Assessment of sustainable groundwater utilization with case studies from semi-arid Namibia

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ABSTRACT

The thesis addresses sustainability of groundwater utilization in arid and semi-arid regions of Namibia. Recharge in this hydrogeological setting occurs as discrete events to aquifers that are bounded in extent. Case studies involving fractured hardrock and alluvial aquifers with aquifer-ephemeral river interaction were considered.

The nature of recharge to arid region bounded aquifers was explored. In arid region aquifers, groundwater storage is depleted during extended dry periods due to pumping and natural discharge. Steady state conditions are rarely achieved. With lowering of the water table, evapotranspiration is reduced thus decreasing aquifer discharge. However, depletion of ephemeral river flow is the primary source of water to boreholes. Physical constraints such as river bed and aquifer hydraulic properties set a limit to the degree of natural replenishment possible during flow events.

An approach to assessing sustainable yield of a fractured rock aquifer associated with ephemeral river flow is discussed using a case study from rural semi-arid Namibia. Limited data required the simulation results to be verified against geological and hydrogeological constraints. The aquifer's gain in storage is estimated through numerical simulation. It provides a basis for groundwater scheme management that rely on limited data in semi-arid conditions in sub-Saharan Africa.

Aspects related to ephemeral river flow and groundwater recharge to strip alluvial aquifers was addressed in the second case study. The processes controlling infiltration, significance of surface water and groundwater losses, and possible artificial recharge options were investigated through numerical simulation. It was concluded that recharge processes in arid alluvial aquifers differ significantly from those in humid systems. Conjunctive use of surface and groundwater resources require artificial augmentation of aquifer recharge due to constrains in natural infiltration rates. The study provides a reference for sustainable management of alluvial aquifer systems in similar regions.

It is seen from the study that high rates of groundwater exploitation deplete surface water resources needed downstream while failure to capture surface flow during flood events cause loss of potential recharge. It is concluded that as water demand in Namibia increases, basin wide combined surface water and groundwater resource evaluation and management have become a necessity.

KEYWORDS

Arid region

Artificial recharge

Ephemeral rivers

Episodic recharge

Groundwater

Groundwater flow modelling

Namibia

Semiarid regions

Surface water

Sustainable yield

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Department of Water Affairs and Forestry, Namibia is gratefully acknowledged for providing valuable past reports, hydrological and hydrogeological monitoring data and opportunity to work on a Namibian ephemeral river. Namib Hydrosearch assisted through flexible work hours, much needed help during field work and logistical assistance. Stefaans Gaeseb and Alice Kaukuetu of Namib Hydrosearch are thanked for their help. Mandy Naidoo, Caroline Barnard and Colleen Brand offered administration and logistical help at the University.

I wish to thank my wife Swapna Sharma for her encouragement and efforts in keeping things going during this long period. Her support was key in completing the study. Our children Abhinab and Nirab are thanked for their understanding and patience. Enthusiastic support from Sophie Simmonds and Glynis Humphrey are gratefully acknowledged.

Declaration

I declare that *Assessment of sustainable groundwater utilization with case studies from semi-arid Namibia* is my own work, that it has not been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged as complete references.

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Chapter 1: INTRODUCTION

Namibia through history has been a sparsely populated arid country where human settlements have been only possible in places close to perennial rivers and shallow groundwater sources. The development of groundwater since the early 1900s made vast tracts of desert savanna available for commercial livestock farming (DWAF, 2012; IWRM Plan Joint Venture Namibia, 2010). During colonial times, scale of livestock farming increased primarily on the basis of establishment of groundwater sources. Since independence, the number of rural and bulk water supply schemes increased many times, developed with the aim to meet the water demand of the entire country's population, mining and agricultural needs. Currently more than seventy percent of the rural population are dependent on groundwater. Figure 1-1 shows aquifer types and surface water dams together with rural population distribution (villages and commercial farms) of Namibia. Dams and higher potential aquifers are being used for urban areas while water demand for rural and farming areas is largely met from smaller groundwater schemes. In addition, several key urban areas including the capital city are partly supplied from groundwater.

While large scale porous and hardrock aquifers such as the Stampriet Artesian Basin (Pacific Consultant International, 2002), Otavi Mountainland Aquifer (Schmidt and Ploetner, 2000) and Windhoek Aquifer (CSIR, 2004) have been studied in considerable detail, smaller schemes serving isolated populations are less understood in terms of recharge and sustainability, and are often susceptible to overexploitation and failure. Most drilling through rural water supply schemes are carried out in response to drought under emergency water supply projects. Information collected and consequently management of the resource is poor. On the other hand, regional scale groundwater resources estimates are sought by planners and policy makers for extensive areas with secluded groundwater occurrences in semi-arid hardrock terrain. Climate change stresses add to the uncertainty in sustainable exploitation of groundwater.

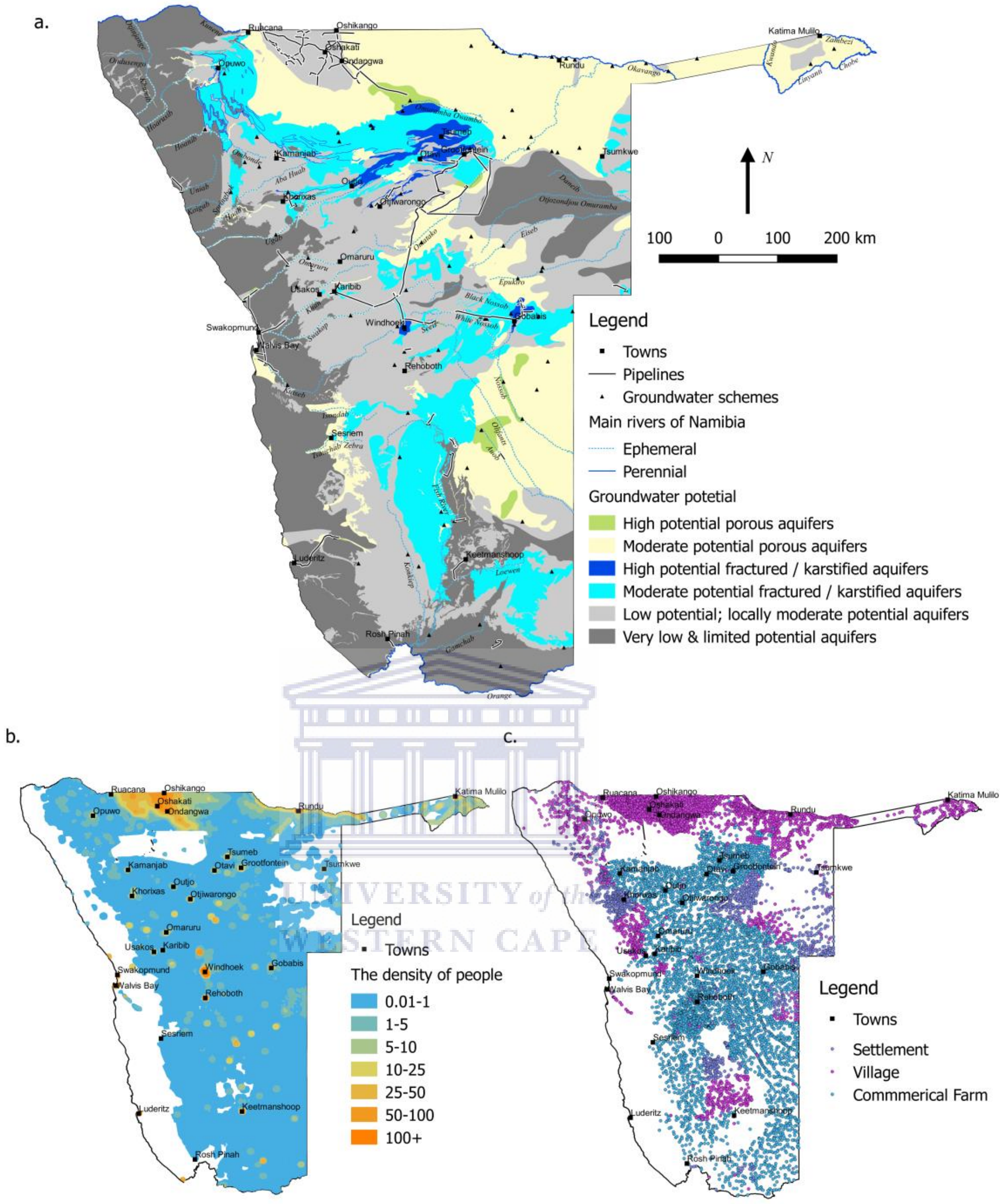

Figure 1-1: Map of groundwater potential map of Namibia (Christelis and Struckmeier, 2001) shown together with b. population density and c. localities as indication of water demand and water requirement in the country (data from Namibia Statistical Agency, 2016)

Water demand has increased with population and economic activity and the country wide projected water demand linear increase rate is 20 million cubic meter (MCM)/year (Figure 1-2). 44% of the water demand was met from groundwater sources in 2009. Assuming a similar fraction of groundwater use, the projected groundwater demand will be 257 MCM/ year by 2020. To answer if future water demand could be met from groundwater sustainably, assessment in a more fundamental level is needed. The concept of sustainable yield being applied so far to arid region in Namibia aquifers needs further examination.

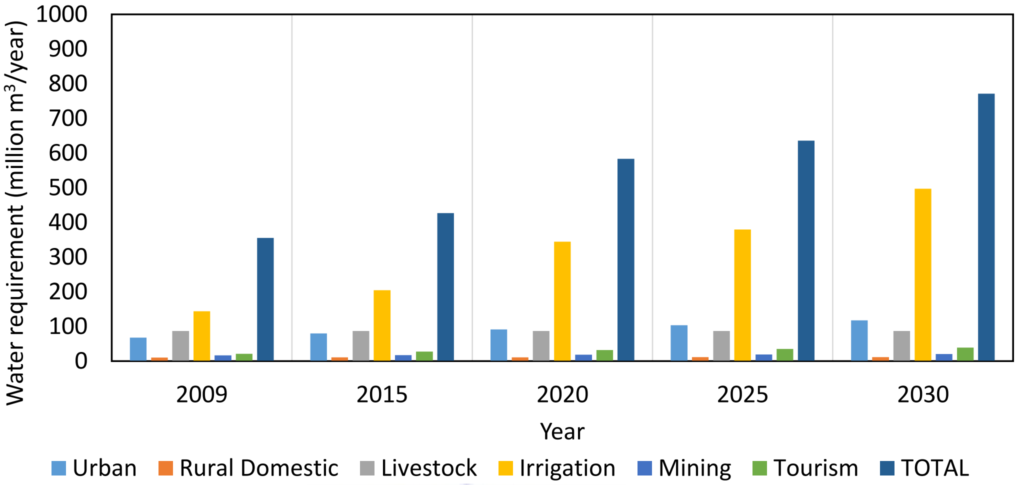

Figure 1-2: Projected water demand for main sectors in Namibia (data from IWRM Plan Joint Venture Namibia, 2010)

1.1 OVERVIEW OF GROUNDWATER IN NAMIBIA

Aquifers in Namibia can be classified at a fundamental level into porous and fractured hardrock types (Figure 1-1). Porous aquifer could be further classified based on its size into the following types

a) aquifers of regional extent often with multiple aquifer units such as the Stampriet Aquifer in the east of the country and the lower Kalahari Aquifers,

b) porous aquifers with limited lateral continuity such as the upper Kalahari aquifer in the northern part of the country and

c) the alluvial strip aquifers associated with ephemeral rivers.

Fractured hardrock aquifers could be

a) extensively fractured bedrock aquifers that can be treated as equivalent porous medium such as the Windhoek Aquifer,

b) fractured and karstified large scale carbonate aquifers such as the Otavi Mountainland Aquifer,

c) fractured and karstified thin carbonate rock aquifers (e. g. Otjiwarongo marble aquifers) and

d) bedrock fractured aquifers of limited extent in basement rocks.

Each aquifer type has its importance and supports different populations, economic activities and ecosystems. The hydrogeological map of Namibia and accompanying publication (Christelis and Struckmeier, 2001) provide description of the aquifer types. The distribution of aquifers in the country in terms of its potential is shown in Figure 1-1.

The high potential aquifers have been relatively well studied and are developed to supply urban populations or economic activities. Fractured rock aquifers (carbonate band aquifers and fractured rock aquifers) and alluvial strip aquifers are of importance in the central, southern and western parts of the country, particularly to isolated communities where other water resources are limited. The fractured aquifers in basement rock have thin or no regolith cover and limited storage in the surrounding country rock. Ephemeral stream alluvium aquifers range from small (e.g. Seeis River Alluvial Aquifer) to large scale such as the Kuiseb River Alluvial Aquifer. The aquifers are dependent on infiltration during seasonal flow in the rivers. Management of these bounded aquifers poses challenges as sustainable yield is difficult to estimate and is the focus of the current study.

1.2 CLIMATIC CONTROLS ON WATER RESOURCES

Perennial rivers are located at the northern and southern borders of Namibia. These river catchments extend over neighbouring countries with higher average rainfall. Perennial rivers have groundwater resource in associated porous aquifers (e.g. Kalahari sediments) that are recharged through river bed infiltration. In the south, the Orange River flows on hardrock terrain and groundwater resources are limited.

Rivers originating in Namibia are ephemeral. Average rainfall distribution and pan evaporation rates in Namibia are shown in Figure 1-3 (a. and b.). Evaporation exceeds precipitation rate and net water deficit conditions prevails in the country. The ephemeral rivers can be grouped as west, east and south flowing (Figure 1-3, c.) and have their headwater in central parts of Namibia that receive relatively higher precipitation. Precipitation rate decreases to the west and south with concurrent increase in evaporation rate (Figure 1-3, b.). The runoff potential of Namibian rivers is therefore low and runoff decreases downstream in contrast to humid region rivers due to lower precipitation and losses due to evaporation, evapotranspiration and infiltration (Jacobson and Jacobson, 2012). The Namibian unit runoff map (Figure 1-4) illustrates the conditions and show downstream decrease of runoff potential in ephemeral rivers. South flowing rivers are mostly endoreic with the exception of the Fish River.

Runoff generation in the headwaters are by infiltration excess or Hortonian flow. Infiltration rates are low as soil and vegetation cover is thin. Surface runoff is initiated rapidly in response to intense summer rain. Downstream river reaches and basement fractured rock aquifer are recharged through infiltration from surface runoff which is estimated to be about 15% of mean annual rainfall. Of this, 14% is lost to evaporation and evapotranspiration (IWRM Plan Joint Venture Namibia, 2010) resulting in 1% effective recharge. Total loss of precipitation to evaporation and evapotranspiration is estimated as 83%. Water resources associated with ephemeral rivers and in alluvial aquifers are given in Table 1-1 where surface water and groundwater resources in water basin scale are compared. Surface water resources play an important part where rivers have been dammed (e.g. Oanob, von Bach, and Omatako Dams).

1.3 SUSTAINABLE YIELD

Walton and McLane (2012) define groundwater supply sustainable yield 'as how much water can be withdrawn from an aquifer system, where and for how long, with acceptable physical, economical, environmental, social, cultural, institutional and legal consequences'. The concept of sustainable yield hence takes into account other existing water demands and possible environmental impacts in assessing available water for use (Todd and Mays, 2005; Healy, 2010).

Table 1-1: Surface and groundwater resources according to water management basins of Namibia (modified after IWRM Plan Joint Venture Namibia, 2010)

Basin	Associated main river type	Water resources potential (MCM/year)			Demand: Surplus / Deficit (MCM/year)	
		Surface	Ground	Groundwater use	2008	2030
Omaruru-Swakop	Ephemeral	41.0	29.5	42%	19.9	-4.4
Kuiseb	Ephemeral	9.8	8.0	45%	8.4	4.2
Nossob-Auob	Ephemeral	8.0	32.5	80%	9.4	5.6
Ugab-Huab	Ephemeral	7.5	19.8	73%	12.6	5.3
Eiseb-Epukiro	Ephemeral	0.0	20.0	100%	11.4	8.8
Tsondab-Koichab	Ephemeral	0.0	1.8	100%	-2.0	-3.3
Orange-Fish	Perennial, ephemeral	379.9	160.0	30%	465.1	420.3
Kunene	Perennial	31.5	26.2	45%	47.7	46.5
Cuvelai-Etosha	Perennial, ephemeral	180.0	24.0	12%	140.3	118.4
Okavango-Omatako	Perennial	250.0	29.6	11%	221.5	64.5
Zambezi-Kwando-Linyanti	Perennial	4,000.0	10.0	0%	3,999.7	3,830.4

Impacts could be unacceptable level of storage depletion threatening existing supply, reduction of discharge to groundwater and surface water bodies, inducing pollution, or land subsidence. The sustainable yield is not a fixed value but is a function of climatic, environmental and management input with time. This differs from the now discarded 'safe yield' concept where the average basin recharge is equated to the total abstractable volume (Todd and Mays, 2005; Bredehoeft, 2002; Alley and Leaky, 2004).

Aquifers bounded in space and input (precipitation) has five supply components (Walton and McLane 2012) that are exploited to the extent allowed by hydrological or environmental conditions. These are storage, discharge to and recharge from surface water bodies, evapotranspiration, rejected recharge and capture of groundwater from adjacent basins.

Commonly, assessment of sustainable yield relies on hydraulic tests and monitoring of groundwater levels and abstraction. Exclusion of the role of other components including surface water flow precludes a full understanding of sustainability. Lack of understanding of the total hydrological system and inappropriate management lead to groundwater mining and environmental impacts.

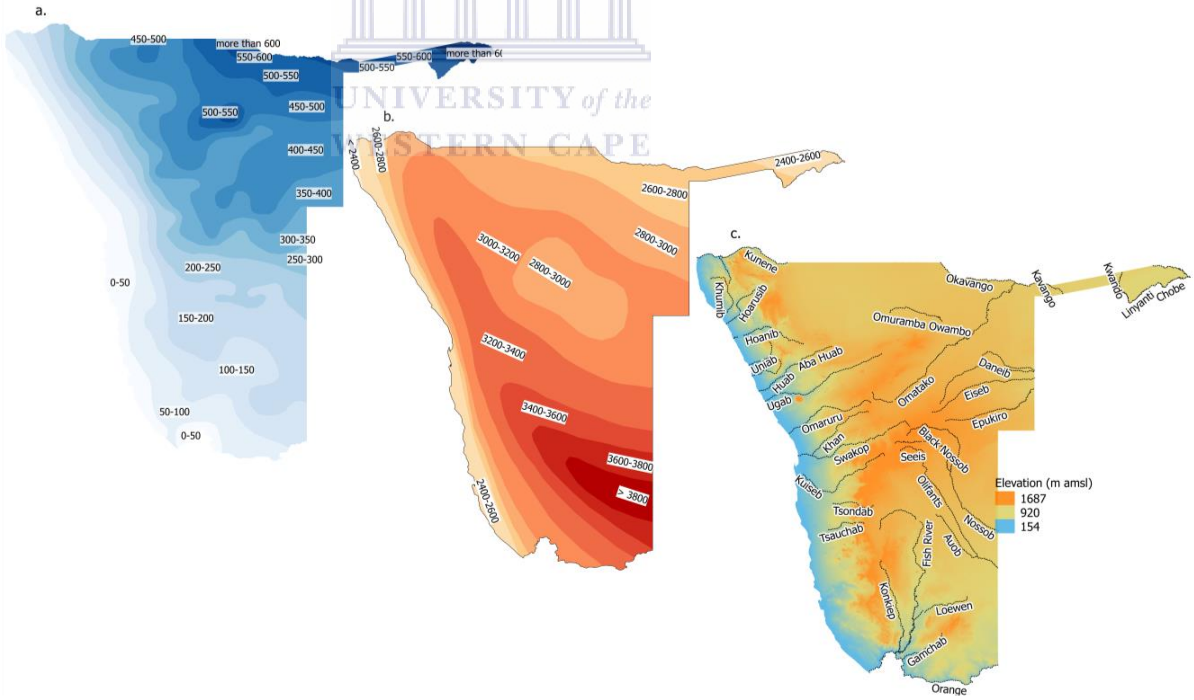

Figure 1-3: a) Average annual rainfall (mm/year), b) average annual evaporation rate (mm/year) and c) main rivers of Namibia (climate and river data from Mandelson et al., 2002; elevation data from www2.jpl.nasa.gov/srtm/)

1.4 THESIS OBJECTIVE AND RESEARCH APPROACH

Regional scale sustainable groundwater resource estimates are sought by planners to guide development strategies. The nature of resource in arid regions of Namibia allows mostly local scale assessments as aquifers have limited spatial extent. The understanding gained through local scale studies however could in the future lead to concepts that can be generalised and applied in a regional scale.

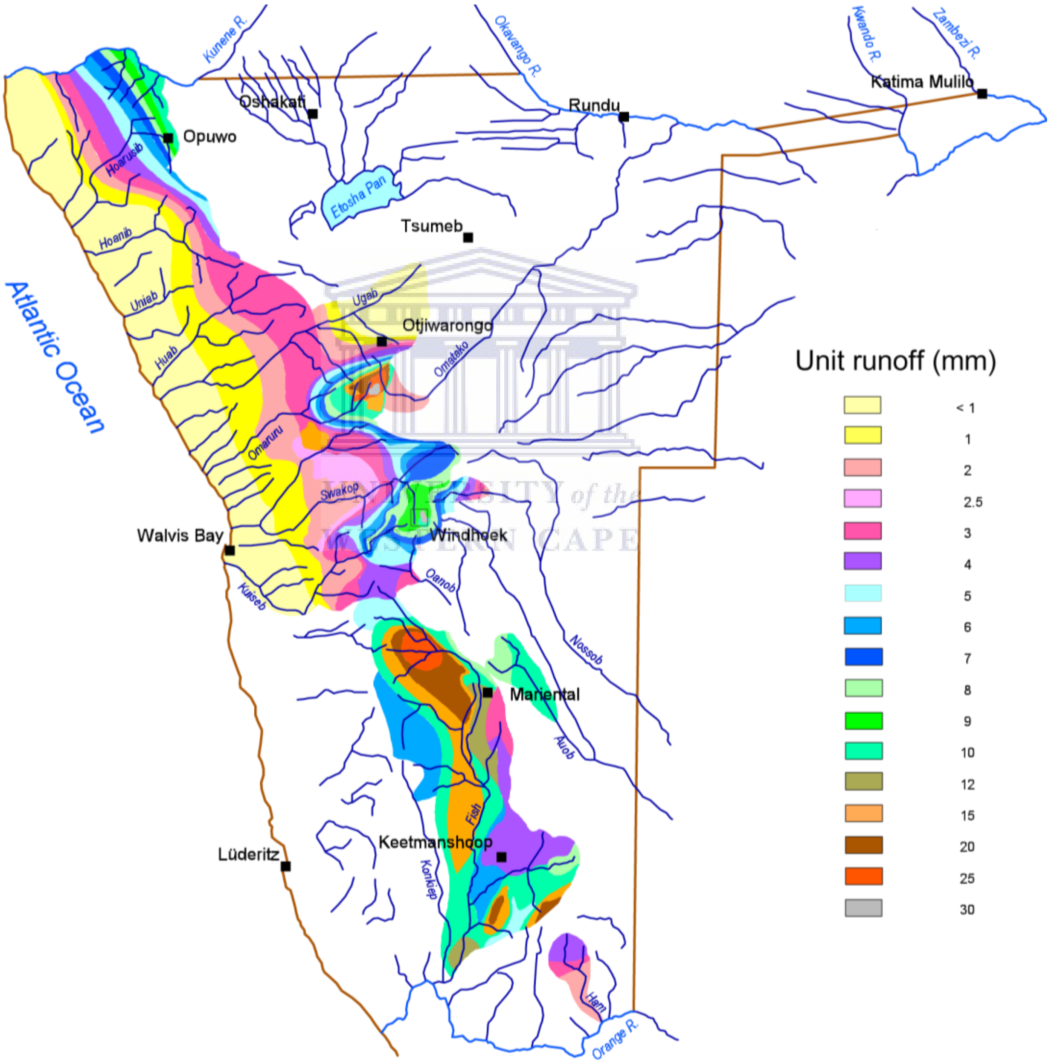

Figure 1-4: Unit runoff map of Namibia (Chirell and Crerar, 1992)

The importance of quantitative groundwater assessments of individual aquifers lies in dealing with spatial and temporal variability of arid region recharge and complexity of the aquifer boundary conditions. These assessments form the basis of forecasting responses to future change in stresses some of which are imminent with increasing water demand and changing rainfall pattern due to climate change.

The objective of the study is to explore approaches for sustainable groundwater utilization of medium to small schemes using data that is routinely collected and innovative use of existing analytical and numerical tools. The basis for understanding episodic recharge through water balance in semi-arid region aquifers is explored through concepts hereto applied to humid or sub-humid climate. Source of groundwater to boreholes is initially theoretically analysed using hypothetical numerical flow models followed by case studies with implications for assessment of sustainable yield.

Two separate types of semi-arid region aquifers have been selected as case studies so as to enhance the understanding of the recharge mechanism. Estimates in fractured aquifer and in alluvial strip aquifers were carried out. Field based studies, existing information and long term monitoring data were utilised for the work. The dynamics of surface water flow in ephemeral streams and relationship to recharge in fractured as alluvial aquifers were examined. The approach used data and geological constraints to define hydrogeological conceptual models that examined the recharge process and available resource.

Given the two key characteristics of aquifers in semi-arid hardrock terrain – recharge predominantly through ephemeral streambed leakage and discharge of groundwater mainly through evapotranspiration - combined management of surface water and groundwater resource is addressed with the aim of maintaining an exploitation rate that ensures perennial yield without adversely affecting dependent ecology.

In summary the main research questions addressed in the thesis are

- Understanding on how groundwater abstraction is sustained in alluvial and fractured hardrock areas in arid to semi-arid climatic conditions of Namibia and the role of input during ephemeral river flow.
- The conceptual understanding of water balance during recharge events and discharge in fractured rock and strip alluvial aquifers in hardrock terrain.
- The means of sustaining arid region bounded aquifers through stresses of increased abstraction and extended drought conditions.

