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A SUB-BASIN WATER RESOURCE QUANTIFICATION AND AQUIFER PRODUCTIVITY ASSESSMENT FOR THE NORTHWEST BOREHOLE SCHEME NEAR OPUWO, NAMIBIA

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By

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A REPORT

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Abstract

Namibia is the most arid country in southern Africa, and is classified as experiencing medium-water stress from 2010-2014 by the Water Resources Institute (WRI) (World Bank , 2015) (Gassert, 2013). Increased water-resources management responsibility at the municipal level, population growth and urbanization trends necessitate community-scale quantification of water resources.

An annual water balance for the contributing sub-basin to Opuwo, Namibia was performed. The Behnke and Maxey method was used to estimate PET, and the methodology outlined by Allen, et al was used to determine soil moisture response to individual rainfall events for one hypothetical year. Water balance results indicate that of the 379 mm of annual rainfall, approximately 84% is lost to evapotranspiration, 15% contributes to surface runoff, and only 1% recharges groundwater resources. Results of the water balance are reconciled with a groundwater flow model (using GMS 9.1 formulating the input for MODFLOW-2005) of the aquifer serving the wellfield in Opuwo.

The aquifer model was based upon abstraction and well data for 2013. The modeled extent covers a land area of 45 km^2 and consists of 1 layer used to represent the alluvial water-bearing structure. Hydraulic conductivity was estimated using the Theis method for unconfined aquifers in AQTESOLV. Through parameter estimation and calibration the MODFLOW model is able to duplicate pumping water levels in the wells within 1 m of observed values. The calibrated model was further used to explore

hypothetical scenarios based upon increased water demand associated with population growth of 50% and 100%. Results indicate that sufficient groundwater flow exists to meet increased demand. However, predicted drawdown levels eliminate utilization of some screened intervals in well casings, negatively impacting production capacity of the boreholes. Rehabilitation of current wells, construction of additional wells, and implementation of check dams to increase recharge in the watershed may buffer against future drawdown as a result of increased pumping rates.

1: Introduction

Namibia is a country located in southwestern Africa, bordered by Angola, Botswana, and South Africa to the North, East, and South, respectively, with the Atlantic Ocean comprising the western border, as shown in Figure 1. The area was first colonized as a German territory in 1884 under the name German South-West Africa; following the conclusion of World War I, German South-West Africa was re-organized under South African administration. The country gained independence from South African rule in 1990 and took the name Namibia, the indigenous name used in recognition of the Namib Desert that dominates the Atlantic coast.

Figure 1: Namibia geographic location (Photo adapted from http://www.countriesfactbook.com/namibia.asp)

Namibia is the most arid country in southern Africa, receiving an average annual rainfall of 285 mm across the country (World Bank , 2015). Water scarcity has been addressed a variety of ways, most notably through addition of community boreholes in rural areas, construction of the New Goreangab Water Reclamation Plant located near the capital city of Windhoek, and utilization of desalination technology on the Atlantic coast for mining use. Although water-supply infrastructure varies strongly between rural and urban areas, in 2011 it was estimated that 95% of Namibians have access to clean water (GRN, 2012).

Development and management of Namibia's water resources have been dictated by evolving national policy. After gaining political autonomy in 1990, the government of Namibia published its first National Development Plan (NDP) in 1995 to guide development across all sectors. The 1995 NDP was the first of a series of seven NDPs, each spanning a five-year timeframe. In 2004, the Government of Namibia published Vision 2030, an overarching framework created to improve quality of life for Namibians through the achievement of objectives related to 8 major themes:

1. Equality and Social Welfare
2. Political Stability and Effectiveness
3. Human Resources Development and Institutional Capacity Building
4. Macro-Economic Issues
5. Population, Health and Development
6. Natural Resources Utilization
7. Knowledge, Information and Technology
8. Environmental Factors

It was intended that Vision 2030 be aligned with the Millennium Development Goals (MDGs) set out by the Millennium Summit of the United Nations held in 2000. Vision 2030 objectives are to be implemented through the policies and programs outlined in NDP 2 through NDP 7. NDP 3 (2005-2010) was the first to be written to directly reflect the eight general objectives in Vision 2030, and acknowledges water resources management and policy as a key underlying component of multiple Vison 2030 development objectives (GRN, 2008). NDP 3 guided the institution of The Water

Resources Management Act of 2004, which states as a fundamental principle "regional diversity and decentralization to the lowest possible level of government consistent with available capacity at such level." Managerial responsibility of water resources is delegated through the creation of water-point user associations at the local level which elect a water point committee tasked with day-to-day operational and financial management of the local water source.

In response to the World Summit on Sustainable Development (WSSD) in 2002 and the African Minister's Council on Water (AMCOW) in 2006, the Integrated Water Resources Management (IWRM) Plan Joint Venture Namibia prepared and published the IWRM Plan for Namibia in 2010 to further facilitate achievement of MDGs, Vision 2030, and NDP 3 goals. A holistic approach to water resources planning and management, the IWRM methodology outlines further decentralization of water-resources management responsibilities and calls for improved groundwater and hydrological modeling capability. Furthermore, IWRM recognizes that participatory decision-making from informed users and self-regulation in regards to water-resources management is more effective and efficient than central regulation and surveillance (IWRM Joint Venture Committee, 2010). The Water Supply and Sanitation Policy (WSASP) of 2008 was written to align with management policies outlined in the 2010 IWRM Plan and distribute responsibilities among the various stakeholders in the water management ecosystem:

- Ministry of Agriculture, Water and Forestry (MAWF) is responsible for "management and regulation of the water cycle and water resources in the country", which includes performing water resource inventories, monitoring and control (GRN, 2008).

- Namibia Water Corporation, Ltd. (NamWater), is organized as a federally-owned parastatal and is responsible for overall water supplies on a national basis.
- Municipal Town Councils have responsibilities for implementation of water supplies in rural and urban areas. This responsibility consists of four policy components in alignment with NDP 3: provision of essential water supply and sanitation services to all Namibians; acceptance of mutual responsibility between local and federal governments; implementation of community-derived solutions and local financial contributions; and pursuit of environmentally sustainable development (GRN, 2008).

The NDP 4 period spans fiscal years 2012-17 and outlines the current national development objectives in Namibia. Public health and national water infrastructure are identified as essential conditions for economic growth and remain as development priorities. Increased access to water for human consumption from 85.5% to 100% of the population and development and maintenance of sufficient water reserves to support industrialization are stated as desired outcomes in the water infrastructure sector during the NDP 4 period (GRN, 2012). Most recently, IWRM was formally integrated into the Water Resources Management Act of 2013 to outline scope and responsibilities and to ensure review of IWRM Plan at intervals of not more than 10 years (GRN, 2013).

Decentralization and delegation of water supply responsibility from federal- to municipal-level government dictate that decision-making regarding water supply will become increasingly reliant on community-level environmental, social and economic factors. Implementation of management policies necessitates reliable data on a broad scope to determine whether national regulatory goals are being met and through investigations in which operation of individual borehole schemes (common term for wellfields in Namibia), water treatment strategies and supply systems can be optimized.

While water-resource policy directs changes in resource management and responsibilities of stakeholders, urbanization and population growth are arguably the most imminent factors driving quantification and future water-resource planning. In the 2011 Population and Census Housing Report, the Namibia Statistics Agency (NSA) estimated the population of Namibia to be 2,112,077 people, representing a growth of 15.4% over the decade from 2001-2011 (Namibia Statistics Agency, 2011). National population growth data is summarized in Table 1:

Table 1: Namibia population change, 2001-2011

Location	**2001**	**2011**	**Percent change**
Namibia	1,830,330	2,113,077	15.4%
urban	603,612	903,434	49.7%
rural	1,226,718	1,209,643	-1.4%

Table 1 indicates that migration and growth are occurring in Namibia. In the 2011 census, the NSA estimated the total population growth in urban areas in Namibia from 2001 to 2011 was 49.7%; some urban areas in Namibia experienced population growth rates as high as 143%. Rural populations have declined over the same time period. Urbanization in Namibia has been increasing rapidly since 1991, as depicted in Figure 2. The population trends show that residents of Namibia are migrating from rural areas to urban centers, and it is plausible that in the upcoming decade Namibia will see for the first time a majority of its population living in urban areas. As a result, potential water demand in Namibia is increasing in response to population growth and becoming increasingly localized geographically as populations become focused in specific areas. It can be expected that if the observed national water demand trends continue, urban centers will experience greater pressures related to water supply than rural areas and may struggle to design and construct infrastructure at a pace capable of satiating demand. The increased demand on aquifers serving urban areas further reinforces the need for water resource quantification at a sub-basin level.

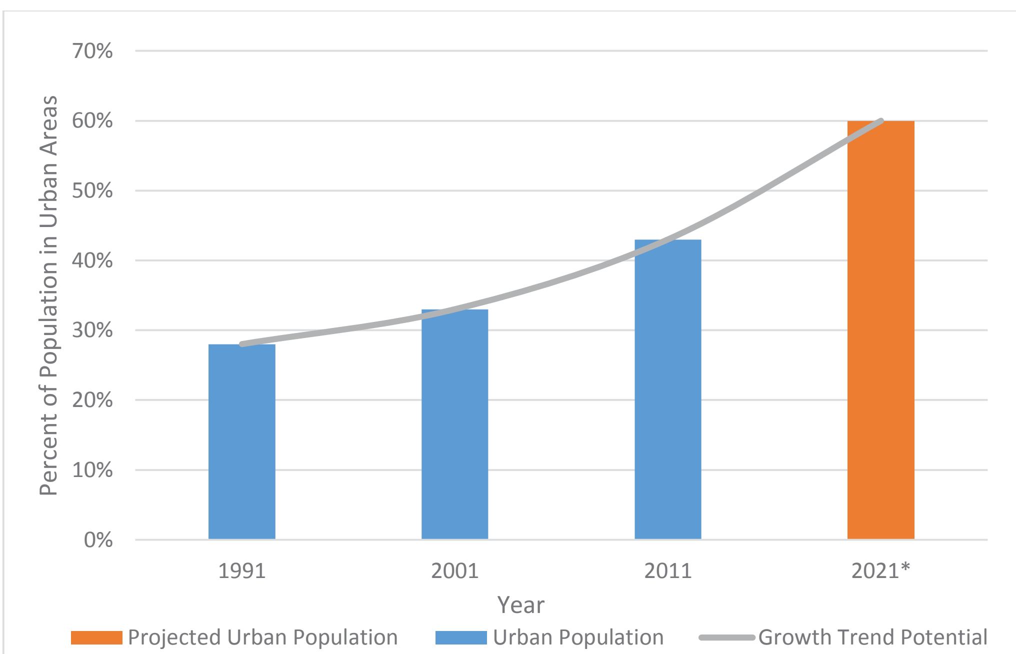

Figure 2: Urbanization trend in Namibia

The population trends illustrate that infrastructure capable of being easily expanded is advantageous for many communities. The intent of this report is to validate and expand upon previous geohydrological investigations by using remote-sensing mapping technologies and numerical modeling techniques to quantify groundwater resources available to the town of Opuwo, Namibia. Similar investigations have been performed on a local-scale in rural Mali (Shonsey & Gierke, 2009) and on a regional-scale in NE Namibia/NW Botswana (Wanke, Dunkeloh, & Udluft, 2008), with results serving as potential reference documents for future water-resource management in the respective study area.

1.1: Motivation

The motivation for this project resulted from the author's service as a United States Peace Corps Volunteer in Opuwo. Community-wide water scarcity in the form of inconsistent and unpredictable water supply existed, despite a well-developed distribution system in the town. Water accessibility averaged only 2-3 days per week, and during unpredictable hours of the day. The brunt of water-collecting responsibility is typically delegated to younger family members; subsequently during times of low water availability it was common to observe children walking around town with empty water containers in search of flowing taps.

Lack of accessibility to treated water is a potential cause for individuals to utilize high-risk water sources such as surface waters or livestock watering schemes. In December of 2013, Opuwo public hospital first detected cases of cholera from patients in rural Kunene Region, and on January 3rd, 2014 a cholera outbreak in Kunene Region was reported to the Ministry of Health and Human Services (UNICEF, 2014). By February, 479 cases and 15 deaths were reported, with the outbreak largely attributed to lack of safe drinking water sources as a result of a prevailing drought in the area. The World Health Organization (WHO), Center for Disease Control (CDC) and Children's Rights and Emergency Relief Organization (UNICEF) collaborated in response to this outbreak, which has since been brought under control. This serves as an example of the risks involved with lack of reliable access to safe drinking water, and provided motivation to gain a comprehensive understanding of the water resources available in Opuwo. The author explored public perceptions regarding water availability and attitudes towards water use. This led to regular visits to the local drinking water treatment plant to build relationships with plant operators and gain insights towards the challenges associated with water supply scheme in Opuwo.

1.2: Objectives

Objective 1: Quantify available water resources in the sub-basin in which the Northwest borehole scheme is located.

Currently production capacity in the Northwest wellfield is greater than the capacity at the water treatment facility; subsequently treatment, not abstraction, is the limiting aspect in the water production and supply system. However, due to rapid population growth recorded from 2001-2011, infrastructure expansions are likely to take place within 5-10 years and knowledge of the capacity and hydrological aspects of the current production scheme would serve as a valuable decision-making tool. Previous hydrogeological studies performed in the area were published in 1985 and 1986 upon the construction of new wells in the wellfield. A comprehensive water balance of the entire contributing basin in which the NW wellfield lies has not yet been attempted. Modern mapping and modeling tools, in conjunction with a greater accessibility of climate data, may be able to more adequately quantify water resources in the watershed.

Objective 2: Model the aquifer serving the Northwest wellfield to determine maximum production capacity and evaluate effects of potential abstraction increases to current borehole scheme and groundwater elevations.

Due to population growth in Opuwo, expansion of all components of the current water supply system must be considered. Dependent on the outcome of Objective 1, near- to medium-term expansions to the water supply scheme in Opuwo may be necessary. Expansions to meet increased demand related to long-term population growth are nearly certain, and may require the construction of additional boreholes to meet rising water demand. In a region with inherent water scarcity such as Kunene, it is imperative that abstraction of water resources is performed through the most appropriate practices given economic, environmental, and social implications.

2: Project Site

Namibia is divided into 14 regions; Kunene Region is located on the Angolan border in the northwest of Namibia. Opuwo, the site on which this study focuses, is the regional capital and is located in the central Kunene Region of Namibia (18°03’18.83’’S, 13°50’25.94”E) at approximately 3800 ft (1150m) above mean sea level (AMSL). Figure 3 shows the location of Opuwo within Namibia, and the political boundaries of the Kunene region and the water management basin. The gray polygon outlines the border of Kunene region, and the green polygon represents the Kunene water management basin encompassing the modeled area and the contributing sub-basin discussed further in this report. In its 2001 Population and Census Housing Main Report, the NSA estimated the population of Opuwo to be 5,101 people. In 2011 the NSA estimated the population to be 7,657 people, placing it as the country’s 13th most populous municipality and representing a growth of 50.1% over the decade from 2001-2011 (Namibia Statistics Agency, 2011).

Figure 3: Site map (adapted from http://forum.nationstates.net/viewtopic.php?f=23&t=71970)

Opuwo serves as the local business and education center for residents of north-central Kunene region. Opuwo consists of 'town proper', which contains the highest density of businesses, Ministry buildings, and schools, as well as the largest private homes. These establishments are connected to a centralized water distribution and sewer system that is operated and maintained by the Namibia Ministry of Works and Transport. Surrounding Opuwo town proper are a number of 'locations', which can best be described as suburbs to Opuwo town. Infrastructure in locations varies from provision of full centralized water and sewage services in permanent homes to illegal, informal settlements in which neither drinking water infrastructure nor sanitary services exist.

2.1: Water Supply

Two borehole schemes exist in the area, and are named based upon their relation to the town of Opuwo: the Northwest wellfield and the Southeast wellfield. The SE wellfield is located approximately 10-15 km southeast of Opuwo, adjacent to the nearby village of Alpha. Due to lack of production capacity, this wellfield is not currently utilized to provide potable water to the town of Opuwo, despite possessing comparatively higher water quality than the NW wellfield. Because it is currently the main source of potable water for Opuwo, and previous geohydrological evaluations show much higher potential for future production capacity (Fry, 1986), the focus of this report lies in the evaluation and expansion of the NW wellfield. The general locations of these schemes in relation to the town of Opuwo are displayed in Figure 4.

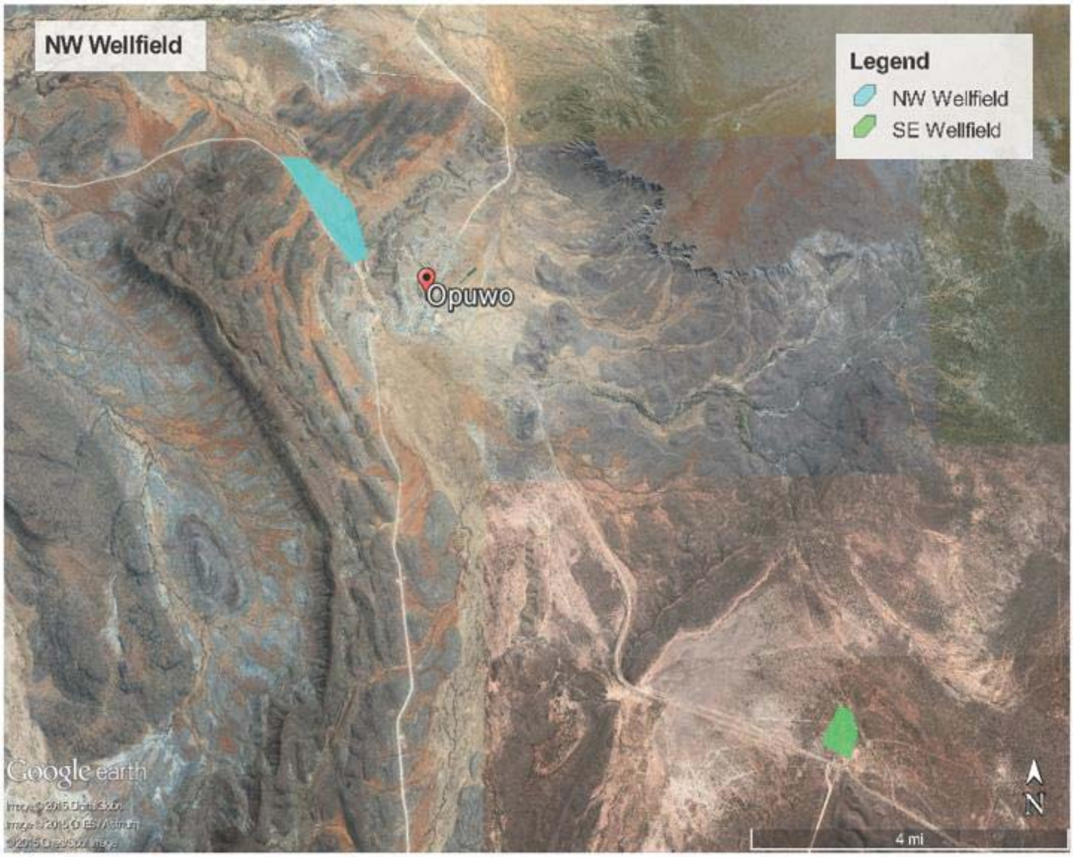

Figure 4: Borehole supply schemes in greater Opuwo area

The NW wellfield consists of five boreholes ranging 90-130 m in depth, located in a flat alluvial plain approximately 1-3 km NW of the town center. Boreholes in the NW scheme are of modern construction. The casing of each well is steel with a diameter of 200mm, with perforations at elevations to match water strikes recorded during drilling. Each borehole is outfitted with a flowmeter and siphon valve, and is protected by a concrete foundation and razor-wire fence. Typical borehole construction is illustrated in the pictures shown in Appendix F. Production volume varies amongst wells, and two wells (WWW22864 and WW23137) are required to be pumped alternately because of their close proximity to each other. Borehole locations in the NW wellfield are shown in Figure 5.

