WATER SUPPLY IN TONGATAPU; PAST, PRESENT AND FUTURE

BY

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Abstract

This thesis presents an investigation of the sustainability of the freshwater aquifer (groundwater) at Tongatapu, the main island of Tonga. Water balance modelling is applied to meteorological data to estimate freshwater recharge at a daily resolution for the period 1980-2018. These results demonstrate a very close coupling between recharge and precipitation but also the critical role played by the ENSO cycle in modulating the supply of freshwater on Tongatapu. They also show that previous water balance modelling for the island, conducted at a monthly resolution, has tended to underestimate the rate of recharge by ~8%.

Historical groundwater extraction rates for Tongatapu are also calculated by compiling monitoring data from operational pumping stations across the island. This shows that extraction rates have increased progressively over the past 50 years and approximately doubled in the last 10 years, as a consequence of increased demand from agriculture, tourism and population growth. Although the freshwater resource appears to be sustainable overall at current rates of supply and demand, there have been sustained periods of zero recharge, notably during strong El Nino events in winter (the dry season).

Climate model projections of future rainfall show that Tonga is situated in a region of great uncertainty, due to shortcomings in our knowledge of how the ENSO cycle will respond to anthropogenic warming, but moreover, climate models are currently unable to simulate the correct positioning of the South Pacific Convergence Zone which strongly influences the amount and seasonal distribution of regional rainfall. Nevertheless, this study also conducted predictive water balance modelling for Tongatapu for the end of the 21st century using the current CMIP5 climate projections for the region under a medium (RCP4.5) and high (RCP8.5) emissions scenario, in both cases showing substantial reductions in freshwater recharge rates compared to the present. These results raise serious concerns for the future sustainability of Tonga's freshwater resource, especially if extraction rates continue to increase and salination of the aquifer increases as is highly likely due to sea level rise.

Although Tonga can do little to influence the global climate change mitigation effort, this research highlights the importance of addressing currently resolvable infrastructural problems in water supply and reticulation.

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List of Abbreviations

AUD	Australian dollar
CBD	Central business district
CMIP	Coupled Model Inter-comparison Project
CRSP	Climate Resilience Sector Project, Tonga
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
EC	Electrical conductivity
ENSO	El Niño-Southern Oscillation
FC	Field capacity
GWR	Groundwater recharge
HMAF	His Majesty’s Armed Forces
IPCC	International Panel on Climate Change
IS	Interception storage
ISMAX	Max interception storage
MEIDECC	Ministry of Meteorology, Energy, Information, Disaster Management, Environment, Climate Change and Communications
ML	Mega litres
ML/day	Megalitres/day
MLNR	Ministry of Lands and Natural Resources, Tonga
MOH	Ministry of Health, Tonga
NEMO	National Emergency and Management Office, Tonga
RCP	Representative Concentration Pathway
SMB	Salinity Monitoring Boreholes
SMC	Soil moisture content
SMZ	Soil moisture zone
SPCZ	South Pacific Convergence Zone
SST	Sea surface temperature
TL	Transpiration from groundwater
TOP	Tongan pa’anga
TWB	Tonga Water Board
UNESCO	United Nations Educational, Scientific and Cultural Organization
WATBAL	Water balance computing software
WP	Wilting point
WRS	Water Resources Section

1. Introduction

1.1. Research aim and objectives

This research is focused on groundwater availability in Tongatapu, the capital island of Tonga. Like many small islands of the South Pacific, Tongatapu faces potential groundwater shortages due to impending natural and anthropogenic causes (Falkland, 2002). In particular, prolonged drought, over-extraction and minimal regulation present significant threats to the sustainability of the resource (White et al., 2009). This research aims to improve understanding of the groundwater resources in the context of past, present and projected future climatic variability for Tongatapu.

The information needed to underpin this aim is provided under the following objectives:

1. To estimate recharge to groundwater in recent decades:
   1a. using a simple empirical relationship between annual rainfall and recharge, and
   1b. using a water balance model WATBAL (White et al., 2009);
2. To estimate the current groundwater extraction rates in Tongatapu; and
3. To estimate future recharge for the end of this century for climate scenarios based on RCP 8.5 and RCP 4.5 pathways.

The ultimate motivation for this work is to provide robust information about the sustainability of Tongatapu’s groundwater resources.

1.2. Scope of work

As detailed in the next chapter, previous work has identified natural and anthropogenic factors that have the potential to increase the vulnerability of the groundwater resources of Tongatapu. Of notable concern are:

- Severe drought may result in zero groundwater recharge as occurred in 1981 and 1983 (White et al., 2009).
- Rates of groundwater extraction are not known for the whole coverage of the island.
- Population and tourism growth as well as intensified agriculture are increasing the demand for groundwater supply and these trends are likely to continue in the future, but to an unknown extent.

This thesis builds on previous work by White et al. (2009) as well as providing a first attempt to consider the consequences of projected climate scenarios on Tonga's groundwater resource.

Data used for this study was collected during a 5-week research trip to Tongatapu in May and June of 2019. Much of the data was obtained from field trips to groundwater extraction wells/boreholes and also from the local database of the Water Resources Section (WRS) of the Ministry of Lands and Natural Resources (MLNR) and from the Tonga Meteorological Service (TMS) of the Ministry of Meteorology, Energy, Information, Disaster Management, Environment, Climate Change and Communications (MEIDECC). Information about future climate conditions during the last 3 decades of this century (2070-2099) were obtained from climate model projections in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012).

2. Background

This chapter highlights the key factors that control the availability of groundwater in Tongatapu. The physical geography, climate and the geology of the island constitute the defining nature of the island's water resources. Rainwater and groundwater are the only two sources of fresh water, with no surface water such as rivers or lakes. The increasing demand for water supply derives from population growth, uncertain future climate patterns, and the institutional factors governing groundwater security (White et al., 2009).

2.1. Location

Tongatapu is the largest island within the Tongan archipelago, located in the South Pacific Ocean, approximately 800 km southeast of Fiji (Figure 1). Tongatapu is situated in the south of the archipelago at 21.1790° S, 175.1982° W, in the transition zone from tropics to subtropics.