1.5 METHODOLOGY OF RESEARCH

The initial research effort was to review theoretically through hypothetical models the hydrological and hydrogeological controls on bounded arid region aquifers that receive recharge episodically. Key surface and groundwater conditions represented in the hypothetical models are arid region conditions such as short duration river flow followed by extended dry periods, and deep groundwater levels that are normally disconnected from surface water bodies. The use of numerical groundwater flow modelling was preferred in assessing the case studies for the following reasons

1. to explicitly incorporate and change boundary conditions to test situations such as high pumping rates and drought
2. to incorporate ephemeral river flow routing and simulation of episodic recharge
3. the possibility of making predictions over extended periods (decades to centuries) and comparing with contrasting scenarios
4. the possibility of identifying key parameters and data to develop a methodology for modelling of real conditions

Insight gained from the theoretical exercise was used to assess the ground conditions in two case studies. The first explores the recharge process and natural groundwater recharge potential in a fractured rock aquifer through a finite difference groundwater flow model. A bounded aquifer consisting of fractured and karstified dipping marble horizon was selected. Simulation of hydraulic test data collected in a pumping borehole and observation boreholes was done. Where data was not available, aquifer and boundary conditions interpreted from field investigations were incorporated. Aquifer hydrological properties of units without data were estimated from first principles. The calibrated model was used to model episodic recharge recorded in hydrographs in response to ephemeral river flow.

In the second case study geological information and, hydrogeological and hydrological monitoring data for an alluvial strip aquifer was assessed for controls on natural recharge. The data was verified and field checks on the ephemeral river and monitoring points were done. Numerical simulation of ephemeral river flow events and aquifer response for over 12 years was carried out. The calibrated model was used to evaluate three scenarios in utilising the aquifer under natural and artificial recharge.

1.6 THESIS OUTLINE

The sustainable yield issue is addressed in the context of arid region hydrogeology focusing on Namibia. The objective and importance of the research in the context of arid region hydrogeology is outlined in the introductory chapter (Chapter 1). Previous work carried out has been reviewed.

In Chapter 2 the thesis addresses the theoretical aspects of ‘source of water to boreholes’ or water budget calculations for a generalised aquifer in semiarid region under episodic recharge. A hypothetical numerical flow model is used to explore the water budget components and results are given in the conclusion of the chapter identifying the key aspects.

Chapter 3 presents a published scientific paper that addresses process and magnitude of natural recharge and sustainable yield in an arid region small scale fractured rock aquifer through a case study in Namibia.

Chapter 4 presents the next publication that addresses water budget during recharge events in an alluvial strip aquifer associated with an ephemeral stream using a second case study from Namibia. A combined numerical surface and groundwater flow model was constructed in this case. The calibrated model was used to assess artificial recharge scenarios and the sustainable utilisation of the aquifer supporting dependent riparian vegetation.

In Chapter 5 the results of the theoretical examination and case studies are synthesised bringing forth specific ideas towards sustainable utilization of groundwater and in emphasising general importance of combined surface and groundwater resources assessment in arid regions.

1.7 PREVIOUS WORK

The evaluation of fractured rock aquifer with complex boundary conditions through numerical flow modelling have been advocated (Walton, 2008; van Tonder et al., 2002) and advantages of the method have been demonstrated (Chiang and Riemann, 2001). However, modelling of fractured small scale fractured hardrock aquifers in Namibia were not found in recent publications and development of a methodology for such evaluation forms part of the study.

Incorporation of the recharge mechanism through river flow infiltration is an important part of arid region aquifer sustainability evaluation. The understanding of arid region ephemeral river systems have improved in recent years (Shanafield and Cook, 2013; Bull and Kirkby, 2002). The hydrological studies on ephemeral rivers of Namibia in the 1980s form the basis of understanding of functioning of these rivers locally (van Langenhove and Church, 1989; Fry 1989, Crerar et al. 1988; Webster, 1984; DWAF 1987; Rawlins and Webster, 1983). The importance of infiltration from ephemeral rivers was realised early in Namibia and a critically important project titled ‘Alluvial bed recharge research project’ was commissioned by the Department of Water Affairs (DWAF, 1987). The findings of the project included identification of silt carried by river water as a major limitation in infiltration rate to strip alluvial aquifers (Crerar, 1987). The possibility of use of surface impoundments to reduce suspended solids and enhance infiltration artificially into river alluvium at the Omaruru River delta was a direct result of this work (Namwater, 1995). It is also realised that recharge to fractured rock aquifers is predominantly through ephemeral river bed leakage, although there are few Namibian studies on this aspect.

Later work on the Kuiseb River hydrology and hydrogeology enhanced understanding of the importance of the ephemeral river resource in an arid setting (Jacobson and Jacobson, 2012; Seely et al. 2003) and the process of infiltration and recharge (Morin 2009; Dahan et al., 2008) as discussed in Chapter 4. Description of geomorphological and related hydrological features of the country's rivers is provided by Goudie and Viles (2015).

On the subject of river-aquifer interaction in Namibian ephemeral rivers, there is limited literature on induced and artificial recharge. Brunner et at. (2011) and Barlow and Leaky (2012) provides basic understanding of river-aquifer interaction, particularly in the context of disconnected rivers. Few studies have addressed conjunctive use of surface and groundwater with the exception of two artificial recharge schemes - Windhoek Aquifer and Omaruru Delta. Previous studies on artificial recharge of the Oanob Aquifer based on limited information on river bed characteristics and aquifer discharge mechanism pointed to limitations such as high aquifer losses (Webster, 1984).

In recent times, several publications and modelling tools have become available on combined river-aquifer assessment including on ephemeral rivers (Hughes et al. 2012, Niswonger and Prudic, 2005; Prudic et al., 2004).

The current study attempts to understand the role of fractured rock and alluvial aquifers associated with river flow based on work carried out internationally and extending the understanding of episodic recharge in response to ephemeral river flow.

Chapter 2: SOURCE OF GROUNDWATER TO BOREHOLES IN ARID REGIONS

2.1 ARID REGION RIVERS IN RELATION TO GROUNDWATER RECHARGE

The sustainable groundwater abstraction assessment in arid region aquifers is challenging due to the apparent dependence of aquifer systems on stored groundwater and limited duration for which water is available for replenishment. The dominant process of replenishment in arid region aquifers is through river bed leakage during flow events in ephemeral rivers. Understanding of this process requires surface water and groundwater interactions to be examined and consideration of the water budget of the entire basin. A brief discussion on ephemeral rivers and interaction with underlying aquifer is thus given here.

River and aquifer relations are described based on relative elevation of river stage and groundwater levels (Barlow and Leaky, 2012; Healy et al., 2007). Three types of ‘end-member’ relationships have been defined – namely gaining, losing and disconnected rivers, although the nature of the interaction may change along a river course. In arid regions, river stages along most of its course are at higher elevations than groundwater levels and often groundwater and surface water is separated by a thick unsaturated zone (Figure 2-1). Such rivers have been called 'remote', 'perched' (Lerner, 2003) or 'disconnected' (Barlow and Leaky, 2012; Winter et al. 1998; Lerner, 2003). Recharge occurs during flow events and magnitude of recharge depends on flow rate, flow duration, channel characteristics such as streambed hydraulic conductivity, saturated and unsaturated zone properties (Barlow and Leaky, 2012, Lerner, 2003).

Flow in ephemeral rivers occurs in response to rainfall and resulting flow lasts for a short duration. In arid region hardrock terrain, infiltration capacity of rocky catchments with thin soils and vegetation is low and runoff is rapidly initiated (Chow, 1988). Catchments are characterised by Hortonian or infiltration excess flow (Chow, 1988; Lerner, 2003). Flow in response to rainfall has little time lag, durations are short and large peak flow rates could result. Sediment loads are usually high and characteristic arid region stream morphology are wide and shallow braided channels (Bull and Kirkby, 2002). Hydrological characteristics of ephemeral rivers with relevance to groundwater recharge are listed here.

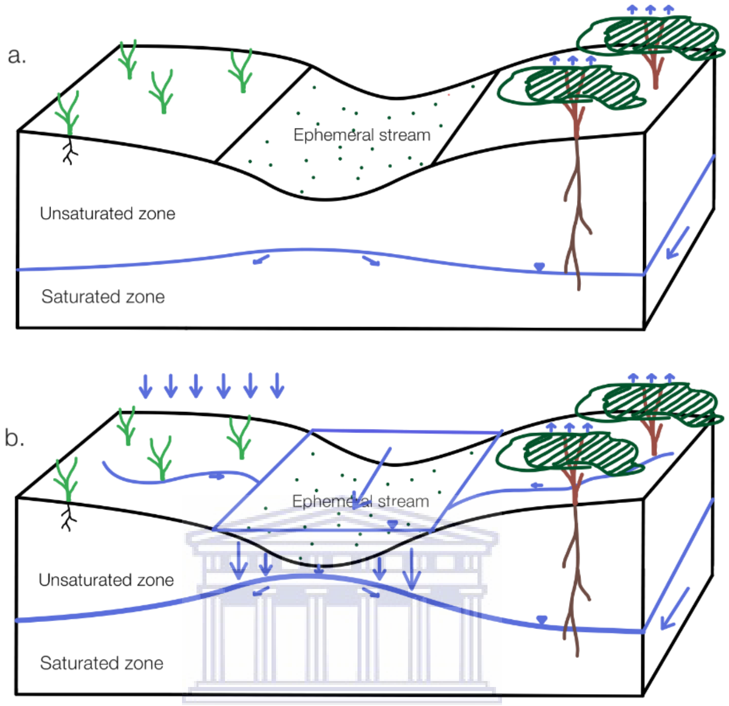

Figure 2-1: a. Dry ephemeral stream and an underlying disconnected aquifer b. The aquifer receives recharge during flow but groundwater level remains below river stage. Arrows indicate water flow components including precipitation, evapotranspiration, surface runoff, infiltration and groundwater flow

1. The rivers experience highly localised and extremely variable rainfall input

2. Hortonian overland flow is dominant with rapid initiation of runoff. Transmission loss is through infiltration and discharge reduces downstream. Baseflow rarely contributes significantly in arid regions to maintain flow.

3. Flow in the river last short durations (flash flood) and hydrographs are sharply peaked with long intermediate periods of no-flow. Flow volumes and durations show high variability.

4. Drainage networks are poorly connected. The largest flood events determine the width of the river. River channel morphology can change with flow.
5. High volume of unsorted sediments are transported in flood events and shallow braided channels are common.

Namibian rivers are characterised by extreme hydrological variability (Jacobson and Jacobson, 2012). Jacobson (1997) reported variation of mean annual runoff of three orders of magnitude in seven west flowing ephemeral rivers that's originate in elevated areas in the east and flow west to the Atlantic coastline. Mean annual runoff and peak discharge show increase from the headwaters to the base of the Great Escarpment and declines thereafter to the coastline (Figure 2-2). The Great Escarpment (Goudie and Viles, 2015) is a topographic feature roughly parallel to the coastline west of which elevations decline rapidly to the sea.

River channels in hardrock terrain are incised that host alluvial deposits of variable thickness often with poorly sorted and immature sediments. Groundwater resource in the alluvial aquifers of larger rivers is significant. The storage capacity is dependent on the nature of the sediments (specific yield) and thickness of the alluvium. The larger rivers (e.g. Kuiseb, Omaruru) have greater thickness (exceeding 15 m) in the productive sections. Smaller rivers with small thickness of alluvium do not form viable aquifers but function as transitional storage (perched aquifers) important for recharge of underlying aquifers. The bedrock is largely impervious except where fault zones or karstified dipping carbonate rock horizons are present. Flow in ephemeral rivers is the main source of recharge through infiltration to both the alluvial and fractured hardrock aquifers. The variability of runoff frequency and duration affect the magnitude of recharge.

Groundwater in the fractured hardrock aquifer receives limited recharge and has higher residence time. Minor discharge of groundwater from fractured hard rock aquifers (baseflow) occur to alluvial sediments resulting in mixing within the aquifer and are usually identifiable due to its elevated mineral content. The fractured hardrock aquifer represents a limited resource. The Ugab River contoured groundwater levels in Figure 2-2 indicate flow in the hardrock aquifer towards the drainage. The main flow component in the alluvial aquifer is along the Ugab River and is separate to the fractured hardrock aquifer.

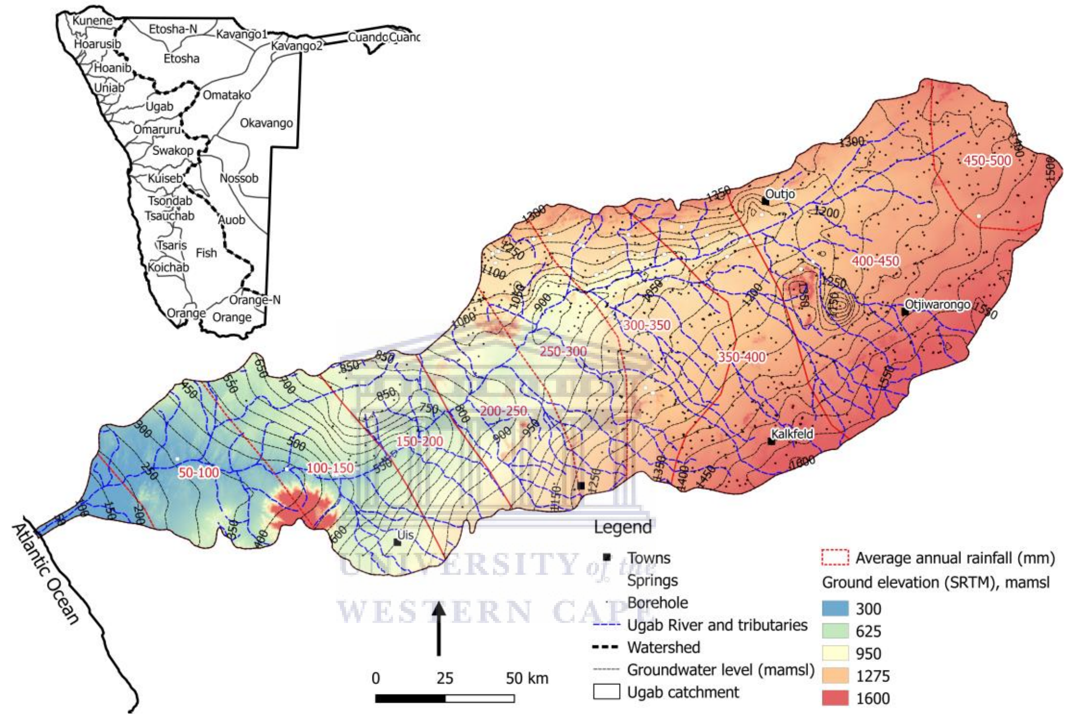

Figure 2-2: The Ugab River and its catchment is shown as a typical example of a large ephemeral river in Namibia. Average annual rainfall is highest at the headwaters to the east (data sourced from Mandelson et al., 2002)

2.2 SOURCE OF WATER TO BOREHOLES

The water balance approach to understanding of source of water to boreholes is reviewed here. Further, the application of the concept to arid regions that receive episodic recharge is investigated.

The source of water to boreholes has been discussed by several authors starting with Theis (1940) who for the first time explicitly stated the various water budget components involved and the concept of sustainable yield (Barlow and Leaky, 2012; Healy et al., 2007; Alley and Leaky, 2004; Bredehoeft, 2002; Alley et al.

1999; Scophocleous, 1997, Alley et al. 1999, Bredehoeft and Durbin, 2009; and Zhou, 2009). Discussions have continued as evident from publications noted above on the subject and the debate on the related issue of an acceptable definition of sustainable yield. Source of water to boreholes in general has been shown to be from depletion of storage, induced recharge in response to pumping and reduction of aquifer discharge (Theis, 1940, Alley et al. 1999). The two components that modify the water balance and eventually lead the aquifer system to a new equilibrium without storage depletion are increase in recharge and reduction in discharge, collectively termed 'capture' (Lohman, 1972; Alley et al., 1999).

In the literature, focus of water budget studies has been largely on aquifers that have perennial surface water or a groundwater source associated. Sustainability of bounded aquifers in arid regions on the other hand poses a problem that differs in two key aspects:

a) no external source of either groundwater or surface water usually exists that is 'connected' and contributes in response to pumping and
b) recharge occurs episodically under irregular rainfall conditions and flow in ephemeral streams of relatively short duration.

Under these irregular recharge conditions the source of groundwater pumped is presumed to be from depletion of storage only with static rates of recharge. Experience in semi-arid and arid regions has however shown that development of groundwater resources can affect surface flow. An approach to managing water resources through understanding of the water budget of the semiarid region aquifers is investigated.

Under steady state or equilibrium conditions long term recharge is balanced by discharge (Bredehoeft and Durbin, 2009; Zhou, 2009).

$R = D$ ….equation 1

where

R = predevelopment recharge

D = predevelopment discharge

With pumping and lowering of the water table, flow is induced from storage and leakage from external source(s), often from a connected surface water body. The water body may be a losing stream that contributes at a higher rate in response to pumping or a gaining stream where flow is reversed if water level in the aquifer is lowered sufficiently. Discharge from the aquifer as outflow, evapotranspiration loss, or discharge to surface or ground water bodies is reduced. The increased recharge and reduced discharge balances pumping and depletion of storage ceases.

Under pumping condition

$\Delta V = (R + \Delta R) - (D - \Delta D) - P$ ….equation 2

where

ΔR = increase in recharge

ΔD = reduction in discharge

P = pumping

ΔV = change of storage.

$\Delta V = 0$ under steady state conditions, i.e., when a new equilibrium between recharge and discharge is attained and as R = D, equation 2 simplifies to

$P = \Delta R + \Delta D$ ….equation 3

Pumping is therefore sustained in the long term without depletion of storage by reduction of discharge and increase of recharge. Increase in recharge is not always significant, being important when direct leakage from surface water bodies is possible. Reduction of discharge is a more important response to pumping. The formation of a cone of depression induces flow and depletion of storage which is the initial source of pumped water from an aquifer while contribution from capture increases gradually with time (Alley et al. 1999). The time taken for significant contribution from capture to occur depends on aquifer dimensions and configuration, distance to recharge source and aquifer diffusivity (ratio of transmissivity/storativity) and can range from years to centuries (Bredehoeft and Durbin, 2009).

The importance of predevelopment recharge to an aquifer in attaining sustainability under pumping conditions has been debated as capture alone is seen to sustain pumping from an aquifer according to equation 3 above (Bredehoeft, 1997; Bredehoeft, 2002). It has however been shown by Zhou (2009) from equation 2 that

$\Delta R + (D - \Delta D) = P$ ….equation 4

where

$(D - \Delta D)$ is residual discharge or predevelopment discharge reduced by an amount ΔD

When $\Delta R = 0$,

$P = D - \Delta D$ ….equation 5

Therefore from equation 5, pumping is sustained by reduction of predevelopment discharge. Depletion of storage will be initiated when ΔD becomes equal to D and residual discharge $(D - \Delta D)$ becomes zero. The magnitude of predevelopment discharge (D) is determined by magnitude of predevelopment recharge according to equation 1 and more water will be available if the recharge amount is large. The recharge rate in this way determines the amount of capture possible.

If abstraction exceeds discharge, depletion of storage would lead to dewatering of the aquifer and pumping will not be sustainable and would impact discharge dependent ecosystems. Evaluation of sustainable yield is closely related to the impact on dependent ecosystems such as vegetation and shallow aquifers fed by discharge. Important Namibian examples of such dependent systems are riverine vegetation along ephemeral streams (e.g. *Acacia erioloba* and *Faidherbia albida*) and desert mammals (e.g. rhinoceros and elephants) dependent on shallow water in alluvial aquifer along the west flowing desert rivers.

2.3 SOURCE OF WATER TO BOREHOLES IN ARID REGION BOUNDED AQUIFERS

The water balance approach to assessment of sustainability often addresses basins where a perennial source of water contributes to the aquifer. In the case of arid regions, decline of aquifer discharge is a more likely possibility as recharge is episodic. It has been shown that in response to pumping, a cone of depression forms and aquifer storage is depleted initially until the drawdown induces flow towards the borehole from recharge and discharge boundaries (Theis, 1940; Bredehoeft, 2002; Zhou, 2009). Proportion of contribution from capture increases with time and is dependent on two main factors – distance to the source of capture water and hydraulic diffusivity of the aquifer. A steady state or equilibrium condition is attained when there is no change in storage.

In arid region aquifers, equilibrium is not attained in the time period between recharge episodes. Fundamental to capture by induced recharge is the availability of a water source that contributes to the aquifer or a significant discharge component that is reduced. As flow in ephemeral rivers is maintained for short duration, induced recharge is possible for a short time. In addition, capture of discharge would mean decrease of evapotranspiration and groundwater discharge. The groundwater discharge component is usually small compared to evapotranspiration.

Under episodic recharge, prolonged storage depletion and short recharge events alternate and result in fluctuation of the water table. Capture occurs as the water table is lowered through pumping and change is storage may be expressed as

$\Delta V = (R + \Delta R) - (D - \Delta D) - P$ ….equation 6

As R = D in the long term

$-\Delta V + \Delta R + \Delta D = P$ ….equation 7

Decline in storage, and contribution from decrease in discharge and increase in recharge sustain pumping under the condition that discharge is balanced by recharge in the long term. Decline in storage is part of the groundwater budget under pumping condition and steady state condition is not attained unless $\Delta V = 0$ and $(\Delta D + \Delta R)$ balances P.

A hypothetical model has been constructed to examine the role of capture and storage depletion of a bounded desert basin aquifer under episodic recharge. Here comparison is made between pumped and predevelopment conditions under identical recharge and boundary conditions over several cycles of recharge and storage depletion. Assessing the importance of capture under episodic recharge conditions cannot be done by comparison with a steady state condition (or long term average water level and flow) as such a state did not exist in the predevelopment period. The capture component is also masked by the fluctuation of water level with recharge events and storage depletion. *But comparison between pre-development water budget covering periods of storage depletion and recharge, and water budget under pumping condition is possible.*

2.4 HYPOTHETICAL MODEL

Konikow and Leaky (2014) created a hypothetical MODFLOW 2005 (Harbaugh, 2005) model that simulated a desert basin aquifer connected to a perennial stream. The model was based on Barlow and Leaky (2012) with modifications. The model was used to demonstrate storage depletion and capture from surface drainage and its effect on downstream flow as pumping from the hypothetical aquifer induced recharge. This hypothetical model was recreated using MODFLOW-NWT and checked against the original published results (Konikow and Leaky, 2014). The use of the Newton formulation of MODFLOW finite difference code together with the upstream weighing solver package (Niswonger et al., 2011) allowed repeated drying and wetting of cells without convergence issues. The original Konikow and Leaky (2014) model was created using MODFLOW 2005 and the water budget calculations were repeated successfully using MODFLOW-NWT (Figure 2-3).

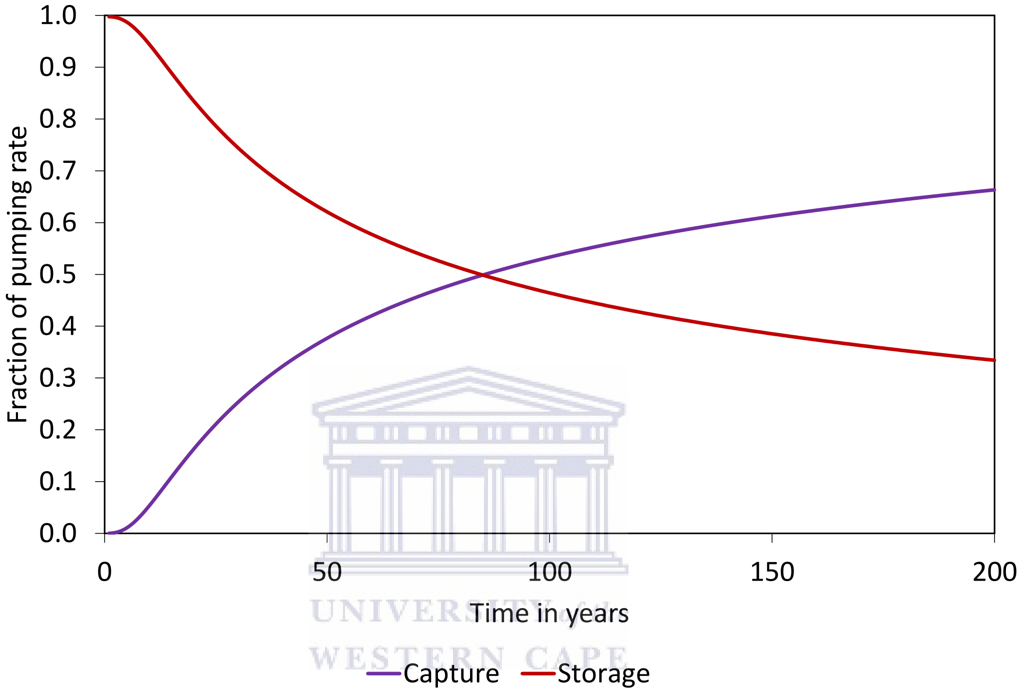

Figure 2-3: Storage and capture from a hypothetical model after Konikow and Leaky (2014) simulated using MODFLOW-NWT

Based on the above model a hypothetical desert basin aquifer model was constructed with hydrological features representative of extreme aridity of Namibian conditions (Figure 2-4 and Table 2-1). The model extent and parameters are taken directly from Konikow and Leaky (2014) but is modified to represent an arid region aquifer that is dependent on episodic flow from a disconnected ephemeral river. The model has a single convertible (unconfined) layer (Figure 2-5) with parameters assigned as given in Table 2-1.

The disconnected river is located in the eastern boundary as the recharge source (that is, the symmetrical left half of Figure 2-4) and is implemented using a kinematic wave equation based package SFR2 (Niswonger and Prudic, 2005;

Prudic et al., 2004). Discharge occurs over the top of the entire domain through the evapotranspiration package (Harbaugh, 2005) representing phreatophyte vegetation. Groundwater outflow through the southern boundary is simulated using a head dependent boundary (General Head Boundary, GHB) package.

