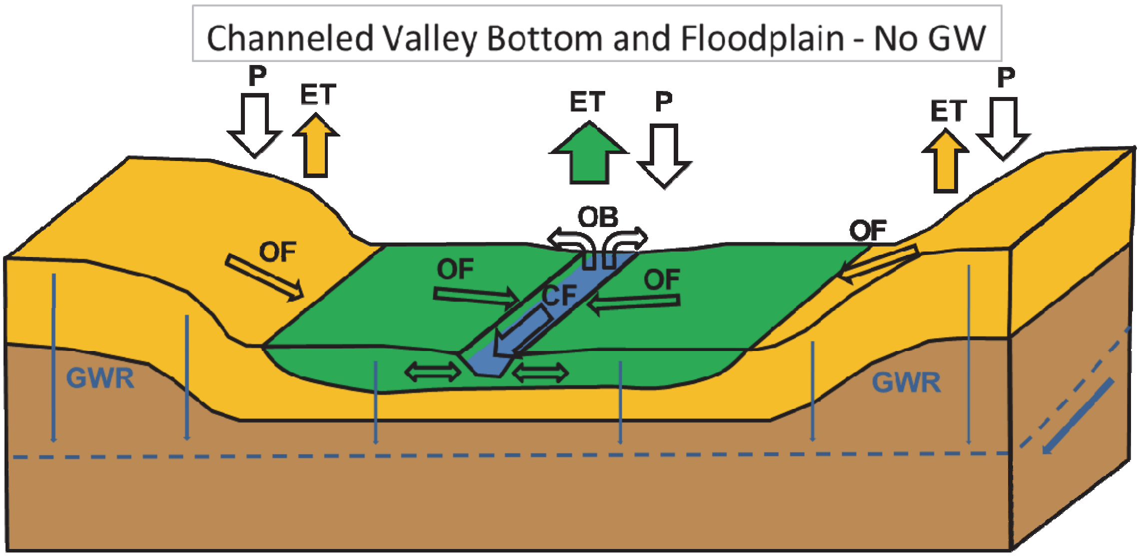


Figure 84 Conceptual flow model for channelled valley-bottom or floodplain wetlands with no groundwater connectivity.

The HGM type is a channelled valley bottom wetland or floodplain shown in Figure 84. Water inputs are mainly from overland flow, rainfall and overbank topping of the channel. Outflows are mainly ET, overland flow, subsurface flows (towards the rivers) and percolation to groundwater. The regional groundwater is not in contact with the wetland; however the wetland could discharge water into the regional groundwater.