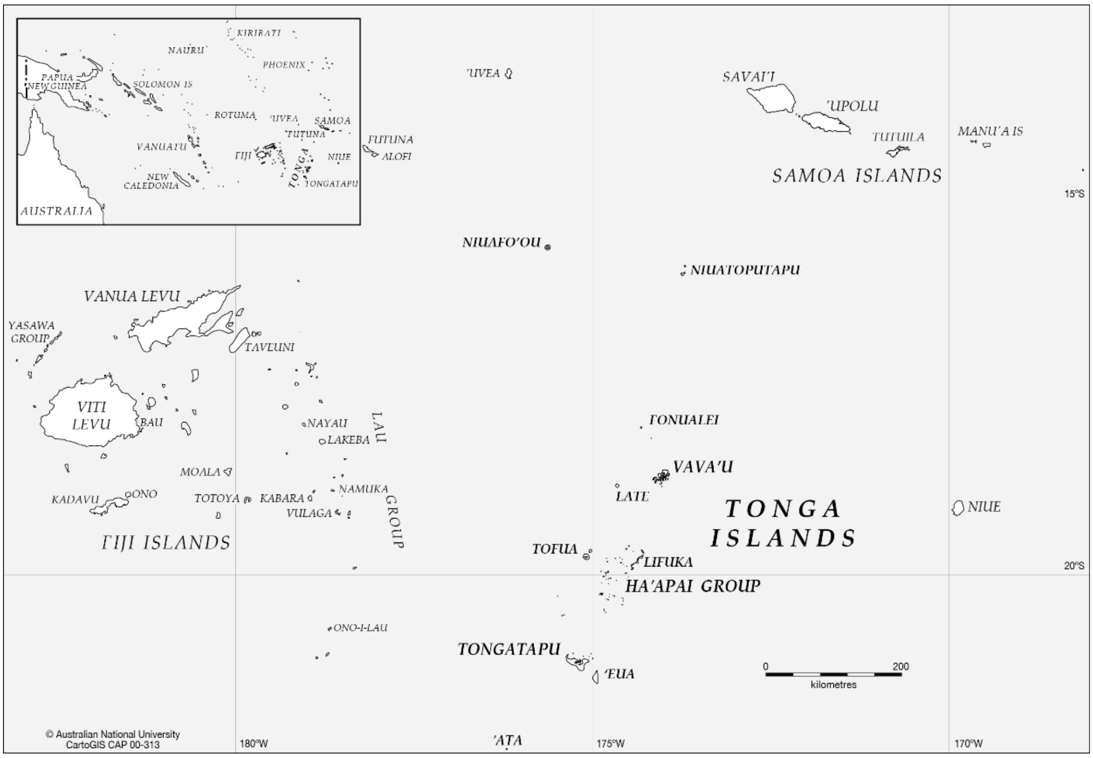

Figure 1: Location of Tonga in the West Pacific (http://asiapacific.anu.edu.au/mapsonline/base-maps/tonga-islands)

The island has a total land area of 260 km^2 with a maximum elevation of 65 m (Furness & Helu, 1993) at the south-eastern end of the peninsula near the country's international airport (Figure 2).

2.2. Population and tourism growth

Tonga's total population in 2016 was 100,651 of which 74,611 or 75% resided in Tongatapu (Statistic Department Tonga, 2018). This island has the largest population and is followed by Vava'u (13,738), Ha'apai (6,125), 'Eua (4,945) and Ongo Niua (1,232). Approximately 30% of the population of Tongatapu live in the capital Nuku'alofa and the others are distributed among 50 rural villages in the Western and Eastern Districts and some small islands to the north? (Figure 2).

Figure 2: The satellite image shows the urban Nuku'alofa, airport and the land cover of the island. (Source: Google Earth).

The population of Tongatapu has increased by more than 10,000 in the last three decades (Figure 3). Relative population growth in Nuku'alofa was greater than the population growth of Tongatapu as a whole in the 1980s to 1990s (Figure 4) and this is attributed to the local migration of people from the outer islands to the main islands to attend school and to find work in the capital.

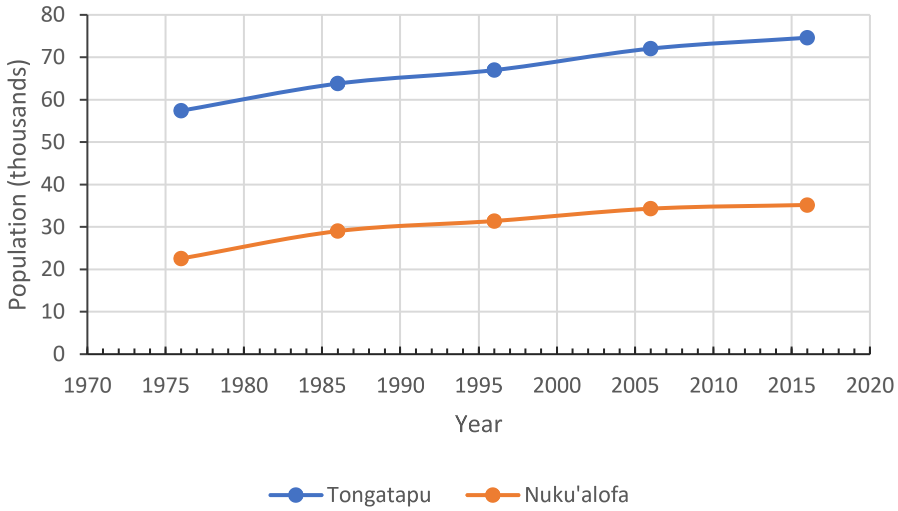

Figure 3: Population growth for Tongatapu; 1976-2016

Population growth imposes greater pressures on groundwater resources in two ways; it raises demand for water and increases the risks of pollution if from increased development in urban, rural and agricultural areas. The pollution risk is particularly high from household waste disposal activities which need to be monitored closely, including surveillance of septic tanks and waste facilities across the island. However, the rate of population growth has decreased since the 1980s (Figure 4) with annual rates of growth for the past two decades averaging <1%.

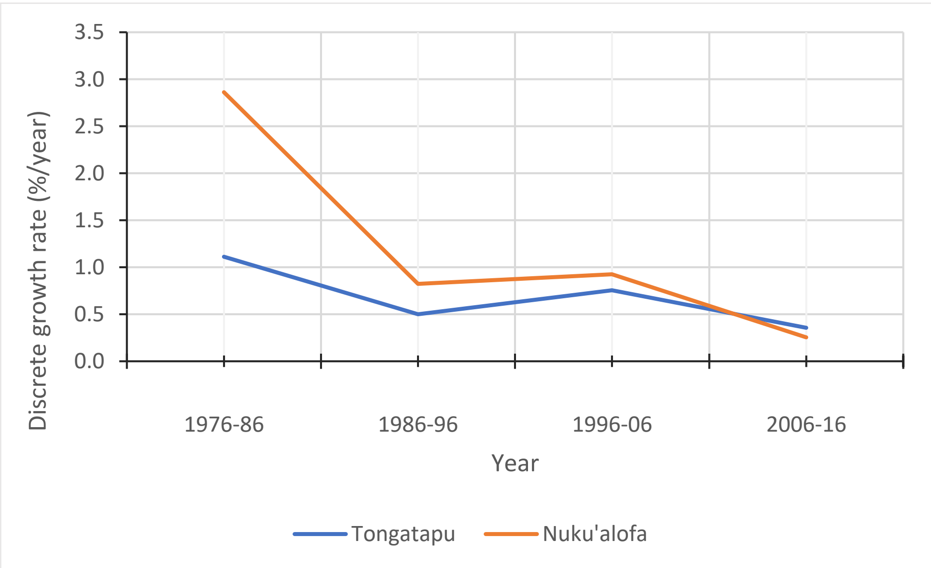

Figure 4: Discrete population growth rate (%/yr.) for the decadal period of 1976-2016.