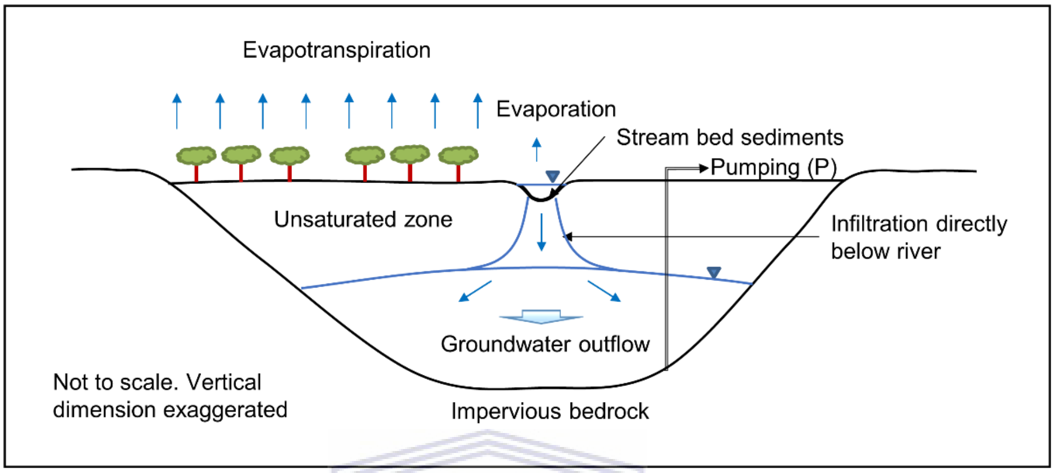

Figure 2-4: Conceptual model of infiltration through streambed from a disconnected ephemeral stream to an alluvial aquifer

Key assumptions and features used in representing the arid region basin and episodic river flow are listed below.

1. The river and aquifer are disconnected, and river flow and recharge occurs for short period of time. In a disconnected river groundwater levels remain significantly below river stage and an unsaturated zone separates the river from groundwater. It is assumed that the unsaturated zone does not have significant intermediate storage and recharge reaches the saturated zone instantaneously.

2. Diffusivity is known to be a key factor in the magnitude and time of response of the aquifer to stresses (recharge, or pumping). Specific yield values used were low (0.05) which are representative of Namibian conditions. Hydraulic conductivity values used are same as in Konikow and Leaky (2014).

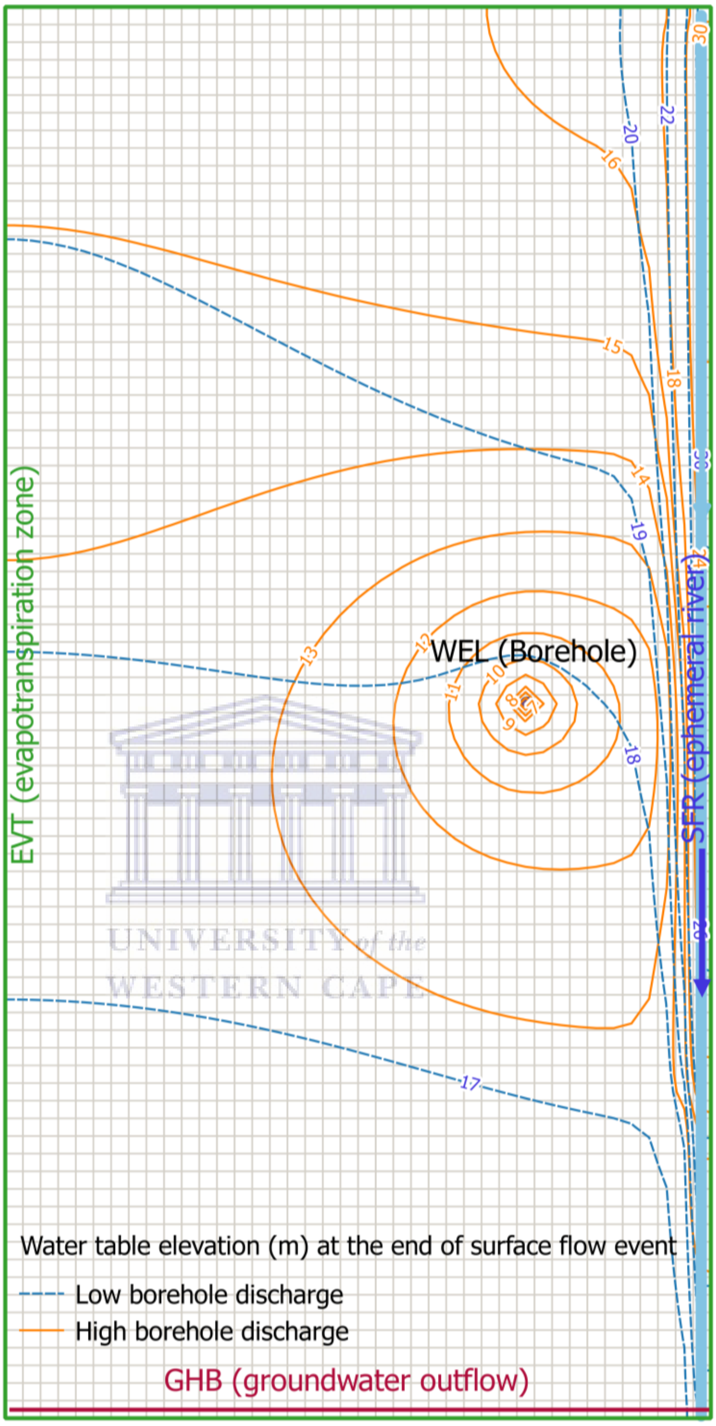

Figure 2-5: Hypothetical model domain and boundaries.

3. River bed leakage occurs during flow and infiltrated water flow vertically through the unsaturated zone. There is no intermediate storage and infiltration reach the water table instantaneously. Flow downstream and

laterally away from the groundwater mound formed below the river occurs as shown in Figure 2-4.

Table 2-1: Parameters and boundary conditions of the hypothetical model (modified after Konikow and Leaky, 2014)

Model component	**Details**
Finite difference grid	Single layer 800 m x 800 m grid cell size 40 columns by 80 rows 32,000 m by 64,000 m model domain
Top of layer	Sloping to the south - 31.03 m (north) 20.6 m (south)
Bottom of layer	100 m below top of layer
Horizontal hydraulic conductivity Vertical hydraulic conductivity	Hx = Hy = 15.24 m/day Hv = Hk/10 = 1.52 m/day
Specific yield	0.05
Evapotranspiration (EVT) package	Covers entire top of model except column 40; extinction depth = 10 m from top of model
General head boundary (GHB) package	Along bottom row (row 40), GHB elevation is at 15 m.
Stream flow routing (SFR2) package	Along eastern boundary of model (column 20), 64, 000 m. Flow once every 10 years at a rate of 1,216,667 m^3/day for 30 days. River profile = Rectangular of 20 m width Stream bed conductivity = 0.3 m/day Stream bed thickness = 0.305 m Stream bed elevation = 31.03 m north; 25.9 m south Manning’s constant = 0.035
Well (WEL) package	Located at a distance of 8,000 m from the river (column 30, row 40). Flow rates low: 2,026 m^3/day; high: 20,260 m^3/day.
Initial water level	18.25 m

4. There is no outflow to the river from the aquifer through baseflow as the river remains disconnected in times without surface flow. The infiltrated water reaches the saturated zone and discharges though the general head boundary as groundwater outflow or through evapotranspiration

when water levels are above the extinction depth. Surface flow that does not infiltrate continues and leaves the model domain at the downstream (southern) end of the river.

5. Discharge through evapotranspiration (EVT) affects the entire model domain. EVT extracts water at maximum rate from surface (top of model) to a depth of 1m, thereafter EVT loss declines linearly to zero at a depth of 10 m below surface.

6. Groundwater discharge is simulated by a head dependent flow boundary using the General Head Boundary (Harbaugh, 2005) package. The elevation of the boundary is kept at the bottom of the aquifer. The use of the package allows discharge of groundwater at a rate determined by the assigned hydraulic conductivity of the aquifer.

7. The pumping site is implemented using the WEL package (Harbaugh, 2005) located 8,000 m east from the river. Pumping rates used in the model, explore effect of low and high rates of pumping as given in Table 2-1.

8. No other source of recharge or discharge is included in the model.

9. The model is sensitive to initial head. The value assigned has the least change in range of evapotranspiration and groundwater flow rates as seen for the non-pumping case. The transient model was run for an initial 50 years when repetitive range of evapotranspiration and groundwater flow rates was established reducing the effect of the initial conditions on the computed heads and flows. Data from this period was not used. The model under non-pumping and pumping conditions were run for 200 years to allow examination of storage depletion and capture components in different scenarios.

10. Ten episodes of 30 day flow each at intervals of 10 years is simulated under transient conditions. In reality, recharge events are likely to occur

more frequently with a high probability of more than one recharge event occurring in a ten year period. River flow and resulting recharge magnitude would however vary. For the purpose of the current study one recharge event at the end of 10 years is assumed.

A kinematic wave equation based routing package, SFR2, is used to simulate river flow. A rectangular channel profile of 20 m width is assumed. Stream depth is calculated as a function of flow using the simplified Manning's equation for rectangular channels (Niswonger and Prudic 2005). Manning's roughness coefficient of 0.035 is assumed, a value typical for sandy channels with low vegetation cover. The flow at the upstream end of the river is assigned and no other addition or removal of surface flows is allowed. The river bed conductivity, aquifer vertical hydraulic conductivity, and head difference between the base of the river bed and stage determines the vertical leakage from the river using equation 8 (Prudic et al. 2004 and Niswonger and Prudic 2005).

$Q_L = KwL\,(h_s - h_a)\,m^{-1}$ ….equation 8

Q_L = Volumetric flow between a given section of river and underlying aquifer (m^3/day)

K = hydraulic conductivity of river bed sediments (m/day)

w = width of stream (m)

L = length of stream corresponding to a volume of aquifer (m)

m = thickness of river bed deposits (m)

h_s = head in the stream above the river bed elevation

h_a = head in the aquifer below the river reach or elevation of the base of the river bed if the head in the aquifer lies below the river bed elevation

River width, river bed hydraulic conductivity (K) and hydraulic gradient across the river bed would determine the volumetric leakage rates for a given river stage.

Here, it is assumed that the river bed leakage is instantaneously added to storage and the flow rate does not exceed the saturated hydraulic conductivity of the aquifer material (Prudic et al., 2004).

2.5 MODEL RESULTS AND DISCUSSION

2.5.1 WATER BUDGET IN AN UNDEVELOPED AQUIFER

The water level in the aquifer decline as water is taken from storage by evapotranspiration vegetation and groundwater outflow. The recharge event at 10 years causes rapid gains in storage during the 30 days of surface flow and river bed leakage (Figure 2-6). Redistribution of storage occurs as water flows laterally and in the downstream direction due to groundwater mounding below the river. This continues to about 5 years following the recharge event. Depletion of storage is seen in response to evapotranspiration and groundwater discharge at decreasing rate as water level in the aquifer declines. Recharge events in successive 10 year intervals show similar response. A dynamic equilibrium is maintained if surface flow occurs at regular intervals.

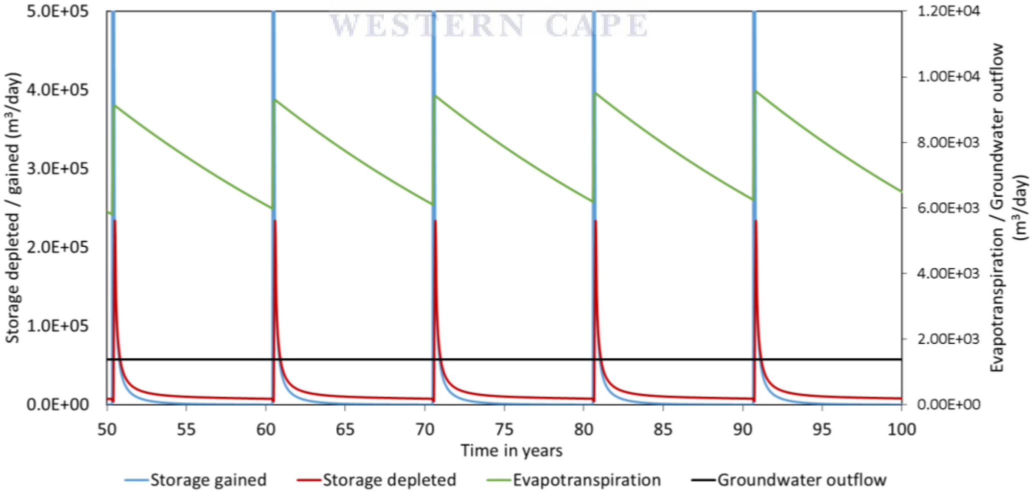

Figure 2-6: Water budget rates under non-pumping conditions are shown from 50 to 100 years. Storage is gained (~1.2E+6 m^3/day) in response to river bed leakage during flow while storage depletion occurs due to evapotranspiration and groundwater outflow (right axis).

2.5.2 CAPTURE UNDER EPISODIC RECHARGE

Comparison of storage depletion, evapotranspiration loss and groundwater outflow with pumping is made with a run of the model for the same time period representing the predevelopment or non-pumping case. Long term average condition represented by the steady state flows cannot be used for comparison as done in other similar models involving perennial water sources (Barlow and Leaky, 2012; Konikow and Leaky, 2014).

In an initial scenario, with moderate level of pumping (2,026 m^3/day), capture of evapotranspiration discharge, induced stream leakage and to a lesser degree of groundwater outflow are evident together with reduction in the rate of storage depletion (Figure 2-7).

The typical increasing capture and decreasing storage curves are seen to apply to the episodic recharge case. The capture component is calculated as the sum of reduction of evapotranspiration, reduction of groundwater outflow and increase in river bed leakage compared to the non-pumping scenario (Table 2-2). Similarly, change in storage is compared to the non-pumping case. A graph following Barlow and Leaky (2012) is used to depict storage depletion and capture rates (Figure 2-8) expressed as a ratio to the pumping rate.

Table 2-2: Calculation of rate of storage change and capture from model water budget information

Component	Calculation
Storage change	[(Storage gained – Leakage) $_{\text{pumping}}$ – (Storage gained – Leakage) $_{\text{non-pumping}}$] ÷ pumping rate
Capture	[(Evapotranspiration $_{\text{pumping}}$ – Evapotranspiration $_{\text{non-pumping}}$) + (Groundwater outflow $_{\text{pumping}}$ – Groundwater outflow $_{\text{non-pumping}}$) + (Leakage gained $_{\text{pumping}}$ – Leakage gained $_{\text{non-pumping}}$)] ÷ pumping rate

Initially water is sourced from storage as groundwater level decline in response to pumping (Figure 2-8). Capture increases with time and the main contribution is from decrease of evapotranspiration. Decrease of outflow from the aquifer is small in magnitude. River bed leakage occurs as episodes (Figure 2-8) and increase in leakage rate is seen till about 100 years. The episodic river leakage peaks make the figure different from the case with a perennial source of water (Figure 2-3). The episodes of leakage at several times the rate of pumping, sustains the scheme through the following no-flow period.

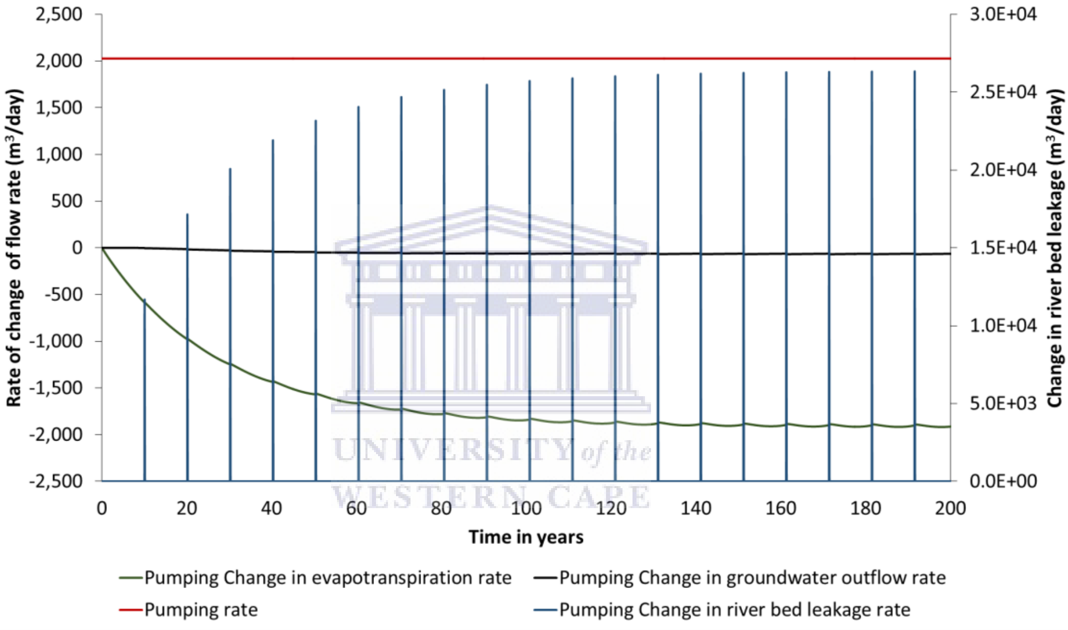

Figure 2-7: Change in rate of evaporation, groundwater outflow, pumping rate (left axis) and river bed leakage rate (right axis) when pumping at 2,026 m^3/day.

Under these conditions as in humid regions, contribution from storage gradually decreases and water is increasingly supplied from capture (ΔD). As capture increases, the predevelopment groundwater level changes with storage depletion and gain may be attained. In Figure 2-8 this is attained in about 100 years after pumping is initiated. River bed leakage is the largest component of capture balancing total discharge from the aquifer (Figure 2-9). Depletion of storage increases during time of no-flow. The pumping rate then represents a near sustainable yield provided the impact due to reduction of evapotranspiration and river flow reduction is acceptable.

The degree and time in which capture of discharge is possible is determined by the process through which discharge occurs in addition to diffusivity and boundary conditions of the aquifer and the extent of river flow capture possible. Capture of evapotranspiration is limited to the amount of water that was originally taken up by vegetation under predevelopment conditions. Key properties and constraints of arid region aquifers are revealed through the simulation of a scenario where a borehole is pumped at a high rate as compared to aquifer storage and river flow rate (Table 2-1). The pumping rate used is ten times the value used in the previous simulation (20,260 m^3/day).

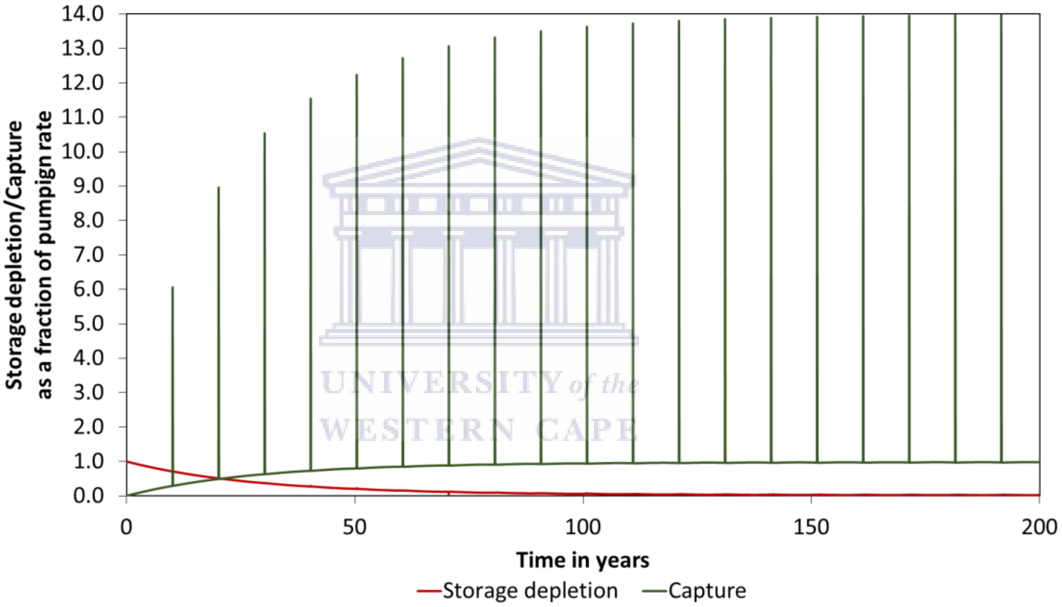

Figure 2-8: Capture and storage depletion due to pumping at 2,026 m^3/day. Episodic high capture rates are seen with river bed leakage during flow.

In this case residual discharge approaches zero ($D - \Delta D \sim 0$), and pumping is sustained by storage depletion and increased river flow capture (Figure 2-10). Evapotranspiration is reduced to zero as groundwater levels are lowered (Figure 2-10). Each succeeding episode of river flow results in higher infiltration till a maximum rate is reached. Downstream flow out of the river ceases after 70 years (Figure 2-11) as the total flow volumes is captured. Storage depletion and evapotranspiration rates relative to non-pumping case is seen to fluctuate as recharge episode and dry periods alternate and dependence on infiltration (river flow depletion) increases (Figure 2-12). Overall storage depletion rate continues to be larger than zero in the 200 year model period and indicates that the pumping scheme is unsustainable.

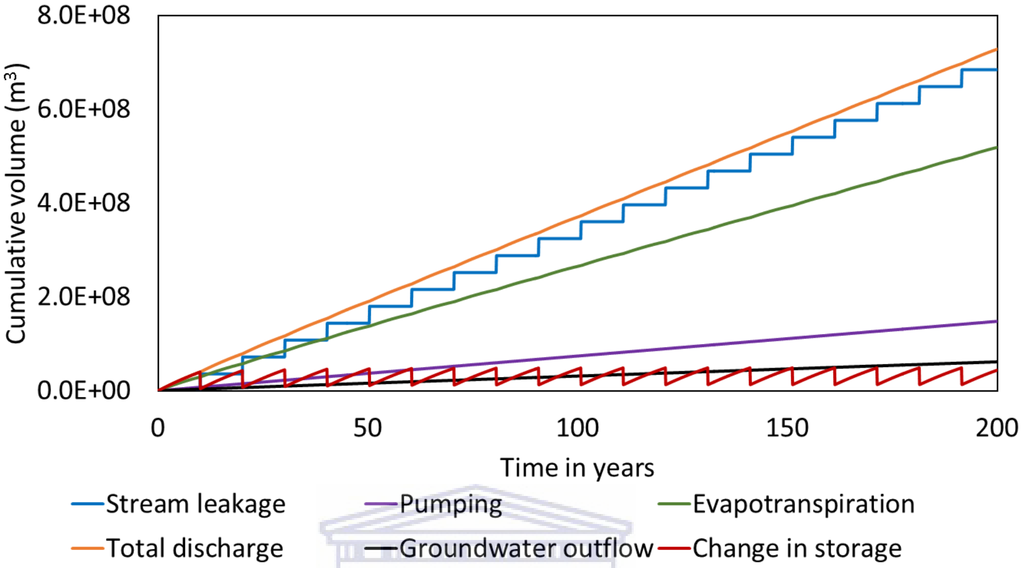

Figure 2-9: Cumulative water budget of aquifer and river leakage for the low pumping rate case where total discharge is the sum of pumping, evapotranspiration and groundwater outflow.

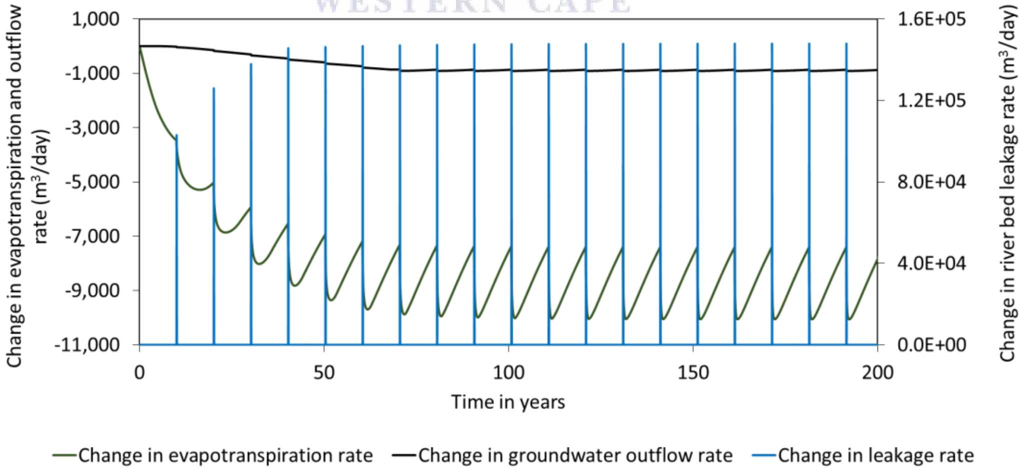

Figure 2-10: Change in rate of evapotranspiration, groundwater outflow, pumping rate (left axis) and river bed leakage rate (right axis) when pumping at 20,260 m^3/day when compared to the non-pumping case.

The cumulative water budget of the flow model is shown in Figure 2-13. Total discharge from the aquifer (pumping, evapotranspiration and groundwater flow) is balanced by storage depletion. Gain in storage from river bed leakage only replenishes part of the storage causing an increasing net decline in storage with time. Infiltration of previously rejected recharge becomes important component of capture with time. Increased infiltration occurs simultaneously with reduction of evapotranspiration.

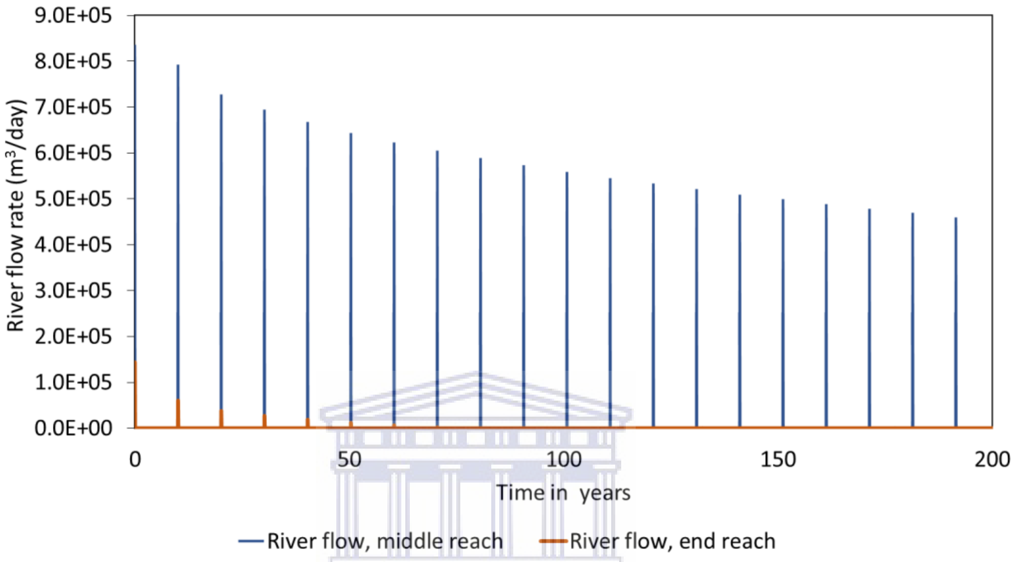

Figure 2-11: River flow rate at the middle reach (row 40) compared to flow at the bottom reach (row 80). Downstream flow out of the river ceases after 70 years of pumping.