Pans

Pan – Perched Groundwater and Leaking

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

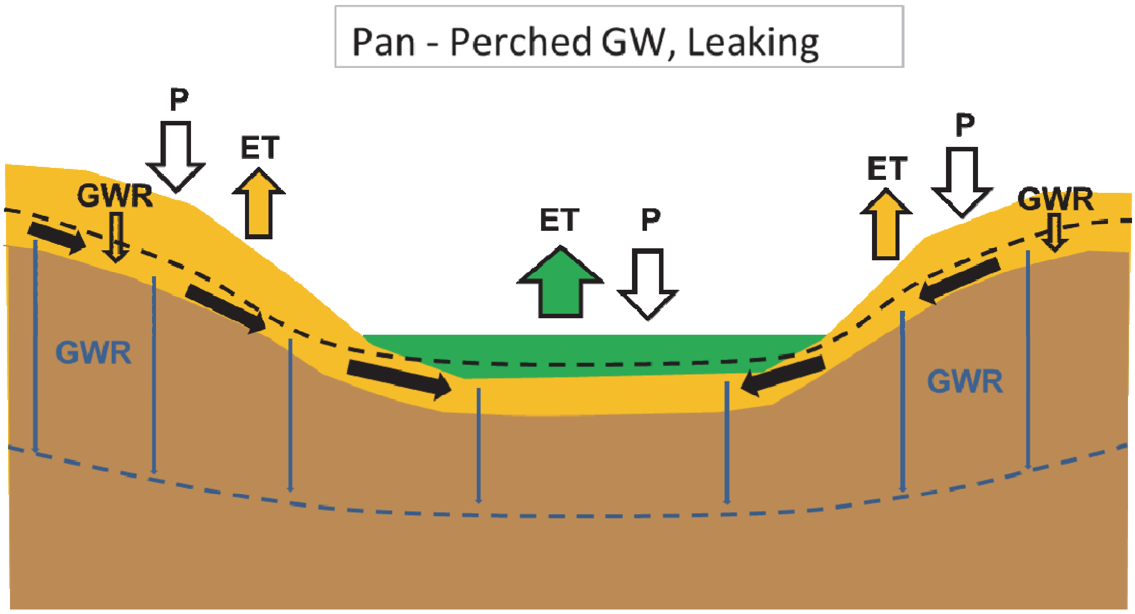


Figure 85 Conceptual flow model for a pan that is characterised by perched groundwater and leaking (discharging) into the regional groundwater beneath it.

The HGM type is a pan shown in Figure 85. Water inputs are mainly from subsurface flow and rainfall. Outflows are mainly ET and drainage into the lower permeability rock. The pan water level is a reflection of the shallow perched groundwater level. Such pans are typically seasonal to perennial depending on the size of the catchment, the permeability of the shallow perched groundwater and the degree of water percolating or discharging into the deeper aquifer.

Pan – Regional Groundwater

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

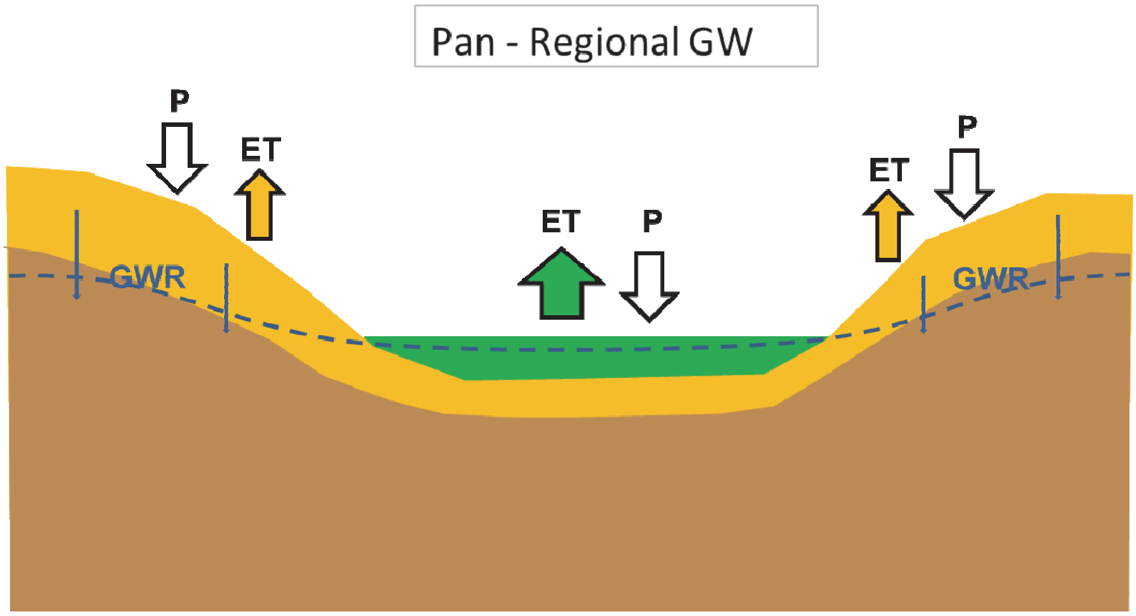


Figure 86 Conceptual flow model for a pan that is connected to the regional groundwater (not perched) as shown.