Tourism growth, however, has been increasing for Tongatapu. The number of tourists visiting Tongatapu increased by 28% from 2010 to 2017, reaching 60,000 in 2017 (Figure 5). This trend is likely to continue, and it will increase the demand for production of bottled water since most tourists prefer bottled water for drinking.

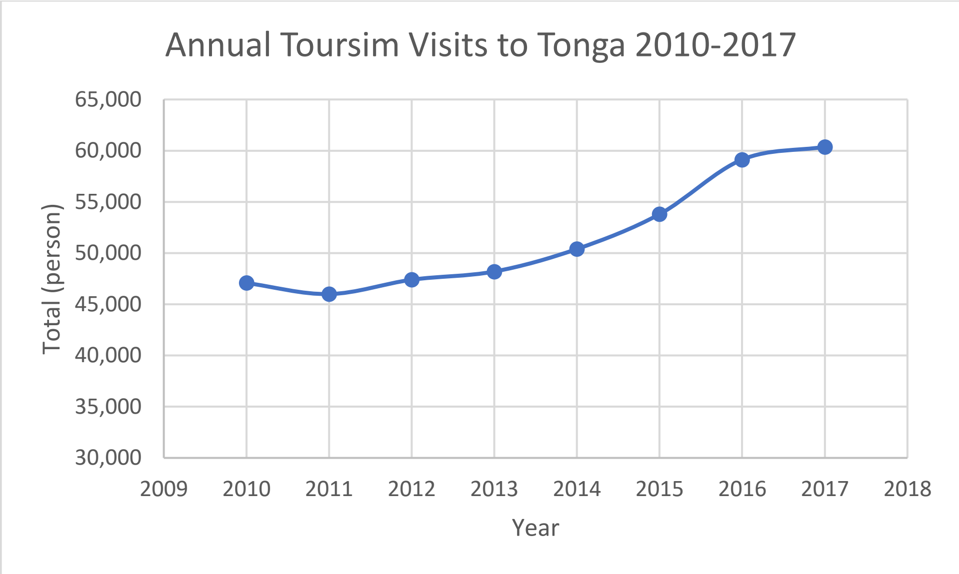

Figure 5: Number of tourists visiting Tonga annually (Statistics Department Tonga, 2018)

Although the population at Nuku'alofa is outpacing the Tongatapu island's growth, it does not represent a great threat to the groundwater quality, since water is supplied to Nuku'alofa from the Mataki'eua-Tongamai wellfield (Figure 15) which is 5 km away from the urban district. This ensures that the groundwater for the urban households is safe from potential increased sources of pollution. Importantly, however, there are an increasing number of residents and agricultural practices that are very near the Mataki'eua-Tongamai wellfield.

As a consequence, a greater threat to groundwater quality comes from the 48% of residents living outside of Nuku'alofa where the production wells are located near residential, agricultural, aggregate mining and livestock raising areas. Although this thesis is not directly concerned with water quality, it is important to emphasize these linkages between groundwater quality and volumes. As discussed later in this chapter, similar linkages apply to saline intrusion into the groundwater aquifer.

2.3. Geology

The Tonga Island Group is located just west of the subduction zone (Tonga Trench) between the Pacific and the Indo-Australian plates. The Group consists of two island chains: a volcanic island chain and a raised coral island chain (Figure 6). Most settlements are on the islands of the raised coral island chain, including those on Tongatapu.

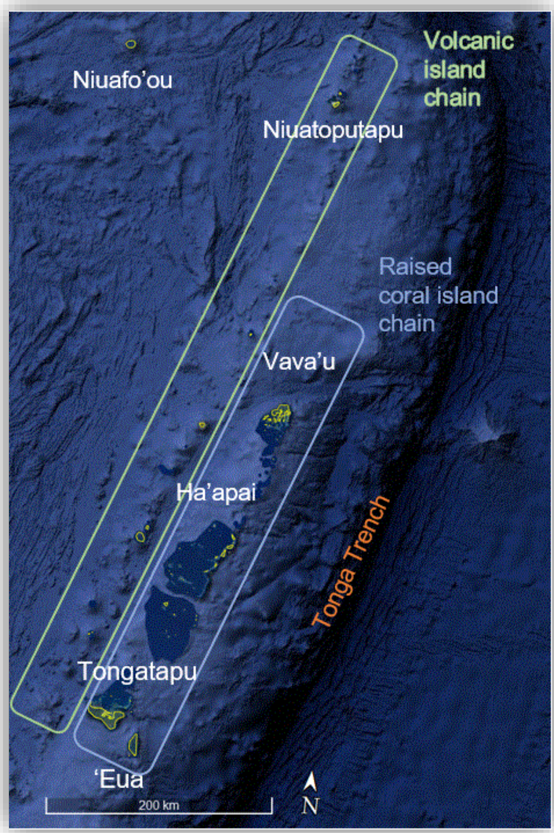

Figure 6: Volcanic island chain and the raised coral island chain of Tonga.

Tongatapu is an island of low to moderate height consisting of a coral reef platform made up of Pliocene and Pleistocene limestone formations overlying Miocene volcanoclastic deposits (Figure 7) (Furness & Helu, 1993). The limestone has a thickness of about 134 m near Nuku'alofa and about 270 m near Fua'amotu (International airport) at the south-eastern coast (Lowe & Gunn, 1986). The coral limestone layer is an important feature because it has groundwater floating above the more saline and denser sea water (Figure 7).

As a consequence of this limestone context, groundwater conductivity levels are high with a range of between 740- 1,025 µS/cm. A transition zone occurs between the fresh groundwater (conductivity ~ 2,500 µS/cm) and the underlying sea water (~50,000 µS/cm).

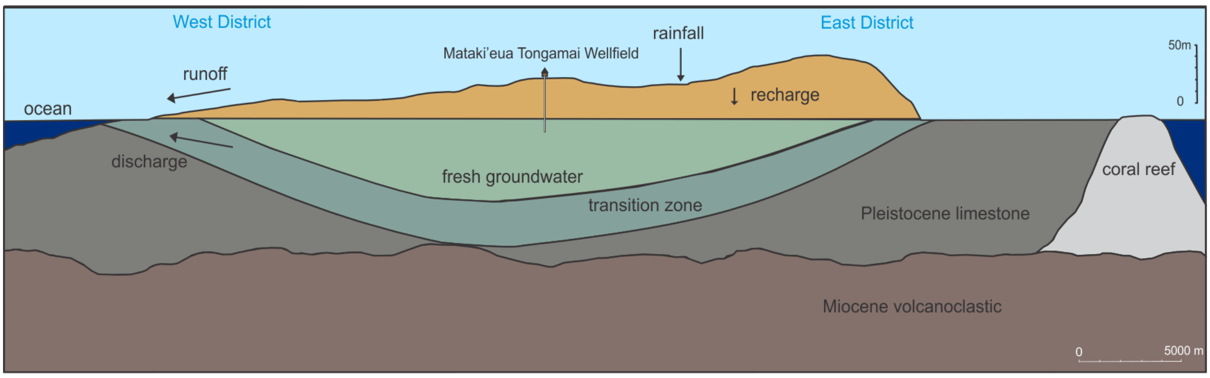

Figure 7: Tongatapu cross section and geography of groundwater characteristic (not to scale).