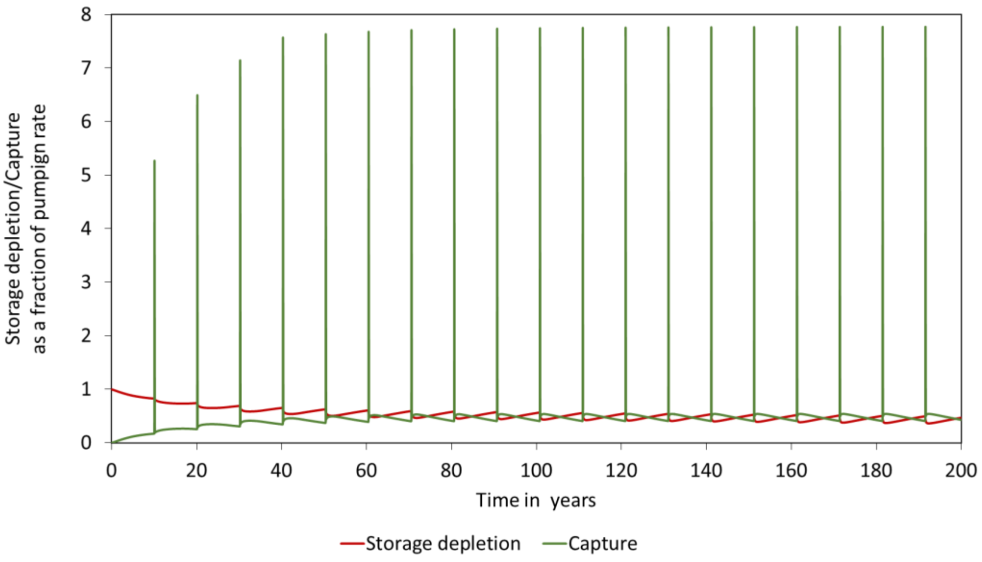

Figure 2-12: Change in storage depletion and capture as a fraction of pumping rate (20,260 m^3/day) in a 200 year period. Recharge occurs episodically once every 10 years through ephemeral river flow.

This result is similar to a case described by Konikow and Leaky (2014) for bounded aquifers where a perennial river flow is entirely captured through leakage due to high rates of pumping. The principle of capture applies to semi-arid and arid conditions where recharge and river flow is episodic. At high pumping rates depleted storage is only partially replenished by river leakage and depletion of storage continues making abstraction unsustainable.

The capture of increasing amount of surface water when pumping volumes are high and resulting decrease in river flow applies to some alluvial aquifers associated with major west flowing ephemeral rivers of Namibia. An example is the Omaruru River and associated alluvial aquifer which has several upstream groundwater schemes (Omaruru, Okambahe and Nai-Nais). River flow is reduced downstream through induced infiltration and few flows have reached its delta at the Atlantic coast in recent times.

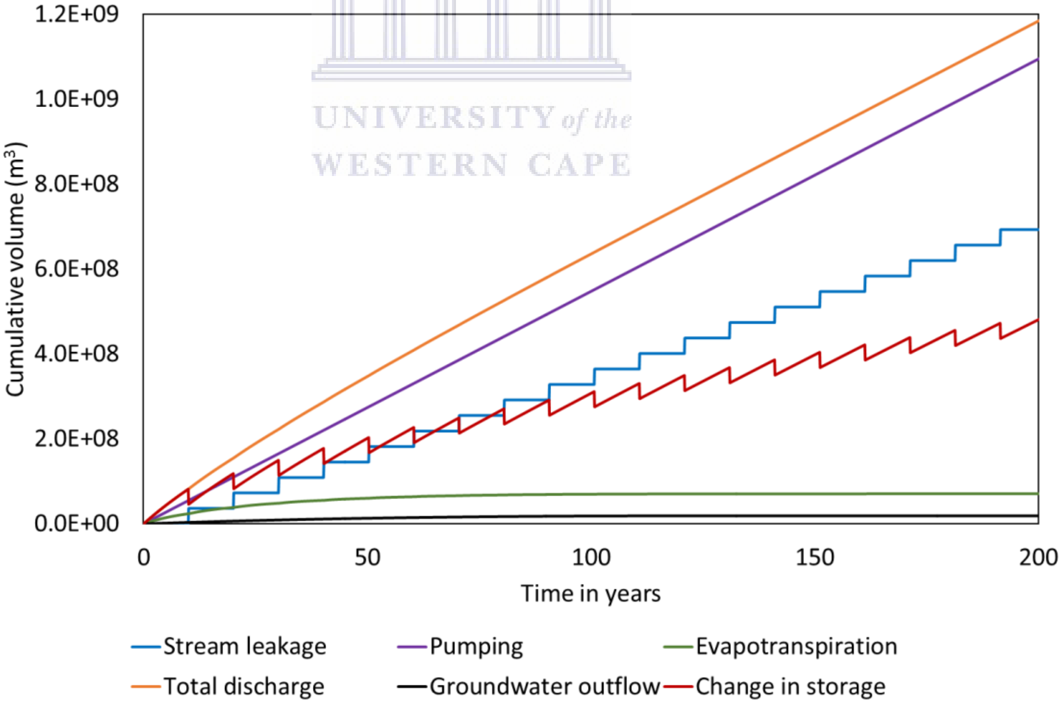

Figure 2-13: Cumulative water budget of aquifer and river leakage in the high pumping rate case where total outflow is the sum of pumping, evapotranspiration and groundwater outflow.

2.5.3 EFFECT OF RIVER FLOW FREQUENCY

Extended periods of no flow between river flow events cause increase in storage depletion in the associated aquifer due to pumping and natural discharge. The capture volumes or river flow depletion would consequently increase during subsequent flow events or may not be sufficient to restore previous conditions. The simulated heads using the model above show recharge events of two equal magnitude flows but separated by twice the time period (Figure 2-14). The water levels are not restored and the overall effect is similar to increase of abstraction rates. Drought conditions are common in Namibia and wet periods following drought, if not exceptional, will not restore pre-drought conditions.

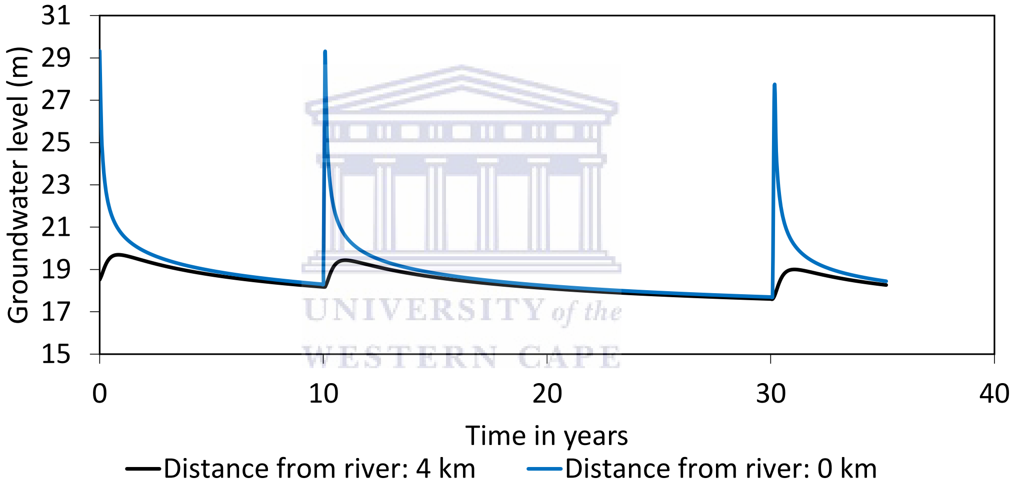

Figure 2-14: Groundwater levels in successive surface flow events separated by different time periods

2.5.4 EFFECT OF RIVER BED CONDUCTIVITY ON INFILTRATION

The effect of streambed conductivity in comparison to unsaturated zone hydraulic conductivity and vertical hydraulic conductivity of the saturated zone was explored by Niswonger and Prudic (2004). Heidbüchel (2007) specifically studied Namibian conditions using data on the Kuiseb River and concluded that the relative values of river bed conductivity and aquifer hydraulic conductivity plays a major part in determining infiltration rates. When river bed hydraulic conductivity is higher than vertical conductivity of the aquifer, the conductivity of the aquifer determines infiltration rates. Groundwater mounds below the river and resulting shallow groundwater level limits infiltration. In the case where streambed conductivity is the limiting factor, infiltration is restricted and a fraction of the surface flow infiltrates. Recharge may be rejected even though additional storage is available in the aquifer. In a simulation of river flow using the SFR package, infiltration to the aquifer during flow periods is seen to be limited by the rise in groundwater levels directly below the river (mounding). Infiltration rates drop when head gradients decrease as a result of mounding (Figure 2-15). This is seen as increase in river flow after an initial steady flow rate. Potential recharge is rejected if hydraulic conductivity of the aquifer is low compared to the river bed hydraulic conductivity and rapid mounding occurs. Low river bed hydraulic conductivity on the other hand would limit the amount of infiltration possible during flow.

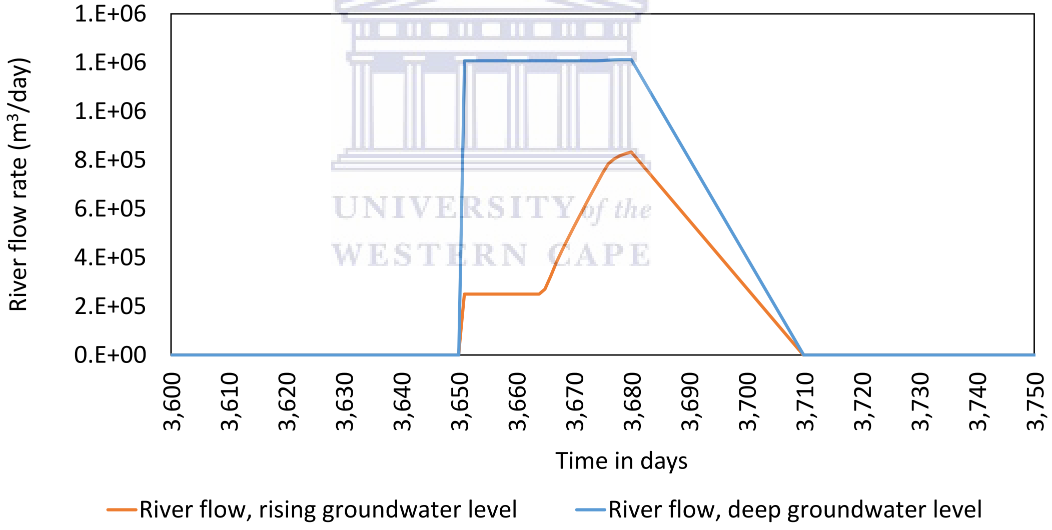

Figure 2-15: Simulated river flow affected by rising groundwater levels

2.6 CONCEPTUAL UNDERSTANDING AND CASE STUDIES

In arid conditions recharge through river flow leakage (transmission loss) from losing ephemeral streams is the dominant recharge process and diffused recharge is negligible. Rapid runoff occurs in response to summer rain in catchments with low infiltration capacity having rocky surface, thin soil cover and vegetation. Runoff is channelized into ephemeral rivers. River flow lasts short durations relative to periods of no flow. Underlying fractured aquifers or alluvial channel aquifers are recharged through leakage as illustrated in Figure 2-4.

The theoretical understanding that under arid region episodic recharge conditions, pumping is balanced by depletion of storage and by capture of discharge and induced recharge is shown through the hypothetical model. In the case of arid regions, per-development recharge and discharge balance in an extended time scale which incorporates cycles of groundwater storage depletion and discrete recharge events. Added stresses alter aquifer heads (storage) and a new dynamic equilibrium may be attained incorporating water level fluctuations in response to recharge events and discharge. This is shown in an example of a long term hydrograph from the Oanob Aquifer (discussed further in Chapter 4) in the south central part of the country (Figure 2-16). Here groundwater levels are initially seen to be maintained within upper and lower limits corresponding to recharge events and discharge from the aquifer (1974-1980). Lowering of average depth to water by approximately 3 m is seen in the hydrograph with beginning of large scale pumping in the 1980s. Subsequently, head and recharge frequency are reduced with completion of a dam upstream in 1990 on the ephemeral river that recharges the aquifer. A new adjusted range of maximum and minimum water level fluctuations is established in response to the added stress. The changes seen on completion of the dam are reduction of storage, likely reduction of discharge, lower recharge frequency but enhanced recharge during flow events seen as larger magnitude water level rise in response to river flow (Figure 2-16).

Capture of river flow is a main process of recharge of alluvial and fractured hardrock aquifers. Infiltration is controlled by hydraulic conductivity of the streambed, vertical hydraulic conductivity of the aquifer and available storage in the aquifer. Recharge may be rejected if hydraulic conductivity of the streambed or the aquifer limits infiltration and recharge. In hardrock terrain as in alluvial strip aquifers, fractured rock aquifers are bounded in extent and lower order hydraulic conductivity of fractured rock aquifers further restrict and limit infiltration during surface flow.

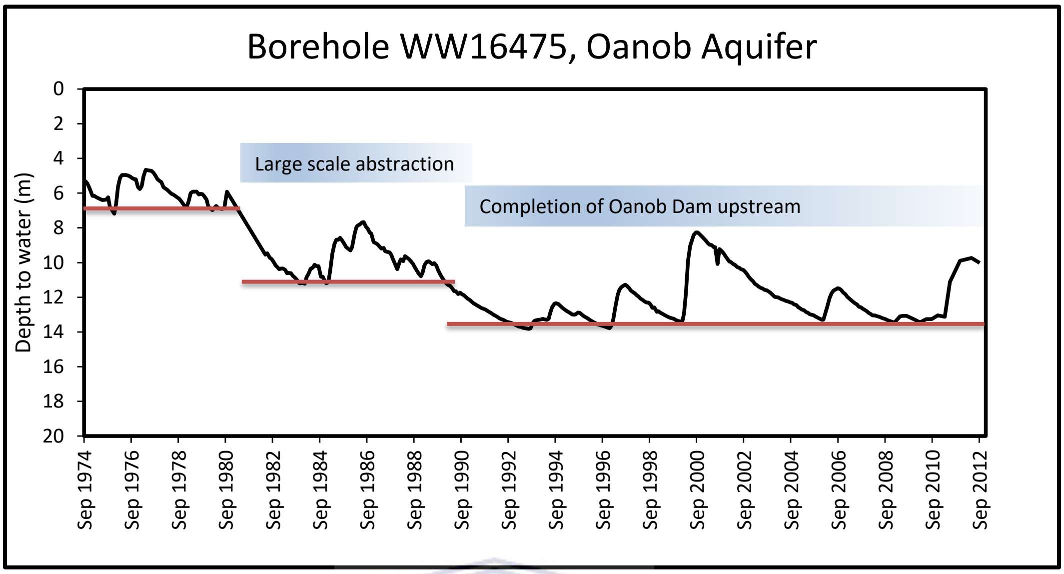

Figure 2-16: Hydrograph showing change in depth to water with imposed stresses in an arid region aquifer

Storage gained during recharge events is balanced by discharge that occurs mainly through evapotranspiration. Pumping induces capture which is essentially reduction of evapotranspiration, capture of river flow, to a lesser degree discharge to shallow aquifers and surface water bodies. If capture is limited or abstraction rates are high, storage depletion would occur and sustainability will depend on frequency and magnitude of flow events for a particular river. It is however seen that when withdrawal rates exceed a limit, recharge events may not fully restore the stored volume in the aquifer and 'reset' conditions to predevelopment levels. Capture of river flow would fill depleted storage to the extent allowed by the hydraulic properties of the aquifer and river. Sustainable utilisation from an aquifer therefore depends on the degree of capture possible in response to pumping while considering impacts to dependent ecosystems and downstream flow.

The balance between the intended use of water and its benefits, and environmental requirement has to be weighed for a scheme. Such assessments have to be done on a basin wide scale incorporating surface water and groundwater as a single resource. Information and data on aquifer boundary conditions, hydraulic properties, interaction between stream and aquifer, and surface water flow conditions is necessary for such evaluation.

Use of numerical flow modelling with three dimensional representation of groundwater and surface flow condition can provide a comprehensive tool for such analyses. Two case studies are presented in the following two chapters that address aspects of recharge to semi-arid region bounded aquifers and sustainable yield under the given conditions. The case studies were selected as examples of water budget of a fractured hardrock and an alluvial strip aquifer.

The following aspects are addressed in the publications:

Chapter 3: An approach to sustainable rural water supply in semi- arid Africa with a case study from Namibia. Hydrogeology Journal (2014) 22: 1681-1692 DOI 10. 1007 /s 10090-014-1178-1

Aquifer boundary conditions were assessed by numerical flow modelling of a hydraulic test in a fractured rock aquifer. Recharge through streambed leakage during ephemeral river flow and losses from the aquifer is estimated for a case where river flow is not gauged. Decline of water level under natural predevelopment discharge rates and gain in storage is estimated following which a long term estimate of storage gained and sustainable utilization is given.

Chapter 4: Recharge process in alluvial strip aquifer in and Namibia and implication for artificial recharge. Hydrogeology Journal (2016) Published online DOI 10.1007/s10040-016-1474-z

Recharge mechanism to an alluvial strip aquifer is explored through numerical modelling of surface water and groundwater interaction. The aquifer response to pumping, storage depletion and effect on riparian vegetation (phreatophytes) is illustrated. The use of artificial recharge to enhance storage and sustain dependent riparian vegetation was studied through simulations.

Chapter 3: AN APPROACH TO SUSTAINABLE RURAL WATER SUPPLY IN SEMI-ARID AFRICA WITH A CASE STUDY FROM NAMIBIA

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Abstract

Sustainable-yield estimation in semi-arid conditions is always challenging, especially for fractured rock aquifers. An approach to assess sustainability is discussed using a case study from rural semi-arid Namibia. The fractured-rock aquifers in the study area have complex configuration. Geology maps, hydrocensus data, geophysical surveys, and drilling and hydraulic testing data were used to produce a conceptual model. Aquifer parameters were estimated based on the hydraulic test data and numerical modelling. Due to lack of data, as is often the case in rural Namibia, the simulation results had to be verified against geological and hydrogeological constraints. It is concluded that the aquifer system is sustained by episodic recharge and the long-term gain in storage (about 3285 m^3/a) represents the maximum extractable volume. It is recommended that the continuous monitoring system for groundwater level, river flow and rainfall should be part of a long-term scheme. The magnitude and frequency of the recharge events and extraction should be monitored in order to sustainably manage the resource. Although the illustrated approach is based on limited data, it provides a basis for management of individual groundwater schemes in semi-arid conditions in sub-Saharan Africa.

Keywords: arid regions, Namibia, fractured rocks, groundwater management, numerical modelling

3.1 INTRODUCTION

In arid and semi-arid sub-Saharan Africa rural communities are dependent on groundwater, a large part of which is located in hardrock aquifers. The management of these low-potential but widely occurring groundwater sources is vitally important to maintain the dispersed communities in drought prone areas (Braune and Xu 2010, Calow et al. 2009) and appropriate management of the resource depends on conceptual understanding of the aquifer systems (Robins et al. 2006, McDonald 2008). The principal issues in fractured aquifer management are knowledge of aquifer boundaries and recharge (Wright 1992). Groundwater supply sources in rural areas are often established under emergency drought relief programs that address the immediate water shortage issues. The large number of boreholes drilled in recent years by governments and under several poverty reduction, water-supply and sanitation programs does not necessarily alleviate the water supply problem when sustainability of the resource is not ensured (Calow et al. 2009).

In this context, an approach adopted for sustainable yield evaluation from a fractured aquifer in semi-arid Namibia is discussed where common hydrogeological tools were utilised but by taking into consideration several key data sets collected at the scale of the rural water supply scheme. About 52% of Namibia by surface area is underlain by hardrock aquifers (Christellis and Struckmeier 2001) and sustainability from these sources has been an issue due to structural complexity of the aquifers, irregular recharge, and often limited resources to carry out detailed investigations. A resource evaluation procedure using numerical flow modelling illustrates the importance of incorporating the structural complexity of the aquifer and understanding of episodic recharge in assessing sustainable yield, an approach not available with conventional projection using analytical methods.

Several approaches have been suggested for evaluation of sustainable yield (van Tonder et al. 2000; Carlsson and Ntsatsi 2000; van Tonder et al. 2002). Generally, sustainable yield of small scale abstraction schemes is estimated on the basis of analytical solutions applied to constant-rate test data and forward modelling with the estimated transmissivity and storativity. The modelled abstraction rate is adjusted to limit the drawdown to a predefined level (usually the uppermost water strike) at the end of a designed production period. Difficulties arise in applying analytical solutions where the simplifying assumptions are not supported by field data (Walton 2008, Cook 2003), complex field conditions cannot be explicitly represented, or where conceptual understanding is incomplete. van Tonder et al. (2002) gave a methodology based on drawdown derivative analyses for determination of the conceptual model and analytical solutions for estimation of aquifer parameters and abstraction rates but cited limitations of the methods and recommend numerical models for cases where aquifer parameters (particularly storage coefficient) cannot be uniquely determined under complicated boundary conditions.

Evaluation of fractured rock aquifers for long term abstraction therefore requires estimation of aquifer properties from hydraulic test data based on a sound conceptual model that incorporates key hydrogeological constraints together with estimates of the recharge rate to the aquifer. The limited number of boreholes drilled into fracture zones in rural water supply schemes rarely provides enough data for a detailed conceptual model or an understanding of the recharge mechanism and requires use of other available datasets (Figure 3-1). The purpose of this study was to formulate and test a hydrogeological model compiled using data collected during field exploration and development of the resource that included geological and structural information, hydraulic testing, and water level monitoring information. The model is tested with a simple finite difference numerical model at the scale of the supply scheme and used to gain insight into the recharge mechanism.

3.2 GEOLOGICAL SETTING

Geological information at the scale of the study area was derived from aerial photo and satellite imagery interpretation, field mapping, geophysical profiling and drilling (Figure 3-1). A steeply dipping (70° south-east) marble band has weathered quartz-biotite schist in the hanging wall side and granitic gneiss to the footwall side. The marble and schist units belong to the Blaukranz Formation, Hakos Group, of the Damara Supergroup. These rocks were tectonised, being part of the southern margin zone of the Damara Orogenic Belt, and were affected by multiple phases of thrust faulting (Miller 2009). The direction of movement is north to northeast against the pre-Damara Supergroup basement rocks, the Hohewarte Metamorphic Complex.

Locally, the marble and quartz-biotite schist units have a north-east strike and the faulted contact between the units dips southeast at a high angle (70°). The marble is karstified to variable degrees and average borehole blowout yield (960 m^3/day) is high (Department of Water Affairs and Forestry – Namibia 2012). Boreholes drilled during this study were located in the down-dip side of the contact, penetrating the weathered hanging-wall quartz-biotite-schist fractured contact zone, followed by marble. The core of the marble band is less fractured, and includes inter-bedded talc schist, sericite-quartz schist and dolomite. The footwall contact with basement rock is, however, fractured and karstified. Its extent along the strike is terminated by faults at approximately 1200m south-west (Figure 3-1) and 2400m to the north-east of the Usip River.

Usip River is the main surface drainage and flows southwards across the north-east striking lithological units. River alluvial sediment forms a cover up to 500 meters wide along the channel but widens towards the south over the weathered schist (Figure 3-1).

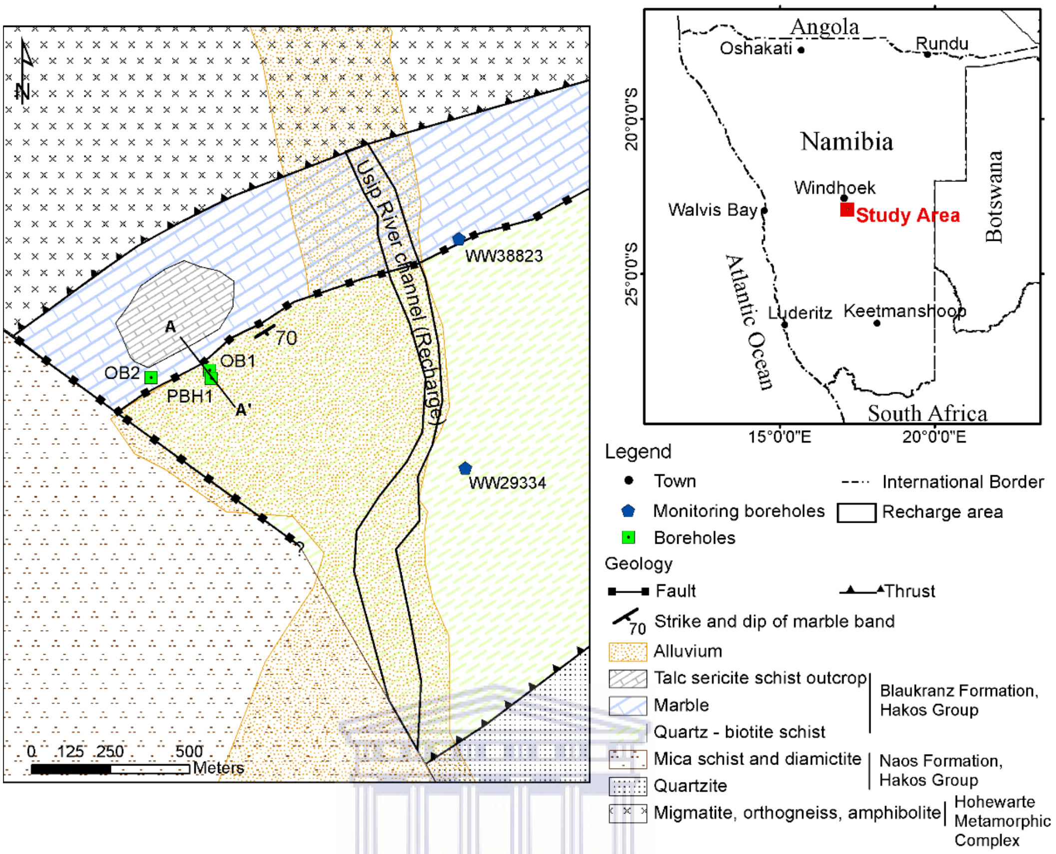

Figure 3-1: Borehole positions and simplified outcrop geology of the study area in Groot Aub, Namibia (pumping borehole PBH1; observation borehole 1: OB1; observation borehole 2:OB2)

3.3 MATERIALS AND METHODS

3.3.1 HYDRAULIC TEST

Constant rate tests (Test 1) carried out in a borehole penetrating the fractured contact zone are seen to be influenced by barrier boundary effects at intermediate to late time. Test 1 consisted of a 2-day constant-rate test at 379m^3/day followed by water level recovery monitoring for 3 days. The tested borehole (PBH1) penetrated the fractured contact zone between 27 and 49 m below ground level followed by the marble unit below. One observation borehole is located in the fracture zone (OB1) at right angles to the fracture direction at a distance of 25.6m from PBH1. A second observation borehole lies in the competent marble (OB2) at a distance of 190m from PBH1 (Figure 3-1).