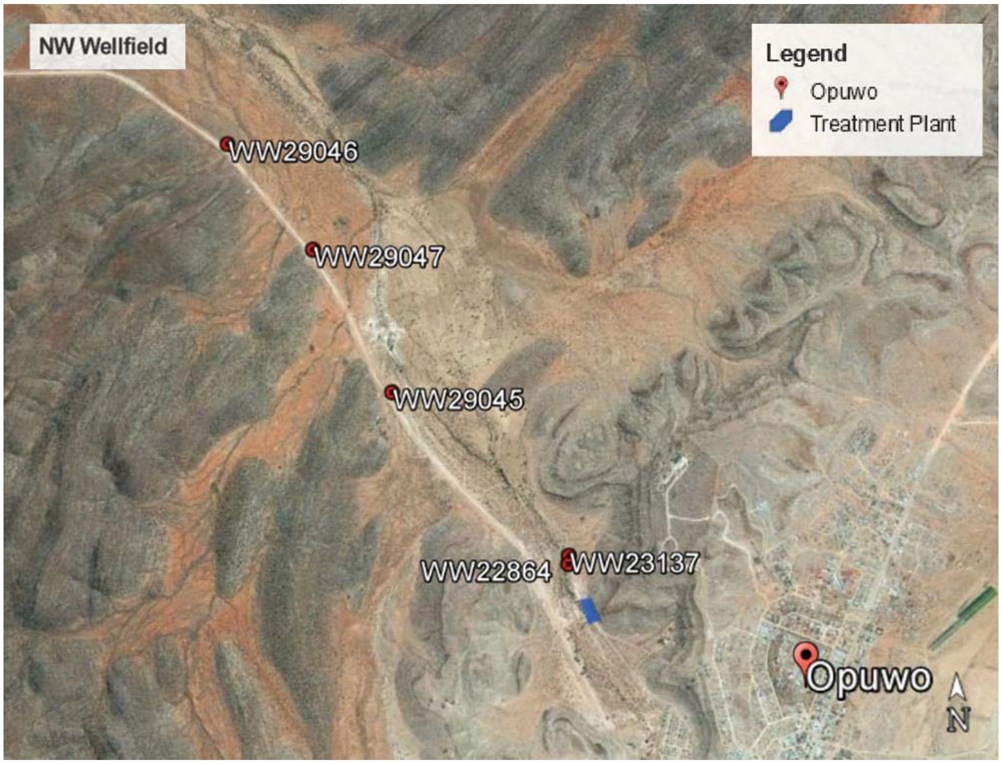

Figure 5: Borehole layout in NW wellfield (approximate scale: 1cm:300m)

After abstraction, water passes through a nanofiltration and reverse osmosis treatment plant that was constructed in 2005 and is currently operated by NamWater. Treated water is pumped approximately 350 vertical feet to two storage tanks located on top of the ridge on which the town of Opuwo lies, and is provided to residents through a branched-network gravity distribution system. It is typical that most homes in the town of Opuwo have at least one tap; however there is a trend of informal settlement in the area in which individuals do not have access to treated water. Outdoor taps are present at various locations in the town and are managed by individual residents.

In accordance with IWRM and the aforementioned national policies, MAWF, NamWater and the Opuwo Town Council possess responsibility for operation and maintenance of the water supply system in Opuwo. Previously organized as the Department of Water Affairs, MAWF assumes most responsibilities associated with the maintenance and evaluation of the boreholes, including monthly water depth records and physical maintenance. MAWF is also responsible for setting national policy related to water resource management and provides directives and education on water quality and usage. NamWater is organized as a federally-owned parastatal; it owns and operates the water treatment plant in Opuwo and additionally collects and monitors data related to production and water quality. NamWater operates as a source of revenue for the Government of Namibia while implementing the drinking water goals and directives set out by MAWF. Opuwo Town Council manages the distribution system to the town of Opuwo, specifically the provision of water on a rotating basis in various supply 'zones' within the town, and maintenance and expansion of the distribution system. The Town Council assumes operational responsibility beginning at the piping network emerging from two cylindrical storage tanks, with the end point being the pipes connecting to taps utilized by residents. A visual overview of this arrangement of responsibilities is shown in Figure 6.

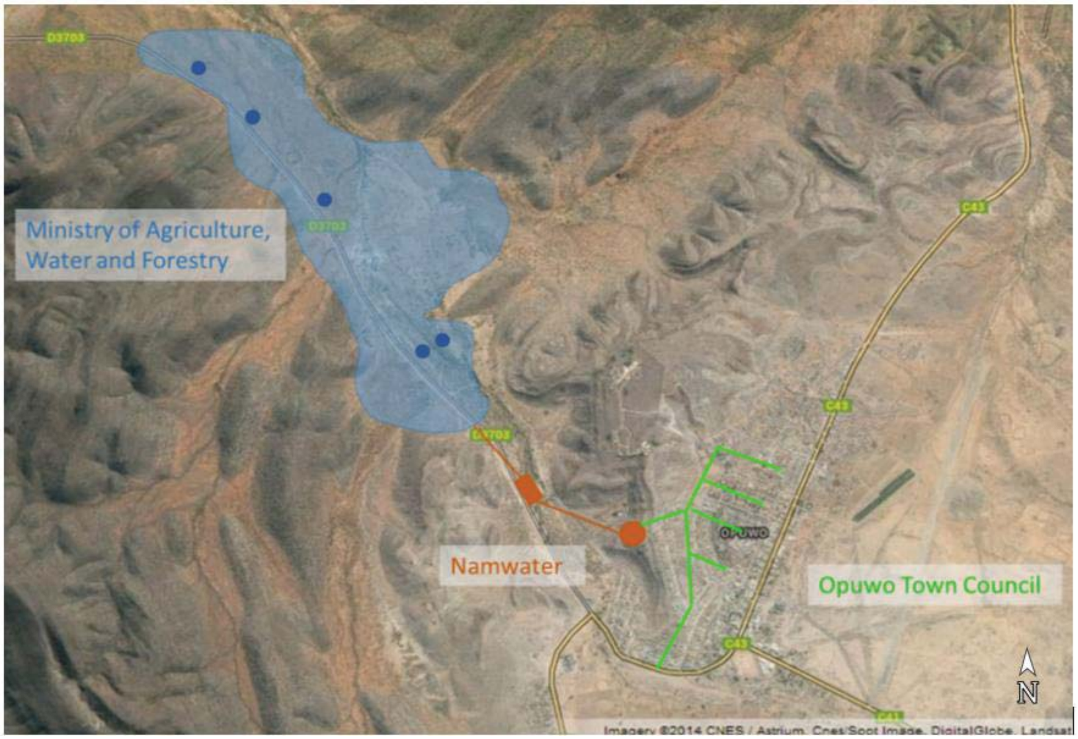

Figure 6: Administrative responsibilities of Opuwo water supply system (approximate scale 1cm:500m)

The current treatment capacity of the NamWater plant is approximately 45 m^3/hr. This fails to meet the demand of the town, which typically ranges from 100-150 m^3/hr. To balance treatment capacity with water demand, the treatment plant is operated 24 hours a day, 7 days per week. To maintain adequate water levels in the storage tanks, gate valves governing flow to the town are typically turned off at 8 pm every day, and turned on at 6 am by NamWater operators at the request of the Opuwo Town Council Water Committee. During times of peak water use (early-mid morning during the dry season), and when the treatment plant is taken offline for maintenance, raw water is routed around the treatment plant and blended with treated water to increase flow to the storage tanks.

2.2: Environmental Conditions

Opuwo is located in a climatic and topographical transition zone in which desert lands along the Skeleton Coast gain elevation and transform into the flat central plateau that typifies north-central Namibia. The threshold between the coastal desert and the central plateau is called the Great Escarpment. The town of Opuwo lies in an area generally considered to be the eastern boundary of the escarpment, with the western boundary a distance of 125-150 km east when variation in local topography becomes significantly reduced (Bubenzer & Bolten, 2004). The topography of the Great Escarpment region is characterized by pronounced ridges and mountains isolated by flat, open plains. The term Kaokoland is typically used to describe this landscape in the North-central Kunene Region.

Recent ecological mapping performed in Kunene Region classifies the greater Opuwo area as an acacia tree and shrub savannah located on the border of karstveld (extensive dolomite and limestone formations) and Kalahari sandveld (expansive plains underlain by sandy soils) terrain (Bubenzer & Bolten, 2004). The soil of the NW borehole scheme consists mainly of lithosols, which in this area are characterized by a rocky substratum that severely limits agricultural development (FAO, 1977). Vegetation is sparse and consists primarily of woody plants 2-8 m in height, with Mopane and various species of acacia trees being prevalent. Within this biome, local wildlife includes springbok, oryx, kudu, elephants and ostriches, while local domesticated animals are typically chickens, goats, sheep and cattle. Strong local land relief is present in the form of dolomite and quartzite hills classified by Fry (1986) that protrude a total vertical height of approximately 100-250 m from surrounding open plains.

Flat plains consist of soils from the Kalahari Group and the Karoo Supergroup. The uppermost layer lies approximately 0-30 m below ground surface (bgs) and consists of fine to medium-grained sand and calcrete. This material is underlain by siltstone and fine sandstone with occasional discrete gravel lenses in the northern boreholes (WW29045, WW29046, WW29047) and carbonaceous shale in the southern boreholes (WW23137 and WW22864). The hills and ridges surrounding the NW wellfield are comprised of dolomite, quartzite and shale. No exploratory drilling in the NW wellfield has fully penetrated the Karoo sediments and total vertical depth is unknown.

2.3: Water Quality

Water quality characteristics unique to this site are briefly discussed because of their relevance to future expansion in water production. Water Act No. 54 was implemented in 1956 by government of South Africa and administered in present-day Namibia until its replacement by superseding legislation (RSA, 1956). The Act classifies water quality according to four groups based upon level of physical/aesthetic, inorganic, and bacteriological constituents. Table 2 displays the water-quality classifications:

Table 2: Water Quality Classification Groups

Group	Description
Group A	excellent quality
Group B	acceptable quality
Group C	low health risk
Group D	high health risk

Laboratory results for water samples obtained from individual boreholes are provided in Appendix D. Water is classified according to the lowest group to which a constituent corresponds; for example, if a water sample contained almost entirely constituent concentrations corresponding to Group A and a single constituent concentration corresponding to Group C, the water would be classified as Group C. Prior sampling in the SE wellfield classified samples from all wells as Group A or B (Fry, 1986). Water quality samples for the NW wellfield characterize each well are illustrated in Table 3.

Table 3: NW borehole Water Quality Groups

Well	Water Quality Classification
WW22864	Group C
WW23137	No Analysis
WW29045	Group C
WW29046	Group C
WW29047	Group D

The water produced from the NW wellfield is of marginal to poor quality. The less-desirable water quality is attributed to high levels of dissolved magnesium, calcium and sulfate, which contribute to both potential gastrointestinal discomfort for some consumers and scaling of piping systems due to precipitation. The SE wellfield produces water of good quality but suffers from low aquifer productivity. Conversely the NW wellfield aquifer has shown to be comparatively productive, but extracted groundwater is of poorer quality.

3: Methods

3.1: Water Balance

Prior to performing water balance calculations, it was necessary to delineate the watershed from which the NW wellfield receives recharge. This was performed by acquiring four 1-arc angle (30 meter) DEM maps to cover the contributing sub-basin area and mosaicking into a single raster using a digital image processing program called ENVI (ver. 5.1, Exelis, Inc., McLean, VA). This raster was then imported to ArcMap 10.2 (ESRI, Redlands, CA) and the watershed was delineated using the watershed toolbox functions. The map was analyzed to determine flow direction and flow accumulation, from which high flow cells were identified. By establishing a 'pour point' near the hydrologic entry to the NW wellfield, the upstream basin could then be delineated. This procedure yielded a total watershed area of 576 km^2. To check reliability of the delineation, the location of the pour point was shifted within the aquifer model area; these shifts yielded an identical delineation of the contributing watershed. The watershed raster illustrating land elevation underlain by satellite imagery is shown in Figure 7.

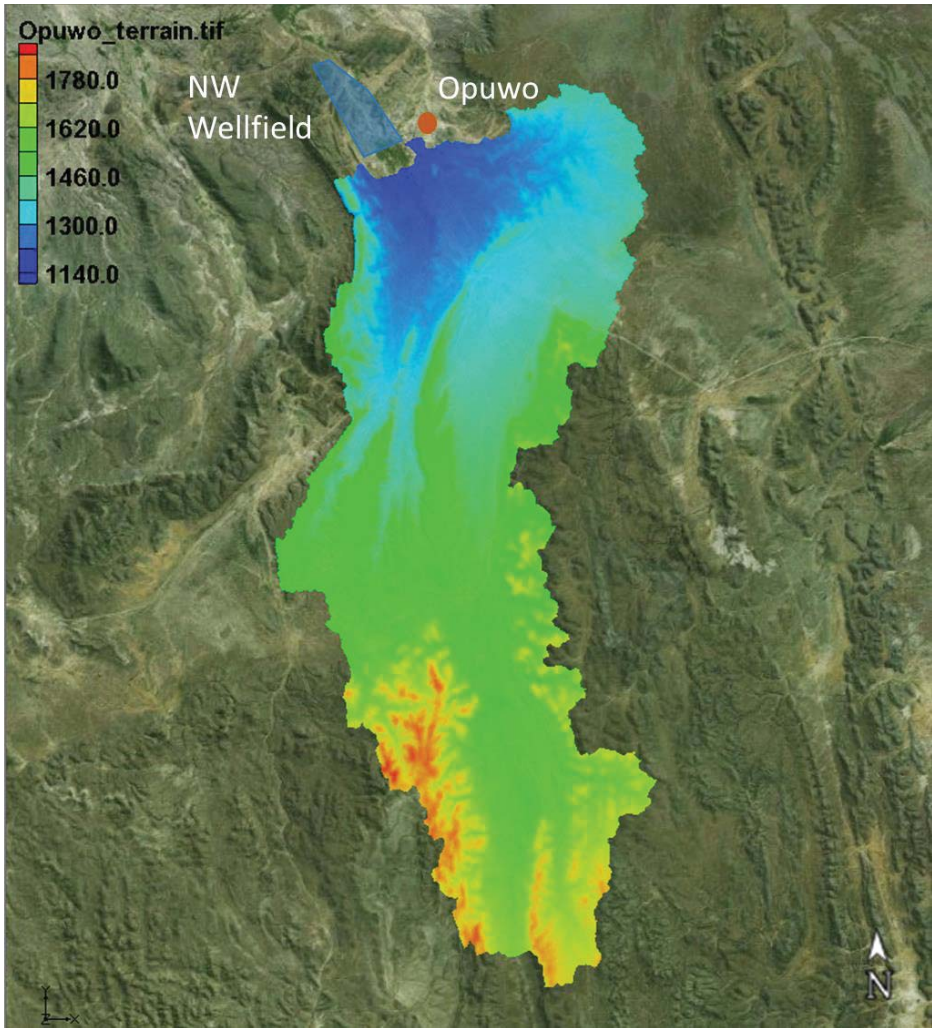

Figure 7: NW Wellfield Watershed, with elevation displayed in meters AMSL (approximate scale 1cm:6km)

Reliable quantification of hydrologic inputs and outputs is required for the contributing sub-basin. The water balance used in this study is adapted from the Regional Water Balance outlined by Dingman (2002):

$$P + G_{in} + H_{in} - (Q + ET + G_{out} + H_{out}) = \Delta S \qquad \textit{Equation 1}$$

Where

P = average precipitation

G_{in}= groundwater flow into the region

H_{in}= human induced inputs in region

Q = surface outflow from the region

ET = evapotranspiration out of region

G_{out}= groundwater flow out of the region

H_{out}= human induced abstractions from region

ΔS= change in storage over the time period

A time period of one year was selected to complete the water balance. Previous studies of the NW wellfield utilized an approach to estimate water resources in the 500 m x 4500 m area immediately containing the boreholes in the NW wellfield (Fry, 1986). This report quantifies water resources for the entire contributing sub-basin of the NW borehole scheme in Opuwo. Results of this study are compared with those found by Fry (1986), and are discussed in further detail in Section 5 of this report.

3.1.1: Precipitation and Temperature

Monthly precipitation data for the time period of 1940-1974 for the Opuwo area was provided by the Namibia Meteorological Service. This data was obtained from a weather station formerly located in Opuwo which is no longer operational. Annual precipitation in Namibia is characterized by a rainy season from November through April, and a dry season from May through October. Prior to calculation of average monthly precipitation, 'zero' values recorded during the rainy season were discarded. It was interpreted that 'zero' values were attributed to lack of recorded data rather than an absence of precipitation. Values of ‘zero’ during the dry season were left unaltered, because of the likelihood of lack of precipitation for that month. Interpolated climatic data was also acquired for comparison. Acacia Project E1, performed through the University of Heidelberg, assembled a GIS-based climate and geography atlas with climate and vegetation data. Additionally, the Royal Netherlands Meteorological Institute (KNMI) compiles climate data from weather stations located worldwide. Monthly precipitation values compiled by KNMI were accessed through the KNMI Climate Explorer portal, from which data for 1940-1974 was collected for comparison with field-recorded values, and data was collected for the time period 2000-2013 to provide an estimate of current precipitation in Opuwo. It was decided that the onsite data from 1940-1974 would be used in water balance calculations because precipitation data from KNMI and Project E1 are interpolated from surrounding weather stations. Precipitation data from KNMI and Acacia Project E1 are presented in conjunction with recorded data in Section 4.1.

Temperature data was obtained from the Climate Research Unit (CRU) at the University of East Anglia, which compiles various data sets widely used in climate research (Climatic Research Unit, 2015). Average monthly temperature data was accessed through the KNMI Climate Explorer for the years 1993-2013; values are based upon time-series of 0.5^{o} x 0.5^{o} grids obtained from weather stations around the world (Center for Environmental Data Archival, 2015). The time-series dataset 3.22 was used in this study because it is the most recent version available from CRU.

3.1.2: Evapotranspiration

Methods for estimating potential evapotranspiration (PET) in a watershed vary in applicability dependent upon data requirements for environmental conditions such as field capacity, root zone depth, precipitation, and solar radiation, amongst other parameters. The Opuwo watershed has a propensity for significant surface runoff in response to precipitation because of sloping surfaces, large areas of exposed bedrock, and high-intensity rainfalls. Due to clear-sky conditions and low plant density, actual evapotranspiration (ET) is driven by solar radiation rather than uptake by plants, contributing to a large percentage of precipitation lost to ET instead of infiltration and eventual groundwater recharge.

The Behnke and Maxey method of estimating PET was performed in this study because of its ability to predict PET values in semi-arid Nevada, which may be extrapolated to other arid and semi-arid environments (Shevenell, 1999) such as Kunene Region. In contrast to areas with high plant density, Shevenell (1999) illustrates that vertical solar radiance strongly correlates with PET values, provided the arid/semi-arid site is located within latitudes of +/- 25^{o} of the equator. The only observation data required by this approach is mean monthly temperature.

The Penman-Monteith and Thornthwaite methods were also considered for this analysis. The Penman-Monteith method was performed for comparison but ultimately not implemented into the model because the method requires maximum and minimum daily temperature and relative humidity data, which were unavailable for Opuwo. To complete the Penman-Monteith analysis, mean monthly temperature was used to replace maximum and minimum monthly temperatures, and relative humidity was calculated based upon estimates of mean monthly temperature. The Thornthwaite method was not used because it is unsuitable for landscapes dissimilar to those found in the East-Central United States (Jensen, 1973).

To estimate ET, PET estimates were adjusted according to the bare soil moisture index outlined by Allen et al (1998). This methodology was chosen due to the nature of soil conditions present in the basin and regional precipitation patterns. Precipitation in the greater Kunene Region typically occurs only in the rainy season, and is characterized by intermittent rainfalls of high intensity with distinct bare-soil wetting and drying cycles. To replicate these conditions, Allen et al (1998) outlined a methodology to determine a soil evaporation reduction coefficient (K_r) that describes the dynamics of soil evaporative response to a specific rainfall event. The volume of evaporable water is defined as

$$TEW = 1000(\theta_{FC} - 0.5\theta_{WP})Z_e \qquad \textit{Equation 2}$$

Where

TEW = total evaporable water, mm

θ_{FC} = soil water content at field capacity, m^3/m^3

θ_{WP} = soil water content at wilting point, m^3/m^3

Z_e = depth of surface soil layer subject to evaporative drying, m

In this water balance, a depth of Z_e= 0.1 m is assumed. The soil evaporation reduction coefficient, K_r, is calculated as:

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW}$$ *Equation 3*

Where

$D_{e,i-1}$ = Depth of evaporated water in previous stage, mm

REW = Ready evaporable water, mm; also represents cumulative depth of evaporation at end of stage 1, mm

Equations 2 and 3 model change in soil moisture following a rainfall event. The model was constructed by allocating the average total measured precipitation rate into a series of precipitation events. A mid-range estimation of number of rainfall events per month was applied based upon observations made in the site 2012-2014. The estimation assumes that rainfall occurs over equally-spaced intervals of each month at equal rainfall intensity. Soil moisture, ET, and net precipitation were calculated from the hypothetical 'standard' month of rainfall events. This method was performed for each month over the duration of one calendar year to create a theoretical year based on average climatic parameters in order to provide a representative estimation of total annual evapotranspiration.

3.1.3: Net Precipitation

Precipitation events in Opuwo, and across Namibia, are typically characterized by isolated, abrupt rainfall events with high intensity and high variability. High-intensity rainfall events coupled with the moderate to severe local topography, low density of herbaceous and woody plants, and prevalence of calcic soils in the area contribute to significant runoff, leading to reduced infiltration and increased erosion. In addition to providing estimates of soil moisture change and ET, the event-based ET/net precipitation calculations described in Section 3.1.2 also served as a predictive tool for estimating the magnitude of runoff response in the contributing basin. Based upon field observations, an assumption was made that 95% of the contributing basin contained soils capable of infiltration; the remaining 5% was comprised of exposed, competent rock.