The HGM type is a pan shown in Figure 86. Water inputs are mainly from subsurface flow and rainfall. Outflows are mainly ET, and depending on the regional groundwater characteristics, to some degree, flows into the aquifer. The pan water level is a reflection of the regional groundwater level. Such pans are typically seasonal to perennial depending on the size of the catchment, the permeability of the aquifer and the regional setting of the regional groundwater flow characteristics.

Pan – Surface Water – Disconnected from the Regional Groundwater

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

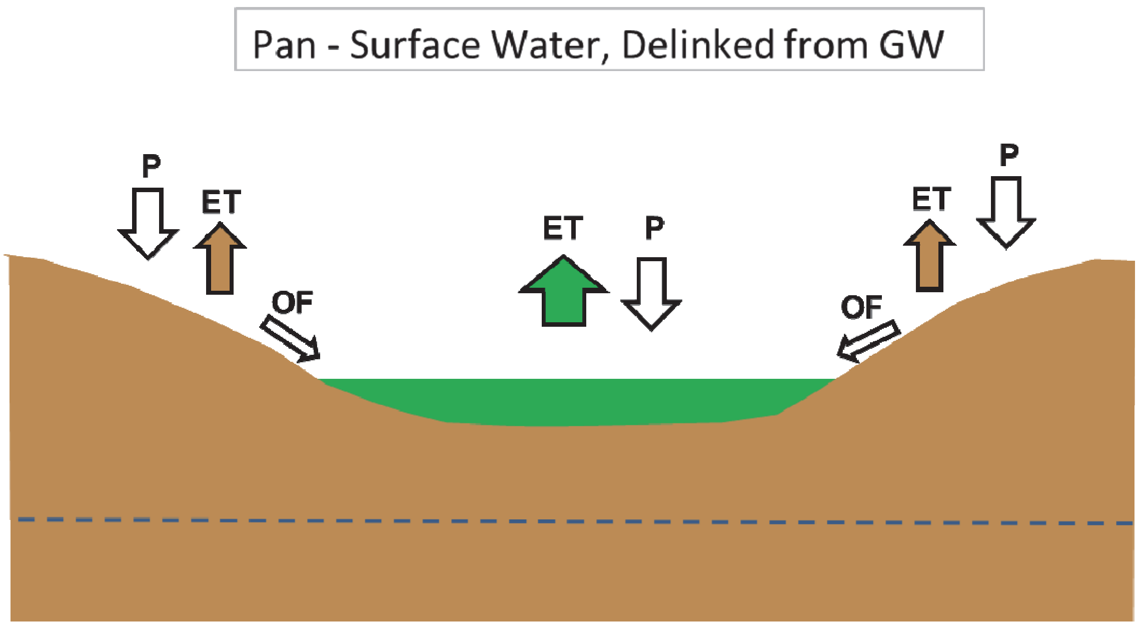


Figure 87 Conceptual flow model for a pan that is driven by surface water and disconnected or delinked from the regional groundwater.

The HGM type is a pan shown in Figure 87. Water inputs are mainly from overland flow and rainfall. Outflow is only ET. The pan water level is delinked from any groundwater. This type of pan is typically ephemeral to seasonal depending on the size of the catchment relative to the size of the pan basin.

Pan – Surface Water and Confined Groundwater

LEGEND

GWR – Groundwater recharge

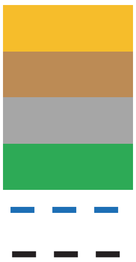
P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow



weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

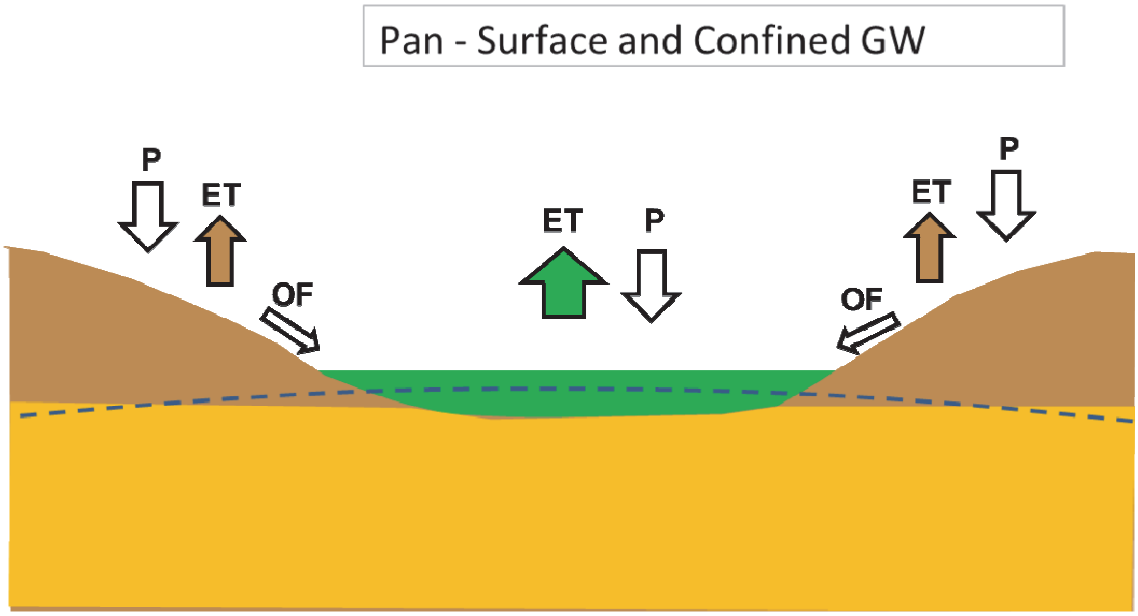


Figure 88 Conceptual flow model for a pan that is driven by surface water and confined groundwater.

The HGM type is a pan wetland shown in Figure 88. Water inputs are mainly from overland flow, rainfall and artesian groundwater. Outflow is only ET. The pan water level is a reflection of the confined aquifer piezometric head or pressure which would be higher than the regional groundwater level in the confined aquifer. Such pans are typically perennial. The regional groundwater is confined with exception of the pan basin where the water discharges at the surface.

Coastal Wetlands

<u>Coastal – Unconfined Primary Aquifer – Regional Groundwater</u>

LEGEND

GWR – Groundwater recharge
P – Precipitation
ET – Evapotranspiration
GWL – Groundwater level
OF – Overland flow
CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)
Bedrock with regional groundwater (relative low permeability)
Very low permeable material such as clay or low permeable rock
Wetland soils
Piezometric head of regional / deep groundwater
Piezometric head of perched / shallow groundwater