Unfortunately, observation boreholes were not drilled in the quartz-biotite schist in the southern direction due to financial constraints.

Interpretation of the constant-rate test with Theis type curve fits (Kruseman and DeRidder 1994; Duffield 2007) is given in Figure 3-2. The semi-log time drawdown plot (Figure 3-2 a) shows a constant positive slope with stabilisation of the drawdown derivative in intermediate to late time (after 10 to 600 minutes) indicating conditions equivalent to infinite-acting radial flow. Theis curve fit is possible under these conditions (van Tonder et al., 2002) and gives a transmissivity value of 75 m^2/day and storativity of 0.0018. The drawdown data up to the first 10 minutes were affected by discharge fluctuations.

At late time, the slope of the drawdown curve in the semi-log plot quadruples (from 0.75 to 3 in OB1 and from 1 to 4 in PBH) and suggests that the aquifer is affected by perpendicular barriers (van Tonder et al. 2002). According to the site geology, barrier boundaries could be expected on three sides of the aquifer – the impervious basement to the north, fault truncated contact to the west and contact with quartz-biotite schist to the south. The best fit to the drawdown data is however achieved with barrier boundaries at right angles to the north and west at distances of 180m and 100m, respectively. Trial with an additional barrier to the south results in poor fit, particularly to the recovery data. The weathered nature of the quartz-mica schist suggests that the contact with the schist cannot be considered a barrier.

To verify the heterogeneity of the aquifer, the data and interpreted curves are shown in a composite plot (Figure 3-2 b). In the composite plot, drawdown is plotted against time data divided by the square of the radial distance to the observation borehole as described in Kruseman and DeRidder (1994) and Duffield (2007). In a homogeneous aquifer, drawdown data from fully penetrating observation boreholes will fit a single type curve, provided that the Theis model is applicable. Drawdown data from complex aquifers with multiple borehole observation data can be plotted in a composite plot to gain insight into the effect of heterogeneities such as barrier boundaries and skin effect.

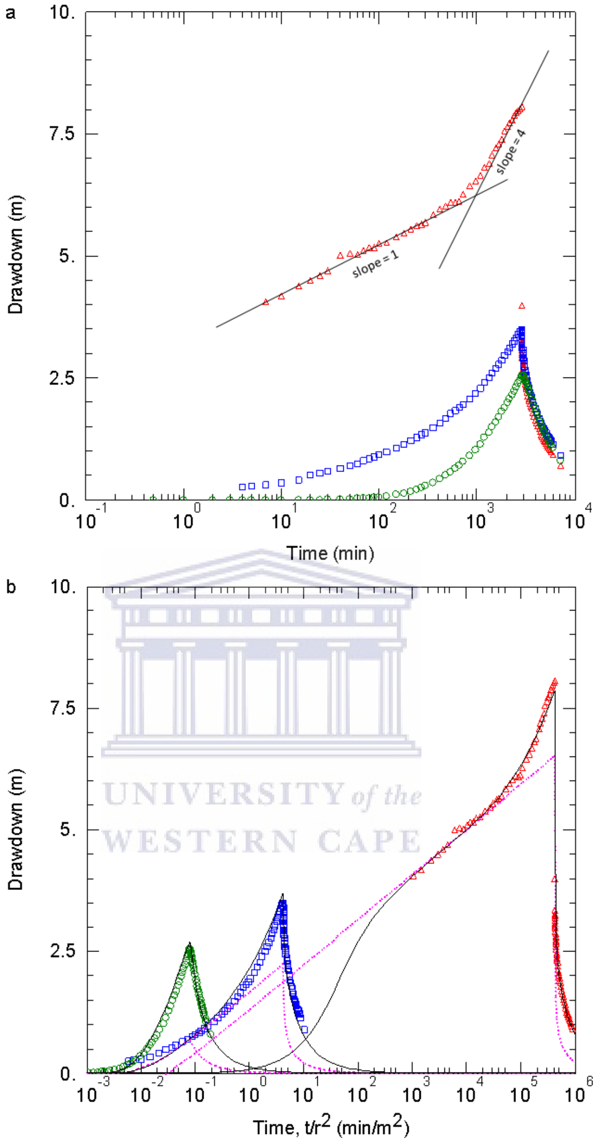

Figure 3-2: a. Semi-log plot of constant-rate test data. b. Constant-rate test data with fitted curve using Theis Method in a composite plot (PBH1 circles; OB1 squares; OB2 triangles). The early time data are influenced by discharge fluctuations. Barrier boundaries are located at right angles at 180 m and 100 m from the pumping borehole. The red dotted line shows the fitted curve without the influence of well bore storage in the pumping borehole and barrier boundaries.

In the composite plot (Figure 3-2 b) the effect of barrier boundaries and skin on the Theis curve fit for a confined homogeneous aquifer is illustrated (red dotted line). The departure of the fitted curve from the Theis fit in OB1 and OB2 is due to the barrier boundaries while the pumping borehole is probably affected by both negative borehole skin and barrier boundary effects. The geological information supports the presence of barrier boundaries at right angles. Recovery of water levels in pumping and observation boreholes following the constant rate test was incomplete in a period of monitoring equivalent to the pumping period. This is interpreted to be due to the bounded nature of the aquifer.

Additionally, Test 1 was carried out during a long period of hydrograph recession after a recharge event. The residual drawdown at the end of the test indicates that replenishment of the bounded aquifer through river bed leakage is not significant and likely to occur only during times of flow in the ephemeral stream.

Analytical methods (e.g. Theis) have limitations in estimating storage coefficient values in a heterogeneous system (van Tonder et al. 2002). Estimation of sustainable yield required that the storage coefficient of the aquifer units and no-flow boundaries be verified.

3.3.2 CONCEPTUAL UNDERSTANDING

The conceptual understanding based on the geology and hydraulic test interpretation that forms the basis of the numerical model setup, and in turn being tested, includes the following.

a) The fractured contact zone between marble and quartz-mica schist forms a transmissive unit. The marble unit in the northern contact is variably fractured and heterogeneous. For the purposes of the study, the marble unit and the fracture zone (Table 3-1) are considered separate aquifer units (Zone 1 and Zone 2 respectively). Zone 3 is the quartz-mica schist unit.

b) The constant-rate test data show that the aquifer is bounded by no-flow boundaries at right angles with impervious basement rocks to the north and termination of the marble unit by faulting to the south-west.

c) At the time of the hydraulic test the groundwater levels had declined for 330 days following a recharge event. The groundwater system, as evident from hydrographs, does not attain steady state within the design time scale of a groundwater supply scheme (typically 20 to 50 years). But, for the purpose of the study, water level data collected prior to the test are used as initial conditions.

d) The Usip River alluvium and weathered bedrock at surface jointly form a continuous unit of limited thickness along the river (Figure 3-1). Recharge occurs during times of flow in the River and inflow from the eastern extent of the marble unit takes place under pumping stress. Higher recharge flux to the marble and fractured contact zone is expected relative to quartz-mica schist.

e) The pumping borehole drilled into the fracture zone is affected by the negative borehole skin.

3.4 SIMULATION OF THE HYDRAULIC TEST

The physical system described above provides a framework for setting up and calibrating a transient numerical groundwater flow model of the hydraulic test using the pumping and recovery water level data as observations. Initial head distribution in the model domain was calculated by calibrating a steady state model under the same boundary conditions using water level observations measured prior to the hydraulic test.

3.4.1 MODEL CONSTRUCTION

The finite difference code MODFLOW-2000 (McDonald and Harbaugh 1988; Harbaugh et al. 2000) was used to construct the models. The finite-difference code numerically solves the three-dimensional groundwater-flow equation under steady or transient flow conditions in a heterogeneous and anisotropic medium (Harbaugh et al. 2000). The layer property flow package and the Observation Process, Sensitivity Process and Parameter-Estimation Process in MODFLOW-

2000 were used for inverse modelling calculations (Hill et al. 2000; Hill and Tiedeman 2007).

Input of hydraulic properties was obtained using parameters and zone arrays (Harbaugh, et al., 2000), which include horizontal hydraulic conductivity, vertical hydraulic conductivity (as a ratio of the horizontal hydraulic conductivity), specific storage and recharge (Table 3-1). The parameters were assigned to all layers, except recharge, which applies to the top-most layer only. The model incorporates the fractured contact and the marble to the north and weathered quartz-mica schist to the south (Figure 3-3 and Figure 3-4) as separate zone arrays. The fractured contact is modelled simply as a narrow zone extending along strike bounded by a zone each to the north and south representing the marble and schist units (Figure 3-3). The model extends to the fault-terminated end of the marble band to the south-west and immediately northeast of the Usip River.

The grid is oriented northeast at 58 degree to north so that the principal hydraulic components align to the orientation of the lithological units (Figure 3-3). The southwest and northwest sides of the grid define no-flow boundaries as conceptualised above. The extent of the southeast side is at the limit of the mapped quartz-mica schist at a considerable distance from the pumping borehole. The northeast extent of the grid is east of the Usip River channel. Inflow from the eastern extent of the marble unit and from leakage from the Usip River alluvium is combined by using the recharge package. The recharge zone array was assigned along the active channel of the Usip River overlying the marble and schist units (Figure 3-3). Outflow from the model is to the south-west boundary using the drain (DRN) package (Figure 3-3).

The top and bottom surfaces were derived from a 30-m grid digital terrain model (Department of Surveys and Mapping – Namibia 2012) and depth to water strikes recorded in 9 boreholes. Most water strike depths ranged from 24 to 50m from surface with one deep water strike reported at a depth of 81 m. The layer of enhanced hydraulic properties conditioning the aquifer is estimated to extend to 60 m depth from this information. The depth at which groundwater is encountered compares well with estimates in other dipping carbonate aquifers reported (Seimons 1989).

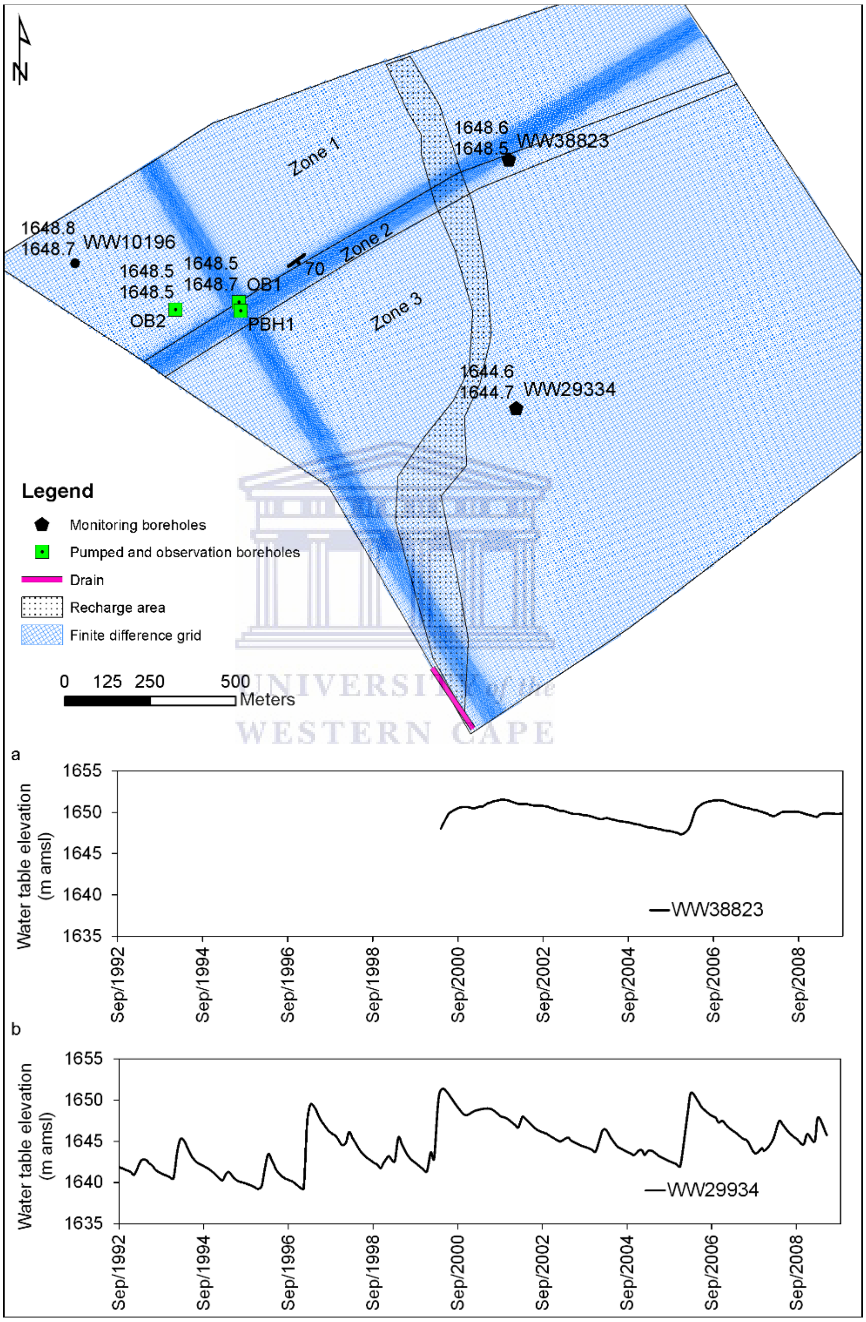

Figure 3-3: Model grid cell and boundaries, and zones. Steady state observed (upper value) and simulated (lower value) heads are shown next to boreholes (meters above mean sea level (m amsl). a. Hydrograph of monitoring borehole WW38823 b. Hydrograph of monitoring

3.4.2 GRID DISCRETISATION

The steady state model grid of the approximately 1500 m by 2000 m model domain is spatially discretised into 20 m by 20 m cells. A single geologic unit was vertically discretised into 5 layers of 12 m thickness each. The grid consists of 107 columns and 95 rows. For the transient model, a finer grid of 10 m cell size was refined with the minimum cell size of 1 m centred on the pumping borehole PBH. The final grid consists of 264 columns and 243 rows maintaining a spatial aspect ratio of 1:10. The vertical component of flow in the dipping marble unit is considered important and the single geologic unit is vertically discretised to 15 layers of equal thickness of 4 m. Trials using larger number of layers, up to 30, showed that a higher degree than 15 layers did not change parameter estimates significantly but required significantly larger computation time.

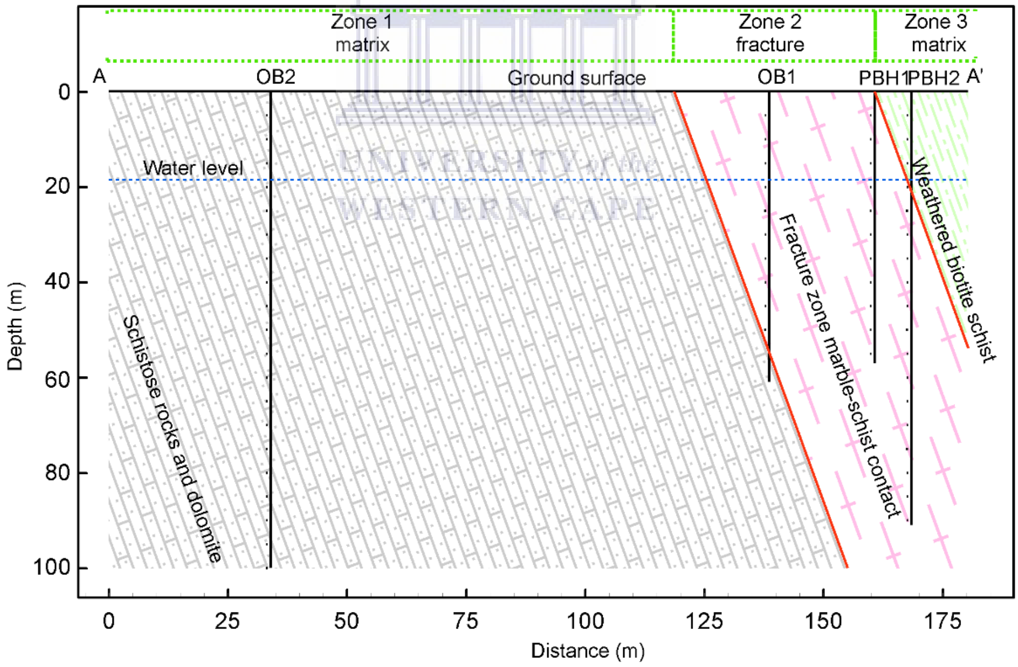

Figure 3-4: North-south cross-section across the marble and quartz-biotite schist contact and modelled zones.

A limitation of using a numerical model based on rectilinear finite difference grids is in simulating axisymmetric flow to boreholes, as head gradients are underestimated in the vicinity of the pumping borehole (Barrash and Dougherty

1997). This is mainly due to the difference between volume of the cell containing the borehole and the actual volume of the borehole, and between hydraulic properties of the borehole and the aquifer material surrounding the borehole. This problem is resolved by derivation of several schemes to modify the grid design, particularly in the case of MODFLOW 2000 (Reily and Harburg 1993; Samani et al. 2004; Langevin 2008). A finer rectilinear discretisation scheme from the borehole outward was successfully used to simulate drawdown in a pumping borehole where well losses are not significant (Barrash and Doherty 1997). In this study the pumping borehole PBH1 shows negative borehole skin.

3.4.3 BOREHOLE SKIN

The drawdown in the pumping borehole PBH1 is affected by borehole skin. The borehole skin is a region immediately around the borehole of very low storage capacity where the hydraulic conductivity differs to that of the formation (Kruseman and DeRidder 1994). A skin zone with higher conductivity, as through interception of the fracture zone, results in a negative borehole skin factor. The drawdown during the pumping phase measured in the borehole with negative skin is less compared to that in the formation immediately outside the skin zone. For a homogeneous infinite aquifer, constant discharge from a fully penetrating borehole with negligible well bore storage will result in a curve parallel to one without skin. In a heterogeneous aquifer, barrier boundary conditions affect the value of skin as shown in van Tonder et al. (2002). The water level recovery data from the pumping borehole is not affected by borehole skin (Kruseman and DeRidder 1994) and is therefore used as observations together with the drawdown and recovery of the observation boreholes in calibrating the constant rate test.

3.4.4 STEADY STATE CALIBRATION

Groundwater head decline from north to south in the model domain and five water level measurements (Figure 3-1) taken preceding the hydraulic tests were available. The data were collected after a prolonged decline of water levels, representing conditions when no significant recharge occurred. Inflow from the extension of the fracture zone and the marble unit to the east is accounted through the recharge package.

Sensitivity analyses carried out prior to steady state model calibration showed that the recharge flux parameter and hydraulic conductivity parameter of Zone 1 are most sensitive with the highest composite scaled sensitivity (CSS) value of 11 while other parameters are insensitive. As the recharge and hydraulic conductivity are correlated parameters, all hydraulic conductivities and the drain conductivity were manually set. Inverse modelling was carried out to obtain the recharge parameter, RCH_Par1 (Table 3-1).

3.4.5 TRANSIENT MODEL CALIBRATION

The observations consisted of 39 constant-rate test and recovery water level measurements for each observation borehole. Only recovery data were used, as observations of the pumping data are affected by borehole skin. No observations from the unit to the south of the fracture zone are available. The preconditioned-conjugate gradient solver (PCG2) and the calibration process were run in 2 stress periods for pumping and recovery stages in 25 steps each.

The transient model was calibrated using a combination of manual and inverse methods. Composite scaled sensitivities (CSS) were calculated for the transient model parameters by using the sensitivity process in MODFLOW-2000 for all the hydraulic-conductivity, recharge, drain and vertical hydraulic conductivity parameters (Figure 3-5) following Hill and Tiedeman (2007). The larger CSS values have greater importance in the estimation of the model simulated water levels. The overall sensitivity of the parameters were low, the maximum value being 3.6. The most sensitive parameters were the hydraulic conductivity of Zone 1 followed by specific storage of Zone 2. The next sensitive parameter is the recharge flux followed by specific storage of Zone 1 and hydraulic conductivity of Zone 2. The model is least sensitive to hydraulic conductivity and specific storage of Zone 3, drain conductivity, and the ratio of horizontal to vertical hydraulic conductivity (VANI) of all three zones. The Zone 2 hydraulic conductivity and specific storage values (1.251 m/day and 6e-5 m^{-1}) were based on early time OB1 drawdown data and adjusted to match the pumping borehole recovery observations (Table 3-1). Zone 1 to the north representing the main marble unit includes the observation borehole OB2 and hydraulic conductivity and specific storage values were determined by inverse modelling (Table 3-1). Vertical hydraulic conductivity is assigned using the interlayer vertical anisotropy parameter (VANI), defined as a ratio of the horizontal to vertical hydraulic conductivity. Within the steeply dipping fracture zone, the vertical component of flow is important and a ratio of 1 was used in the absence of any data.

The largest uncertainty lies in the value of specific storage of Zone 3. In the absence of field data, the specific storage was calculated using Jacob's equation (equation 9) as given in Domenico and Swchwartz (1998).

$$Ss = \rho\, g\, (\beta p + n\, \beta w) \qquad \text{….equation 9}$$

where Ss = specific storage, ρ = mass density of water (kg/m^3), g = acceleration due to gravity (m/s^2), βp = matrix or skeletal compressibility (Pa^{-1}), n = porosity (dimensionless ratio) and βw = compressibility of water (Pa^{-1}).

With measured values of vertical compressibility and porosity, specific storage can be calculated with known compressibility of water. A range of vertical compressibility values for fissured rock is given in Domenico and Schwartz (1998) and range from 3.3e-10 to 6.9e-10 Pa^{-1}. A measurement in schist reported in du Preez et al. (2007) gives a value of 5.68e-10 Pa^{-1}. Specific storage values of 3.28e-6 to 6.98e-6 m^{-1} (5.61e-6 to 5.79e-6 m^{-1} in schist) were calculated using the range given in Domenico and Schwartz (1998) using porosity values of 1 to 5%. The porosity values were based on range of estimates for fractured aquifers reported in Adams et al. (2004) for similar rock types in arid north western South Africa. The model converges with the lower and higher value of specific storage (3.28e-6 to 6.98e-6 m^{-1}) with minor adjustments in other parameters (Table 3-1).

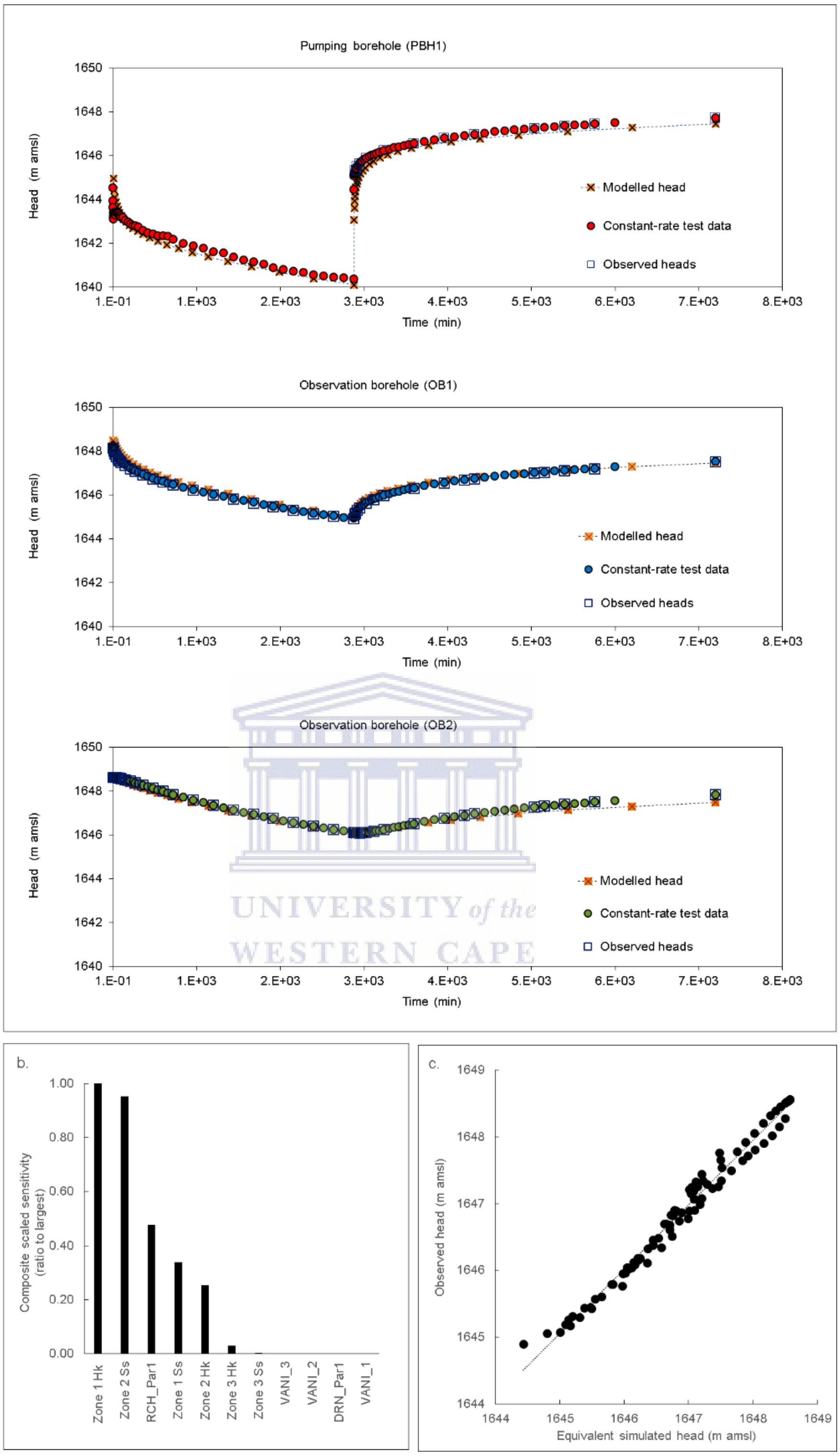

Figure 3-5: Model of constant-rate test calibration results. a. Modelled and actual drawdown data, and pumping and recovery periods of the constant-rate test. b. Composite scaled sensitivity of parameters (see Table 3-1). c. plot of observed and simulated heads

Table 3-1: Model input and estimated parameters. Location of Zones 1 to 3 is shown in Figure 3-3. Parameter value estimates are given for a high and low specific storage of Zone 3. Values marked with an asterisk have been estimated through inverse modelling (MODFLOW 2000). Higher and lower 95% linear confidence intervals are given in parentheses.