In water budget calculations, net precipitation is calculated as the surplus of precipitation after losses due to ET. Net precipitation contributes to surface runoff through ephemeral stream channels and overland flow and to aquifer recharge via infiltration and subsequent subsurface flow. To determine the proportions of runoff and recharge, a comparison was drawn between the net precipitation based upon precipitation observations and ET calculations, and boundary flow values that gave best-fit results in the groundwater model, discussed in Section 4.4. It is assumed that all infiltrated water from the contributing watershed passes through the NW wellfield, and that storage volume of the upstream aquifer is constant. The volume of surface runoff was determined to be the difference between net precipitation and estimated aquifer recharge.

Additional recharge likely occurs in the form of losing streams following precipitation events. For watersheds greater than 100 km^2, channel flow processes tend to dominate even-response models (Dingman, 2002). Channelized flow and saturated soil conditions immediately following high-intensity rainfall events suggest that additional recharge is likely to be small in comparison to infiltration volumes over the expanse of the recharge area, and thus additional recharge is neglected.

3.1.4: Human Inputs and Withdrawals

No population centers are present within the contributing sub-basin. Human inputs and withdrawals exist in the form of scattered homesteads in the watershed. Agriculture is limited to small-scale gardening with no commercial crop exportation, and grazing of cattle, goats and sheep. Due to these observed factors, it was concluded that human inputs and outputs from rural locations in the upstream contributing basin to the NW wellfield are negligible in the overall water balance. The SE wellfield serving the village of Alpha, previously discussed in Section 2.1, abstracts negligible water volume and is also omitted from water budget calculations.

A significant volume of water is abstracted from the NW borehole scheme and various calculated withdrawal scenarios were made based upon current and projected water demand of Opuwo. Table 4 shows recommended abstraction rates given by Fry (1986), average actual abstraction rates from 2009-2013, and anticipated abstraction in the year 2021. The estimated water usage in 2021 is based upon current population growth rate and unchanging water usage patterns.

Table 4: NW wellfield abstraction scenarios

Well	Abstraction, m³/day				
	Recommended	***Actual Average***	***1-Month Maximum***	***1-Month Minimum***	***Projected 2021***
WW22864	600	499	1620	0.1	749
WW23137	175	213	741	0	320
WW29045	600	499	1339	0	749
WW29046*	333	97	870	0	146
WW29047	233	229	914	0	344

**WW29046 values obtained from 2011-2013 data.*

Water balance parameters were varied, and effects on annual ET and runoff+recharge volumes noted to evaluate the sensitivity of the assumed parameters. Field capacity was analyzed at three values: a mid-range field capacity estimation intended to function as the closest approximation of field conditions, as well as high-range and low-range field capacity estimates which were calculated to provide a range of potential runoff volumes for comparison with inputs to the aquifer model. Potential evapotranspiration was also varied to determine impact on predicted runoff and recharge volumes in the model.

3.2: Hydraulic Conductivity

In the geohydrological evaluation of the NW wellfield performed by Fry (1986) for the Department of Water Affairs (now MAWF), constant-discharge pumping tests were conducted on each of the five production boreholes in the NW wellfield. Three of the boreholes (WW29045, WW29046, and WW29047) were newly constructed, and the remaining boreholes (WW22864 and WW23137) had been installed approximately 8 years prior to testing. The results of these pumping tests were used as the basis for evaluation because the boreholes were recently constructed and not subject to accumulated scale associated with abstraction of mineral-rich groundwater. The pump tests performed during the 1986 investigation represent the most comprehensive data obtained regarding the NW borehole scheme.

Pumping test data was available from NamWater in hard copy only. Prior to analysis the plots were digitized by importing scanned images to a spreadsheet and placing a transparent plot over the top of the image. After aligning axes, points were plotted to match the pumping test curve, and the numerical data points determined from this method were used for analysis. A software package called AQTESOLV (ver. 4.50, Duffield, G., Reston, VA) was used to analyze the pumping test data for the NW borehole scheme. AQTESOLV is a widely-used program capable of modeling aquifer characteristics by utilizing well construction and aquifer formation data. Various analysis tools are available, including estimated values for hydraulic conductivity, transmissivity, and storativity. Through analysis of drilling logs it was determined that the NW wellfield aquifer is likely partially-confined. The Theis solution for unconfined aquifers was used to approximate the partially-confined conditions in the wellfield because of its applicability to site conditions and minimal data requirements. Curve-matching was performed on observation well data in favor of pumping well data to further reduce likelihood of skewed results due to well losses. The distances of observation wells from pumping wells ranged from 52 m (WW22864 and WW23137) to approximately 800 m (WW29045 and WW29046)

3.3: Borehole Scheme Performance

Historical values for abstraction volume, static water level (SWL) and pumping water level (PWL) of the wells were evaluated. Additionally, specific capacity of each well was calculated based upon pumping test data from initial construction, and compared to 2013 production data. An attempt was made to identify trends in abstraction rates and groundwater levels both seasonally and inter-annually and to identify potential causes for these trends.

3.4: Groundwater Model

A modeling software package called Groundwater Modeling System (GMS) (ver. 9.1, Aquaveo, Provo, UT) was used to compile GIS data and construct a parameter-based conceptual model of the NW wellfield aquifer. GMS served as the computational environment for using MODFLOW to simulate the groundwater flow system. MOFLOW is a numerical model that solves the 3-dimensional groundwater flow equations that was developed by the United States Geological Survey (USGS) first in 1988 (Mcdonald & Harbaugh, 1988) and subsequently has evolved to accommodate more complex flow processes. This work utilized the 2005 version of MODFLOW. MODFLOW is considered to be the international standard in groundwater simulations, and is widely used in modeling of groundwater flow, aquifer response to environmental change, stratigraphy, and pollutant transport, amongst other applications (USGS, 2014). The GMS+MODFLOW software package was selected for use in this study because of its flexibility in importing and utilizing GIS and other map data, ability to replicate site conditions through the creation of a conceptual model, and expansive range of modeling and analytical capabilities. The GMS conceptual model is assembled by delineating and defining the following:

- hydrologic inputs/outputs
- surface elevation data
- geological attributes
- applicable system boundaries
- recharge characteristics

Hydrologic Inputs and Outputs:: Boundary flow volume (input) and well data including location, depth, and abstraction rate (output) were implemented in the model. GPS locations and elevations for each of the five boreholes in the NW wellfield were acquired in the field using a handheld GPS. Monthly records of abstraction rates, static water level (SWL), pumping water level (PWL), pumping hours, and abstraction volume for each borehole in the wellfield are maintained in spreadsheet format at the NamWater office in Windhoek. This data served as the basis for production-related measures such as specific capacity and drawdown, as well as the definition of average abstraction rates and long-term trends in groundwater depth.

Surface Elevation Data: Topography data was obtained through an online geophysical database in which digital earth models (DEMs) were acquired through the Earth Explorer interface (ver. 2.0, USGS, Reston, VA) on the USGS website and subsequently mosaicked using ENVI, a digital image processing program, into a single

DEM raster image. When imported to GMS, the top layer of the conceptual model was mapped to the elevation data contained within the raster.

Geological Attributes: One hydrologic layer was used to represent the aquifer in the conceptual model despite additional geological features observed in the drilling logs. The hydraulic conductivity values obtained from the AQTESOLV analysis and the implications of these results are discussed further in Section 4. Because hydraulic conductivity values amongst the boreholes were comparable, the entire layer of alluvium was modeled with an average hydraulic conductivity value obtained from pumping tests in the five production wells. As displayed in Figure 8, a polygon was created to model groundwater flow within the dolomite ridge on the western border of the wellfield; this polygon was assigned a hydraulic conductivity value through the Parameter Estimation (PEST) tool in MODFLOW, with maximum and minimum conditions set at typical values for dolomite structures. During evaluations, PEST determined optimum hydraulic conductivity values for given environmental conditions as observed against average pumping water level (PWL) in each well for the year 2013. The bottom extent of the water-bearing structure in the NW wellfield is undetermined, and the base of the aquifer was estimated to lie 20 m below the lowest drilled depth. Land surface elevation, surface drainage patterns and recorded water levels in the production wells indicate that subsurface water flow enters the wellfield from the SE and travels in a NW direction until it exits the modeled area through an ephemeral river valley, as shown by the vectors in Figure 8.

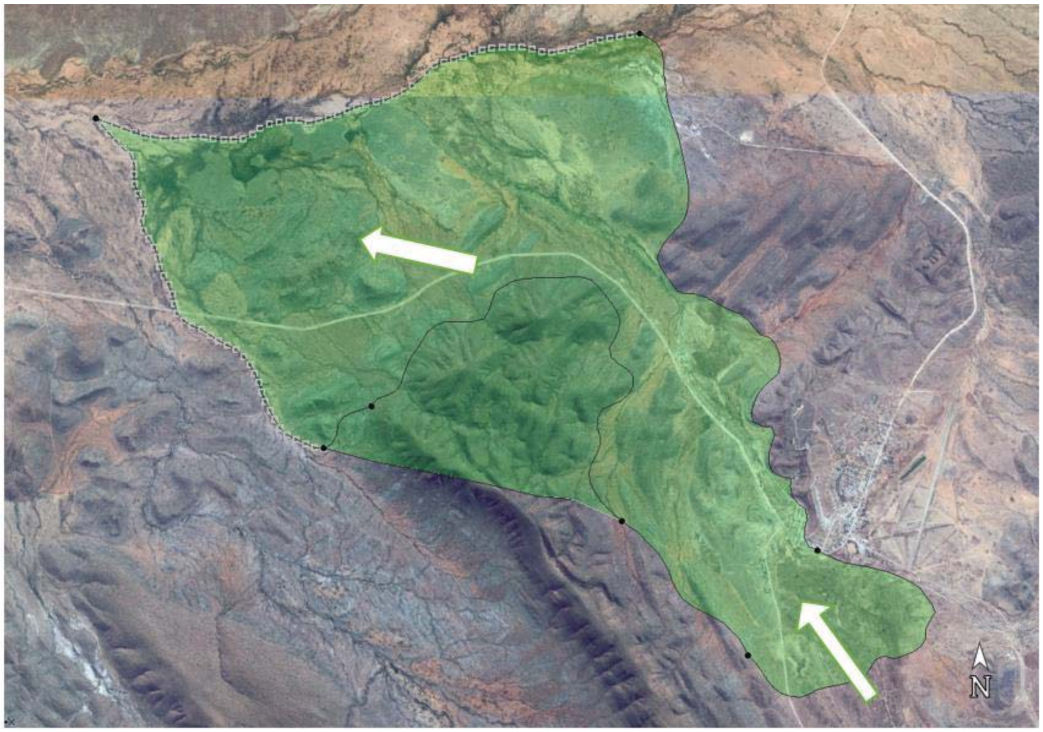

Figure 8: Flow direction and boundaries of modeled area (approximate scale 1cm:1km)

System Boundaries: Model boundaries were delineated at the interfaces between alluvial soils and other geomorphological or hydrologic features. In GMS, the downstream (NW) boundary was specified as the western-flowing ephemeral stream that eventually reaches the Atlantic Ocean. This boundary is designated by the gray dashed line in Figure 8. In the conceptual model this arc was defined as a drain with a conductance of 200 m^2/d/m through which groundwater exited the model area. The elevation of the drain arc was set at four meters below ground surface to match the estimated ephemeral river bed elevation. The east and southwest boundaries were specified at the point of intersection between the surface of alluvial soils and the dolomite ridges that lie immediately east and west of the NW wellfield. These arcs were modeled as no-flow boundaries because the surrounding hills are exposed competent dolomite/quartzite with low hydraulic conductivity relative to alluvium. The upstream (SE) boundary was delineated on a topographical basis, and was defined as a specified-flow arc in the lower right-hand portion in Figure 8. When analyzed in MODFLOW, this arc was modeled as a series of injection wells in which volume was varied to calibrate the model to match observed static water levels in the wells. Darcy's equation was used to obtain a starting boundary flow volume through the NW wellfield for model calibration:

$$Q = kiA \qquad \textit{Equation 4}$$

Where

Q = volume of groundwater flow through NW wellfield, m^3/day

K = hydraulic conductivity, m/d

i = hydraulic gradient of wellfield, m/m

A = average cross-sectional area of wellfield alluvial soils, m^2

Recharge Characteristics: Direct recharge is modeled as the fraction of precipitation that contributes to the aquifer through vertical infiltration. Indirect recharge (boundary flow) is modeled as subsurface flow from upstream in the basin that contributes to groundwater volume in the modeled area. Direct recharge was assumed uniform over the modeled area, and was refined using the PEST function, discussed in further detail below.

Once completed, conceptual model attributes were mapped to a 3D grid and evaluated through the MODFLOW analysis package. A steady-state analysis was used to develop a model based upon 2013 annual data. In the steady-state analysis, three parameters were adjusted to calibrate the model: direct recharge, hydraulic conductivity in the alluvial soils (large polygon in Figure 8), and recharge via the specified flow arc located upstream of the wellfield. The model was calibrated to pumping well levels (PWL) in four of the production wells (all but WW23137), using starting values for hydraulic conductivity and boundary flow calculated using Equation 4. Well WW23137 was omitted as an observation point because it is pumped alternately as a backup to WW22864.

The PEST function was utilized to determine optimum values of recharge and hydraulic conductivity during model calibration to most accurately match observed PWLs in the boreholes. Parameter Estimation is established by manually setting maximum, minimum, and starting values for specified parameters. The values are automatically varied, and resulting PWLs estimated through MODFLOW are compared to observed average PWLs in the boreholes during 2013. Iterations are repeated until the best fit has been determined. These results were then compared with those obtained from historical field data and hydraulic conductivity values determined using AQTESOLV. In 2013, the standard deviation of the PWL in each well ranges from 2-3 m; the model was able to calibrate PWLs to within 0.9 m of observed values in the year 2013. Given that the degree of error in the model was smaller than one standard deviation present in the data set, the model was considered calibrated.

Stochastic Analysis (Monte Carlo) was used to analyze model response to variations in hydraulic conductivity in dolomites, hydraulic conductivity in alluvial soils, and recharge. The parameter randomization method was selected for the analysis, with Latin Hypercube chosen as the approach due to its increased confidence with reduced iterations in comparison to the random sampling approach. Stochastic analysis results in a range of model results, which if averaged, equal the best fit. After being determined, the mean values for hydraulic conductivity, recharge, and PWL predicted by the Monte Carlo analysis were then compared to those obtained through the PEST analysis and observed values.

After calibration and stochastic analysis, increased-demand scenarios were modeled. A forward analysis of MODFLOW was performed with an abstraction rate of 0 m^3/day was first applied to duplicate SWL in non-pumping conditions. The average abstraction rate from each well in 2013 was multiplied by 150% and 200% to estimate hypothetical water demand increases. The resulting PWL in each well is compared to the average PWL from 2013, and implications for screened depths are discussed.

4: Results

4.1 Precipitation

Historical precipitation in the watershed is strongly variable. Based upon meteorological data from a weather station formerly located in Opuwo, the adjusted total annual average rainfall for Opuwo is 379mm, of which 360 mm falls during the rainy season and 19 mm during the dry season (Namibia Meterological Service, 2014). As shown in Table 5, interpolated data from ACACIA Project E-1 (2004) classifies Opuwo as falling into an area with 300-350 mm of mean annual precipitation, and

KNMI Climate Explorer (2015) data for the time period of 2000-2013 estimates an annual average of 344 mm. When compared to recorded data over the 1940-1974 time period, it is determined that KNMI interpolated data provides a representative estimation of annual rainfall in Opuwo when compared to field observations.

Table 5: Opuwo monthly precipitation estimates

Source	**Time Period**	**Estimate (mm)**
NMS	1940-1974	302
NMS (adjusted)	1940-1974	379
KNMI	1940-1974	357
KNMI	2000-2013	344
ACACIA Project E-1	n/a	300-350

On a monthly basis, all data sets indicate that the majority of precipitation occurs from January through March, with smaller precipitation volumes also occurring early in the rainy season during the months of November and December, as shown in Figure 9. Given the basis on field measurements in Opuwo and the lack of specificity of data from the ACACIA project, the monthly estimate from Namibia Meteorological Service was used in water budget calculations.

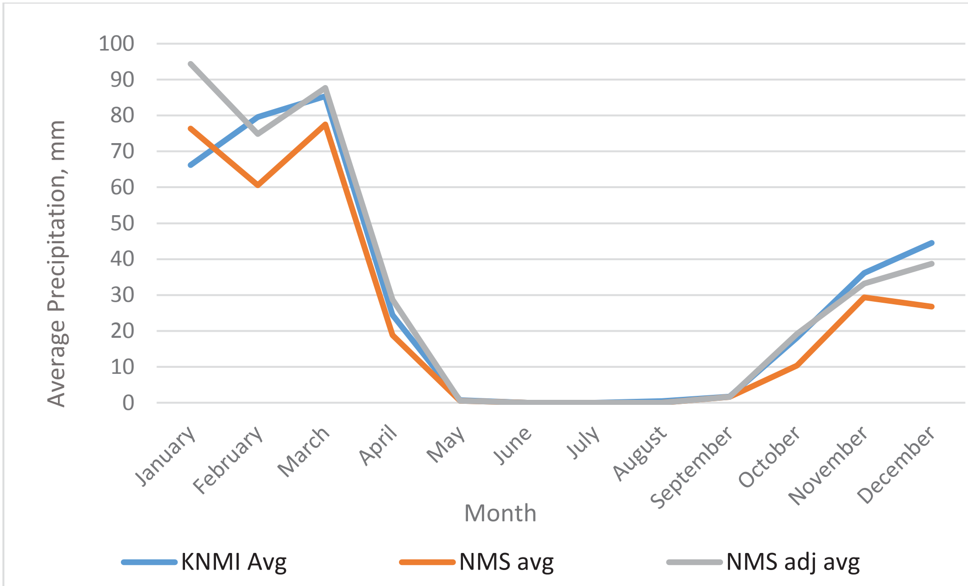

Figure 9: Average monthly precipitation in Opuwo for the time period 1940-1974

The watershed delineation performed in ArcGIS determined that the contributing basin upgradient of the NW wellfield encompasses an area of approximately 576 km^2 (576,000,000 m^2). This recharge area is in addition to the 45 km^2 MODFLOW model area available for recharge. The mean total annual rainfall volume within the upstream watershed is calculated to equal $2.16x10^8$ m^3. Figure 10 shows the contributing sub-basin outlined in blue and the NW wellfield modeled area. Surface water flow direction was determined using ground elevation depicted in Figure 7 in Section 3.1 and ephemeral streambeds visible in Figure 10.

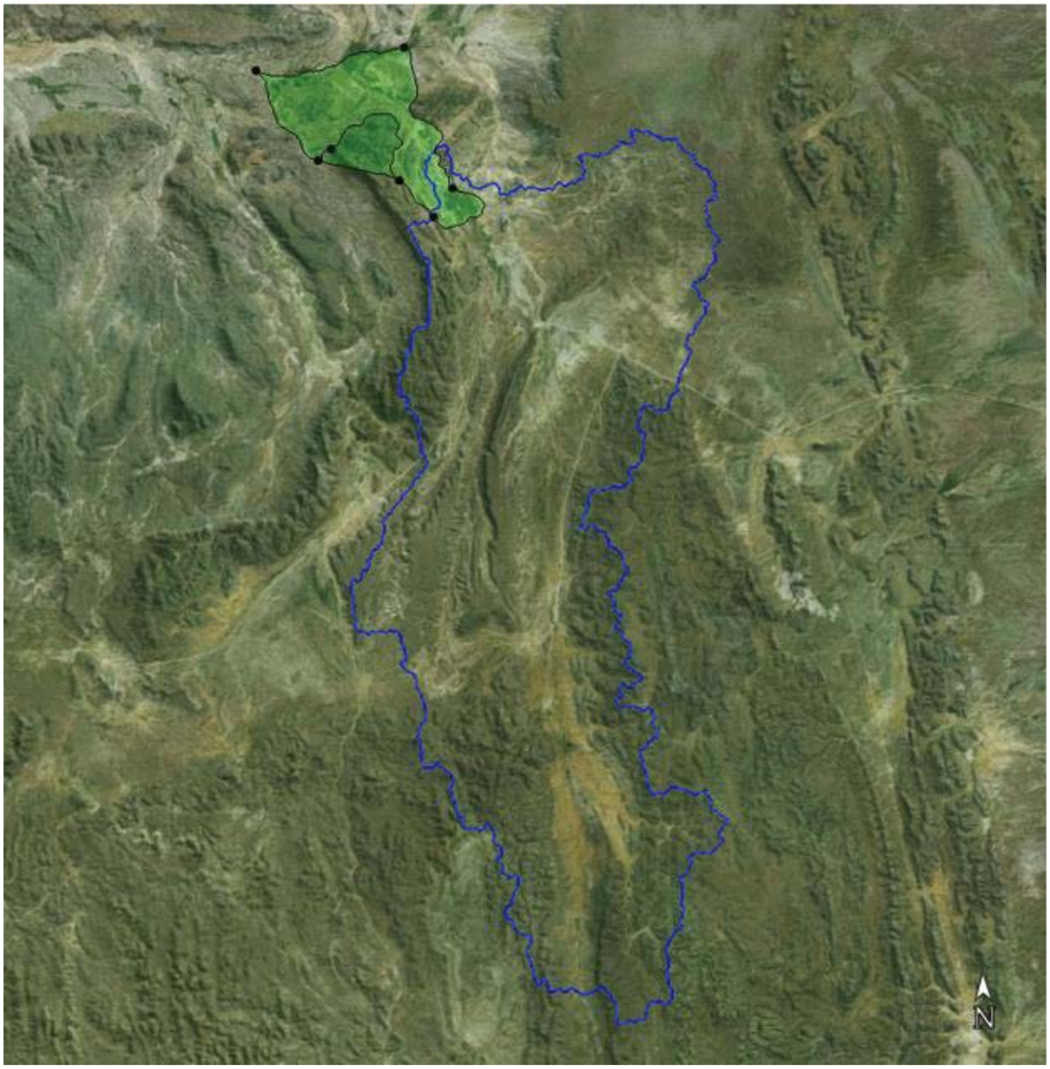

Figure 10: Model area and contributing basin recharge delineation (approximate scale 1cm:6km)

4.2 Evapotranspiration and Net Precipitation

The Behnke and Maxey method for estimating PET yielded values ranging between 4.6 mm/day in June and 11.6 mm/day in January. By comparison, the values estimated through the Penman-Monteith methodology ranged from 3.0 mm/day in June to 5.4 mm/day in January. The total annual PET predicted using the Behnke and Maxey method was 2992 mm, while the total annual PET predicted using the Penman-Monteith method was 1594 mm.