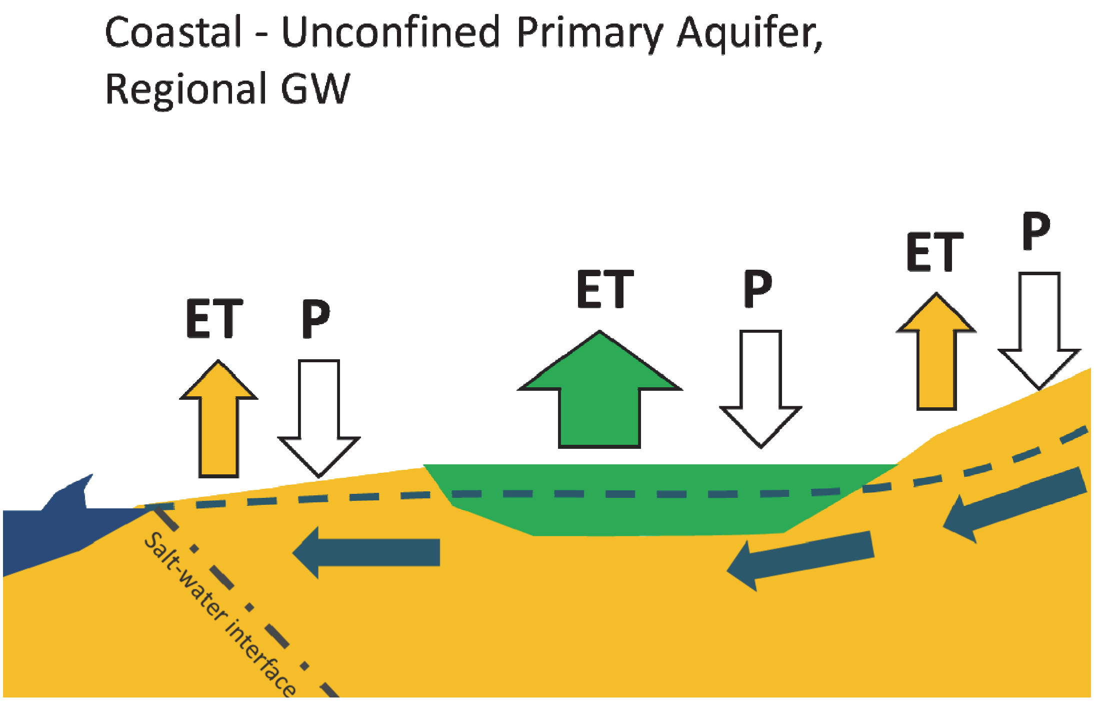


Figure 89 Conceptual flow model for a coastal wetland located on a primary (sandy) aquifer and connected to the regional groundwater table.

The coastal wetland is situated on a primary aquifer and connected to the regional groundwater table as shown in Figure 89. Water inputs are mainly from rainfall and regional groundwater. Outflow is ET and discharge into the regional groundwater water. The wetland water level is a reflection of the regional groundwater. Such wetlands are typically perennial. The water within the wetland typically reflects the regional groundwater unless significant evaporation takes place in which case it will be more saline.

Coastal – Unconfined Primary Aquifer – Perched Groundwater/Interflow

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

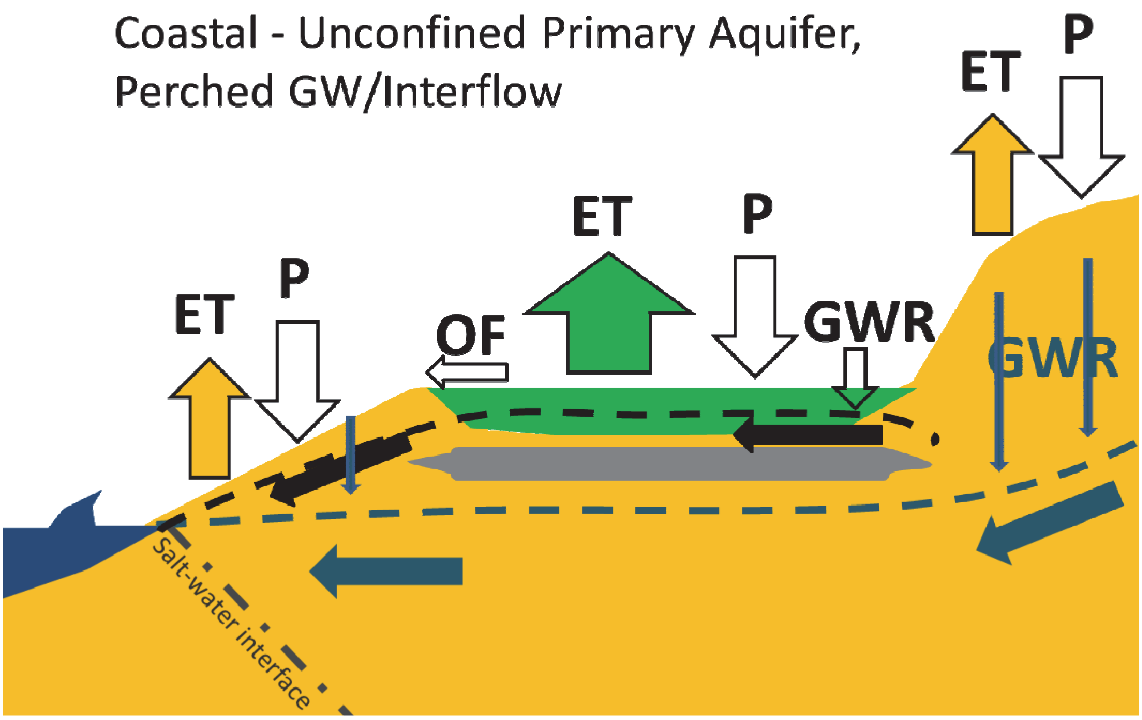


Figure 90 Conceptual flow model for a perched coastal wetland located on an impermeable, or lower permeability, layer and disconnected from the regional groundwater table.