Parameter (units)	Value 1	Value 2	Description
Zone 1 Hk (m/day)	2.82* (3.15 / 2.52)	2.87* (3.22 / 2.56)	Hydraulic conductivity (Hk) of fractured marble. Initial value from hydraulic test is 1.5 m/day.
Zone 2 Hk (m/day)	1.050	1.050	Hydraulic conductivity of contact zone. Starting value from hydraulic test is 1.25 m/day; manually adjusted.
Zone 3 Hk (m/day)	0.035	0.035	Hydraulic conductivity of quartz-biotite schist; manually adjusted.
Zone 1 Ss (m^{-1})	1.34e-6* (2.06e-6 / 8.67e-7)	1.77e-6* (2.46e-6 / 1.28e-6)	Specific storage (Ss) of fractured marble.
Zone 2 Ss (m^{-1})	5.70e-5	6.04e-5	Specific storage of contact zone. Starting value from hydraulic test is 6e-5 m^{-1}; manually adjusted.
Zone 3 Ss (m^{-1})	6.98e-6 (high)	3.28e-6 (low)	The model was run in two scenarios using a low and a high specific storage value of the quartz-mica schist unit.
DRN_Par1 (m/day)	0.50	0.50	Drain (DRN) conductivity. Estimated from steady state model
RCH_Par1 (m/day)	0.0026*	0.0026*	Recharge (RCH) flux. Estimated from steady state model
VANI_1	1	1	Ratio of horizontal to vertical hydraulic conductivity (VANI) of zone 1
VANI_2	1	1	Ratio of horizontal to vertical hydraulic conductivity of zone 2
VANI_3	10	10	Ratio of horizontal to vertical hydraulic conductivity of zone 3

The overall simulated heads agree well with the observed values (Figure 3-5) and the standard error of regression value is 0.175. The water level recovery data show slightly larger simulated values for PBH1 and OB2.

3.5 SIMULATION OF GROUNDWATER HYDROGRAPH

Two monitoring boreholes maintained by the Namibian Department of Water Affairs and Forestry (DWAF) are located approximately 900m east and south-east of the pumping borehole, on the left bank of the Usip River (Figure 3-1). Monitoring borehole WW38823 is located on the marble and schist contact zone, while WW29334 is located in quartz-biotite schist. The data show three significant recharge events in 2001, 2006 and 2010 with relatively minor events in 2008 and 2009 (Figure 3-3). The Windhoek rainfall record (Namibia Meteorological Station, unpublished data, 2012) is shown in the groundwater hydrograph as no river gauging records are available. To test the recharge process the period from 1997 to 2009 of a hydrograph record (WW29334) was simulated using the calibrated models with two sets of parameters values given in Table 3-1 and assigning recharge parameters to each event (stress period). Inverse modelling with the hydrographs records as observed heads was carried out using MODFLOW 2000. Instantaneous response to rainfall event (and flow in the river) is seen in WW29334 while a much smoother hydrograph record is seen in borehole WW38823. WW29334 was modelled, as the hydrograph of WW38823 is complex with a lag in response of 4 months probably due to intermediate storage in the alluvium, which is not been considered in the model.

The duration of recharge events were derived from rainfall records as no river gauging data were available. Runoff in the ephemeral rivers in rocky terrain is a direct result of rain in the catchment, usually with little delay. Visually, no influence is seen in the hydrograph for events of less than the long term monthly average of 40 mm. Events larger than 40 mm/month occurred within the wet summer months from November to May. These periods were selected and, to be used as recharge periods.

3.6 RESULTS AND DISCUSSION

The observed heads of the constant rate test are reproduced by a simple transient numerical model (Figure 3-5) representing dipping aquifer units bounded by no-flow boundaries in two sides. The initial hydraulic conductivity and specific storage estimates from curve fitting are comparable to the values obtained (Table 3-1) for the fracture zone (Zone 2). Hydraulic conductivity estimated for the main marble unit (Zone 1) is higher but is reasonable considering the fractured nature of the unit.

The partial recovery of water levels in all observed boreholes after a period equivalent to the duration of pumping (Figure 3-5) was reproduced, with the model water balance showing water is sourced from storage during pumping within the limited extent of the model domain. The low inflow rate, modelled using the recharge package at a rate calibrated in the steady state model, leaves a residual drawdown in a time period equivalent to the pumping period and recovery of water levels to pre-pumping levels would take more than 2 times the pumping period. Thus, under 'normal' conditions net outflow rates (including extraction) could exceed rate of inflow and groundwater levels would decline. Abstraction would effectively be from the stored volume within the bounded aquifer. Episodic recharge events replenish the aquifer after long intervals, when rainfall exceeds a certain threshold value (van Tonder and Bean 2003) and cause substantial flow in the ephemeral river. This is consistent with the general model put forward for episodic recharge in semi-arid areas including Namibia by Xu and Braune (2010).

Episodic recharge is further examined by simulation of the hydrograph of WW29334. The water balance in each stress period, when rainfall exceeds a threshold value, involves recharge, discharge through the Drain package, and volumes in and out of storage in the aquifer (equation 10).

Recharge IN + Storage IN = Drain OUT + Storage OUT ….equation 10

Except during the recharge events, recharge (Recharge IN) and storage gained by the aquifer (Storage OUT) are zero and Storage IN balances Drain OUT, i.e., the aquifer storage is drained and the hydrograph shows a decline. During recharge events, when recharge exceeds aquifer losses, the Storage OUT value is positive representing actual gain of storage to the aquifer. The Storage OUT values are part of the output from the water balance data of the model and are used to calculate storage gained over the model domain for each event (Table 3-2).

The modelled hydrographs using the two sets of parameters in Table 3-1 gave similar water budgets with estimates of yearly storage gained in the range of 3054 to 3711 m^3. The results (Table 3-2) show that episodic events can account for all recharge with very limited inflow during the remaining period. Long term recharge over the approximately 12 year modelled period is 0.3% of annual rainfall. Recharge events vary from 0.04% to 0.6% (Table 3-2) of annual rainfall. Significant recharge events are related to higher intensity rainfall events that are separated by periods of up to 5 years, e.g., 1999-2000 to 2005-2006 (Fig 6), similar to the estimate of the one in 5 to 9 years for such events in semi-arid South Africa (van Wyk et al. 2012). In addition, rainfall events that follow on a major recharge event does not produce a similar water level response (Fig 6). Based on the sum of the aquifer storage gained in the long term (12 years), it is seen that a limited volume (3054 to 3711 m^3/annum or 8 to 10 m^3/day) is taken into storage. At a WHO recommended basic water requirement of 25 l/ capita/day (WHO 2003) the scheme can support a population of about 360 taking the average value of 9 m^3/day. This value is an estimate of the maximum long term available resource taking into account all existing outflow from the model domain and presuming that the current climate conditions persist. Uncertainty of the estimate primarily arises from the localised distribution and small number of observation points around the pumping borehole and the absence of observation boreholes in the quartz-mica schist unit. The quartz-mica schist is the largest unit in the domain and uncertainty in its specific storage estimate has large influence on the total calculated resource. The lack of local rainfall and ephemeral river flow monitoring data adds to the uncertainty of the sustainable yield estimate.

Table 3-2: Modelled recharge values derived from simulation of hydrograph of borehole WW29334 using the upper estimate of Zone 3 specific storage together with identified recharge events from rainfall data

Hydrological year	No. of months when rainfall exceeded 40mm/month	Rainfall in period (mm)	Total rainfall in year (mm)	Gain in storage (Storage OUT) during recharge event (m^3)	Modelled recharge as % of total rainfall in year
1997-1998	2	178.8	230.4	39	0.01%
1998-1999	2	149.6	269.8	2,885	0.62%
1999-2000	4	545.6	623.7	9,632	0.56%
2000-2001	4	408.4	459.4	6,412	0.50%
2001-2002	3	345.0	376.4	2,224	0.21%
2002-2003	3	210.7	281.7	2,089	0.32%
2003-2004	4	422.2	475.8	2,172	0.16%
2004-2005	7	467.6	467.6	643	0.04%
2005-2006	6	689.6	715.7	11,163	0.52%
2006-2007	1	56.0	189.9	0	0.00%
2007-2008	3	342.2	387.6	5,524	0.52%
2008-2009	5	581.1	637.2	3,030	0.17%

The use of a numerical model however allows incorporation of the complexity of the aquifer interpreted through the geological and hydraulic test data to be represented and continued evaluation of the scheme during production period against observed water level, abstraction and rainfall and river flow monitoring data. The initial solution obtained may not be unique but serves as a starting point to be tested against observations.

3.7 CONCLUSIONS

Fractured rock aquifers in semi-arid regions are sustained by recharge from exceptional rainfall events. Inflow rates into aquifers are generally low and extraction of groundwater is from storage in the aquifer, which is replenished through episodic recharge events. The aquifer extent and boundary conditions derived from direct field observations were represented in the numerical model.

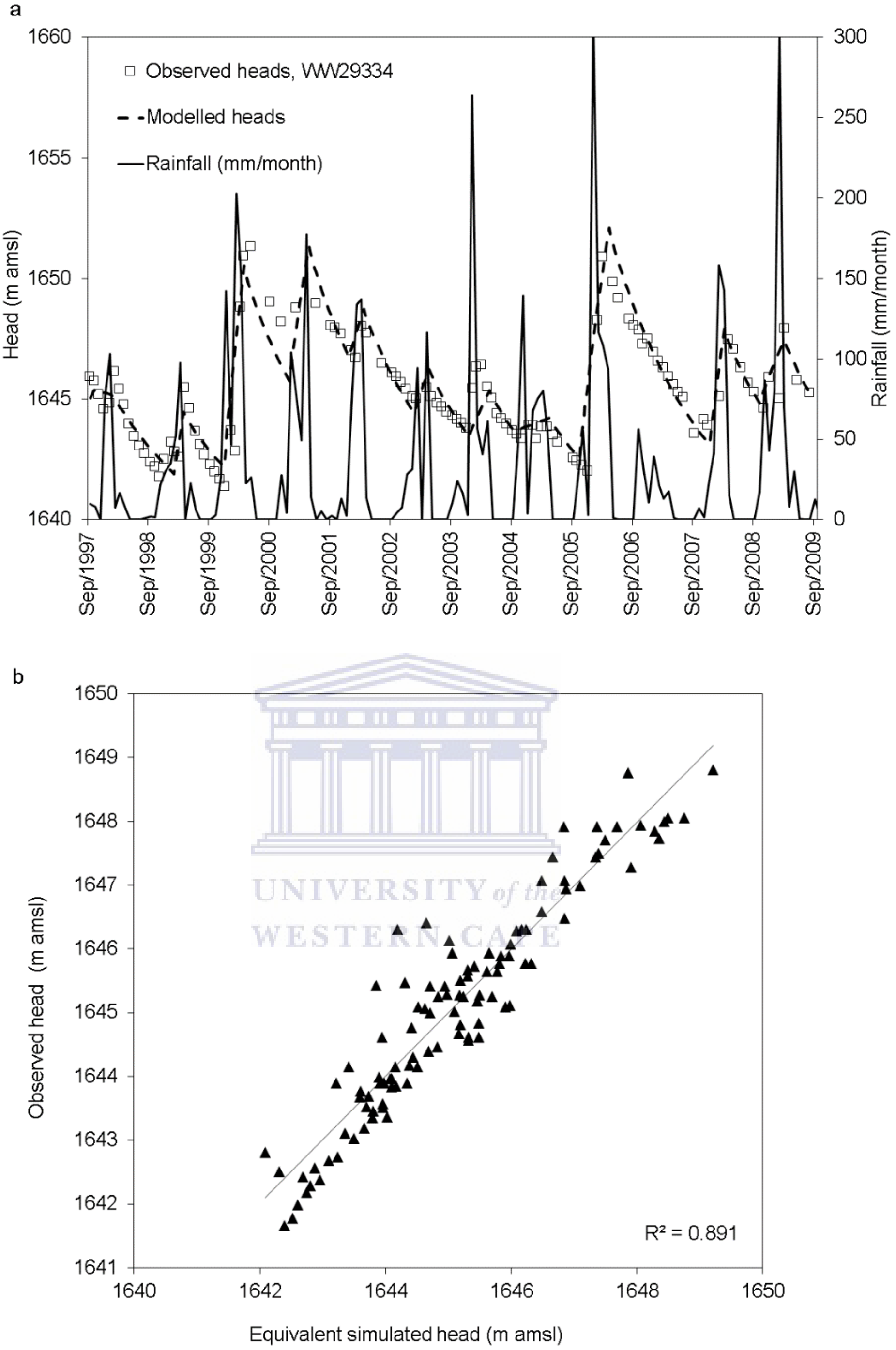

Figure 3-6: a. Groundwater hydrographs of borehole WW29334 (with modelled heads). b. model calibration results – plot of observed and simulated heads

The conceptual aquifer model, including the recharge mechanism, was tested and serves to show the limited resource available and dependence on the episodic recharge events. The lack of data makes similar evaluations difficult in common rural water supply schemes. A policy to include data collection and continued assessment of isolated rural schemes would increase security of supply. This paper demonstrates a useful approach to arrive at sustainable yield for a rural area under arid-semi and arid conditions.

3.8 ACKNOWLEDGEMENT

F. Bockmühl located the boreholes and provided the basic drilling information. The authors are grateful to Mountain View Development Company for permission to use the data. The Geohydrology Division, Department of Water Affairs and Forestry, Namibia, is acknowledged for the groundwater monitoring data and use of the GROWAS database. We would very much like to thank the reviewers, whose suggestions and comments improved the paper significantly.

Chapter 4: THE RECHARGE PROCESS IN ALLUVIAL STRIP AQUIFER IN NAMIBIA AND IMPLICATION FOR ARTIFICIAL RECHARGE

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Abstract

Alluvial strip aquifers associated with ephemeral rivers are important groundwater supply sources that sustain numerous settlements and ecological systems in arid Namibia. More than 70 % of the population in the nation's western and southern regions depend on alluvial aquifers associated with ephemeral rivers. Under natural conditions, recharge occurs through infiltration during flood events. Due to the characteristic spatial and temporal variability of rainfall in arid regions, recharge is irregular making the aquifers challenging to manage sustainably and they are often overexploited. This condition is likely to become more acute with increasing water demand and climate change, and artificial recharge has been projected as the apparent means of increasing reliability of supply. The article explores, through a case study and numerical simulation, the processes controlling infiltration, significance of surface water and groundwater losses, and possible artificial recharge options. It is concluded that recharge processes in arid alluvial aquifers differ significantly from those processes in sub humid systems and viability of artificial recharge requires assessment through an understanding of the natural recharge process and losses from the aquifer. It is also established that in arid-region catchments, infiltration through the streambed occurs at rates dependent on factors such as antecedent conditions, flow rate, flow duration, channel morphology, and sediment texture and composition. The study provides an important reference for sustainable management of alluvial aquifer systems in similar regions.

Keywords: Alluvial strip aquifers, Arid regions, Artificial recharge, Numerical modelling, Namibia

4.1 INTRODUCTION

Ephemeral rivers and associated strip aquifers are important water resources in Namibia that sustain populations, economic activities and ecosystems in the arid to hyper-arid western and southern regions. The importance of the Namibian ephemeral rivers are discussed in Jacobson et al. (1995) and Jacobson and Jacobson (2012). Rivers that flow westward and south (Figure 4-1) have headwaters in areas of relatively higher precipitation and flow to regions of increasing aridity (Figure 4-1 b).These rivers have been described as forming 'linear oases' in these water scarce areas and are therefore of greater per capita importance as water sources (Seely et al. 2003) than is apparent from the size of their surface flow volumes and associated groundwater resources.

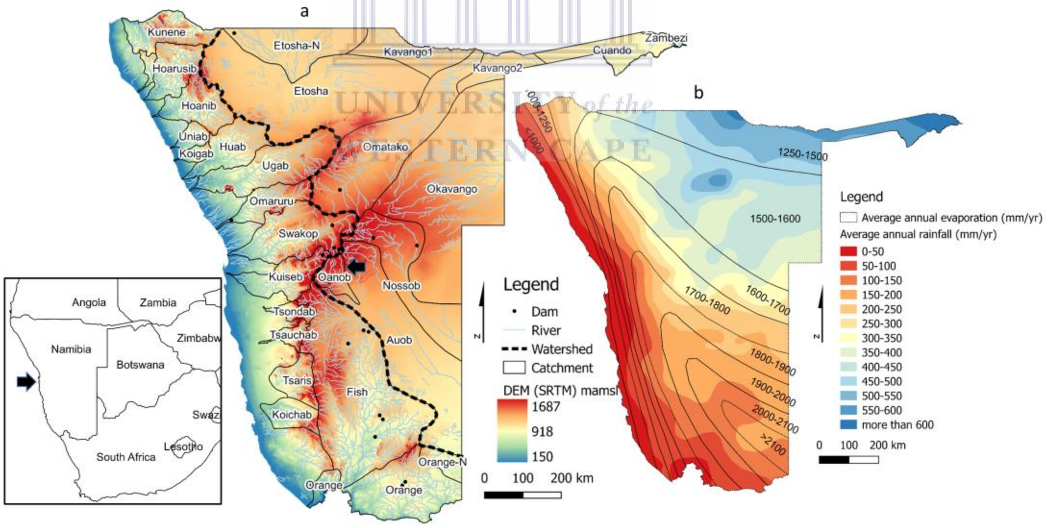

Figure 4-1: a Location of project area, ephemeral rivers and their catchments in Namibia. Location of Namibia and the Oanob catchment are shown by filled arrows. (DEM = digital elevation model). b Contoured rainfall and evaporation rates, showing that arid to hyper-arid conditions prevail over most of the lower catchments. Average rainfall is higher in the north central part of the country but limited to upper parts of the catchments (after Mandelson et al., 2002)

The ephemeral rivers are characterised by extreme variability in flow with typically extended dry periods followed by runoff that is initiated rapidly during precipitation events in catchments with exposed bedrock, thin soil cover and vegetation (Bull and Kirkby 2002; Nanson et al.2002; Chow et al. 1988). Sustainable use of the associated alluvial groundwater resource is complex (Jacobson et al. 1995) as river flow and resulting recharge to the aquifer is episodic, a condition that is likely to be intensified by changing climatic conditions (MAWF 2010).

The current rate of increase in water demand in urban areas of Namibia is not sustainable as most known sources are developed and other available resources are at large distances away (MAWF 2010). Climate change predictions are yet uncertain but commonly indicate higher rainfall intensity and increased drought periods (MAWF 2010; MET 2008) and, therefore, increased water stress, making ephemeral rivers important as artificial recharge and groundwater storage sites. Most infiltration studies in Namibia date back to the 1980s (DWAF 1987; Crerar et al. 1988). A recent review of quantitative estimate of recharge through infiltration from ephemeral rivers by Shanafield and Cook (2014) lists few studies in the arid regions of southern Africa. An example of a successfully implemented artificial recharge scheme is the Omaruru Delta scheme (Omdel) on the Omaruru River (NamWater 1995).The scheme has enhanced recharge and water security in a hyper-arid coastal area of Namibia. The Omaruru River flow is impounded in a dam allowing suspended silt to settle and the clear water is used for infiltration. The frequency of river flow, flow volumes and recharge however remains uncertain with three flood events reaching the dam since completion in 1994. Future schemes therefore require infiltration components of ephemeral rivers and their significance be considered carefully.

Past records indicate that the volume of runoff during these infrequent flood events often exceeds the storage capacity of the underlying aquifer, therefore sustaining surface flows through saturation excess which are subject to evapotranspiration losses. The impounding of surface flow in dams for artificial recharge has been promoted as a solution to increase water security. The following investigation and discussion is based on a case study that identifies major hydrological processes in an ephemeral endorheic basin typical of Namibian conditions. The available data on the Oanob River and aquifer provide an opportunity to assess the water budget of an unexploited surface water and groundwater system and the relative importance of infiltration, evapotranspiration and groundwater outflow that impact effective recharge. Water level in the Oanob aquifer has been monitored for the past three decades, and together with the upstream dam water release and spillage data, constitutes the basic information for the assessment. Major rainfall events are seen to cause dam spillage at least once in 5 years, typical of most ephemeral river flow frequency in arid regions of Namibia.

The approach adopted to assess recharge is by simulation of surface flow and long-term groundwater hydrographs. Past studies related reduced infiltration rates to suspended silt content in surface flow (Crerar et al. 1988).Release of apparently clean water with negligible suspended sediments since the 1990s, after completion of an upstream dam, did not result in increased infiltration and the streambed hydraulic conductivity has been found to be the overriding factor. The results suggest that it is necessary to enhance infiltration artificially while optimising the limitation of losses.

4.2 HYDROGEOLOGICAL SETTING

Ephemeral rivers of Namibia (Figure 4-1) include the 12 west flowing rivers, the endorheic Cuvelai system in the north, and the southern drainage systems (Fish River). The headwaters in the central areas experience relatively higher rainfall, while in the down-flow direction to the west and south, rainfall decreases (Jacobson et al. 1995). High evaporation (Figure 4-1), far exceeding rainfall, results in low or negligible diffuse recharge. Infiltration during flood events in ephemeral systems is the main recharge process of the underlying aquifers.

The Oanob River, the subject of the case study, is an ephemeral endorheic river and is a part of the larger Auob River catchment. The associated aquifer consists of alluvial sediments laid down in a narrow incised valley cut into the basement meta-sediments of the Marienhof Formation, Rehoboth Sequence (Sarma et al. 2010; DWAF2009; DWAF 1989a). The Oanob aquifer is 21.5 km long and on average 2.5km wide (Figure 4-2).These sediments are poorly sorted and immature with inter-layered sand, gravel, boulders and finer fractions (clay and silt). The south-west flowing river has its headwater at elevations of 1,800–1,450 m above mean sea level (amsl) in hard rock terrain. Below 1,400 m amsl, immediately east of a regional north–south fault at Rehoboth (Figure 4-2), the aquifer has developed through deposition of sediment in gentle topographic gradients. Elevated bedrock at 6 km from the upstream (northwestern) end of the aquifer (Figure 4-2) separates it into an upstream and a downstream compartment (DWAF 1989a). Bedrock depth is estimated to be 11 m below ground level (bgl) at the divide (Figure 4-2). In the upstream and downstream compartments, maximum sediment thickness is more than 40 and 70 m respectively.

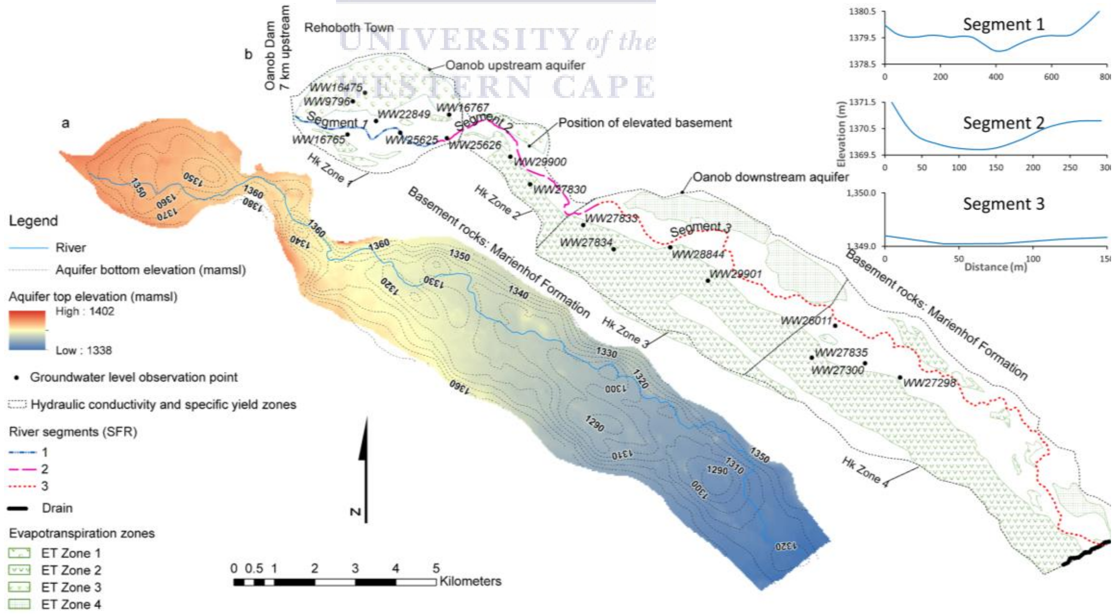

Figure 4-2: a Model domain, boundaries and parameter zones of the Oanob aquifer. b Shown are typical river profiles in the upstream (Segment 1), middle (Segment 2) and downstream section (Segment 3).