2.4. Climate

Tonga lies to the north of the Tropic of Capricorn (23.5°S). It has a subtropical climate with a distinct seasonal temperature variation. There are two seasons: summer and winter. The summer marks the wet season and typically stretches from November to April with the highest temperatures and rainfall in February and March (Figure 8). Almost two-thirds of the average annual rainfall occurs during the wet season. The winter marks the dry season and starts in May and ends in October with lowest temperatures typically in from July to September (CSIRO and Australian Bureau of Meteorology, 2011).

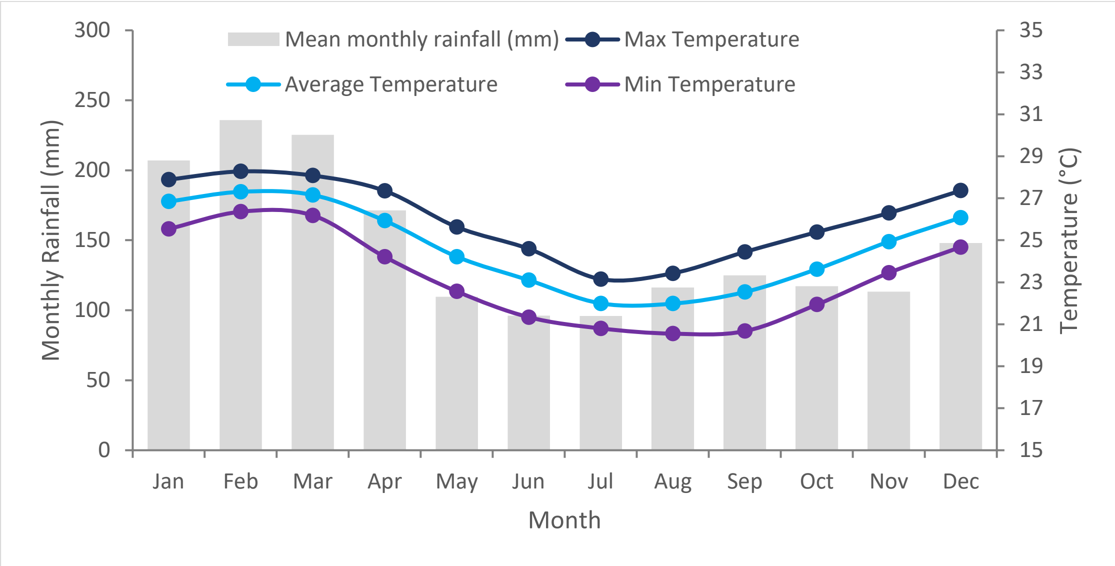

Figure 8: Monthly average rainfall and Temperature for Tongatapu.

These seasonal changes are driven by the sea surface temperature (SST) change of the surrounding ocean and by advection of cooler and dryer air from the sub-tropical high-pressure system to the south during the winter season. The average annual rainfall for Tongatapu from 1980-2018 was ~ 1600 mm/year, but with much inter-annual variability. For example, annual rainfalls in 1983 and 1999 were 835 mm and 2,539 mm respectively (Figure 9).

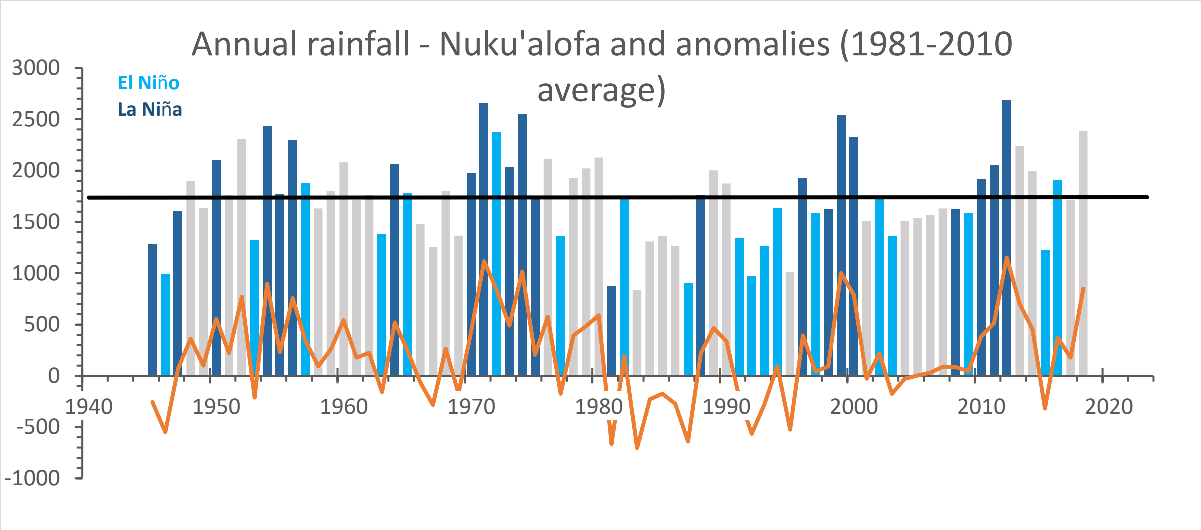

Figure 9: Total annual rainfall from Nuku'alofa weather station (bars). La Nina (dark blue) and El Niño (light blue) events are blue shaded, and the grey bars represent 'normal' ENSO conditions. The black bar shows the 1981-2010 average rainfall, and anomalies from the average are shown by the orange line.

Both seasonal and inter-annual rainfall variability in Tonga is dominated by the variability in the position and intensity of the South Pacific Convergence Zone (SPCZ). The SPCZ (Figure 10) is a zone of low-level convergence between the south-east trades in the eastern tropical Pacific and the semi-permanent easterly flow in the western Pacific, extending south-eastward from the equator at approximately 140˚E to 120˚W at 30˚S (Vincent, 1994). The band of convergence is approximately parallel to the equator from 140˚E to 160˚E and has a more diagonal south-eastward orientation at higher latitude from 180˚W to 120˚W. Much of the inter-annual variability of the SPCZ is driven by the El Niño-Southern Oscillation (ENSO) where oceanic-atmosphere interactions play a key role (Folland et al., 2002).

There is a pervasive seasonal shift in the SPCZ. During mid-winter, June to August, the colder SST of the south-west Pacific reduces convective instability and weakens the poleward extension of the SPCZ with the result that the SPCZ becomes less defined and loses its band shape as the instability weakens and the convergence spreads out over a greater area. The near-surface flow becomes much drier resulting in less rainfall for Tonga during winter (Figure 10, right). The opposite occurs during mid-summer, December-February, when the convergence band is more concentrated resulting in higher accumulation of moisture and the higher SST results in more convective instability. As a consequence, during the South Pacific summer (November-April), Tonga receives more rainfall (Figure 10).