The perched coastal wetland is located on an impermeable layer (e.g. clay) within a primary aquifer and disconnected from the regional groundwater table as shown in Figure 90. Water input is only from rainfall. Outflow is ET, overland flow, and discharge along the perched groundwater flow path. No recharge to the regional groundwater table occurs from the wetland because of the impermeable layer. Such wetlands may be ephemeral depending on the rainfall. The water within the wetland is typically characteristic of the rainfall and not the regional groundwater.

Coastal – Unconfined Primary Aquifer – Leaking Regional Groundwater

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

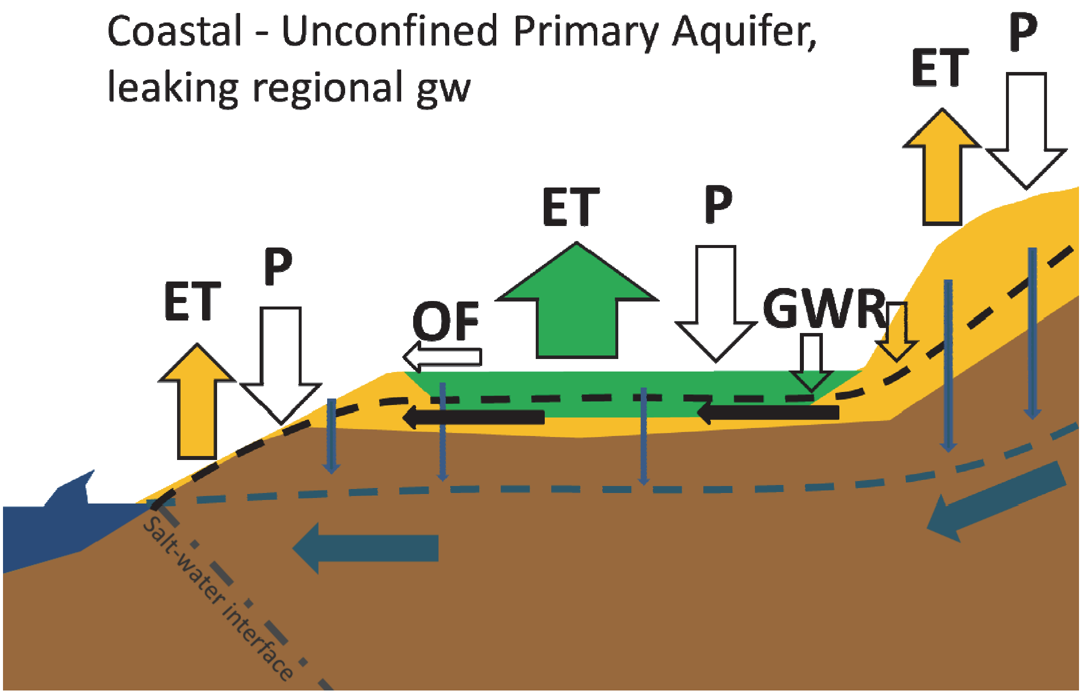


Figure 91 Conceptual flow model for a perched coastal wetland located in a primary aquifer and leaking into the regional groundwater.

The perched coastal wetland is located within a shallow primary aquifer on top of basement rock as shown in Figure 91. Water input is mainly from rainfall, overland flow and the shallow groundwater. Outflow is ET, overland flow, discharge along the perched/shallow groundwater flow path as well as discharge from the wetland into the regional groundwater table. Such wetlands may be permanent depending on the shallow groundwater. The water within the wetland will be characteristic of the shallow groundwater and not the regional groundwater, however the regional groundwater may reflect characteristics of the shallow groundwater depending on the amount of leaking that occurs.