Quantitative estimates for net precipitation and ET volumes are dependent upon field capacity, θ_{fc} and depth subject to evaporation, Z_e. Field capacity measures the volume of water capable of being stored by a specific volume of soil; values were utilized in the water balance in a high-range parameter estimation (0.22 m^3/m^3), a mid-range parameter estimation (0.18 m^3/m^3), and a low range parameter estimation (0.14m^3/m^3). Figure 11 shows that the net precipitation available for aquifer recharge is reduced at high field capacity due to increased water retention. At soil field capacity ranging from 0.14-0.22, it is reasonable to anticipate that 64-99% of precipitation is lost to ET; the remaining net precipitation available for surface runoff or recharge is estimated to be 1-36% of total precipitation volume.

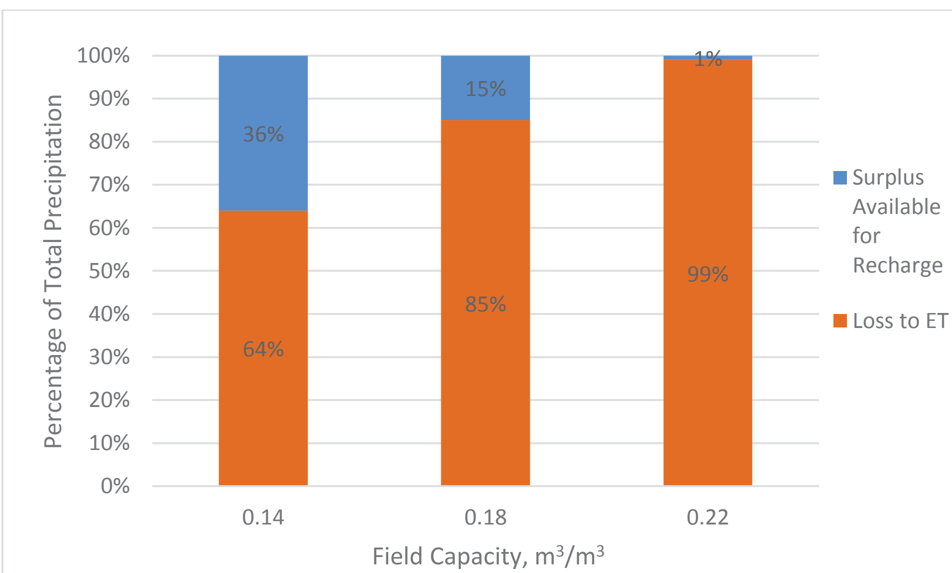

Figure 11: Fraction of rainfall available for groundwater recharge

High-intensity rainfall events in Kunene Region produce large runoff volumes. As a result, aquifer recharge likely represents a small fraction of net precipitation. The portion of net precipitation that recharges the aquifer was determined by comparing boundary flow volume determined in the MODFLOW model to boundary flow volumes calculated in the water balance. Net precipitation ranged from 8,231 m^3/day to 217,472 m^3/day. Table 6 illustrates that at low- and mid-range field capacity values, the specified recharge depicted in MODFLOW represents a small fraction of the total available net precipitation.

Table 6: Flow fractions at various field capacity values

Net Precipitation, m^3/day	**Field Capacity, m^3/m^3**	**MODFLOW Recharge, m^3/d**	**Fraction of Total**
217,472	0.14	4,800	2%
96,391	0.18	4,800	5%
8,231	0.22	4,800	58%

Direct recharge is estimated to be 3.6 mm/year by using the recharge volume determined through PEST analysis in MODFLOW. The calculated recharge to the aquifer through vertical infiltration represents 1% of the annual average precipitation. Estimated direct recharge and boundary flow illustrate that the groundwater level in the NW wellfield is largely determined by transfer of groundwater through alluvial soils, rather than on direct infiltration of precipitation. Table 7 summarizes average precipitation, number of rainfall events per month, and calculated monthly volumes of net precipitation and ET at the mid-range parameter value for field capacity, θ= 0.18 m^3/m^3. The mid-range parameter was selected for presentation of hydrologic data because it most closely represents a typical field capacity value for the observed soil type in site. Additional data illustrating the annual water balance at high and low parameter values is provided in Appendix H.

Table 7: Average monthly temperature and potential evapotranspiration values

Month	Avg. Temp. °C	Behnke and Maxey PET	Average Precip. mm	Number of Rainfall Events	Average Rainfall Intensity mm/hr	Net Precip. mm	ET mm
January	19.0	10.4	94.4	6	15.7	8.9	85.5
February	19.0	10.3	74.8	4	18.7	17.8	57.0
March	18.5	9.3	87.6	5	17.5	16.4	71.2
April	17.6	8.4	28.7	2	14.4	0.2	28.5
May	15.3	6.0	0.6	1	0.6	0.0	0.6
June	13.4	4.0	0	0	0.0	0.0	0.0
July	12.9	4.1	0	0	0.0	0.0	0.0
August	14.0	5.4	0	0	0.0	0.0	0.0
September	16.3	8.2	1.6	1	1.6	0.0	1.6
October	17.7	10.1	19.2	2	9.6	0.0	19.2
November	18.5	10.9	33.2	2	16.6	4.7	28.5
December	18.8	11.1	38.7	2	19.4	10.2	28.5
SUM:			**379**	**25**		**58**	**321**

As described in Section 3.1.2, soil moisture change was modeled for individual rainfall events in which ET rate is dependent upon the cumulative depth of evaporation in the soil. Figure 12 illustrates the fluctuation in ET rate at the mid-range parameter value for field capacity and average PET value of 9.3 mm for the month of March. Actual ET approaches 0 mm/day within approximately 4 days as the volume of evaporable water in the soil is nearly depleted. The typical soil moisture/ET rate cycle nearly exhausts all evaporable water in the soil prior to the arrival of the next rainfall event. In the absence of empirical field data regarding soil moisture change in response to precipitation events, observations indicate the wet/dry cycle modeled in this water balance adequately depicts environmental conditions. Additional discussion regarding soil moisture change, post-precipitation ET rate, and sensitivity of the water balance methodology to the PET values determined using the Behnke and Maxey method are provided in Section 5 of this report.

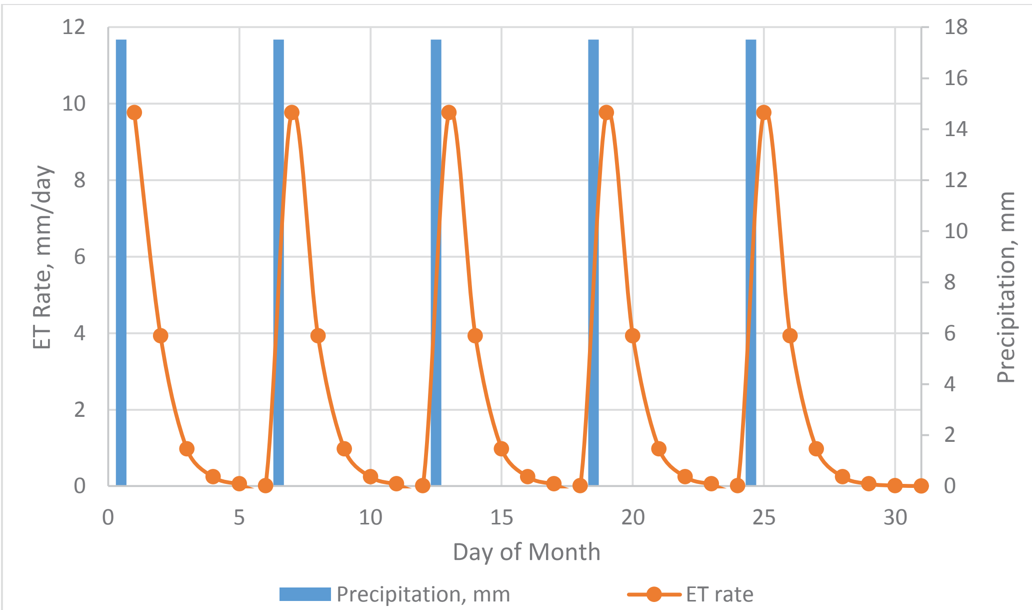

Figure 12: Evapotranspiration rate in soil during precipitation response

In the mid-range scenario, the summation of monthly balances for one calendar year illustrates that of 379 mm total precipitation, approximately 320 mm is lost to evapotranspiration. Recharge is estimated to be 3.6 mm (6% of net precipitation), with the remaining 54 mm (94% of net precipitation) lost as surface runoff. Fraction of ET, recharge, and runoff as total precipitation are illustrated in Figure 13.

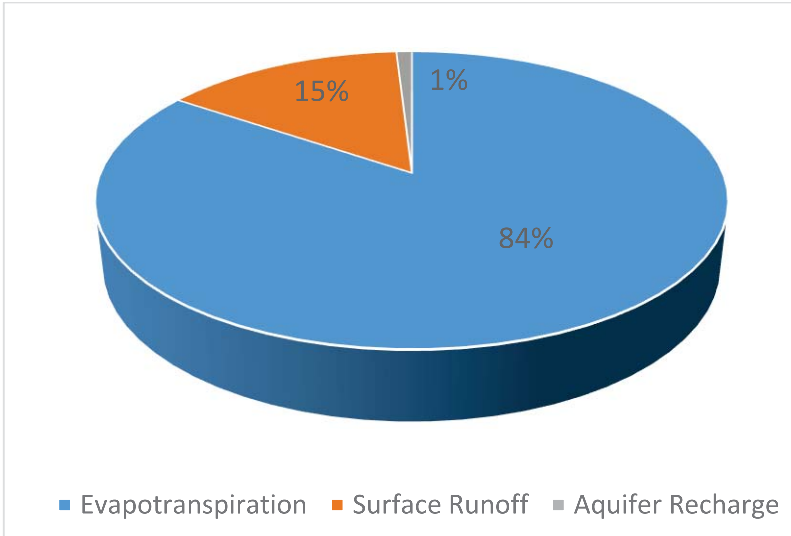

Figure 13: Resultant fractions of precipitation

Figure 14 shows that surface runoff occurs in high-precipitation summer months only. Beginning in June, the water balance becomes 'dormant,' with no modeled ET or precipitation taking place.

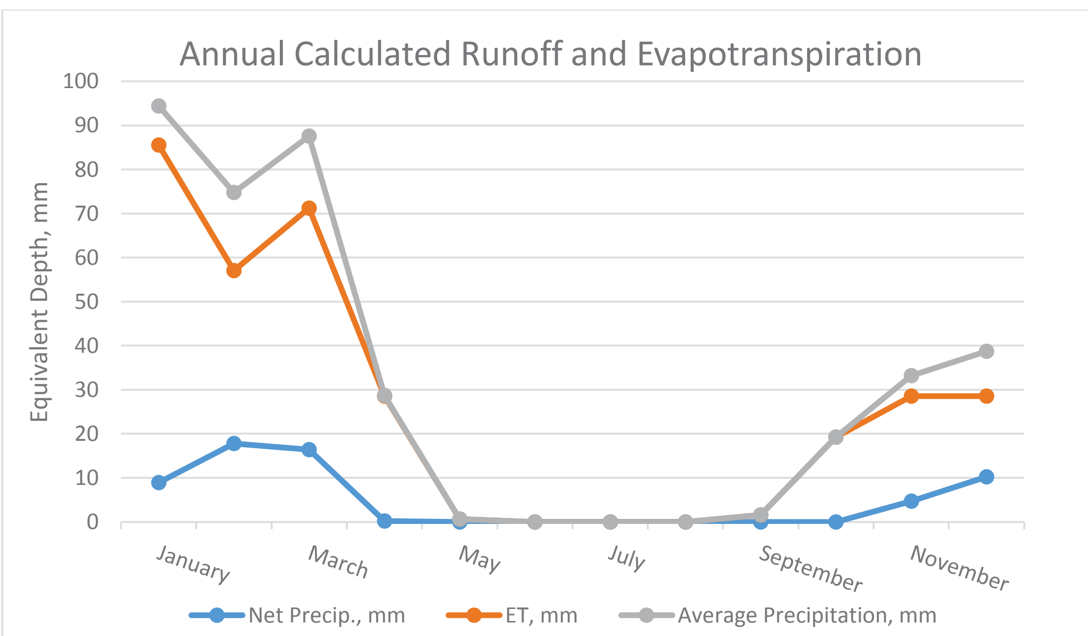

Figure 14: Monthly Water Budget Estimations of net precipitation and ET for NW wellfield contributing basin

4.3: Borehole Scheme Performance

Figure 15 shows that abstraction volume is variable and no significant increase in production has occurred from 2000-2013. In 2013 the average abstraction was 1630 m^3/day. A large decline in net abstraction is observed in two instances: 2005-2007 and 2010. The production depression in 2005-2007 is the result of decline in production volume in WW22864 and the absence of pumping in WW29046, likely for maintenance reasons. All wells were being pumped during the production decline in 2010, but WW22864 and WW29045 decreased in abstraction during that year.

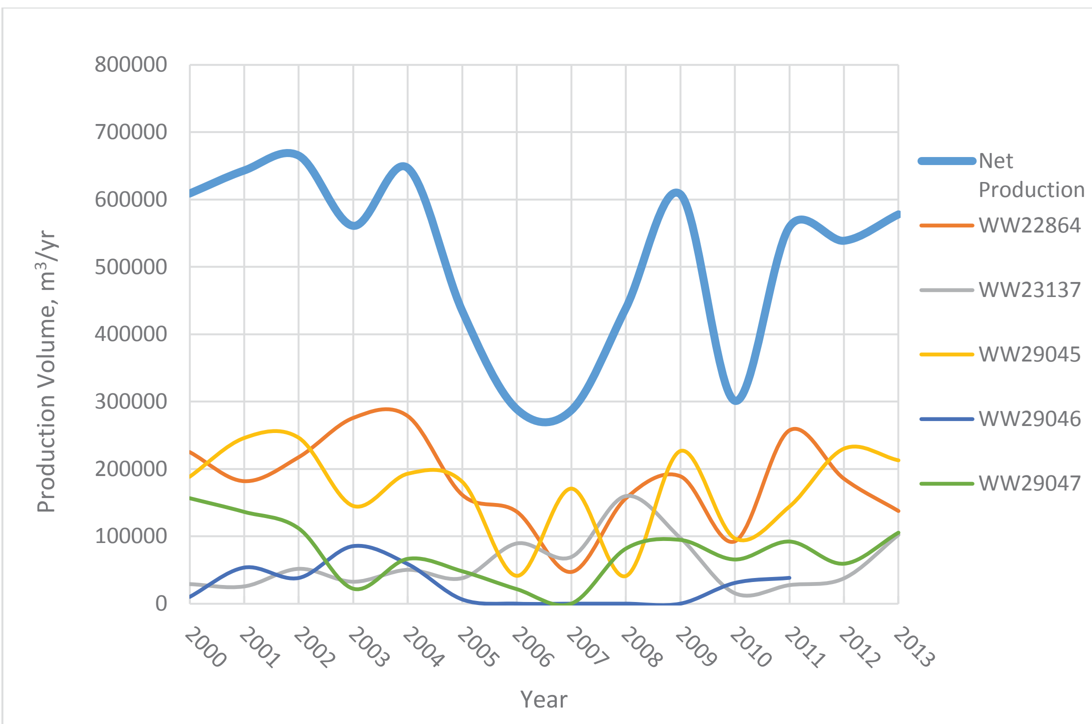

Figure 15: NW wellfield annual production volumes

During the time period 2000-2013, average groundwater level in the wellfield has risen by 12.3 m, while production has decreased by only 8%. Change in measured

SWL is consistent despite variable production volumes, suggesting abstraction volume is small in comparison to the recharge volume available in the contributing sub-basin. Previous studies have illustrated that in arid regions, climatic parameters may have a greater impact on groundwater levels than increased pumping rates (Lutz, 2008), and additional climatic factors may be impacting groundwater levels in the basin. Potential climatic causes of the measured groundwater level increase are discussed in Section 5 of this report.

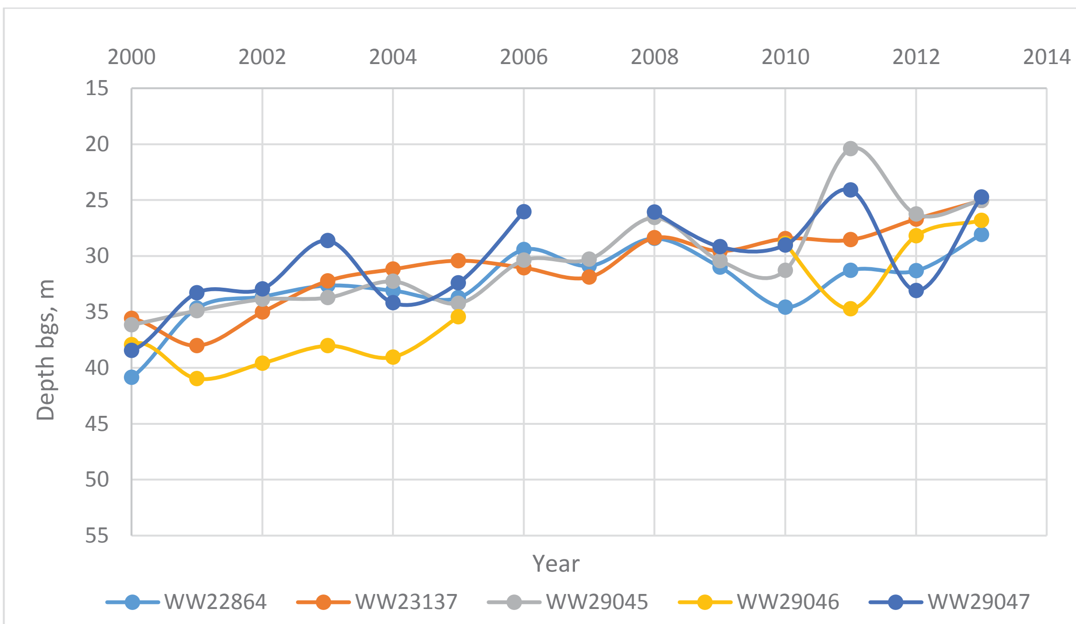

Figure 16: Static Groundwater Level in NW Wellfield

Change in observed groundwater level was not uniform amongst the five boreholes in the NW wellfield. Because WW22864 and WW23137 are pumped alternately due to their close proximity, they are considered together when analyzing production, SWL, and PWL data. Production between WW22864 and WW23137 decreased by 8.2%, while SWL rose by 11.8 m (29%) and 14.3 m (41%), respectively.