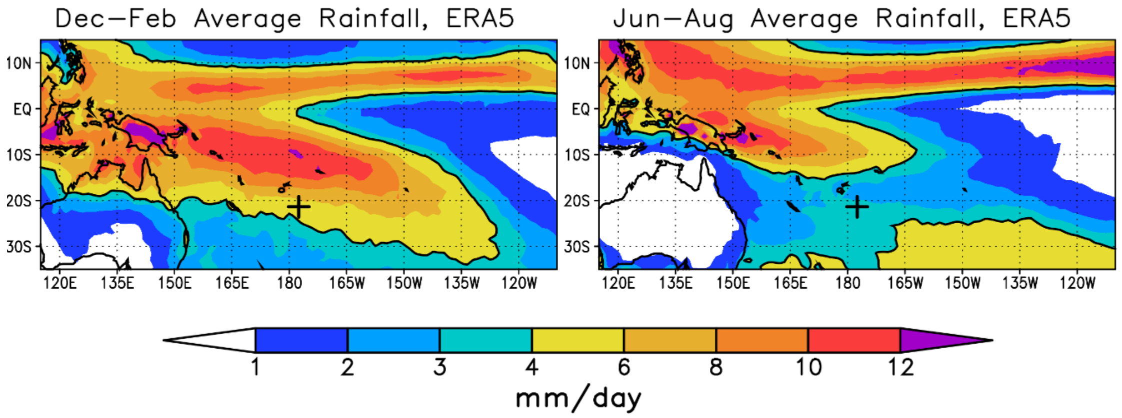

Figure 10: The 1981-2010 climatological rainfall in the South Pacific islands, in mm per day, during summer (wet, left) and winter (dry, right). The bold black contour shows the 4 mm per day isohyet denoting the region of heavy tropical convection; the SPCZ extends south-eastward from the equator near 140E and is commonly defined as the region where rainfall exceeds 4 mm per day (bold black contour). The cross shows Tonga's location. Rainfall data come from ECMWF's fifth generation reanalysis (ERA5).

2.4.1. ENSO

ENSO is generated by oceanic-atmospheric interactions in the tropical Pacific and consists of irregular El Niño and La Niña conditions occurring typically every 2 to 7 years with neutral conditions often occurring in between. The El Niño and La Niña episodes are caused by the strengthening and the weakening of the pressure gradient between the West Pacific warm pool and the cooler waters of the East Pacific (Zhang, 1997).

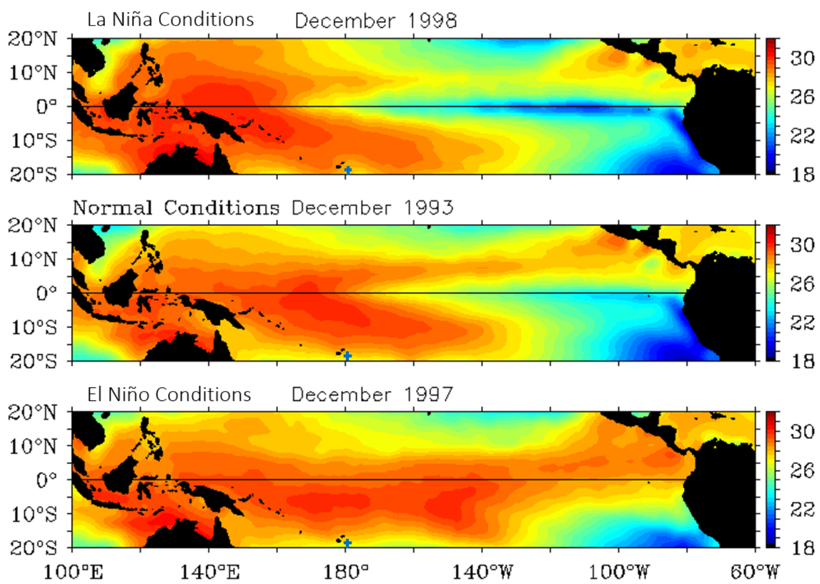

Figure 11: ENSO variability in terms of monthly SST (˚C) across the Pacific for December of 1993 (normal conditions), 1997(El Niño conditions) and 1998(La Niña). Tonga represented by the blue cross east of Fiji. (www.pmel.noaa.gov/elnino/sites/default/files/thumbnails/image/monthly-sst-lanina-normal-elnino.gif)

Normally in the tropical and subtropical zone, the West Pacific is warmer and has lower atmospheric pressure than the Eastern Pacific, which results in the easterly trade winds pushing cooler water westward along the equator where it is heated by high insolation and accumulates in the western Pacific warm pool. A strong east-west pressure gradient exists in normal conditions, and during La Niña events these conditions strengthen with stronger than normal trade winds and warmer than normal waters accumulated in the west Pacific warm pool (Figure 11, top). El Niño conditions occur when positive temperature anomalies develop in the Eastern Pacific and reduce the temperature/pressure gradient across the equatorial Pacific hence weakening the easterly trade wind. This allows warm water to move eastward and accumulate in the central and eastern tropical Pacific (Figure 11, *bottom*), also weakening the upwelling of cold water from the deeper ocean along the western coast of South America (Trenberth, 1997).

The SPCZ also responds to ENSO cycles. During La Niña events, the SPCZ typically located farther south-west than normal over Tonga, and during El Niño events further north-east. As a consequence, El Niño tends to bring lower than average rainfall to the Tonga region during the wet season whilst La Niña brings significantly higher rainfall during the wet season (Folland, 2002), as demonstrated by Figure 9.

2.5. Vegetation and agriculture

Agricultural land use largely defines the type of vegetation cover in Tongatapu. Most of the land has been cleared by the “slash and burn” method used by subsistence farmers and those practising mixed farming. Today, 11% of Tongatapu’s land area is covered by village settlement; 56% by mixed coconut palms; guinea grass and shrub forest; and about 23% by other grasses (Wiser et al., 1999). Small pockets (3%) of rainforest occur near the coast (Manu, 2000), the remnants following extensive land clearance for coconut plantations in the 1970s when the copra market expanded to reach 70% of the nation’s export (Somasekharan et al., 2017). Today 70% of the population practices farming and this extends across a large portion of the land area (Manu, 2000).

Despite the economic importance of agriculture, there is limited control on agricultural practices including its irrigation and use of fertilisers and pesticides. Sustainability of the groundwater resource is now a major issue especially in relation to irrigation and the use of agricultural chemicals. Uncontrolled extraction for irrigation poses a threat to the volume of groundwater resources and the chemicals pose a threat to the health and safety of the people using the groundwater. For this reason, it is recommended by the WRS that agricultural practices should not occur within 1 km diameter of groundwater pumps. However, this is not commonly practiced and most of the pumps, at rural villages, are located near agricultural plots and residential areas (information gathered during 2019 field work).

From a water balance viewpoint, there are two classifications for the vegetation in Tongatapu; shallow-rooted vegetation and deep-rooted vegetation. Shallow-rooted vegetation has roots that only penetrate to a maximum of 1 metre below the surface Deep-rooted vegetation penetrates further although usually not deep enough to reach groundwater and it is assumed that there is no transpiration directly from the water table (White et al., 2009). Coconut palm trees, comprising more than half of the trees on the island, are considered deep-rooted vegetation.