Coastal – Confined aquifer delinked from regional groundwater

LEGEND

GWR – Groundwater recharge

P – Precipitation

ET – Evapotranspiration

GWL – Groundwater level

OF – Overland flow

CF – Channel flow

weathered zone / perched aquifer / soil interflow zone (relative high permeability)

Bedrock with regional groundwater (relative low permeability)

Very low permeable material such as clay or low permeable rock

Wetland soils

Piezometric head of regional / deep groundwater

Piezometric head of perched / shallow groundwater

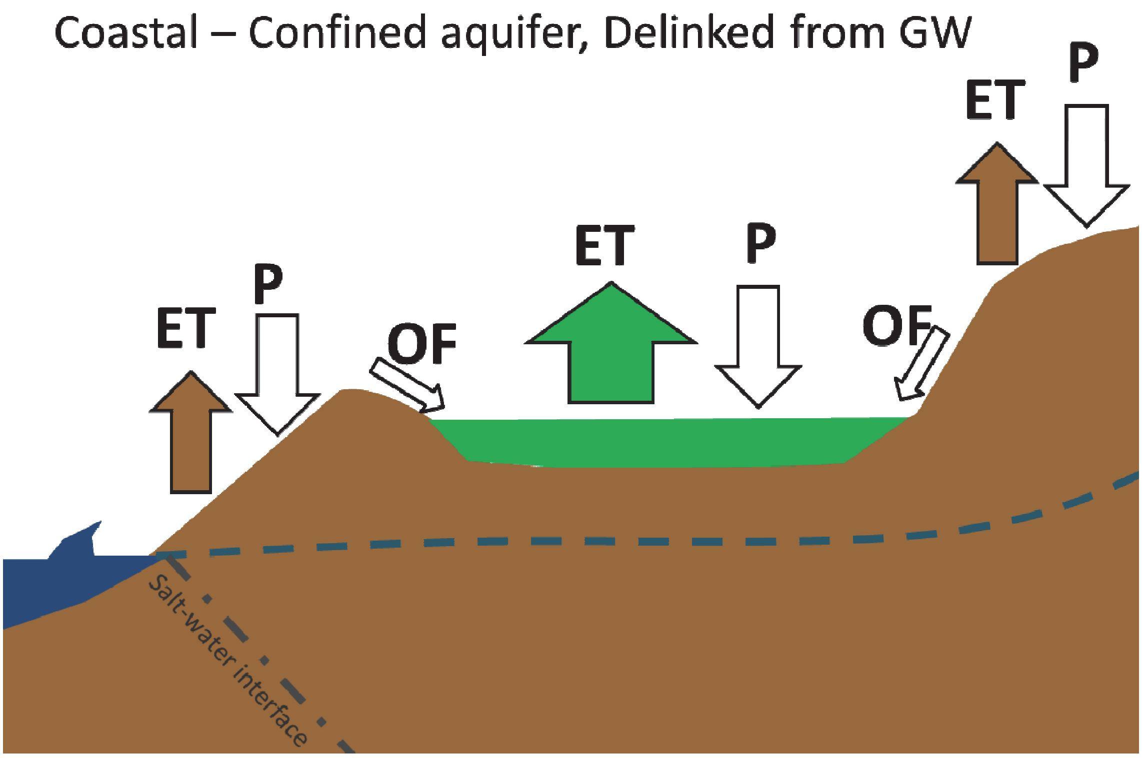


Figure 92 Conceptual flow model for a coastal wetland located on bedrock that is disconnected from the regional groundwater.

The coastal wetland is located on hard rock and disconnected from the regional groundwater table as shown in Figure 92. Inflow into the wetland is only from precipitation and overland flow. Outflow is only from evapotranspiration. The water within the wetland will be characteristic of the rainfall and not the regional groundwater.