Table 8: Groundwater level comparison: 2000 and 2013

Location	**Static Water Level meters bgs**		
	2000	2013	Rise, m
WW22864	40.9	29.1	11.8
WW23137	35.0	20.8	14.3
WW29045	36.1	24.0	12.2
WW29046	37.9	27.5	10.4
WW29047	38.4	25.8	12.6
Scheme avg.	37.7	25.4	12.2

Table 9: Production comparison: 2000 to 2013

	Production, m^3/yr			
Location	2000	2013	Change, m^3	Percent Change
WW22864	243255	154044	-89211	-37%
WW23137	51705	116551	64846	125%
WW29045	188380	185842	-2538	-1%
WW29046	9994	25953	15959	160%
WW29047	156510	112243	-44267	-28%
Scheme net	649844	594633	-55211	-8%

Table 10 displays that specific capacity, the volume of water abstracted per unit of drawdown length, increased in four of five wells the NW wellfield. This increase likely results from the observed trend of rising SWL and PWL in the NW wellfield from 2000-2013. Specific capacity is measured as the volume of groundwater produced divided by length of drawdown; the reduced drawdown associated with rising groundwater levels corresponds to higher specific capacity values calculated in each well.

Table 10: Specific capacity values

Location	Specific Capacity Upon Construction, $m^3/hr/m$	2000-present Average Specific Capacity, $m^3/hr/m$
WW22864	4.4	5.7
WW23137	3.3	9.7
WW29045	6.5	6.3
WW29046	4.3	10.1
WW29047	2.3	4.7

4.4 Hydraulic Conductivity

Values for K calculated from the AQTESOLV analysis ranged from 0.86 to 3.41 m/day, with an average value of 1.6 m/day. For transmissivity calculations, the depth of water-bearing structure for each well was considered to be the distance from the top of the static water level to the depth of the lowest recorded water strike. Table 11 shows Transmissivity values ranged from 60-290 m^2/day, and storativity values ranged from 1.09×10^{-6} to 0.1116. Drilling logs indicated that water flows preferentially through gravel lenses at various depths in the aquifer; this characteristic is not reflected in the AQTESOLV calculations. The calculated values for hydraulic conductivity represented the only field source of such data and were used as the starting hydraulic parameters for the aquifer model. Pumping test data performed as part of the 1986 geohydrological investigation is shown in Appendix C.

Table 11: AQTESOLV estimated parameters

Location	Transmissivity, m^2/d	Storativity,	Hydraulic Conductivity, m/d
WW22864	95.8	0.0020	1.37
WW23137	91.7	0.0003	1.18
WW29045	290.3	0.0008	3.41
WW29046	60.5	1.09×10^{-6}	0.86
WW29047	123.8	0.1116	1.21

4.4 Aquifer Model

The first MODFLOW analysis was a steady-state model with conditions based upon average annual precipitation, hydraulic conductivity, and 2013 production data. Pumping water levels calculated by the MODFLOW model were compared with average PWL recorded during 2013. Figure 17 displays a comparison of the observed PWL and the modeled PWL in each of the four wells in the NW wellfield, with error bars used to represent the standard deviation in PWL during 2013.

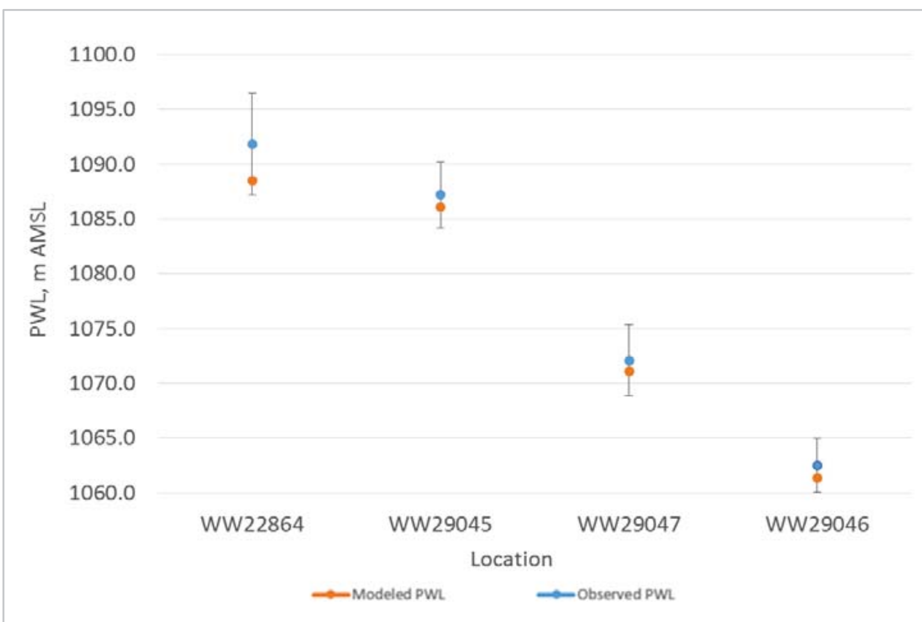

Figure 17: Model prediction of PWL levels in the NW wellfield

As shown in Table 12, during the year 2013, the standard deviation in each well ranged from 2.42 m to 7.33 m. After applying corrections for the difference between grid cell size and well casing diameter, the MODFLOW calculated PWLs fell within one standard deviation of 2013 PWLs. Because the residual head is smaller than the standard deviation amongst the wells, the model was considered acceptably calibrated for use in hypothetical pumping scenarios.

Table 12: MODFLOW residual head vs. standard deviation of field data

Location	**SWL 2013 Standard Deviation, m**	**MODFLOW Residual Head, m**	**Percentage of Standard Deviation**
WW22864	4.64	-0.41	9%
WW23137	7.33	n/a	n/a
WW29045	3.01	0.93	31%
WW29046	2.42	0.33	14%
WW29047	3.23	-0.87	27%

Based upon the hydraulic gradient calculated from field records of PWL in WW29046 and WW22864, average alluvial depth of 170 m, and average width between bordering dolomitic ridges, Equation 4 (Darcy's Equation) yielded a volumetric subsurface flow estimation of 4956 m^3/day. Utilizing the PEST function in MODFLOW, the daily recharge volume corresponds to an average hydraulic conductivity of 1.56 m/d in the NW wellfield. Table 13 shows the comparison between the calculated parameters using Equation 4 and the best fit parameters gained utilizing the PEST function in MODFLOW.

Table 13: Steady state analysis at abstraction = 1630 m^3/day

Parameter	**Method of Evaluation**	
	PEST	***Eq. 4/MODFLOW***
Hyd. Cond. Alluvium (m/d)	1.47	1.56

Hyd. Cond. Dolomite (m/d)	0.15	0.110
Recharge (m/d)	$1.0x10^{-5}$	$6.6x10^{-6}$
Boundary flow (m^3/d)	4800	4956
Absolute Mean Residual (m)	0.62	1.13
Abstraction Rate (m^3/day)	1630	1630

A stochastic analysis was applied to the model parameters at additional boundary flow volumes of 6240 m^3/day (+ 30%) and 3360 m^3/day (-30%). Table 14 below shows the best estimate from each range of solutions at each boundary flow volume. Of the random parameters created at a boundary flow volume of 4800 m^3/day, the best fit is nearly identical to the best-fit calculated through the PEST function. Table 14 also illustrates that alluvial hydraulic conductivity had the highest impact when matching model head values to observed values.

Table 14: Stochastic analysis summary

Parameter	**Boundary Flow Volume (m^3/day)**		
	6240	4800	3360
K, alluvium (m/d)	2.2	1.49	0.72
K, dolomites (m/d)	0.16	0.15	0.14
Recharge (m/d)	$9.7x10^{-6}$	$9.1x10^{-6}$	$8.1x10^{-6}$
Absolute mean residual error (m)	0.74	0.63	0.89

Figure 18 illustrates that PWL decreases in absolute elevation towards the upper-left portion of the model area. While the difference in hydraulic conductivity between the polygons contributed to preferential flow patterns in the model, it did not contribute to significant head variation between the two polygons.

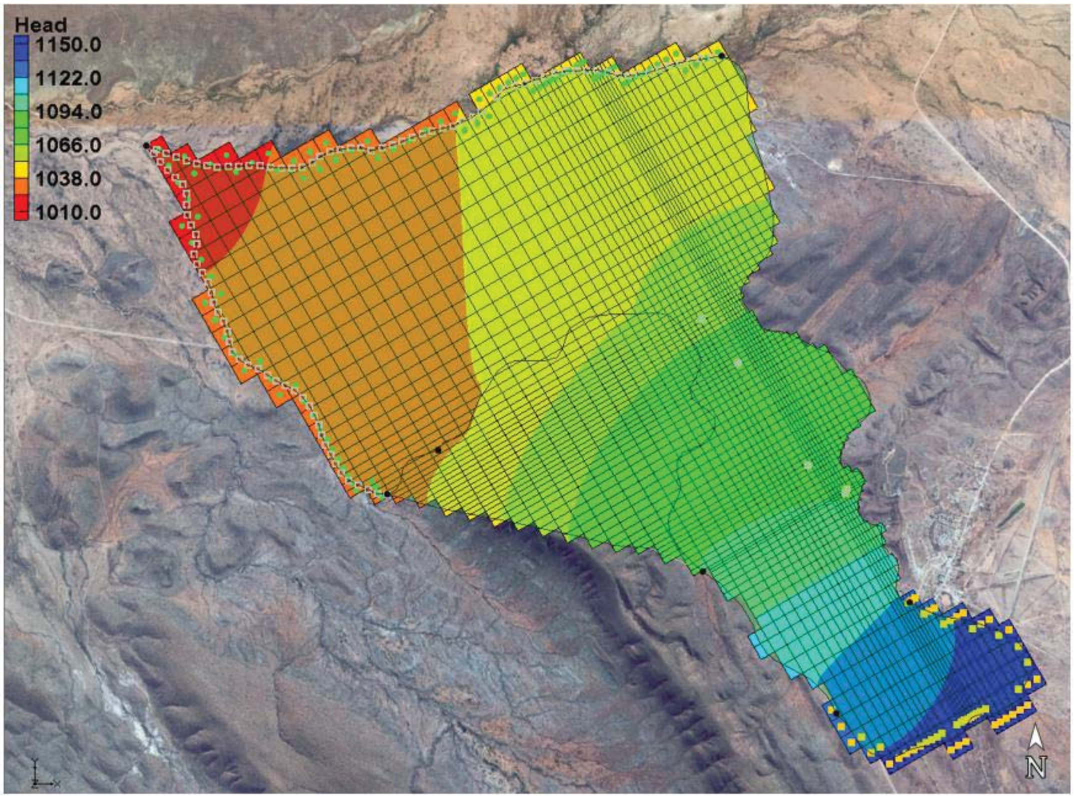

Figure 18: MODFLOW groundwater model head level in meters AMSL (approximate scale 1cm:700m)

In contrast to PWL in the modeled area, groundwater flow velocity is dictated by the hydraulic conductivity values modeled in the polygons. Figure 19 illustrates the propensity of groundwater to travel through the alluvial soils in the flat plains between ridges and suggests that the majority of indirect recharge to the NW wellfield comes from the alluvial sediments upstream in the contributing sub-basin.

Figure 19: Preferential flow through alluvial soils in model (m/day) (approximate scale 1cm:700m)

After calibration and stochastic analysis of the steady-state model, demand scenarios were modeled in which water demand is increased by 50% and 100%. If current population growth rate remains constant and water-use per capita is unchanged, the 50% increase in demand will be realized in 2023, and the 100% demand increase will be realized in 2030. The required increase in abstraction rate for each well and the total abstraction volume is shown in Table 15.

Table 15: Increased abstraction rates

Location	2013 pumping rate, m³/d	Percent Increase	
		50%	*100%*
WW22864	422	633	844
WW23137	319	479	639
WW29045	510	765	1019
WW29046	71	107	142
WW29047	308	461	615
Daily Average Volume, m^3	**1630**	**2444**	**3259**

The resulting PWL profile in the four wells chosen for observation is shown in Figure 20. A decrease in PWL ranging from 16.9m in WW29046 to 27.7 m in WW22864 is observed when abstraction volume is increased to twice the 2013 average.

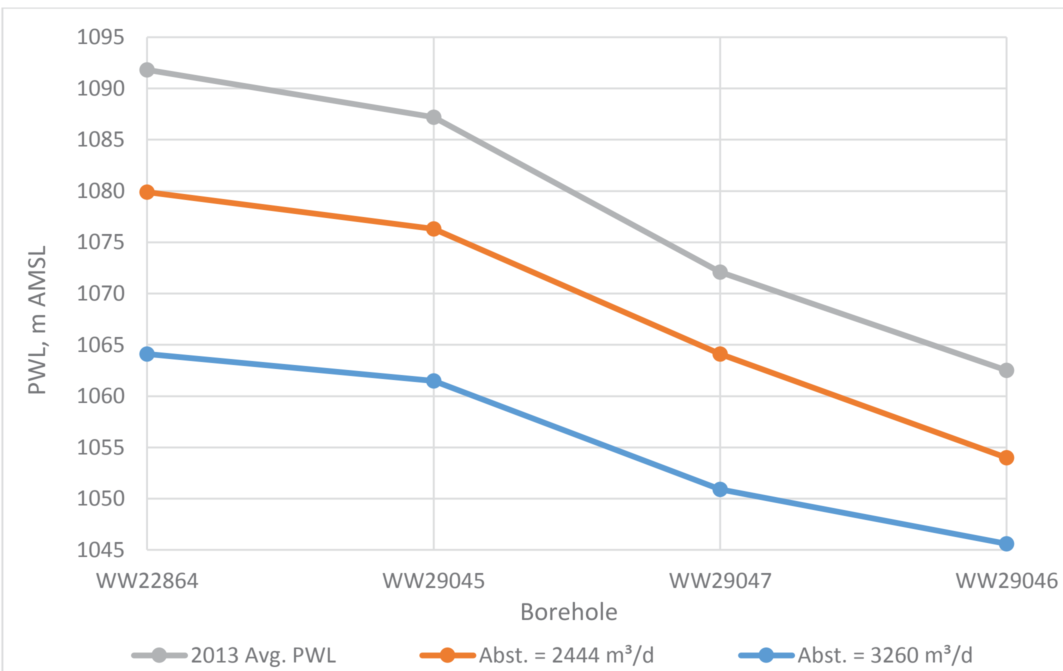

Figure 20: Resultant PWL profile in increased abstraction scenarios

At high abstraction volumes, the height of the water column in the wells decreases below the depth of some screened intervals. Figure 21 shows that three perforated sections in the WW29045 casing are screened below PWL under current pumping rates. If the abstraction rate is doubled, the modeled PWL is projected to be 57.5 m bgs and only a portion of one perforated length is utilized.

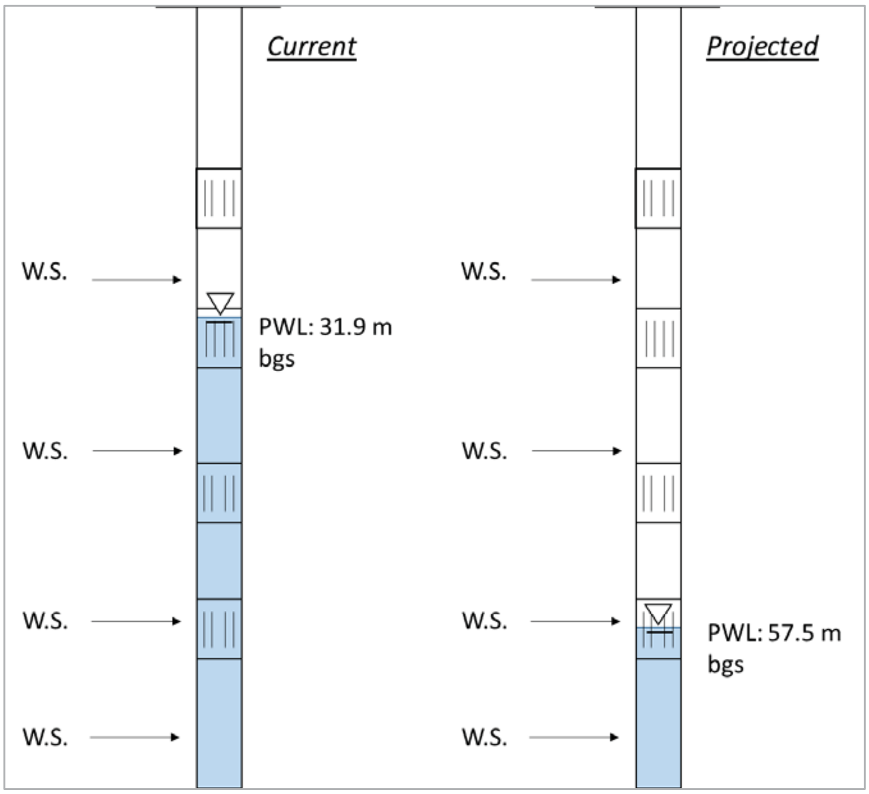

Figure 21: WW29045 water column change due to increased abstraction

Table 16 below illustrates similar results in the other production wells in the NW wellfield at this abstraction rate. Practical implications of increased drawdown depths are discussed in Section 5.2.2.

Table 16: Current and projected PWL and submerged screen length in NW Wellfield

Location	2013 Calculated Values		2030 Projected Values	
	PWL, m bgs	Submerged Screen Length, m	PWL, m bgs	Submerged Screen Length, m
WW22864	37.3	39	64.9	17
WW29045	31.9	18	57.5	3
WW29047	28.8	36	50.1	16
WW29046	31.4	16	48.4	12

5: Discussion

5.1 The Water Balance

The predominant challenge of this water balance was accurately depicting hydrologic response of the basin to high-intensity rainfall events in the absence of field measurements. The procedure utilized in this report addresses this problem with the creation of a typical year based upon observations made from the area, use of standard method for estimating PET, and use of precipitation data previously collected in the site.

5.1.1 Parameter Sensitivity

Calculations show a relative lack of sensitivity of PET at high PET values. Summing daily ET volumes for the month of March in this hypothetical year at a PET rate of 9.3 mm/day yields a total monthly ET volume of 71.2 mm. Reducing the PET rate by half to 4.7 mm/day yields a monthly ET volume of 67.2 mm, a reduction of only 5%. Based on the model assumptions, sufficient time exists between rainfall events for TEW to become nearly completely depleted at both high and low PET values, resulting in nearly identical volumes of water lost to ET. Figure 22 illustrates that the rate of PET impacts ET volume most prominently in the 3-4 days following a rainfall event. Using this methodology, PET rate is most influential in environmental conditions where rainfall occurs with high regularity.

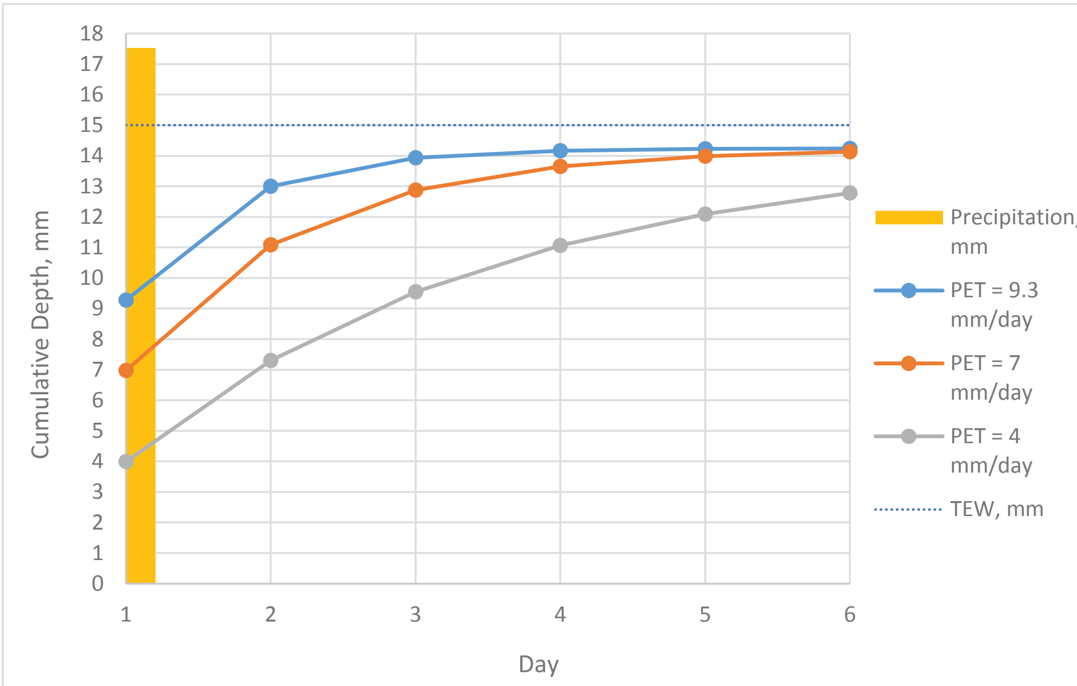

Figure 22: Model sensitivity to PET

The Behnke and Maxey and the Penman-Monteith methods gave significantly different estimates for total annual PET (2992 mm according to Behnke and Maxey, 1596 mm according to Penman-Monteith), but Table 17 shows that ET and net precipitation volumes calculated using the two methods are comparable. As previously mentioned, the Behnke and Maxey method was selected because of the congruence of its data requirements with data available for this study. Because it is evident that multiple PET calculation methods provide adequate estimations in this context, emphasis should be placed on collection of soil moisture change and rainfall intensity data when utilizing this water balance methodology in arid climates.