In the north of Tongatapu and around the coastal area of Fanga'uta Lagoon, mangroves have been depleting as a result of development in the past several decades leaving remnants totalling just 1,000 ha (Ellison, 2000). Mangroves have also been exploited by local people for wood, herbal medicine and for traditional art colouring using the sap. As mangroves act as a buffer to land degradation, along with other 'ecosystem services', their depletion raises concerns in the context of future sea level rise. As sea level is gradually increasing at 6 mm/year at Tongatapu. (CSIRO and Australian Bureau of Meteorology, 2011), higher tides may cause saline intrusion further inland. With an estimated sea level rise by the end of the century of a metre (IPCC, 2013), and as natural coastal ecosystems are degraded or disappear, Tongatapu clearly faces a threat from saline intrusion.

2.6. Soils

Most of Tongatapu has a clay soil layer consisting of a fine andesitic tephra deposit on top of a porous limestone aquifer (Cowie, 1980). The tephra covers 90% of the island and is derived from eruptions from the western volcanic islands, possibly from Kao and Tofua and other submarine volcanoes (Cowie, 1980; Gibbs, 1976; Manu, 2000). Soil thickness is governed by the degree of the weathering of the limestone base exposed and also the source of the volcanic ash deposit. The soils on the west side of the island have an average thickness of 5 m while on the east side of the island they are less than 1 m thick (Manu, 2000).

The soil distribution map (Figure 12) for Tongatapu (Shin et al, 2019) shows 4 major categories: Vaini, Lapaha, Nuku'alofa and Sopu Soil. These soil categories were constructed from the original distribution map by Gibbs (1976). Shin et al, (2019) collected data from 5 sites from Tongatapu and measured a soil moisture content (SMC) of 40% and 45% for Vaini clay and Lapaha clay, respectively, over 23 days from March 12 to August 3, 2017 (Figure 12).

These are the two dominant soils (Vaini clay and Lapaha clay) and most of the island soil are highly permeable, allowing for increased infiltration and less runoff. The soils of Tongatapu can be considered homogenous due to the small difference in water holding capacity (or SMC) between the various soils. In a previous study (Falkland, 1992), field capacity (FC) and wilting point (WP) of 0.55 (55%) and 0.40 (40%), respectively, were assumed to apply for all the soils of Tongatapu, and the difference of 0.15 (15%) was used for soil water availability.

The numbers above were based on soil moisture measurements, within the soil moisture zone (SMZ), where most of the roots of shallow-rooted vegetation and shallow roots of trees are found and transpire much of the water from infiltrating rain. This SMZ value was extracted by incorporating a homogenous average for the whole island where all plant roots can penetrate to maximum depth (rooting depth). The SMZ for Tongatapu extends to 1000 mm below the ground surface and the field capacity and wilting point were assumed to be 0.55 (550 mm) and 0.40 (400 mm) respectively, following Falkland (1992).

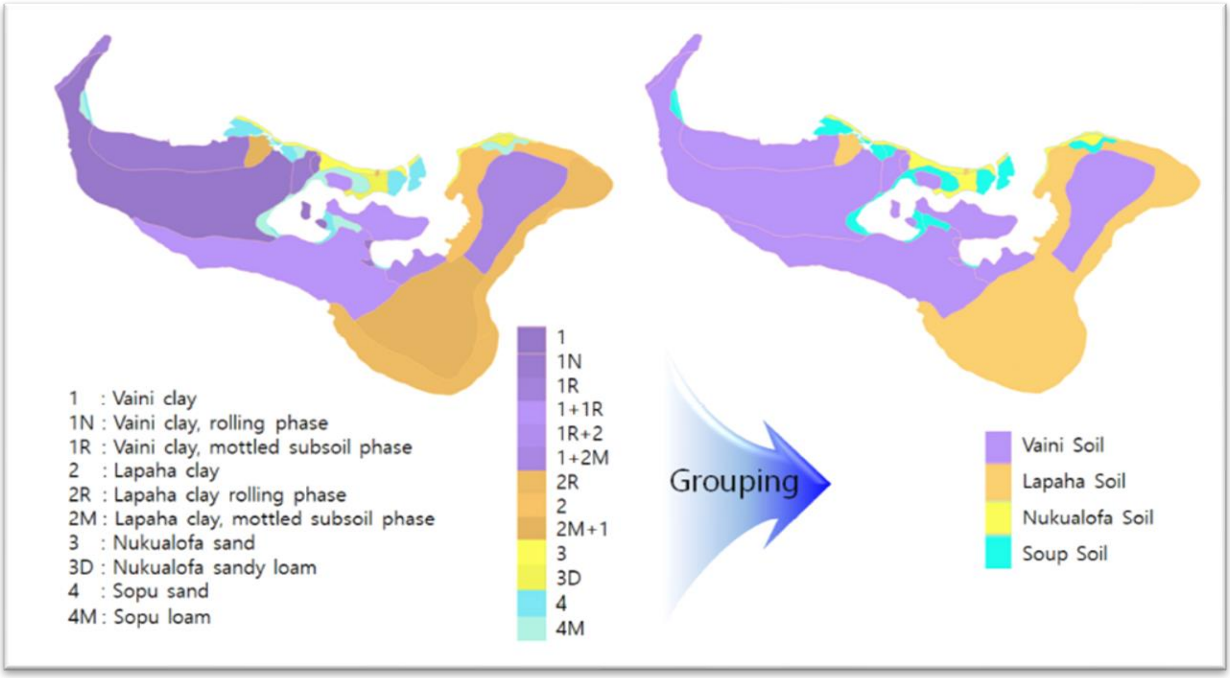

Figure 12: Soil distribution grouping for Tongatapu (Shin, 2019).

2.7. Tongatapu water resources

As stated earlier, the population of Tongatapu depends on two main sources of water: fresh groundwater extracted from wells and boreholes; and rainwater harvesting, for drinking and other household use and for agricultural practices. Of these two, rainwater is the main source for drinking water (see section 2.7.2) whereas groundwater is mainly used for other household purposes. Groundwater is not generally used for drinking because it has a higher salinity than rainwater. The average conductivity for rain water and groundwater are 100 µS/cm and 1100 µS/cm, respectively, indicating a ~1000% increase in salinity.

Figure 13 shows the range of maximum, average and minimum thickness for the period when the monitoring of SMB commenced, (1997 to current years).The 2016 Tonga Census reports that 88% of the households rely on piped water distributed by groundwater systems for household activities such as bathrooms and for cleaning purposes (Tonga Statistics Department, 2017). It is important to mention that the use of desalinated and bottled water available from several private companies is increasing. Also, there are a few seawater desalinisation equipment on the island owned by the National Emergency and Management Agency (NEMO), Tonga and others emergency stakeholders.