4.2.1 CONTROLS ON INFILTRATION OF SURFACE FLOW

Namibian ephemeral rivers are typically losing and remain hydraulically disconnected to underlying aquifers except during flow periods. The thickness of the unsaturated zone is dependent on aquifer hydraulic properties, thickness, and frequency of surface flow, infiltration rates, and rate of groundwater loss. The best studied ephemeral river and associated alluvial aquifer in a similar setting to the Oanob is the Kuiseb River (Dahan et al. 2008; Morin et al. 2009). Dahan et al. (2008) reports change in moisture content in a homogeneous sandy unsaturated zone, surface water level, and ground water level recorded in real time during five flood events in 2006. The flood, after an extended dry period, caused immediate changes in water content in the unsaturated zone with increased unsaturated zone moisture content from an initial 5 % to 8–14 % without reaching saturation level. Water level rise was noted when the wetting front progressed to the water table. Flow duration was found to be a sensitive parameter for recharge, while river stage had little influence.

Monitoring of subsequent floods showed that antecedent conditions were important. Later flood events results in lower infiltration. Overall infiltration rates were found to be in the order of 0.01 m/h in the test site.

Arid region ephemeral rivers have characteristic wide and shallow streambeds (Nanson et al. 2002). While streambed hydraulic conductivity and width control seepage rates for the given flow duration, stream flow depth has limited effect on seepage rates (Dahan et al. 2008). In cases where the unsaturated zone is thick, hydraulic conductivity of the unsaturated zone, river width, initial moisture content, and unsaturated zone thickness (Niswonger and Prudic 2005) are important. Silt content of floodwater is an additional factor determining the fraction of surface flow that can infiltrate (Crerar et al. 1988; DWAF1987).

The Oanob Aquifer has received recharge from river flow in the past. Since the completion of the Oanob Dam in 1990, located 7 km upstream of the aquifer, natural flow in the river has been stopped. The flow events on record are from the releaseofwaterin1992andwaterspillageinsubsequentyears of exceptional rain. It was planned that ‘surplus’ water in the dam would be released by the managing authority on a regular basis to sustain the vegetation downstream (DWAF 1989b) but this was discontinued after the 1992 release failed to raise groundwater levels. The suspension of pumping and flow (resulting from spillage at intervals) has maintained the dependent vegetation, although water level in the upstream aquifer has lowered by approximately 2.5 m since the completion of the dam. Recently observed maximum unsaturated zone thickness is 18 m. The observed monthly groundwater level data show response to flow without time lag close to the river course. The influence of the unsaturated zone lasts for a period that is not detectable in the groundwater level data collected in approximately 1-month intervals. Groundwater mounding and redistribution of recharge through lateral flow (Figure 4-3) can explain the delay in response at observation points away from the river. Infiltration rate is therefore estimated using the available data on groundwater levels, saturated zone aquifer properties and surface flow rates and duration.

4.2.2 EVAPOTRANSPIRATION LOSS

Evapotranspiration is an important discharge method in arid regions (Shanafield et al. 2015) and in the Oanob Aquifer (Sarma et al. 2010). The Normalized Difference Vegetation Index (NDVI) calculated using an Aster satellite image dataset collected during the rainy season (image acquired on 26 December 2008 after 63.6 mm rain in November and December 2008) highlights tree vegetation dominated by the species *Acacia erioloba* (camelthorn). Based on the density of *A. erioloba* species, four zones of evapotranspiration flux were identified (Figure 4-2) and initial estimates of flux were calculated (Table 4-1) using daily average evapotranspiration rates from *A. erioloba* species reported in Obakeng (2007) from Botswana Kalahari. *A. erioloba* species is largely dependent on groundwater with the capacity to tap water from large depths (Lubczynski 2000; Gardiner et al. 2006; Obakeng 2007). The growth and survival of the species is linked to the depth of the groundwater (Schachtschneider and Reinecke 2014) and mature trees are unable to adapt to falling groundwater levels or a large change in soil moisture (Ward and Breen 1983).

4.2.3 AQUIFER PROPERTIES

The aquifer material is poorly sorted with variable clay and silt content. Four zones (Figure 4-2) based on the amount of fine grained material can be identified based on lithological information (DWAF1989a). These are the upstream compartment, the upper and lower parts of the downstream compartment, and a narrow zone connecting the upstream to the downstream compartments. The highest clay content is present in the upper part of the downstream compartment (Figure 4-2) and hydraulic conductivity estimated from hydraulic tests reflects the influence of clay content (Table 4-1). Specific yield of the aquifer is low (6–8 %) and also attributed to the poorly sorted nature of the sediments.

4.3 MATERIALS AND METHODS

4.3.1 SIMULATION OF HYDROGRAPHS

The transient numerical groundwater flow model was constructed to simulate flow events covering a 12-year period from 1994 to 2005. The model initial heads were calculated in a steady-state model. Observed steady-state heads were measured at a time when water level decline rates were the lowest.

The finite difference numerical flow model was built using MODFLOW-NWT and UPW solver package (Niswonger et al. 2011) implemented using ModelMuse 3.6.3.0 (Winston 2009). The Newton formulation of MODFLOW was preferred as the thin unconfined aquifer is subjected to repeated wetting and drying cycles. The model is set up with two convertible (unconfined) layers discretised into 75-m grid cells. The aquifer top is approximated using a 30-m grid digital terrain model. The base of the model was set to the bottom of the alluvial aquifer determined from borehole information and vertical electrical sounding data in DWAF (1989a). The average saturated hydraulic conductivity and specific yield values determined from test pumping for each aquifer zone were input as known values (Table 4-1).

4.3.2 MODEL BOUNDARIES

Groundwater discharge can be via groundwater outflow from the aquifer, evapotranspiration and abstraction. With the construction of the Oanob Dam, large-scale abstraction from the aquifer was discontinued in 1990, and pumping is limited to approximately 40 m^3/day by small-scale stock farmers. The aquifer discharge is mainly through evapotranspiration and groundwater outflow.

The EVT package (Harbaugh 2005) was used to simulate evapotranspiration from the top convertible (unconfined) layer. Four evapotranspiration zones were defined based on density of the *A. erioloba* species (Figure 4-2). Convergence problems are encountered when the EVT package removes water from dry cells that remain active in MODLFOW-NWT (Niswonger et al. 2011). Via application of the ModelMuse 3.6.3.0 pre-processor, the extinction depth was therefore adjusted by 0.25 m above the bottom of the aquifer in the thin (less than 15 m) vertically distorted part of the grid along the edges of the aquifer, whereas in all other cells, an extinction depth of 15 m was assigned.

The Drain (DRN) package (Harbaugh 2005) was used in the south-eastern extremity of the model along which groundwater is discharged from the aquifer. The DRN elevation is set equal to the elevation of the bottom of the aquifer. The DRN package removes water at a rate proportional to the head above the base of the aquifer. If groundwater head falls to or below the base of the aquifer, the DRN package has no further effect. The drain hydraulic conductance is the constant of proportionality between the flow and head difference; thus, to ensure minimal influence of the drain on outflow volumes, a high drain hydraulic conductance (100 m/day) was assigned.

4.4 SIMULATION OF SURFACE WATER INFILTRATION

Flow in the river originates from the Oanob Dam through spillage and releases that enter the upstream segment. Lateral inflow is negligible and is not included in the model. Examination of groundwater hydrographs close to the river channel show that recharge occurs by direct infiltration with negligible time lag. Infiltrated water flow is essentially vertical below the streambed and is distributed through lateral underground flow (Figure 4-3).

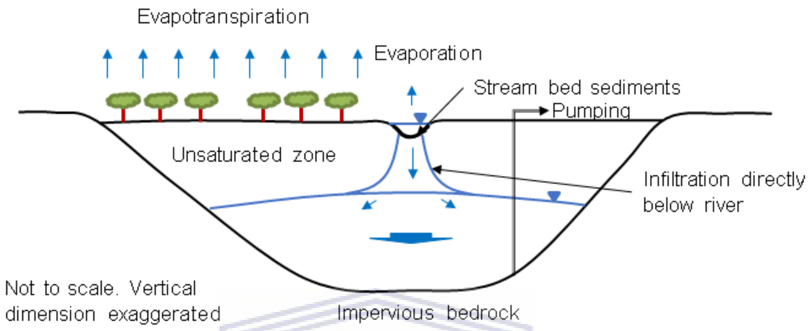

Figure 4-3: Schematic cross-section showing vertical leakage during river flow episodes and groundwater redistribution by lateral flow components within the saturated zone. The groundwater flow component perpendicular to the cross-section towards the down channel direction is indicated with a large filled arrow.

Available hydrological data for the Oanob River are limited to daily flow data (release and spill) from the Oanob Dam and channel characteristics interpreted from field data, aerial photo and elevation data. There are no hydrological observation points in downstream locations; thus, the choice of model is guided by experience on a similar study in Namibia. The kinematic wave model (KWM) was used successfully in the lower reaches of the Kuiseb River under similar hydrological conditions (Morin et al. 2009). Simulated hydrographs have shown that the KWM produced a closer representation of the observed data compared to a diffusive wave model. River morphology (wide and shallow river channels) and gentle slopes in the modelled lower reaches of the Kuiseb River (less than 0.1 %) are comparable to the Oanob River (slope ~0.2 %).

A key purpose of the current study is to assess the rate of infiltration and groundwater recharge from river flow. Reported parameters sensitive to infiltration in losing ephemeral rivers in Namibia are channel width and streambed conductivity (Dahan et al. 2008; Morin et al. 2009), while river stage was shown to be insensitive (Dahan et al. 2008) indirect field observations. A KWM, the Stream Flow Routing or SFR2 package (Niswonger and Prudic 2005; Prudic et al. 2004), is therefore used to simulate ephemeral river flow. Channel-wide flow and flow durations are correctly simulated by the SFR2 package, while uncertainty remains in the estimated stage. The resulting infiltration and recharge due to surface flow determines the groundwater level rise observed in the aquifer. Since aquifer hydraulic properties and river width were estimated through independent methods and entered as known values, the streambed hydraulic conductivity could be calibrated by inverse modelling, which provides the required infiltration volumes during river flow. Streambed conductivities are not correlated with other parameters estimated in the model (evapotranspiration fluxes). The sensitivity of the model to river stage was examined by changing the Manning's roughness coefficient (n) over a range +30 % to – 30% in the calibrated model. Head in the stream is calculated in the SFR package using the Manning's equation in eight point and rectangular profiles (Prudic et al. 2004). The resulting change in root mean square error (RMSE) was minor, supporting the assumption of insensitivity of the river stage (n range from 0.0245 to 0.0455 with corresponding change in RMSE from 1.521 to 1.481 m).

Three river segments were defined based on the nature of the streambed (Figure 4-2).The upstream section of the river has a wide flood plain formed by release of flow from a restricted channel in bedrock to areas of gentler slope. An eight-point river profile (Prudic et al. 2004) in SFR2 was used to define the segment (segment 1). Further downstream, the channel narrows as it passed through bedrock outcrop but retains the wide and shallow profile of arid-region rivers. A rectangular profile is used to approximate the channel profile in this segment (segment 2), while in the downstream segment, the channel profile is wider and is also represented by a rectangular profile (segment 3). The channel width decreases downstream to the southeast end, a typical feature in arid region ephemeral rivers (Bull and Kirkby 2002) where a flow is affected by infiltration. The river channel continues further southeast and discharges to a wide pan beyond the extent of the underlying aquifer (and model domain) where bedrock outcrops are present at shallow levels. Daily dam spillage data were used as inflow on the upstream end of the first segment ignoring losses along the incised channel on hard rock basement rock. Infiltration was found to be sensitive to streambed conductivity (Table 4-1). The presence of a clay and silt rich layer was noted in excavations on field checking that validated the findings (Figure 4-4); see the following for more detail. The lag in groundwater level responses away from the river channel due to lower lateral flow rates is reproduced in the model.

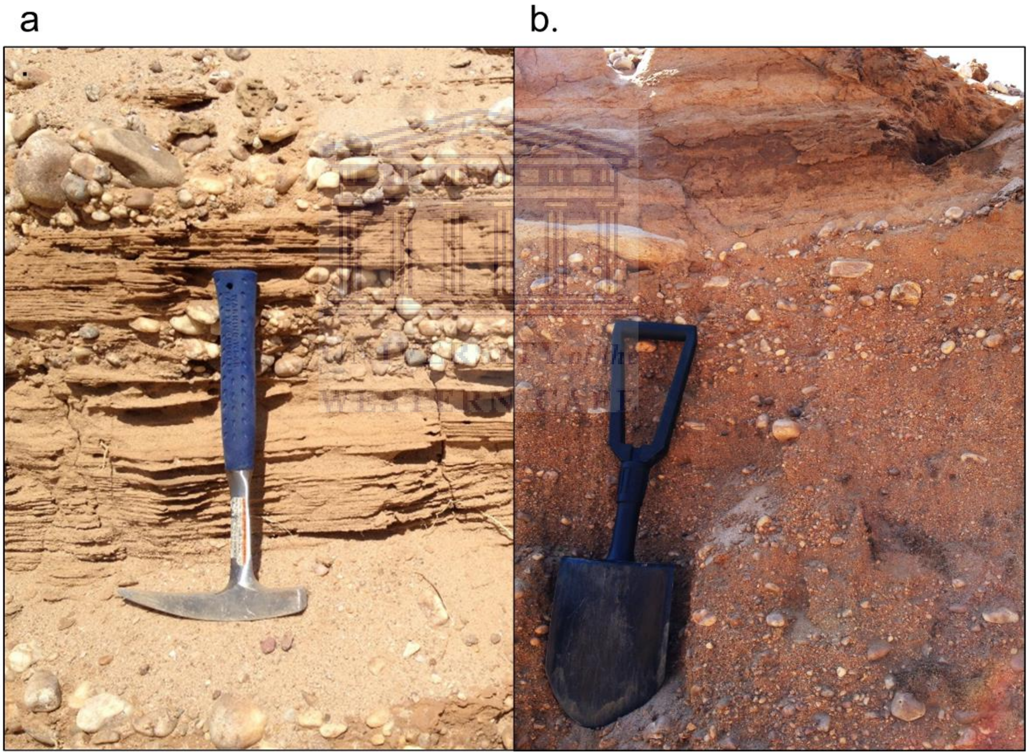

Figure 4-4: Field observations of streambed sediments in excavations in the upstream aquifer. a. normal aquifer material in the flood plain. b. finer streambed sediments (silty fine sand) found as a 0.20 m to 0.4 m layer above coarser aquifer material

4.4.1 MODEL CALIBRATION

The observations used for model calibration were hydraulic heads from monthly water level monitoring data from 18 monitoring boreholes, of which six representative hydrographs are shown in Figure 4-5 a. Hydraulic conductivity and specific yield of the aquifer were estimated by reinterpretation of available hydraulic test data (DWAF 1989a) and were input as known parameters (Table 4-1). Hydraulic conductivity zones were defined based on the data and reflect the clay content in the sediments. Hydraulic conductivity estimates in Zones 1 and 3 show high variability probably due to the poorly sorted heterogeneous nature of the sediments deposited as the river emerges into a wider channel. Zone 2, which connects the upstream and downstream aquifers, is of limited cross section area and has higher conductivity, while hydraulic conductivity and thickness of sediments decrease downstream in Zone 4.

Parameters were defined for streambed conductivities SFR_Par1 to SFR_Par3 in the SFR2 package for three river reaches (Figure 4-2). Four zones of evapotranspiration (Figure 4-2) were simulated using the EVT package and parameters were defined for EVT flux (EVT_Par1 to EVT_Par4). Initial evapotranspiration rate estimates were calculated based on reported range of transpiration (Obakeng 2007) and estimated canopy cover derived from satellite imagery. The evapotranspiration extinction depth was estimated to be 15m below the top of the model layer through trial and error. The streambed conductivity parameters SFR_Par1 and SFR_Par3 and evapotranspiration rates EVT_Par1 and EVT_Par2 were sensitive (Figure 4-5 b) and were calibrated by inverse modelling using UCODE (Poeter et al. 2005). Other parameters, namely, streambed conductivity SFR_Par2, EVT_Par3 and EVT_Par4 were adjusted manually while minor adjustments were made in hydraulic conductivity within the range of known values (Table 4-1).

4.5 RESULTS AND DISCUSSION

4.5.1 INFILTRATION AND RECHARGE

Groundwater mounding below the riverbed due to infiltration during surface flow events and lateral saturated flow is simulated under the condition that infiltration is added instantaneously to the water table in the model. The primary control on infiltration rate is the streambed conductivities. Past studies on recharge of alluvial aquifer concentrated on suspended silt grade material in surface flow that is responsible for limiting inflow to the aquifer (Crerar et al. 1988; DWAF1987). Dam releases and spillages of water with low suspended solids from the upstream dam is seen to have similar inefficient recharge that points to the riverbed sediments as the factor-limiting infiltration in the case of Oanob. Field observation of the riverbed sediments revealed the presence of a silt rich sandy layer varying from 10 to 20 cm in excavations (Figure 4-4). Simulated streambed leakage is 17% of the total river flow volume in the modelled period, less than the previous estimate of 30 % infiltration (DWAF 1989a, 1987). Simulated losses of infiltrated water for the entire modelled period by groundwater outflow and evapotranspiration were in the order of 1 and 15 % of surface flow (6 and 87 % of infiltration) respectively. Gain is storage accounted for 1 % of total surface flow and 6 % of infiltration. The overall relation of recharge events to change in storage and discharge through evapotranspiration and groundwater outflow is shown in Figure 4-6 a, while in Figure 4-6 b, the water budget during an infiltration event is examined in more detail using the model output data.

During periods of river flow and resulting streambed leakage, saturated zone storage is gained. Simulated surface-water infiltration is subject to evapotranspiration and groundwater flow that is seen as the difference in the streambed leakage rate and rate of storage gain (arrows in Figure 4-6 c). Redistribution of water occurs in the saturated zone following a recharge event as groundwater flows down gradient from the mound formed below the riverbed. Comparable declining curves of storage gain and storage depletion in Figure 4-6 c following a recharge event indicate that redistribution of water in the aquifer continues at decreasing rates but without overall change in storage due to redistribution, whereas losses due to evapotranspiration and groundwater flow are seen as small differences in the rates (arrows in Figure 4-6 c). Discharge occurs primarily through evapotranspiration (93 %) and the remaining 7 % via groundwater outflow from the aquifer. Groundwater outflow is significant only when head gradients are high after recharge events, and declines rapidly with falling heads. Episodic recharge events therefore do not progress to a steady-state condition as water is continuously sourced from storage with groundwater level declining (Figure 4-6 d) until the next recharge event occurs.

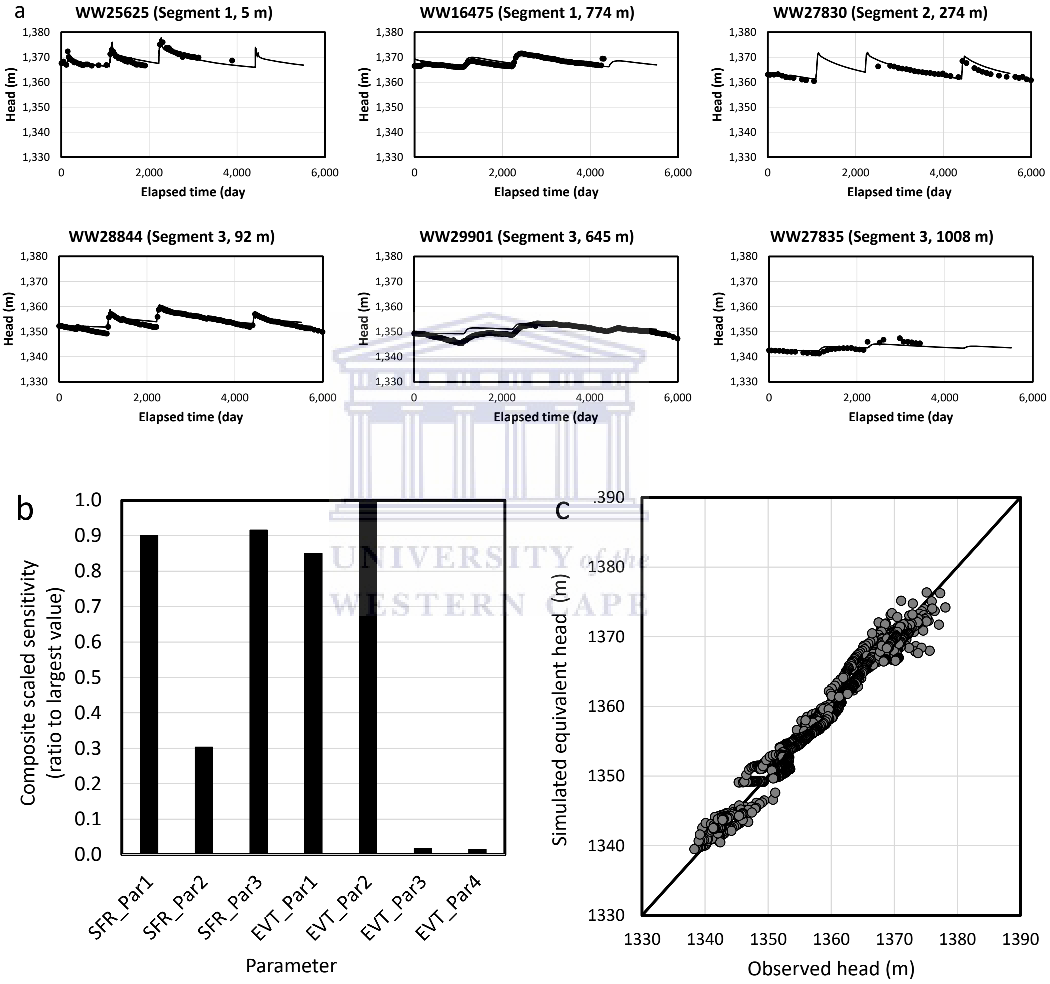

Figure 4-5: a. Selected groundwater hydrographs of modelled (line) and observed heads (points). The closest river segment and distance to the segment are indicated, along with the borehole identification number. Borehole locations are shown in Fig. 4-2 b. Composite scaled sensitivities of parameters (see Table 4-1) c. Model calibration results – plot of observed and simulated heads.

4.5.2 ARTIFICIAL RECHARGE

Under natural conditions, infiltration occurs through the streambed. Any optimisation of flow release from the dam to increase infiltration will have limited impact on increasing recharge due to the low streambed conductivity. The requirement therefore is for infiltration structures that bypass the surficial fine sediments. Possible structures could include infiltration galleries and injection wells when using clear water such as from the Oanob Dam.

Table 4-1: Model input and estimated parameters. Location of hydraulic conductivity and specific yield zones and evapotranspiration zones are shown in Fig 2. Hk is hydraulic conductivity and Sy is specific yield. Values marked with an asterisk have been estimated

Data sets or boundary	Parameter	Value	Remarks
Hydraulic conductivity defined by zone arrays	Zone 1 Hk (m/day)	16	Estimated average values estimated from hydraulic test interpretation. Vertical hydraulic conductivity of the zones are assumed to be 0.1×Hk
	Zone 2 Hk (m/day)	578	
	Zone 3 Hk (m/day)	3.64	
	Zone 4 Hk (m/day)	3.98	
Specific yield defined by zone arrays	Zone 1 Sy	0.075	Estimated average values estimated from hydraulic test interpretation.
	Zone 2 Sy	0.085	
	Zone 3 Sy	0.055	
	Zone 4 Sy	0.055	
Drain Package	DRN_Par1 (m/day)	100	Assumed large drain conductivity
Evapotranspiration (EVT) Package	EVT_Par1* (m/day)	0.00227 (0.00200/0.00253)	Evapotranspiration flux of zones 1 to 4
	EVT_Par2* (m/day)	0.00115 (0.00104/0.00126)	
	EVT_Par3 (m/day)	0.00030	
	EVT_Par4 (m/day)	0.00005	
Streambed conductivity in SFR2 package	SFR_Par1* (m/day)	0.04401 (0.03959/0.04844)	Streambed hydraulic conductivity of segment 1, upstream aquifer
	SFR_Par2 (m/day)	0.09900	Streambed hydraulic conductivity of segment 2, section joining upstream and downstream aquifer
	SFR_Par3* (m/day)	0.05862 (0.05305/0.06420)	Streambed hydraulic conductivity of segment 3, downstream aquifer

Assuming that an efficient infiltration rate is achieved through injection wells, three 5-year groundwater pumping scenarios are simulated (Table 2). The calibrated model and initial head conditions are used to explore the effect of abstracting 2 million m^3/year on the sustainability of the aquifer and dependent vegetation.