Table 17: PET methodology comparison

PET Method	**Precipitation Fractions**	
	ET, mm	Net Precipitation, mm
Penman-Monteith	309	70
Behnke and Maxey	321	58

Alteration of field capacity had significant effects on the ET/net precipitation ratio. Field capacity is a measure of the volume of rainfall that the soil is able to store before saturation-excess overland flow occurs. Table 6 in Section 4.2 shows that a 22% decrease in field capacity yielded a 126% increase in net precipitation. Change in net precipitation on a monthly basis is illustrated in Figure 23.

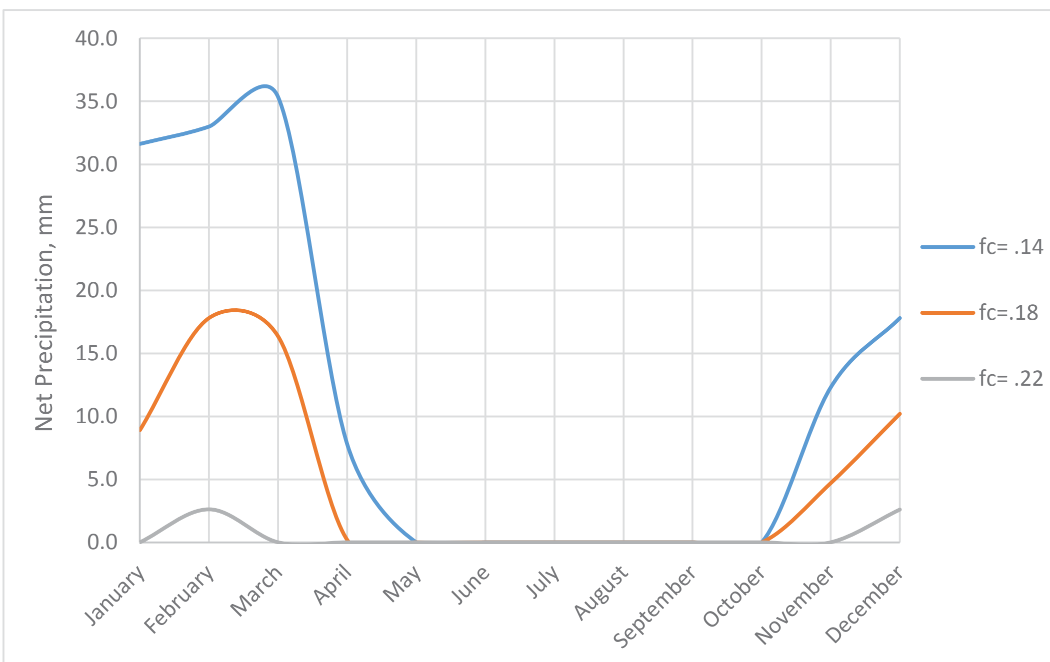

Figure 23: Model sensitivity to Field Capacity, θ_{fc}

Water balance results are also significantly affected by changes in rainfall intensity. Table 18 shows various rainfall intensity values for the month of March and the resultant calculated net precipitation.

Table 18: Net precipitation estimates with varying rainfall intensity values for the month of March

Number of Rainfall Events	Average Precipitation, mm	Rainfall Intensity, mm/event	Net precipitation, mm/month
6	87.6	14.6	2.2
5	87.6	17.5	16.4
4	87.6	21.9	30.6

Results of the water budget are dependent on assumed values for field capacity and rainfall intensity. The results summarized in Figure 14 in Section 4.2 agree with observed hydrologic trends in Opuwo. Due to the variability in rainfall not only an event basis, but also on a monthly and annual basis, it is not the intent of this study to replicate historical responses to precipitation events. This water balance uses time-averaged data to quantify typical flows for reference in water resources management. Historically, ET/net precipitation has been evaluated qualitatively; this analysis reasonably quantifies previously unknown resources and relates the calculated volumes to recharge volumes estimated in the MODFLOW model area.

5.1.2 Environmental Factors

Temporal observation data indicates a gaining aquifer in the NW wellfield, despite only minor reduction in average annual abstraction rate from the year 2000 to 2013. Decreased abstraction alone is likely not responsible for the observed rise in groundwater levels. Precipitation in the contributing watershed for the years 2000 to

2013 is estimated through interpolated data to be 344 mm (KNMI, 2015), comparable to the site-data annual average of 379 mm used in the water balance. However, rainfall in the region is extremely isolated and local rainfall in the sub-basin may be significantly higher than indicated by either field data recorded in Opuwo or interpolated data from KNMI. Additionally, results from the Gravity Recovery and Climate Experiment (GRACE) mission, a project jointly carried out between the National Aeronautic Space Administration (NASA) and the German Center for Aerospace (Deutschen Zentrum fur Luftund Raumfahrt, DLR), indicate that groundwater levels in the Zambezi and Okavango basins are rising at 16.68 mm/year and 15.35 mm/year, respectively, without significant increase in precipitation (Ahmed, Sultan, Wahr, & Yan, 2014). The average SWL rise from 2000-2013 in the NW wellfield is 0.94 m/year. The GRACE study (2014) identifies warming of the Atlantic Ocean as one climatic factor leading to increased terrestrial water storage (TWS) in central and western Africa.

If attempting to reproduce the water balance methodology used in this project in other arid areas, priority should be placed on the collection of field measurements of soil moisture change in response to rainfall events and rainfall event intensity. Hydrology data could be compared to results calculated from equations developed by Allen et al (1998). Similarly, field data collected in the NW wellfield would validate the level to which this procedure agrees with observed values.

5.2 The Aquifer Model

5.2.1 Parameter Sensitivity

Recharge, alluvial hydraulic conductivity and boundary flow volume were evaluated in the model sensitivity analysis. These parameters were selected because of dependence on environmental factors and significant anticipated impact on the model, and were varied from 50%-150% of best-fit values to determine model response. Figure 24 shows that PWL is reduced by approximately 1 meter if recharge rate is reduced by 50%. Residual head is measured as (observed PWL)-(model PWL); a negative residual head value corresponds to a calculated PWL higher than the observed PWL.

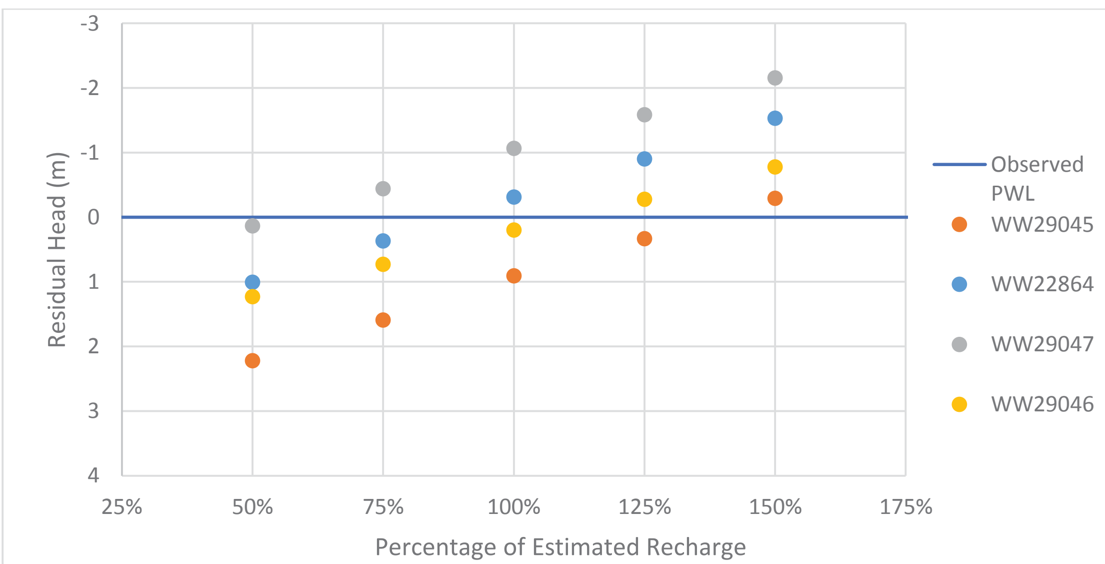

Figure 24: Model sensitivity to recharge rate

Figure 25 illustrates that reducing alluvial K by 50% results in an overestimation of PWL by 15-28 m in the wellfield. Figure 26 shows that reducing boundary flow volume by 50% results in an underestimation of PWL by 27-44 m in the wellfield.

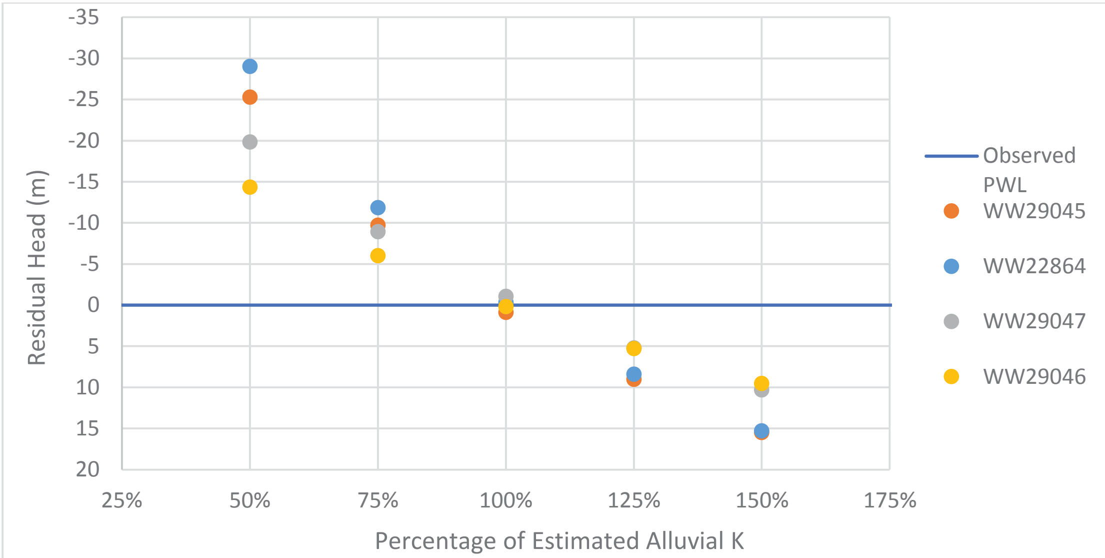

Figure 25: Model sensitivity to alluvial K

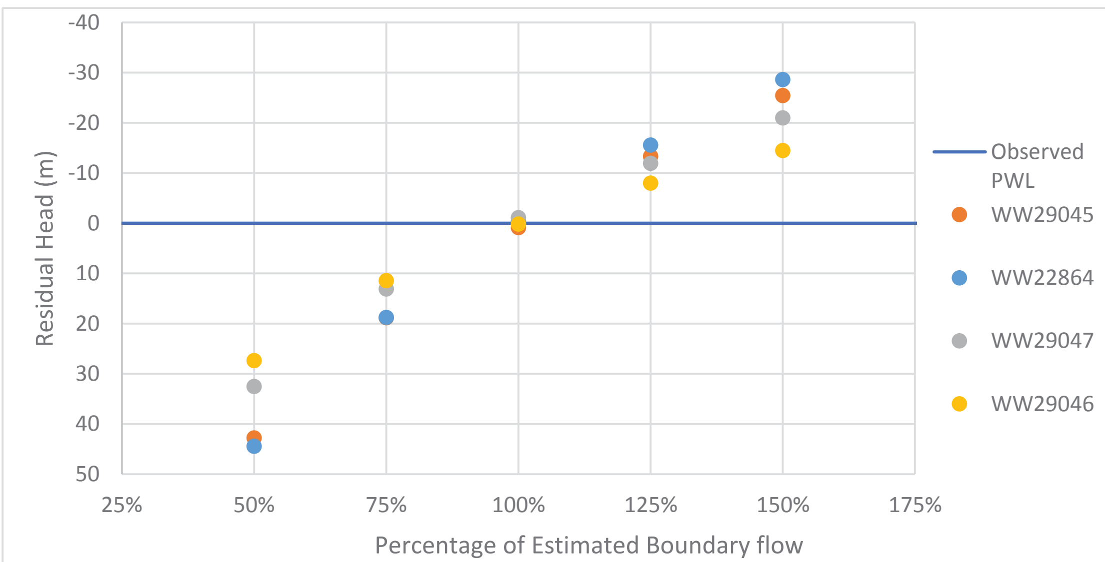

Figure 26: Model sensitivity to boundary flow

Figures 24-26 illustrate that the MODFLOW model contains greater sensitivity to hydraulic conductivity and boundary flow than to recharge. Effects of changes in recharge in the modeled area are minimal because recharge volume is small in comparison to boundary flow volume. Increased confidence is placed in model results because parameters to which the model is most sensitive are based upon field measurements rather than assumed values.

5.2.2 Practical Implications

In the 1986 geohydrological evaluation of the NW wellfield, hydrochemistry and pumping test data were used to evaluate the water resources available in the NW wellfield. Hydrochemistry data suggest that 44.1% of the subsurface flow is a result of indirect recharge from the surrounding dolomites; of the remaining volume of water, 9.9% is from direct recharge due to precipitation, and the remaining 46% is boundary flow from upstream in the contributing basin (Fry, 1986). MODFLOW modeling indicates that alluvial soils act as a conduit for groundwater, with subsurface flow accounting for approximately 90% of groundwater storage in the NW wellfield. Because groundwater levels in the NW wellfield are dependent upon upgradient hydrologic conditions, management of only the NW wellfield as a storage basin may be shortsighted. Water resources management decisions must incorporate the entire contributing sub-basin in order to fully quantify and maximize resources.

In MODFLOW and AQTESOLV modeling, the aquifer was approximated as isotropic with horizontal groundwater flow throughout the entire vertical length of the water-bearing structure. Drilling logs indicate preferential flow through horizontal gravel lenses. In the MODFLOW model, the casing screen is assumed continuous from the top elevation of the screen to the bottom elevation. In WW29045 and WW29046, the casings are perforated in 6 m segments at depths corresponding to observed water strikes while drilling. As shown previously in Figure 13, it is plausible that PWL in the boreholes decreases below recorded water strikes and productive capacity of wells is further deteriorated as fewer high-conductivity lenses are utilized. To maintain abstraction rate, increased head loss in the well due to high velocity of groundwater being forced through reduced perforated casing area is expected, negatively impacting power consumption and longevity of pumping equipment. In this pumping scenario it is likely that the borehole yield will significantly decrease.

Prior drilling successes and failures in the NW wellfield have illustrated the importance of aligning well screens to intersect high-conductivity lenses. A groundwater model approximates some hydraulic characteristics of an aquifer, but when calibrated it can be a useful tool in water management decision-making. The model does not serve as a predictive tool for individual well construction or well productivity, as these aspects are dependent on the ability of the drilling operator to locate and screen water strike depths.

6: Recommendations and Future Work

The NW wellfield aquifer could be more reliably modeled if the depth of alluvial soils was determined. Construction of additional exploratory wells would provide additional data on water strike depths and total depth of sedimentary water-bearing layers, providing additional basis for increased confidence in estimation of total aquifer storage and long-term water-resource planning. Modeling indicates that it is likely the aquifer and current borehole scheme can accommodate short-term growth expected in Opuwo, and that future expenditures be directed towards expansion of water treatment capacity in favor of water production capacity. This study reinforces the recommendation made by Fry (1986) that effort to increase abstraction capacity be initially aimed at rehabilitation of existing boreholes, since reduction in performance is most likely the result of accumulation of scale due to high concentration of dissolved minerals in the groundwater.

In the context of long-term planning, the NW wellfield can be expanded upstream in the watershed (expansion towards SE) or downstream in the watershed (expansion towards N). To capitalize on recharge resources that are as of yet not fully quantified, downstream expansion is more advantageous. The alluvial plain immediately downstream of WW29046 becomes expansive and offers flexibility in borehole placement. A watershed delineation performed in ArcGIS shows that the alluvial soils immediately north of WW29046 potentially comprise a major subsurface flow channel, and additional recharge is present from a 962 km^2 sub-basin located north of Opuwo. This watershed is nearly double the area of the contributing watershed to the NW wellfield. The two basins combine north of the modeled area and flow west as land elevation descends across the Great Escarpment. While omitted from the MODFLOW because it lies downgradient of the NW wellfield, surface drainage patterns indicate that there is hydraulic advantage to expansion of the current borehole scheme to the North, as opposed to remaining near the gravel road and expanding towards the WNW. When planning future expansions, societal and economic considerations must also be weighed, and especially given land-use considerations and water quality constraints, additional borehole locations cannot be based strictly upon aquifer modeling.

The water balance illustrates that a large portion of precipitation is lost to ET and surface runoff. Practices to increase infiltration would provide additional hydrologic input to the aquifer on a long-term time scale. The topography and precipitation patterns in this region lend it well to the implementation of check dams to increase infiltration rates in the basin. Check dams are constructed by placing commercial materials such as stone or block and wire fencing, or locally-sourced materials such as stones, logs, brush and other natural detritus, across a surface runoff channel, as shown in Figure 27. Check dams are intended to slow the flow of water in a channel and create an ephemeral pool immediately upstream of the dam. Correct implementation of check dams in a waterway leads to a series of terraced pools that increase infiltration, reduce sediment transport in a watershed, and provide temporary livestock watering areas.

Figure 27: Check dam (photo adapted from http://www.permies.com/t/18489/desert/ready-plant-desert-south-Makkah)

As previously stated, national policy changes have driven the decentralization of water resources management responsibility to the municipal level. It would be beneficial if technical resources became more accessible to municipal water management officials. One-way flow of information was observed in the Opuwo water supply scheme: data is collected in the field, recorded, and forwarded to management officials, where it is compiled and stored. The greatest concentration of technical knowledge, experience, equipment, and data in regards hydrogeology are present with MAWF and NamWater in Windhoek. Dissemination of technical resources to municipal management officials would help facilitate quantification of water resources on the municipal level, a task that MAWF lacks the manpower to accomplish. Dissemination could potentially occur in a variety of forms:

- regional or local workshops focusing in education of a specific skill or technology, such as ArcGIS or field methods for determining PET or soil moisture change
- regional-level conferences to present findings, gain feedback, exchange ideas, and foster collaboration between MAWF, NamWater, and municipal water-management officials
- central database with precipitation, temperature, abstraction, and water level data accessible to municipal water-management officials

The successful institution of IWRM is reliant on participation of various stakeholders in water-resources management decisions. For this to be effective, increased accessibility to data and capacity-building for stakeholders is not only necessary, but should be continually encouraged and fostered when possible.

7: Conclusions

Namibian national policy has placed increased water-resources management responsibility on municipal-level governments. Additionally, population growth and urbanization in Namibia indicate focused water demand increases in towns, and likely represent the most pressing factors driving water-supply infrastructure expansions. Sub-basin level quantification of water resources is increasingly important for local officials to make water supply decisions. Precipitation and infiltration rates in Kunene region are low; however, due to the large catchment area of the contributing sub-basin, the water balance performed in this study indicates that sufficient water resources are available to meet the short- and medium-term needs of the town of Opuwo. Of the approximate 379 mm of annual precipitation, it is estimated that 84% is lost to evapotranspiration, 15% contributes to surface runoff, and the remaining 1% infiltrates to recharge the aquifer. Infiltration rates could be improved by the implementation of check dams in ephemeral waterways throughout the contributing sub-basin.

The MODFLOW model is able to match PWL in the NW wellfield within 1 m of the 2013 average observed values. Hydraulic gradient calculations and MODFLOW modeling indicate that the boundary recharge to the NW wellfield is approximately 4800 m^3/day. Direct recharge to the NW wellfield is estimated to average 452 m^3/day ($1.0x10^{-5}$ m/d), and average abstraction volume in 2013 is 1630 m^3/day. Future scenarios were modeled in which abstraction is increased by 50% and 100%, and the aquifer model suggests that sufficient groundwater flow is present to sustain these abstraction rates. In practice, however, the current borehole scheme is unlikely to achieve medium- to long-term production requirements. Increased drawdown in the wells eliminates utilization of specific water strikes noted during well construction, suggesting a potential reduction in borehole yield as head loss in the well is increased. Observation of abstraction volume and SWL in the each borehole indicates that average SWL in the NW wellfield has been rising consistently from 2000-2013, while abstraction volume has remained nearly constant. Spatial variations in precipitation causing a discrepancy between actual and recorded values, and warming of the tropical Atlantic Ocean causing high-intensity monsoon rains in the basin in which the

Opuwo watershed lies (Ahmed, Sultan, Wahr, & Yan, 2014) are potential causes of this trend.