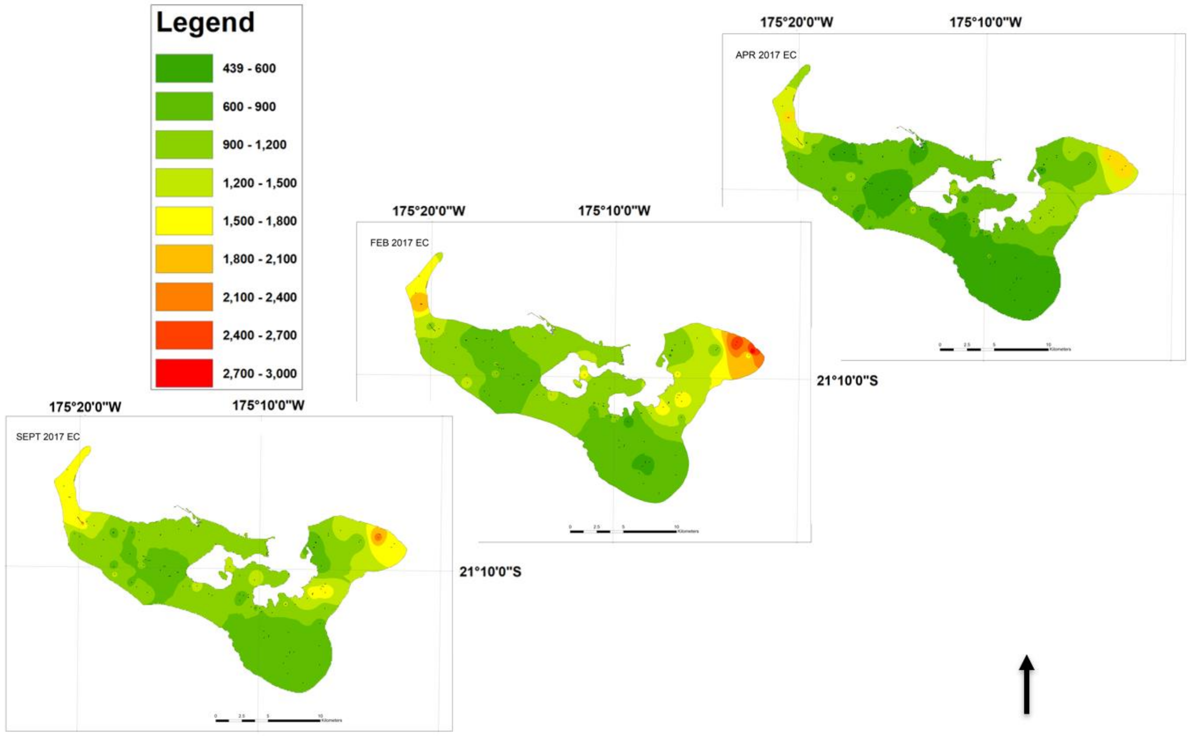

Figure 13: Maximum, average and minimum freshwater thickness for SMB 1-16 for the period 1997-2018.

2.7.1. Groundwater

The WRS of the MLNR is the lead water agency in monitoring, analysis and reporting on water resources in Tonga although it is important to note that there is no legal basis for protecting the groundwater from harmful activities such as pollution and over-extraction. This is because the draft Water Resources Bill has yet to be enacted by the Government of Tonga. It should also be noted that there are conflicting perspectives between the MLNR and the Ministry of Health (MOH) as to whose responsibility it is to order the closure of production wells when they are contaminated or are unusable due to increases in salinity or pollution sources.

Groundwater quality measurements from the production (pumping) boreholes and wells around Tongatapu are collected on a quarterly basis by the WRS. The WRS groundwater monitoring template summary (Table 1) includes various on-site measurements of parameters including depth to water table, salinity (electrical conductivity), pH, temperature of groundwater in wells, general maintenance and readings from the flow meters neat the pumps. In addition, samples are analysed at the WRS laboratory for faecal coliforms and nutrients (phosphate, ammonia and nitrate).The Tonga Water Board, disinfects (using chlorine) the groundwater from the Mataki'eua - Tongamai wellfield for supply to Nuku'alofa, the village water supply systems mainly untreated groundwater. The number of villages that chlorinate water is unknown.

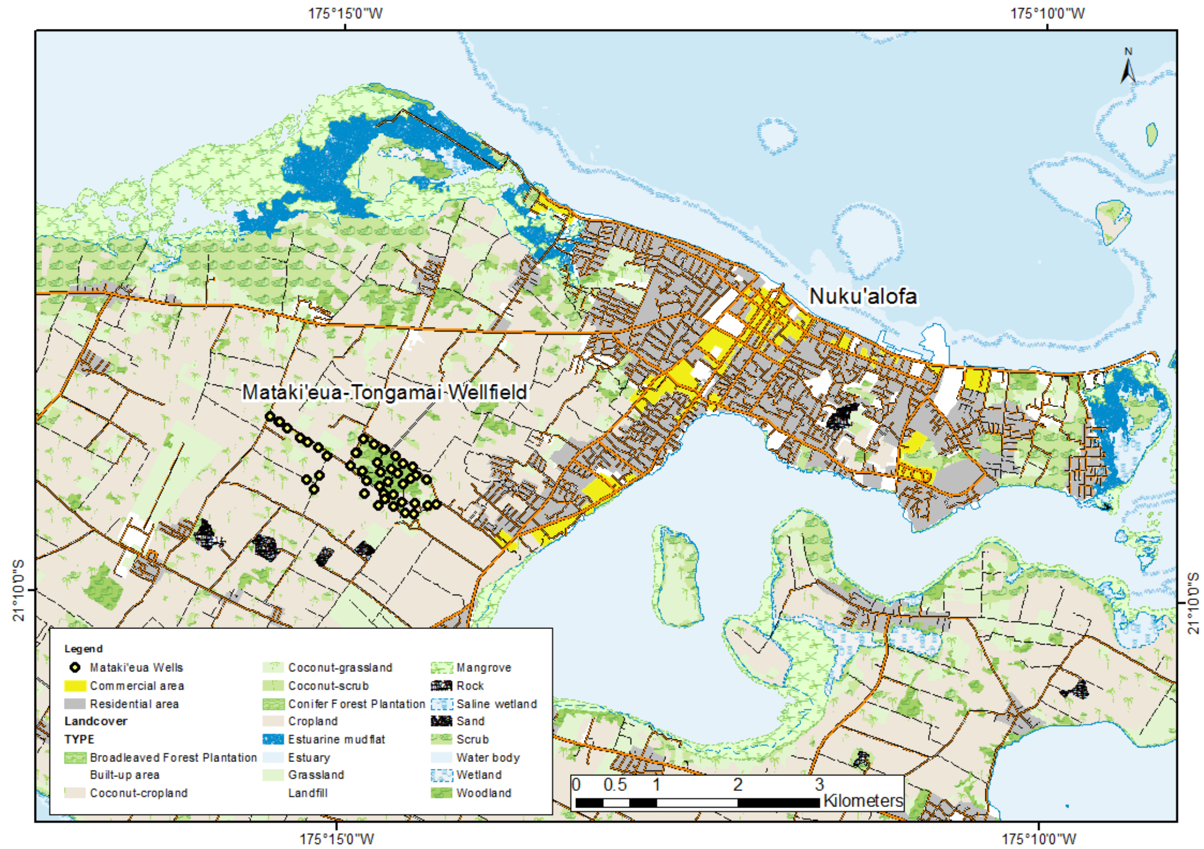

Figure 14: Inverse distance weight interpolation of conductivity (salinity-µS/cm) for Tongatapu for February, April and September 2017 groundwater monitoring showing that there are places where groundwater conductivity is much higher as in nearer the coastal and along places with thinner land mass.