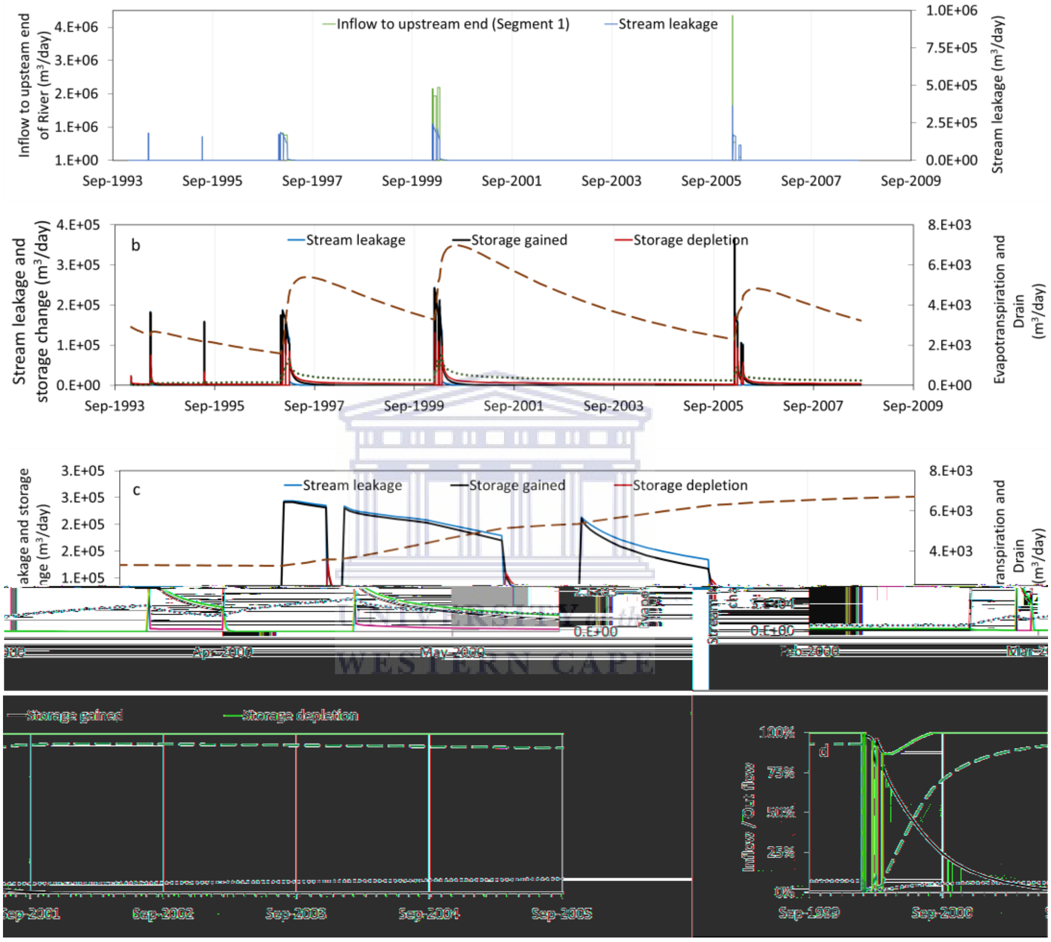

Figure 4-6: a. Inflow rate to the upstream segment (segment 1) and simulated infiltration from river flow to the aquifer. B. Overall relationship of river flow, leakage, storage, evapotranspiration and groundwater flow components with time during the modelled period. C. Expanded view of the water budget components during a recharge event (see arrows indicating time interval in a.). d. Percentage of inflow and outflow water budget components during and after a recharge event

The simulations are carried out for 5 years assuming a dam spillage (recharge) frequency of once in 5 years. While the abstraction rate represents 50% water demand of the nearby urban area, it is seen from the calibrated model that, under non-pumping conditions, evapotranspiration rates vary from 1,588– 6,984 m^3/day from the aquifer depending on water level elevation (Figure 4-7). The dependent *A. erioloba* vegetation has persisted through this period and the model provides a range of evapotranspiration rates for the survival of the vegetation. In the first scenario (A), abstraction is carried out from the aquifer assuming current conditions with an initial stress period that includes a recharge event by river flow lasting 20 days at an average flow rate of 750,000 m^3/day (15 million m^3). The duration and flow rate represent the average of significant events recorded in the last 15 years. Water is extracted from the aquifer for the entire 5-year period using 10 boreholes (Figure 4-8) at a rate of 550 m^3/day (10.04 million m^3). In the second scenario (B), streamflow is excluded and recharge is effected artificially through ten injection wells (Figure 4-8) at a rate of 850 m^3/day per borehole (15.51 million m^3) placed along the length of the aquifer at points of highest aquifer thickness (and transmissivity). It is assumed that water for artificial recharge will be sourced from the Oanob Dam. Groundwater is abstracted at the same rate as in scenario A. In scenario C, initial river flow recharge is applied at the beginning of a 5year period as in scenario A, and artificial recharge and pumping is applied as in scenario B. Results (Figure 4-9) show that abstraction of water would require added artificial recharge for sustainable utilisation of the aquifer.

Table 4-2: Flow components of three modelled abstraction scenarios that include Scenario A (a river flow episode), Scenario B (recharge through injection wells but no river flow) and Scenario C (a river flow episode and recharge through injection wells).

Scenario	River Flow	Injection through wells	Abstraction
A	15 million m^3 (20 days x 750,000 m^3/day)	Nil	10 million m^3 (5,500 m^3/day x 5 years)
B	Nil	15.5 million m^3 (8,500 m^3/day x 5 years)	10 million m^3 (5,500 m^3/day x 5 years)
C	15 million m^3 (20 days x 750,000 m^3/day)	15.5 million m^3 (8,500 m^3/day x 5 years)	10 million m^3 (5,500 m^3/day x 5 years)

In scenario A, 23% (3.47 million m^3) of the total river flow (15 million m^3) infiltrates through leakage (Figure 4-9). The pumped volume in the 5-year period is almost entirely supplied from storage (9.5 million m^3). Falling water levels reduces evapotranspiration loss from 4,034 m^3/day during recharge to 229 m^3/day at the end of 5 years (Figure 4-9). The scenario is clearly not sustainable due to depletion of storage and impact to dependent vegetation (Figure 4-7). In scenario B, 15 million m^3 is directly injected assuming no loss in the injection process and feasibility of attaining the required injection rate; in this case, evapotranspiration, groundwater outflow and abstraction balance inflow, while change in storage is close to zero indicating a near steady-state condition (Figure 4-9) and the evapotranspiration rate reduces marginally from 2,926 to 2,807 m^3/day (Figure 4-7).

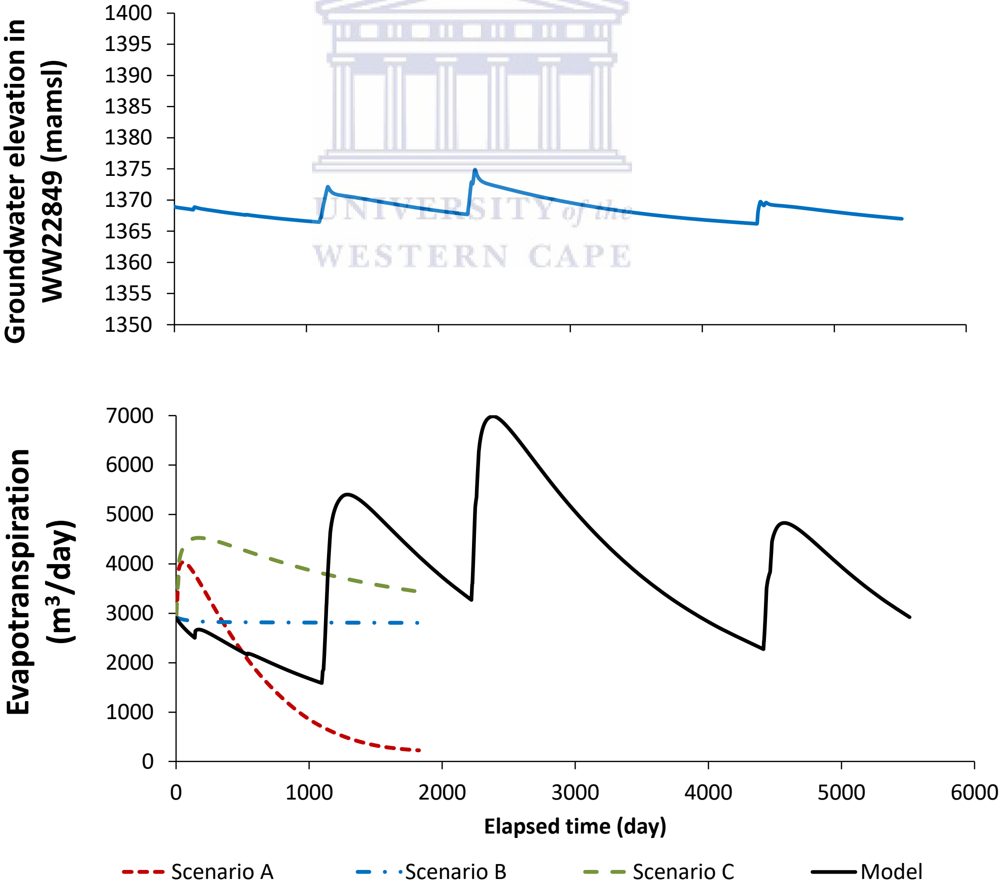

Figure 4-7: Change in water-level elevation at one observation point during the entire modelled period, plotted together with evapotranspiration flux variation.

Variations of evapotranspiration flux in the three scenarios are included for comparison with natural non-pumping conditions.

Scenario C includes one recharge event through river leakage, artificial recharge and abstraction. The inflow is balanced by pumping, evapotranspiration, groundwater outflow losses and net storage gain of 6 % (Figure 4-9). Evapotranspiration rates are higher than in other cases (4,524–2,960 m^3/day) but the simulation suggests the aquifer can be used for additional storage and supply incorporating evapotranspiration losses under these conditions. Storage for longer duration without pumping would however increase losses via evapotranspiration.

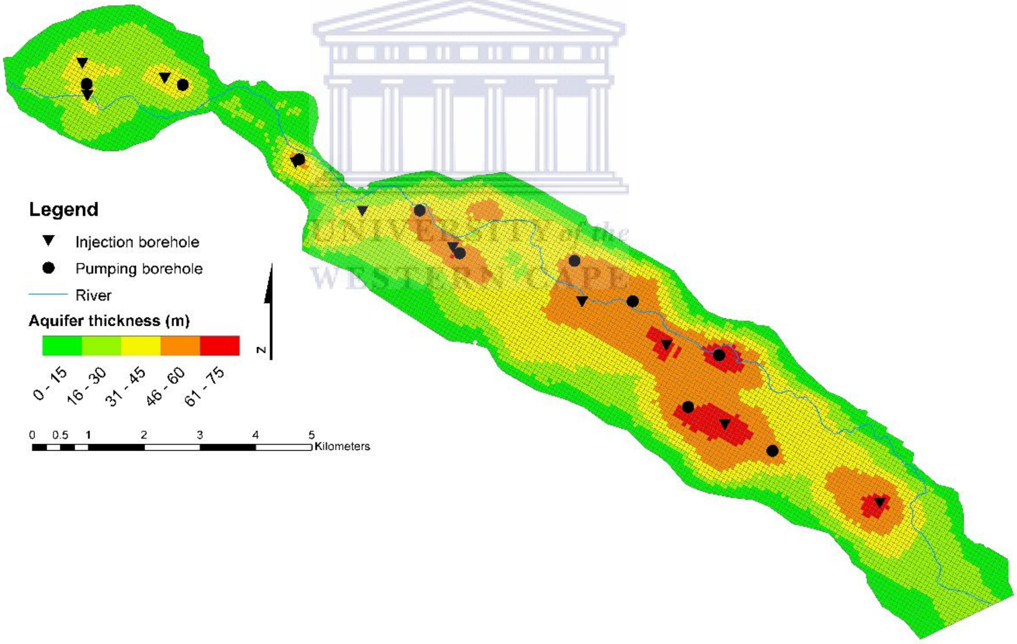

Figure 4-8: The position of pumping and injection boreholes is shown in relation to the thickness of the aquifer and Oanob River

With increasing water demand, the occurrence of severe groundwater storage depletion is likely to become more frequent under natural recharge conditions as recharge to aquifers are restricted in space and time. The combined surface water and groundwater balance on the other hand show that, at natural groundwater infiltration rates, a large component of surface water is lost through evaporation. The understanding of the infiltration process allows artificial recharge schemes to be designed to address specific issues such as the low hydraulic conductivity layer in the case of the Oanob Aquifer. For sustainable groundwater usage, exploited aquifers should attain a steady-state condition with no long-term change in storage (Alley et al. 1999; Healy et al. 2007; Zhou 2009), a condition that will be difficult to achieve in arid regions such as Namibia. With exploitation rates exceeding sustainability, artificial recharge using surface water sources during times of flow becomes a possible strategy. Understanding of both surface and groundwater processes and joint management of the resources is key to such designs.

5. Conclusions

Strip aquifers associated with ephemeral rivers in arid west and south Namibia are highly important water sources. Recharge to the aquifers occurs episodically through streambed leakage. The sustainable use of these aquifers has been challenging due to lack of understanding of the recharge process and increasing water demand. A combined surface water and groundwater numerical flow model was calibrated using long-term flow and groundwater-level-monitoring data of an aquifer under non-pumping conditions. It is shown that streambed material (conductivity) is the controlling factor determining the rate of infiltration. Evapotranspiration by riparian vegetation is the main discharge mechanism. Under natural conditions, a recharge event is followed by extended periods of groundwater storage depletion without attaining a steady-state condition. Artificial recharge can be a viable solution for sustainable use of such aquifers. The natural rapid runoff can be controlled and used to increase storage in aquifers avoiding high losses in water scarce regions.

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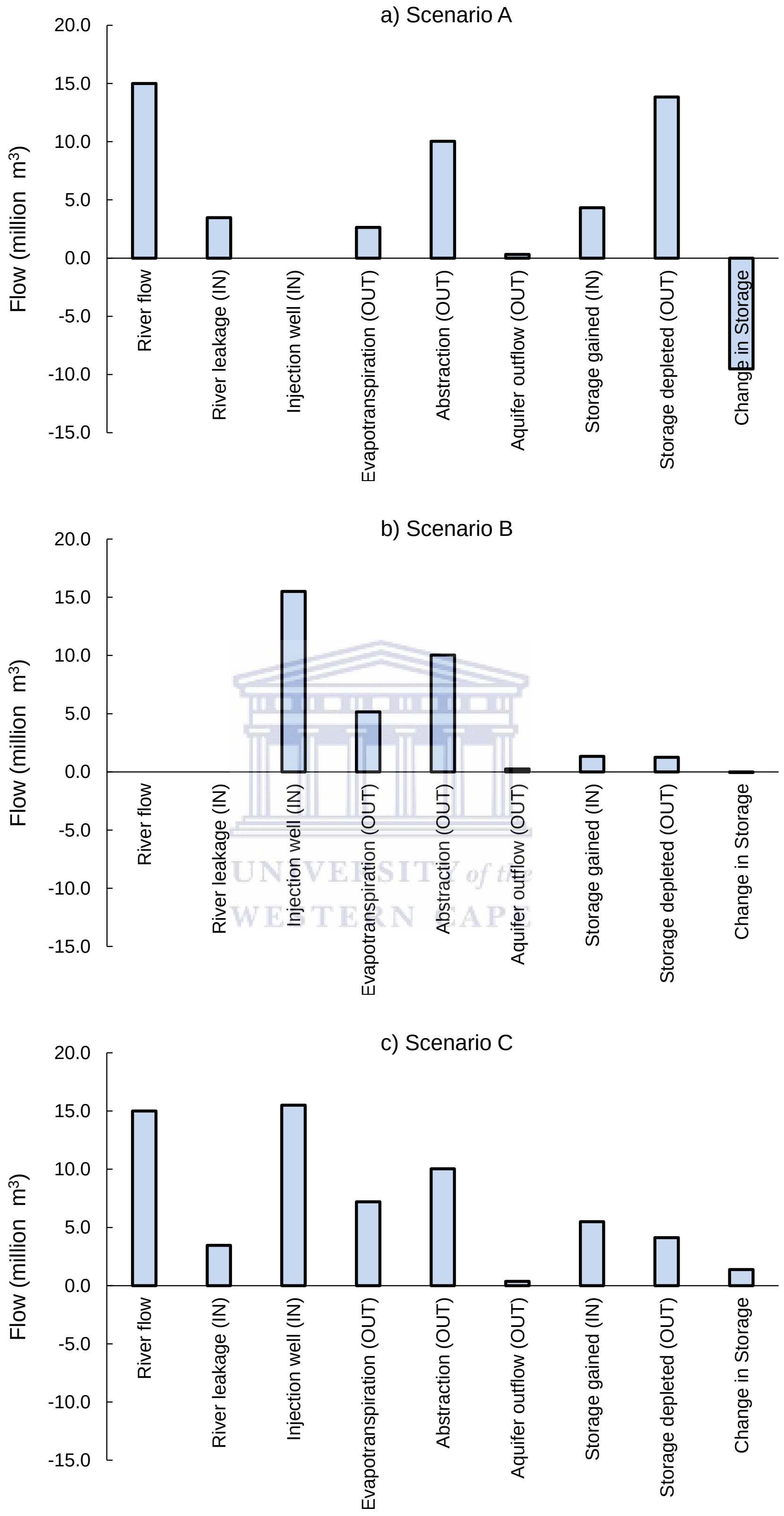

Figure 4-9: Water budget of three abstraction scenarios from the aquifer under different conditions of recharge by river flow and artificial recharge

Chapter 5: SYNTHESIS - SUSTAINABLE YIELD IN ARID REGION AQUIFERS

The primary objective of the thesis was to assess sustainable utilization of groundwater in a scenario where recharge occurs as discrete events to an aquifer that is bounded in extent. Both fractured hardrock and alluvial aquifers were considered including interaction with ephemeral rivers (Chapter 3 and Chapter 4). From theoretical assessment it has been shown that sources of groundwater to boreholes can be storage depletion, reduction of evapotranspiration and capture of river flow (Chapter 2). The sustainability of these aquifers can be assessed based on combined evaluation of both surface water and groundwater components, and ecological water demand.

5.1 ARID REGION SUSTAINABLE YIELD

Sustainable groundwater yield estimation in conventional practice assumes an aquifer system that is similar to a closed reservoir. As recharge occurs in discrete events and aquifers are bounded, pumping results in depletion of storage. A fraction of the stored resources is taken as being available for use for a design period, calculated as a projected drawdown. Borehole design, aquifer boundary conditions and hydrogeological properties affect the yield calculated. In the first case study (Chapter 3), where gain in storage to a heterogeneous fractured hardrock aquifer was assessed based on episodic surface flow, actual storage gain is seen to be related to surface flow and being effected by aquifer boundary conditions and low storage coefficients. The incorporation of surface flow events in the water budget calculation was necessary for a realistic understanding of the aquifer behaviour.

In arid region aquifers, storage could be depleted for extended periods due to pumping and natural discharge, and an equilibrium or steady state condition is rarely achieved. With lowering of the water table, evapotranspiration is reduced thus inducing a capture component. An aquifer where pumping is entirely balanced by reduction of discharge (evapotranspiration) is usually not feasible as most riverine vegetation and aquifer discharge would be eliminated with time (partial destruction of phreatophytes vegetation due to abstraction have been reported in the past – see Ward and Breen,1983). Capture of river flow during flow events is the primary source of water to boreholes. The capture component would increase in response to the lowering of the water table in subsequent flows till a new range of water level variations due to storage depletion and infiltration is established. Depletion of storage as a result of drought or high abstraction rates would be followed by additional river flow capture consequently reducing downstream surface flow.

Actual physical constraints such as river bed hydraulic conductivity and hydraulic properties of the aquifer sets a limit to the degree of natural replenishment possible during the short duration of flow in ephemeral rivers. Variability of surface flow frequency and duration adds other complex dimensions to assessing sustainability. Aspects related to surface flow and groundwater recharge has been illustrated in the second case study (Chapter 4). In the case study sustainability of abstraction required surface and groundwater interaction to be considered including streambed properties, flow frequency, rate and duration together with aquifer hydrogeological properties, boundary conditions and response to pumping. Conjunctive use of surface and groundwater resources required artificial augmentation of aquifer recharge due to constrains in infiltration rates.

High rates of exploitation of groundwater resources will deplete surface water resources needed downstream. On the other hand, failure to capture surface water during flow events may cause rejection of potential recharge and the water being lost to evaporation. As water demand in the country increases, basin wide combined surface and ground water resource evaluations have become a necessity. A continuous evaluation process for combined surface and groundwater resources management is suggested in Figure 5-1.

5.2 THE ROLE OF ARTIFICIAL RECHARGE IN LONG TERM GROUNDWATER MANAGEMENT STRATEGY

The rate of groundwater exploitation increased substantially in the last three decades in Namibia with water shortage being experienced in several areas, particularly in the central part of the country. In this context the benefits of induced recharge is well worth examining as significant rejected recharge is implied in the Oanob case study (Chapter 4) and in past literature on surface-groundwater interaction in Namibia (Crerar et al. 1988).

The arid region basin water balance equation (adapted from Healy et al., 2007) is

$$P = ET + \Delta S + RO + Q_{gw} \qquad \text{....equation 11}$$

Where P = precipitation

ET = combined evaporation and transpiration loss from surface, soil and aquifer

ΔS = change in water storage at surface, unsaturated zone and as groundwater

RO = surface runoff

Q_{gw} = groundwater discharge

While O_{gw} rate are low and not significant in many cases under low hydraulic gradients, ET losses and RO components could be managed to enhance groundwater storage artificially. This aspect is discussed in Chapter 4 with a case study on alluvial aquifer associated with an ephemeral river.

Source of water and underground storage space are the fundamental prerequisites for artificial recharge projects. The short duration of flow in ephemeral rivers precludes direct use of this surface water to replenish aquifers. Careful consideration is therefore required of rainfall runoff characteristics of catchments and means of increasing storage that could be lost to evaporation. Candidate groundwater reservoirs selection for appropriate projects needs a nationwide survey. Potentially, all groundwater abstraction schemes under operation in the country could be assessed for potential for implementation of artificial recharge. Artificial recharge schemes could increase reliability of aquifers as proven in many similar projects worldwide (Dillon et al., 2009; Gale, 2005). Currently, only two artificial recharge projects, Omaruru Delta and the Windhoek Aquifer, are operational. Few new artificial recharge schemes are being considered.

Further, increasing underground storage space can be a strategy to capture part of the rejected recharge. This requires structures such as sand dams to artificially increase sediment thickness in alluvial aquifer systems (Hoogmoed, 2007).

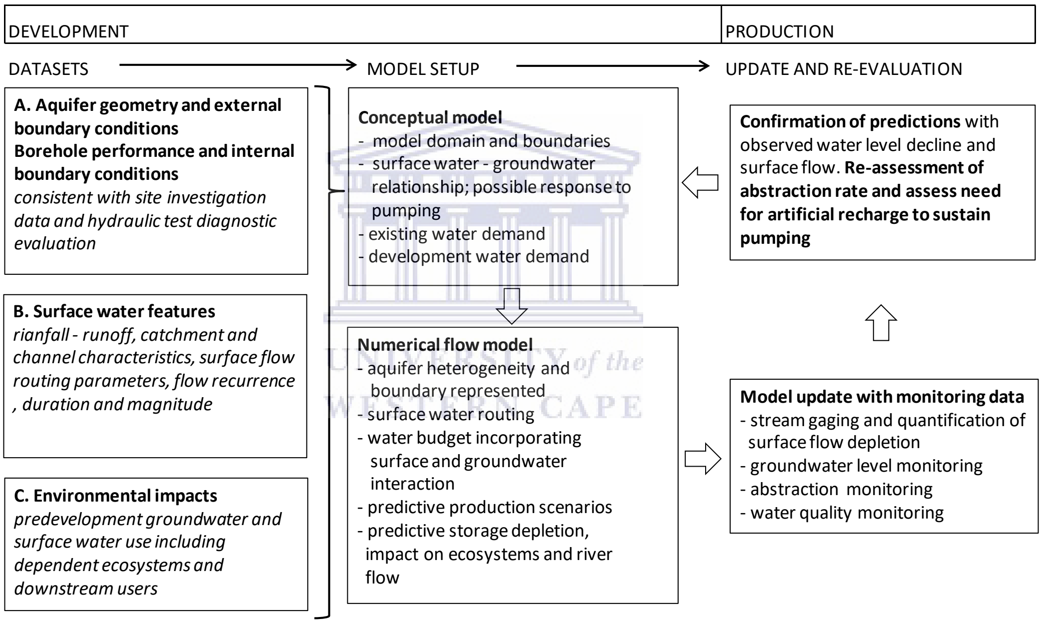

Figure 5-1: Management of aquifer-surface water system for sustainable utilisation

5.3 SUGGESTIONS FOR ADDITIONAL RESEARCH

The need for additional research and data collection on certain key aspects were identified during the study. The following is a list of requirements noted.

a. Treatment of surface and groundwater as combined resource. Use of combined surface and groundwater models as a routine groundwater management strategy. Increased monitoring of surface flow of ephemeral streams as part of groundwater management.

b. Develop understanding of surface water infiltration mechanism in both fractured rock and porous aquifer and the related siltation problem.

c. Studies on effect of pumping on desert vegetation phreatophytes and interception of runoff and infiltration by vegetation.

d. Quantification of the overall water budget and updating of unit runoff maps of catchments together with basic but major components such as evapotranspiration, groundwater recharge, and assessment of the water demand.

e. Assessment of future water needs and potential for artificial recharge in all existing groundwater schemes. Exploration of the possibility of enhancing aquifer thickness with structures such as sand dams.

5.4 CONCLUSIONS

The following are concluded from the study.

a. Ephemeral river flow and infiltration are main recharge mechanisms to bounded alluvial and fractured rock aquifers in arid and semi-arid parts of Namibia.

b. Arid region groundwater sustainable yield differ from humid regions in the fact that capture of surface water is only possible during times of river flow. Decrease of aquifer discharge in arid regions mainly involves reduction of evapotranspiration. Characteristics of capture similar to humid regions are however seen and loss of surface flow through infiltration in succeeding flow events occur as aquifer storage is depleted with pumping. Therefore sustainability can only be evaluated by considering groundwater and surface water as a combined resource. Understanding of ephemeral river systems is needed for assessment of associated aquifers. Information on river flow duration, volumes, river bed characteristics, unsaturated zone properties, and runoff could be routinely collected. This information together with aquifer properties and boundaries can be used to fully assess the sustainable yield from an aquifer. Water demand of dependent ecosystem should be a part of the assessment of sustainable yield.

c. Infiltration of surface water to aquifers may be enhanced by lowering of the water table in response to pumping. The depletion of surface flow could have impacts on the environment such as reduction of evapotranspiration, lowering of water table and reduced flow for downstream water users. The impact of underground water use on downstream surface water users is not apparent in many cases and should form part of a sustainable yield assessment.

d. River bed characteristics and aquifer properties have a large influence on surface water infiltration rate and potential recharge may be rejected. Artificial recharge through direct injection at optimised rates could enhance storage bypassing river beds of limited hydraulic conductivity, allowing more efficient replenishment at lower infiltration rates over prolonged periods, and affecting recharge over a larger volume of an alluvial aquifer.

e. For quantification and management of resources it is required that combined assessment of surface and groundwater is carried out. Close monitoring of surface and groundwater flow, infiltration and discharge from an arid region catchment is needed for adequate management of resources as climatic and hydrological processes are transient and extremely variable.

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