Increased accessibility of data and technical capacity must accompany the decentralization of water resources management responsibility. The greatest concentration of materials, data, equipment, and technical experience in regards to hydrology and water-resources resides with NamWater and MAWF in Windhoek. Increased involvement on the part of municipal management officials towards investigating and quantifying water resources on the local level is needed to achieve the goal of IWRM in Namibia. Enhanced accessibility of data amongst water management stakeholders can further propel the implementation of IWRM, and ensure that water resources in Namibia are managed efficiently and appropriately for future generations.

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Appendices

Appendix A: Cultural Attributes

The OvaHerero are a tribe considered indigenous to Namibia that are separated geographically into two main groups: those residing in the East-Central Otjozondjupa region of Namibia and those residing in North-Central Kunene Region, and hence, in the greater Opuwo area. The OvaHerero are closely related to the OvaHimba (to which the region is most famous within the international tourism industry) and OvaZemba, thus remarks and observations made in this section regarding Herero people typically hold true for Himba and Zemba tribal members as well, with specific exceptions. Although they fill a multitude of employment positions in Opuwo and other locations, many Hereros traditionally describe themselves as farmers; the overwhelming majority of farming efforts are invested towards grazing cattle, goats, and sheep. Of these herd animals, cattle are by far the most culturally relevant and are the animal with which the OvaHerero most closely identify. Maize, pounded to flour and cooked as a porridge called oruhere, and meat (cattle and goat) are the dietary staples of the OvaHerero. Agricultural farming is less common, but takes place in the form of small- to medium-sized food plots in which maize and various root vegetables are grown. Vegetables form a relatively small part of the local diet.

Other less populous ethnic groups that settle in the area include OshiWambo, Damara, Kavango and Zambezi tribes, as well as immigrants from Angola. All of these ethnic groups originate from other areas of Namibia, but individuals and families move to Opuwo for professional opportunities. Opuwo, being the regional capital, boasts a mixed ethnic population with the above groups, in contrast with the surrounding village homesteads which are homogenously Himba or Zemba. In the last several decades Opuwo town has developed at a considerable rate and now contains a full offering of modern services; this development, in addition to increasing number of automobiles and road accessibility over the same period of time, has heavily influenced the trade and commercial dynamic between village and town residents. It is now common for village residents to depart on ventures into Opuwo for commercial purposes; these stays typically last for 2-4 days in which village residents acquire multiple weeks' worth of food and other items to bring back to the homestead.

Christianity is outwardly the most common religious practice. Local churches are active and include Seven-Day Adventist, Lutheran, Methodist, and Catholic, amongst others. While many community members in Opuwo attend a Christian Church, there appears to be a certain amount of holdover from traditional religious/ideological views, and these two ideologies are combined to form a modern Namibian religious view. In Opuwo, monogamy is the typical marital arrangement; in rural Himba and Zemba homesteads however it is acceptable for a man to acquire multiple wives depending on wealth.

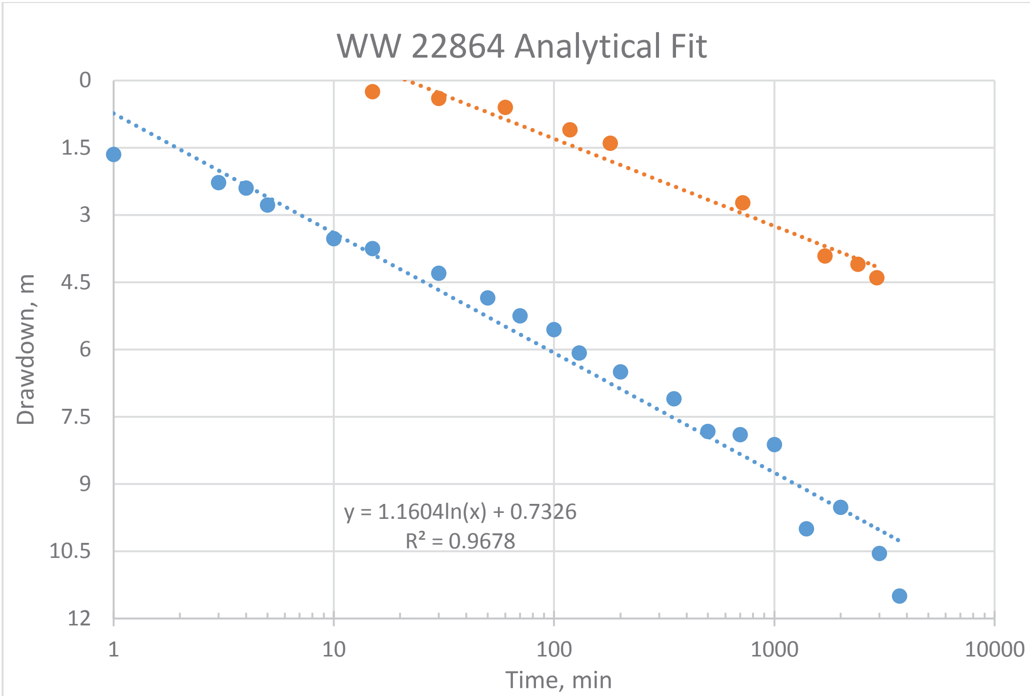
The most commonly spoken language in Opuwo is the language of the OvaHerero, Otjiherero. A slight dialectal difference amongst the members of OvaHimba and OvaZemba tribes exists but does not significantly affect verbal or written communication. Other languages present in Opuwo include the various Owambo languages; KhoeKhoe, spoken by the Damara ethnic group; and Portuguese as a result of immigration from Angola. While English is taught in schools beginning in grade 1, the medium of instruction is Otjiherero from grades 1-5, after which the medium of instruction becomes English for the remainder of educational system. Due to the structure of the education system, most Namibians are educated through grade 10. Students must pass a series of standardized tests in grade 10 prior to moving to grade 11 and subsequently in grade 12 students are required to pass another series of standardized tests prior to attending a university-level institution.

Social hierarchy dominates within Herero village homesteads. A village contains a senior male leader called a Headman, who possesses specific land-use rights, makes final business and administrative decisions related to the village, acts as spiritual leader, and settles disputes. Legally a dispute can be settled by members of the Namibian Police Force or by the village Headman, but seldom are both involved. Age plays a predominant role in an individual's status, with older individuals holding a higher social rank than comparatively younger individuals; traditionally it is culturally unacceptable for one to question or challenge the decision of an elder individual. A person's sex typifies both status (men above women) and expected duties, which include finances, herding and administration for men and cooking, cleaning, and fetching water for women.

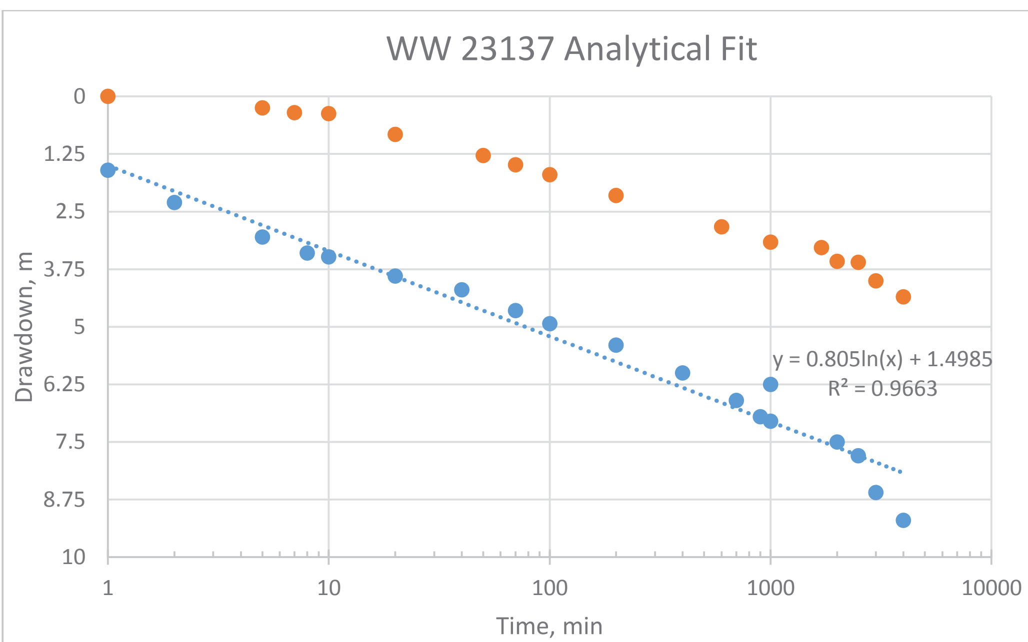
Tourism is an increasingly important source of income for the OvaHimba and OvaZemba, although the Himba tribe is most widely noted as the integral tourist attraction in the area. A number of local individuals act as liaisons to facilitate tours to traditional villages, in which a group of tourists pay a fee to the guide and an amount of food, presented to the village Headman as a gift, to see firsthand the traditional way of life in which many of the rural OvaHimba still follow. The fee given to the guide is split between the guide and the Headman, to be spent for the homestead at his discretion. Additionally, females from both the Himba and Zemba tribes craft pottery and jewelry in the form of various necklaces and bracelets to sell in the town of Opuwo.

Appendix B: Pumping Test Data

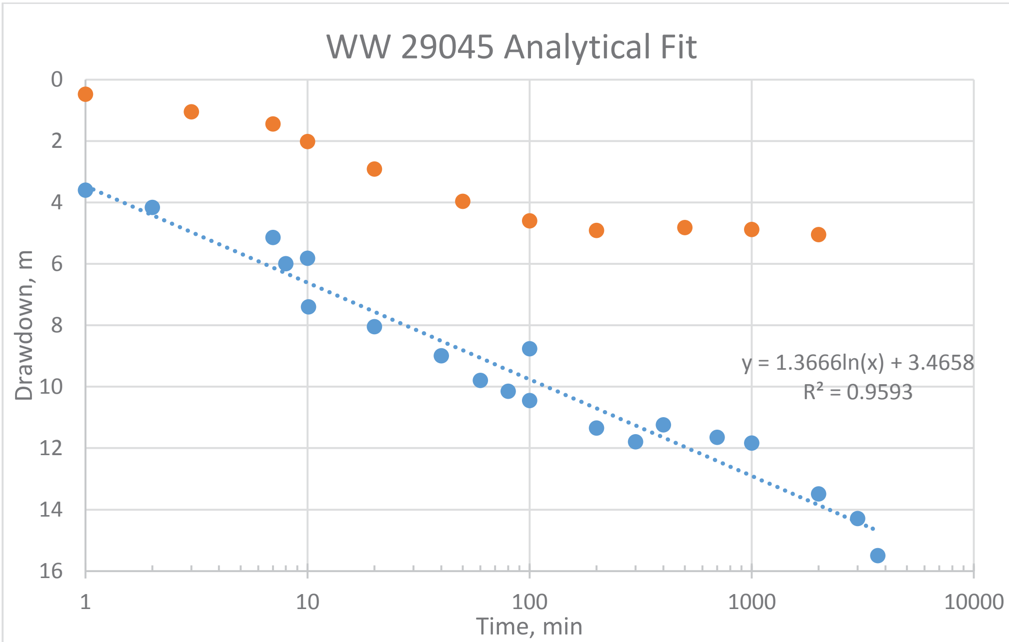
<u>WW22864</u>



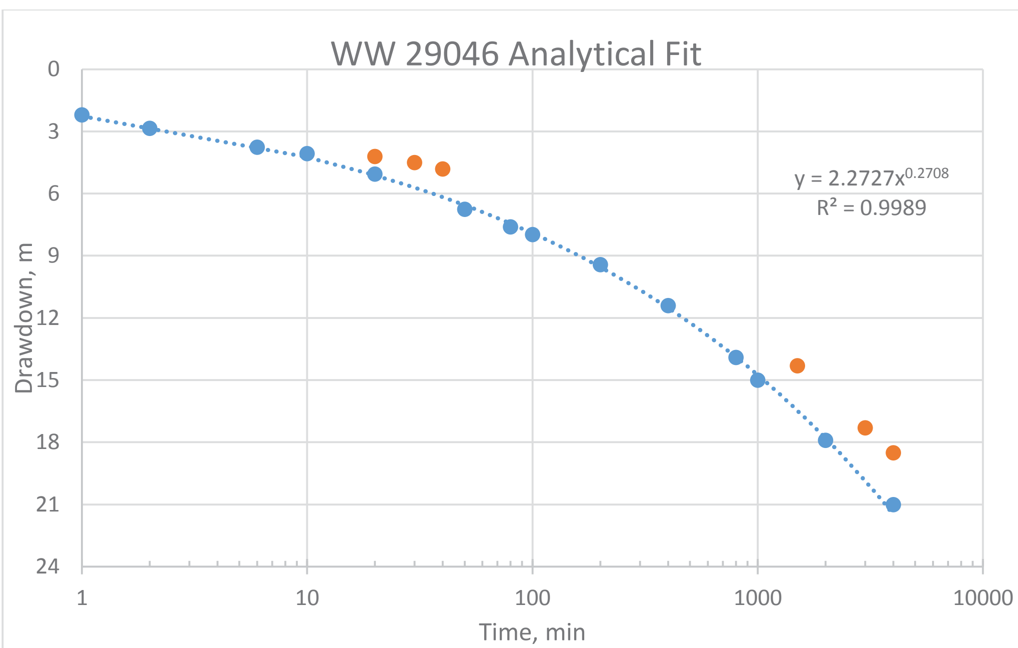
<u>WW23137</u>



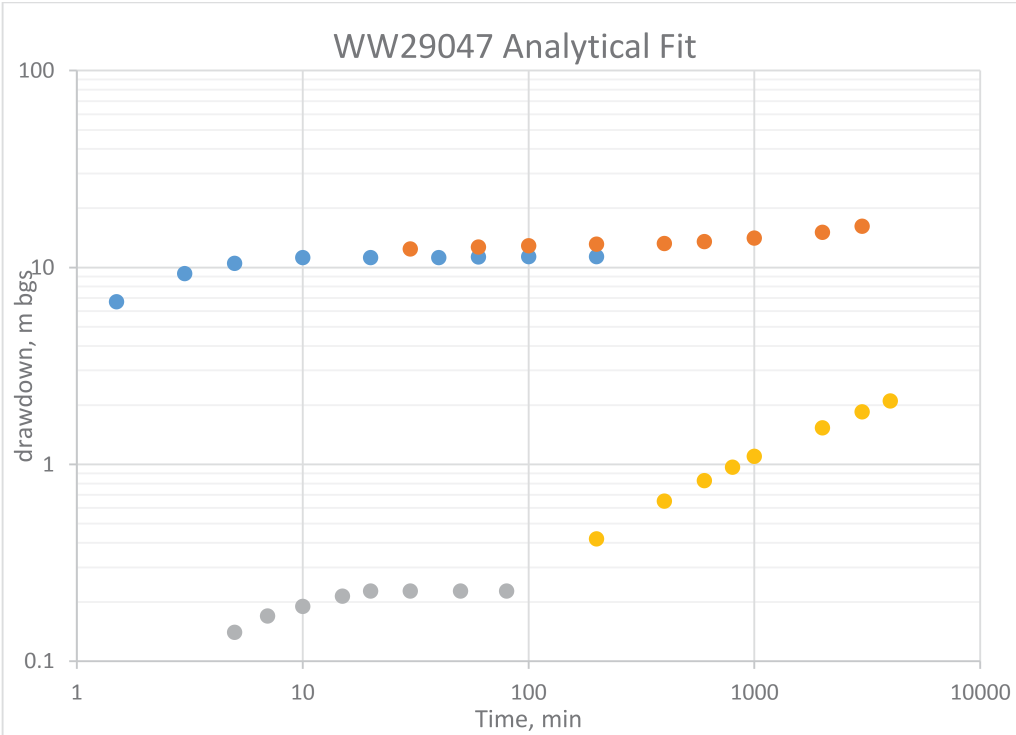
WW29045



WW29046

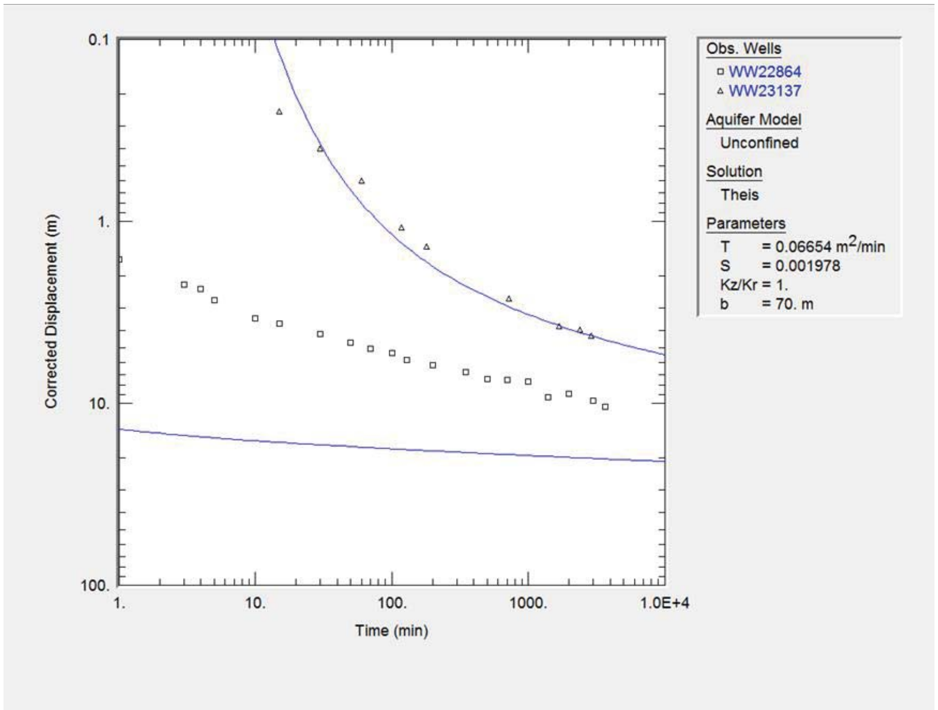


WW29047


WW29047 Analytical Fit
100
10
1
0.1
drawdown, m bgs
1
10
100
1000
10000
Time, min

Appendix C: AQTESOLV Results

WW22864



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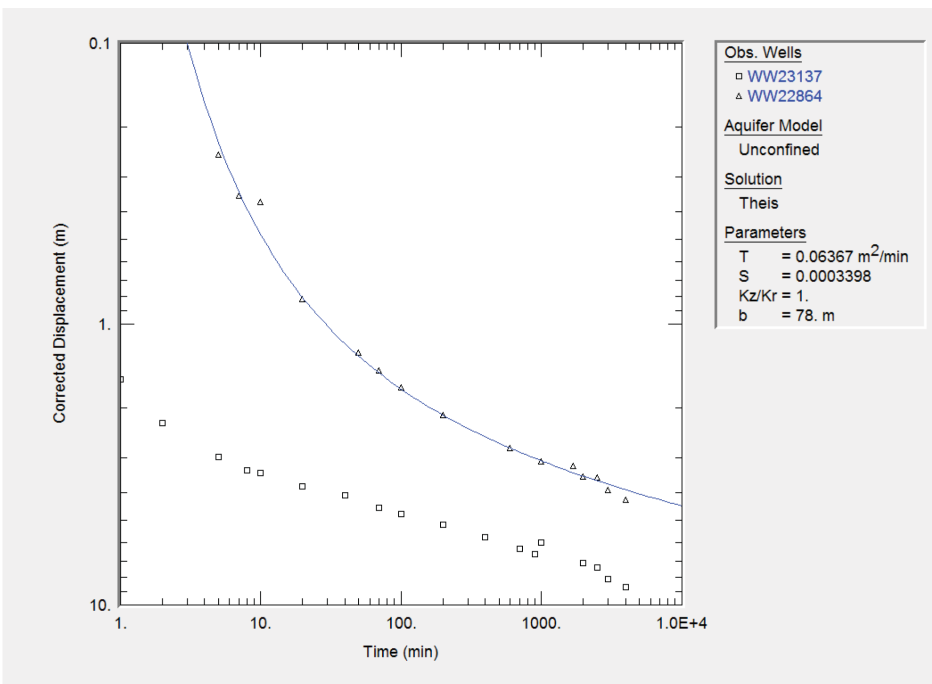
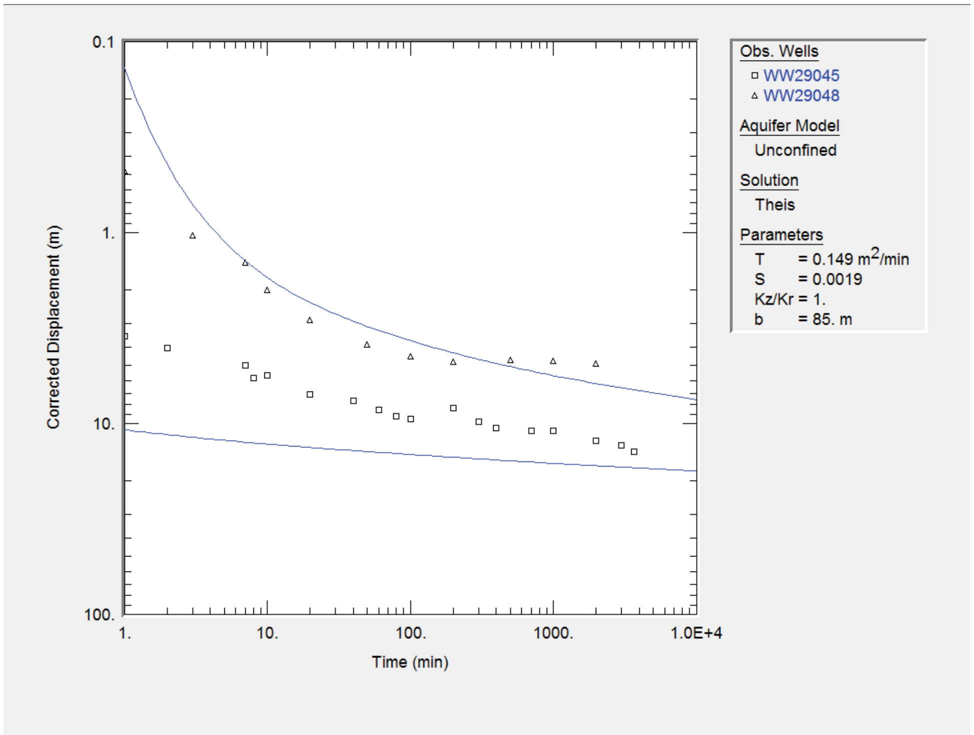
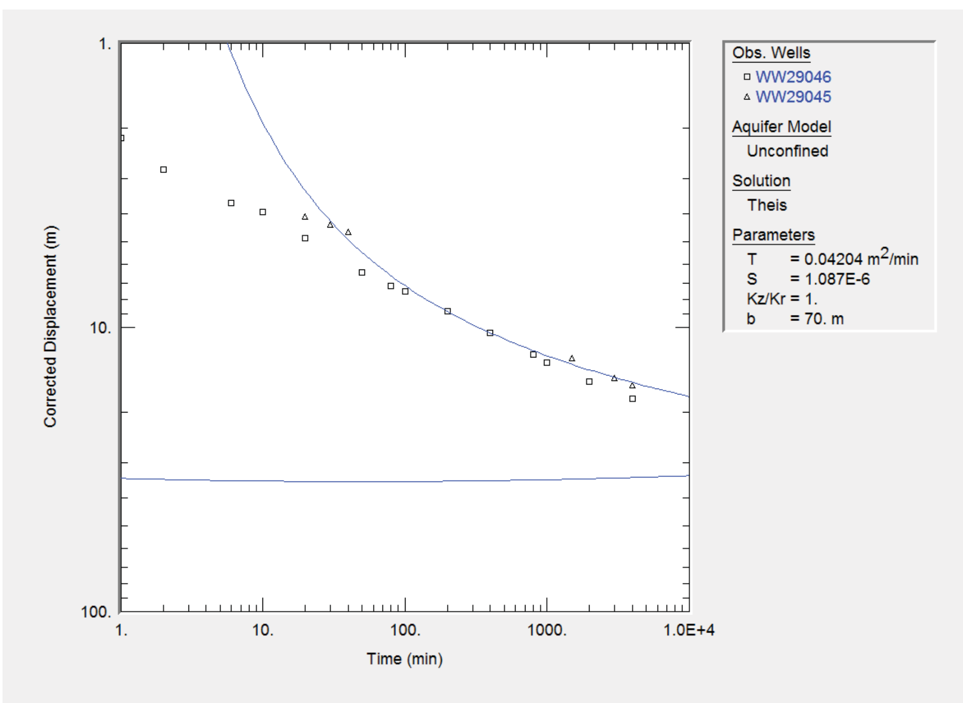


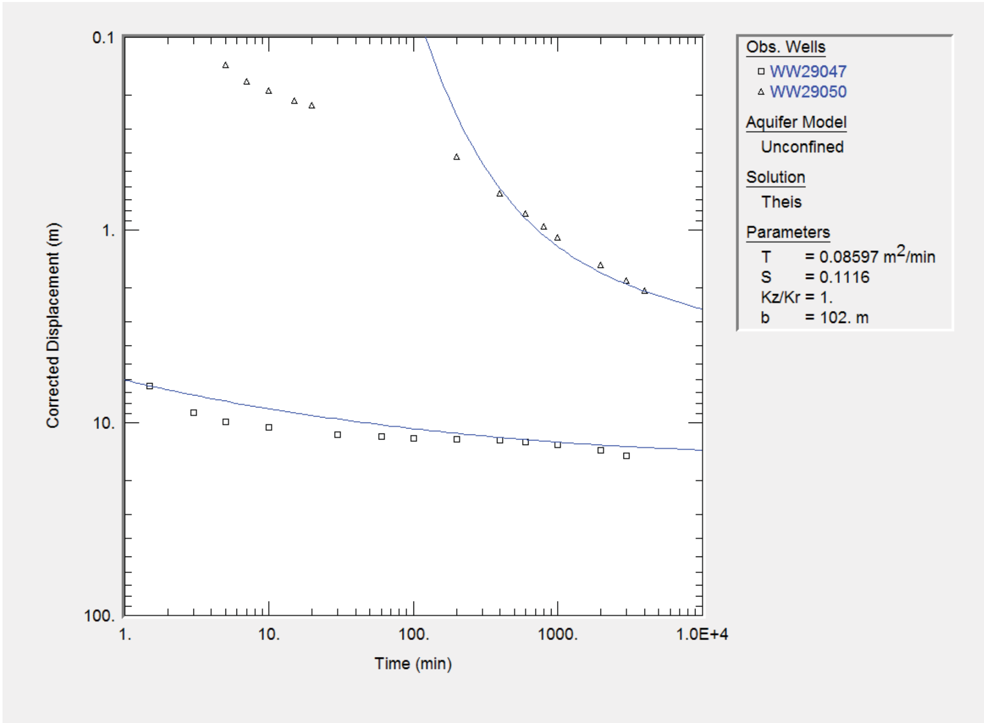
WW29045



WW29046



WW29047


0.1
1.
10.
100.
Corrected Displacement (m)
1.
10.
100.
1000.
1.0E+4
Time (min)
Obs. Wells
WW29047
WW29050
Aquifer Model
Unconfined
Solution
Theis
Parameters
T = 0.08597 m2/min
S = 0.1116
Kz/Kr = 1.
b = 102. m

Appendix D: Water Quality Classification Criteria

Physical and Aesthetic Determinants:

DETERMINANTS	UNITS*	LIMITS FOR GROUPS			
		A	B	C	D**
Colour	mg/l Pt***	20			
Conductivity	mS/m !at 25 °C	150	300	400	400
Total hardness	mg/l $CaCO_3$	300	650	1300	1300
Turbidity	N.T.U****	1	5	10	10
Chloride	mg/l Cl	250	600	1200	1200
Chlorine (free)	mg/l Cl	0,1- 5,0	0,1 – 5,0	0,1 – 5,0	5,0
Fluoride	mg/l F	1,5	2,0	3,0	3,0
Sulphate	mg/l SO_4	200	600	1200	1200
Copper	µg/l Cu	500	1000	2000	2000
Nitrate	mg/l N	10	20	40	40
Hydrogen Sulphide	µg/l H_2S	100	300	600	600
Iron	µg/l Fe	100	1000	2000	2000
Manganese	µg/l Mn	50	1000	2000	2000
Zink	mg/l Zn	1	5	10	10
pH****	pH-unit	6,0 – 9,0	5,5 – 9,5	4,0 – 11,0	4,0 – 11,0

* In this and all following tables "l" (lower case L in ARIAL) is used to denote dm^3 or litre

** All values greater than the figure indicated.

*** Pt = Platinum Units

**** Nephelometric Turbidity Units

***** The pH limits of each group exclude the limits of the previous group

Biological Determinants:

DETERMINANTS	LIMITS FOR GROUPS			
	A**	B**	C	D*
Standard plate counts per 1 ml	100	1000	10000	10000
Total coliform counts per 100 ml	0	10	100	100
Faecal coliform counts per 100 ml	0	5	50	50
E. coli counts per 100 ml	0	0	10	10

* All values greater than the figure indicated.

** In 95% of the samples.

Inorganic Determinants:

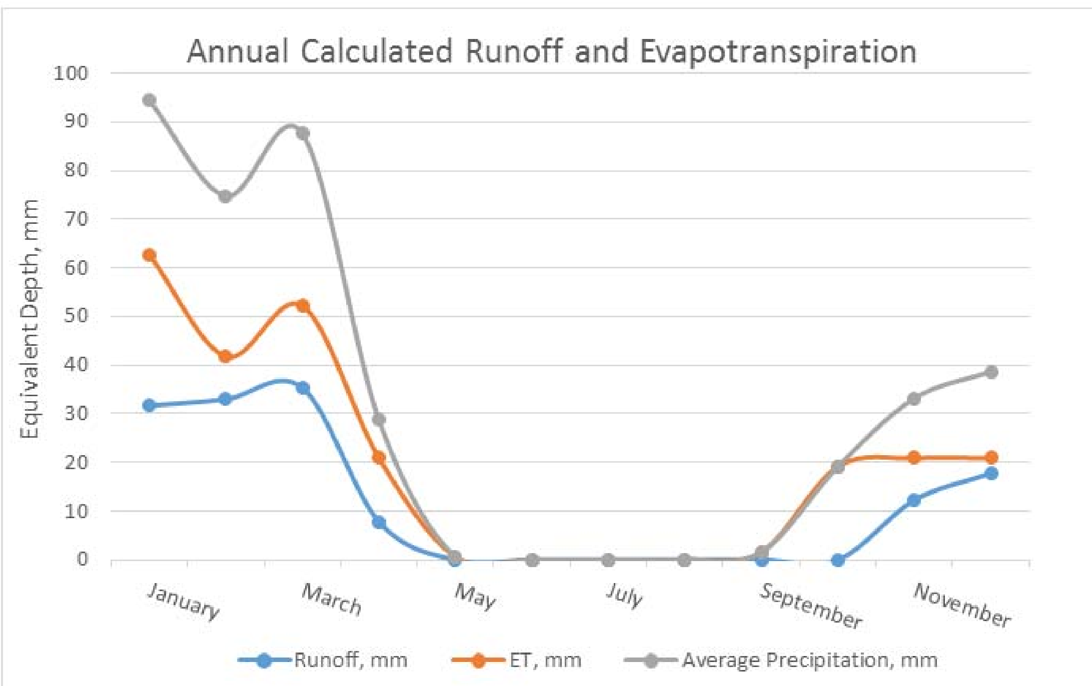
DETERMINANTS	UNITS	LIMITS FOR GROUPS			
		A	B	C	D*
Aluminium	µg/l Al	150	500	1000	1000
Ammonia	mg/l N	1	2	4	4
Antimonia	µg/l Sb	50	100	200	200
Arsenic	µg/l As	100	300	600	600
Barium	µg/l Ba	500	1000	2000	2000
Beryllium	µg/l Be	2	5	10	10
Bismuth	µg/l Bi	250	500	1000	1000
Boron	µg/l B	500	2000	4000	4000
Bromine	µg/l Br	1000	3000	6000	6000
Cadmium	µg/l Cd	10	20	40	40
Calcium	mg/l Ca	150	200	400	400
Calcium	mg/l $CaCO_3$	375	500	1000	1000
Cerium	µg/l Ce	1000	2000	4000	4000
Chromium	µg/l Cr	100	200	400	400
Cobalt	µg/l Co	250	500	1000	1000
Cyanide (free)	µg/l CN	200	300	600	600
Gold	µg/l Au	2	5	10	10
Iodine	µg/l I	500	1000	2000	2000
Lead	µg/l Pb	50	100	200	200
Lithium	µg/l Li	2500	5000	10000	10000
Magnesium	mg/l Mg	70	100	200	200
Magnesium	mg/l $CaCO_3$	290	420	840	840
Mercury	µg/l Hg	5	10	20	20
Molybdenum	µg/l Mo	50	100	200	200
Nickel	µg/l Ni	250	500	1000	1000
Phosphate	mg/l P	1	See note below	See note below	See note below
Potassium	mg/l K	200	400	800	800
Selenium	µg/l Se	20	50	100	100
Silver	µg/l Ag	20	50	100	100
Sodium	mg/l Na	100	400	800	800
Tellurium	µg/l Te	2	5	10	10
Thallium	µg/l Tl	5	10	20	20
Tin	µg/l Sn	100	200	400	400
Titanium	µg/l Ti	100	500	1000	1000
Tungsten	µg/l W	100	500	1000	1000
Uranium	µg/l U	1000	4000	8000	8000
Vanadium	µg/l V	250	500	1000	1000

* All values greater than the figure indicated.

Appendix E: Additional Water Balance Calculations

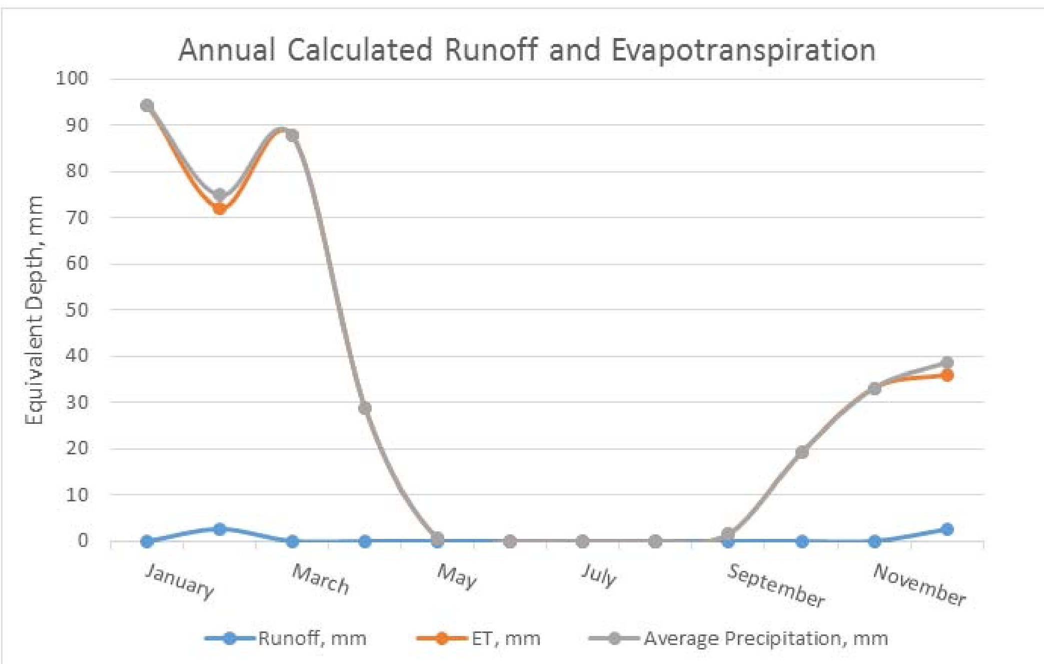
Low Range Parameter

Month	Avg. Temp, deg C	Model PET, mm/ day	Average Precip., mm	# of Rainfall Events	Avg. Rainfall Intensity , mm/hr	Runoff , mm	ET, mm
Jan	19.9	11.58	94.4	6	15.7	31.6	62.8
Feb	19.7	11.40	74.8	4	18.7	33.0	41.8
Mar	19	5.10	87.6	5	17.5	35.6	52.0
Ap	18.1	8.40	28.7	2	14.4	7.8	20.9
May	16	6.14	0.6	1	0.6	0.0	0.6
June	13.9	4.63	0	0	0.0	0.0	0.0
July	13.5	4.74	0	0	0.0	0.0	0.0
Aug	14.9	6.33	0	0	0.0	0.0	0.0
Sep	17.4	8.83	1.6	1	1.6	0.0	1.6
Oct	18.8	10.65	19.2	2	9.6	0.0	19.2
Nov	19.4	11.31	33.2	2	16.6	12.3	20.9
Dec	19.7	11.41	38.7	2	19.4	17.8	20.9
SUM:			378.8	25		138	241



High-Range Parameter

Month	Avg. Temp, deg C	Model PET, mm/day	Average Precip., mm	# of Rainfall Events	Avg. Rainfall Intensity, mm/hr	Net Precip., mm	ET, mm
Jan	19.9	10.9	94.4	6	15.7	0.0	94.4
Feb	19.7	10.8	74.8	4	18.7	2.6	72.2
Mar	19	9.5	87.6	5	17.5	0.0	87.6
Apr	18.1	8.6	28.7	2	14.4	0.0	28.7
May	16	6.3	0.6	1	0.6	0.0	0.6
June	13.9	4.1	0	0	0.0	0.0	0.0
July	13.5	4.3	0	0	0.0	0.0	0.0
Aug	14.9	5.7	0	0	0.0	0.0	0.0
Sep	17.4	9.0	1.6	1	1.6	0.0	1.6
Oct	18.8	10.8	19.2	2	9.6	0.0	19.2
Nov	19.4	11.4	33.2	2	16.6	0.0	33.2
Dec	19.7	11.7	38.7	2	19.4	2.6	36.1
SUM:			378.8	25		5	374



Appendix F: Field Photographs

NW Wellfield area

WW29045, characteristic of boreholes construction in the NW wellfield


Typical pump arrangement

WW29047 with leak (1/19/2014)

WW29047 under maintenance (2/24/2014)

Storage Tank for Opuwo water distribution system

Erosion channel in ephemeral streambed near NW wellfield.


Pipeline from NamWater Plant to storage tanks. Note old pipe situated parallel to current pipe.

Appendix G: Example Soil Moisture Change Calculations

EXAMPLE 31
Determination of the evapotranspiration from a bare soil

Determine the evapotranspiration from a bare loamy soil surface ($K_{cb} \approx 0.15$) for ten successive days following a heavy rain. The reference evapotranspiration during the drying period is ET_o = 4.5 mm/day, and the climate is subhumid with light wind.

From Table 19	For Loam: TEW ≈ 20 mm and REW ≈ 9 mm
For rain on bare soil	f_{ew} = 1
From Eq. 72	$K_{c\ max}$ = 1.20

(1) Day	(2) D_e start mm	(3) Stage	(4) K_r	(5) K_e	(6) $K_e\ ET_o$ mm/day	(7) D_e end mm	(8) ET_c mm/day
1	0.00	1	1	1.05	4.73	4.73	5.4
2	4.73	1	1	1.05	4.73	9.45	5.4
3	9.45	2	(20-9.45)/(20-9)=0.96	1.01	4.53	13.98	5.2
4	13.98	2	(20-13.98)/(20-9)=0.55	0.57	2.59	16.57	3.3
5	16.57	2	(20-16.57)/(20-9)=0.31	0.33	1.47	18.04	2.1
6	18.04	2	(20-18.04)/(20-9)=0.18	0.19	0.84	18.88	1.5
7	18.88	2	(20-18.88/(20-9)=0.10	0.11	0.48	19.36	1.2
8	19.36	2	(20-19.36)/(20-9)=0.06	0.06	0.27	19.64	0.9
9	19.64	2	(20-19.64)/(20-9)=0.03	0.03	0.16	19.79	0.8
10	19.79	2	(20-19.79)/(20-9)=0.02	0.02	0.09	19.88	0.8

(1) Day number.
(2) Depletion at beginning of the day (= depletion at end of previous day).
(3) Soil evaporation stage (stage 2 starts if D_e > REW = 9 mm).
(4) K_r (K_r = 1 for stage 1. Use Eq. 74 for stage 2).
(5) From Eq. 21: $K_e = K_r (K_{c\ max} - K_{cb}) = K_r (1.20\text{-}0.15) = 1.05\ K_r \le 1.20$.
(6) Evaporation component: $K_e\ ET_o = K_e$ (4.5 mm/day).
(7) Depletion at end of day = (2) - (6).
(8) $ET_c = (K_{cb} + K_e)\ ET_o = (0.15 + K_e)\ ET_o = (0.15{+}K_e)$ 4.5 mm/day, where $K_{cb}\ ET_o = (0.15\ ET_o) \approx 0.7$ mm/day is basal, "diffusive" evaporation from the soil, possibly from beneath the Z_e depth (~ 0.10 to 0.15 m). Since the soil in this situation is bare, one could set the K_{cb} equal to zero so that maximum K_e becomes $K_e = K_{c\ max}$ = 1.20. Then all of the evaporation would be deducted from the surface soil layer.

The example demonstrates that the estimation of K_r requires a daily water balance calculation. This is further developed in the section on the daily calculation of K_e.

Sample calculations retrieved from FAO Irrigation Paper No. 56