Due to saline intrusion near the coast based on current knowledge of groundwater salinity, it is always safer to drill production boreholes at distances of not less than 500 m from the coastline, where the groundwater is fresher.

Two previous investigations have estimated groundwater recharge for Tongatapu using different methods: one by White et al (2009) using a similar approach as in this study; the other by IJzermans and Waterloo (2017) using the Hydrus-1D model (of Simunek, 2008). This thesis follows the White et al (2009) WATBAL approach, modified to use daily-resolution input data rather than White et al's monthly-resolution approach, which is not able to capture the impact of heavy convective rainfall events that typically occur daily timescales or less. The alternative, Hydrus-1D model method, was not used here due to limitations in obtaining accurate calibration parameters for that model, including soil hydraulic parameters, pressure head, water contents concentration and various fluxes. This approach also enabled a direct evaluation of the efficacy of the WATBAL model applied at a daily resolution compared to a monthly resolution.

Category	Location	Frequency	Parameters
Village Water Supplies	Tongatapu	Quarterly	• Water level (where accessible) • Salinity (EC), pH & temperature • Faecal coliforms (bacteria count) • Nitrate • Phosphate • Ammonia • General Maintenance • Flow reading and flow rate (where functioning flow meter present)
	‘Eua, Ha'apai & Vava'u	Bi-annually	
	Niua’s	Annually	

Table 1: WRS summary of village groundwater supply monitoring. Source: (Hyland, 2017)

2.7.2. Urban water supply

The water supply to the Nuku’alofa urban area is extracted from the Mataki’eua-Tongamai Wellfield located 5 km south-west of the capital (Figure 15). This water supply is managed by the Tonga Water Board (TWB) which is one of the Combined Public Utilities in1966. TWB’s responsibilities include the operation, maintenance and monitoring of water production and distribution to the urban area of Nuku’alofa. There were initially 36 production wells and boreholes. More recently, another 18 production wells were added to the wellfield but have not started operating. The wells and boreholes run 24 hours per day pumping water into storage tanks from where the water is distributed to urban households (Figure 15). Supply to the urban households are metered and billed. A recent investigation by TWB reported that 50% of water from the total extracted from the wellfield was unaccounted for, pointing to significant leakages in the water distribution infrastructure (Combine Utility Board, 2018). This raises management issues around the supply and distribution of water to the population in the urban settlements and is directly relevant to the context of water sustainability in Tongatapu.

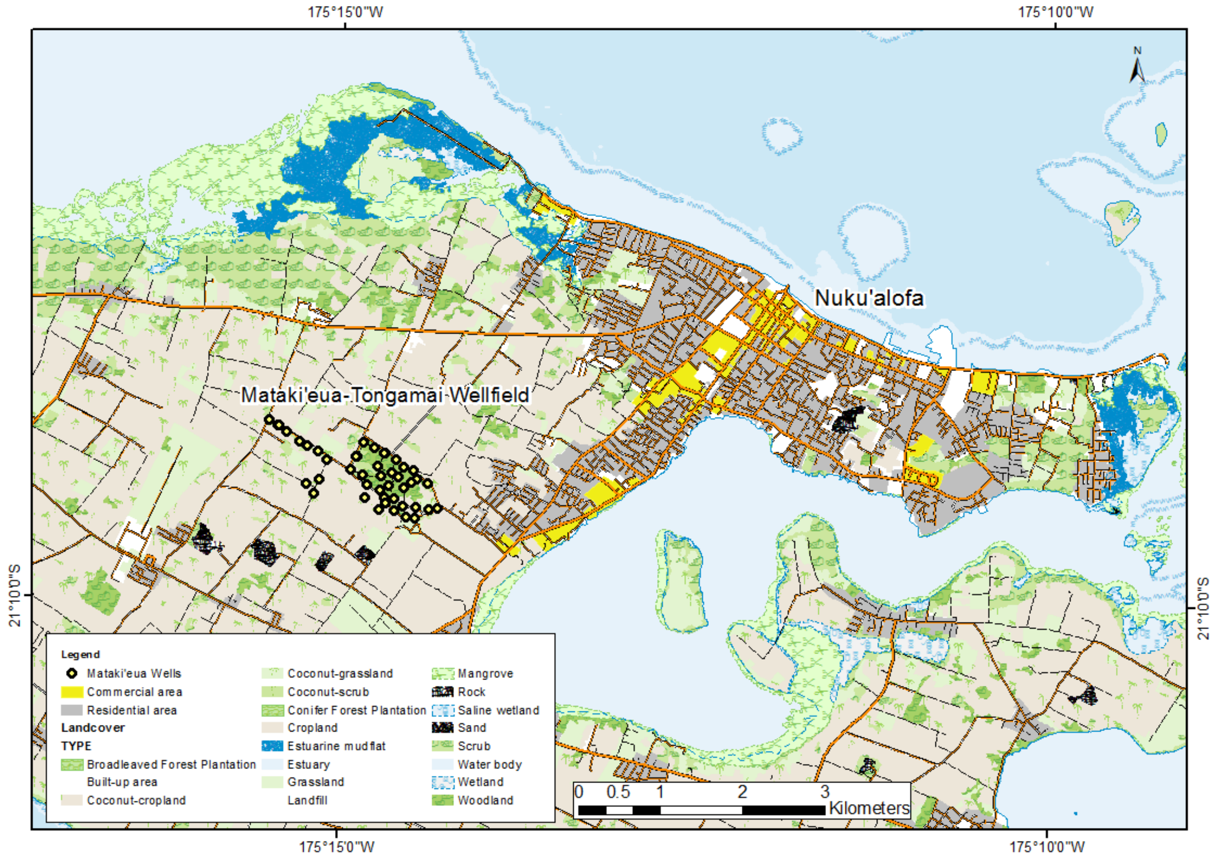

Figure 15: Location of Mataki'eua-Tongamai Wellfield.

2.7.3. Village water supply

Groundwater extraction at in Tongatapu villages is mainly managed by local Village Water Committees (VWCs). The VWCs are responsible for operation and maintenance of the groundwater pumping and distribution systems and ensuring that household water needs are met. Each village contains at least one community production well/bore and one or more community storage tanks from which water is distributed to households through a reticulation pipe system. On-site water level and quality measurements extend back to 1961 when reticulated water supplies were first installed in a few villages on Tongatapu. These historical data records, although scattered and discontinuous, are stored in the WRS e-Database which enables analysis of long-term effects of groundwater extraction on salinity and water level.

A small number of VWCs have distributed flow meters to all households while the remainder pay a fixed monthly fee, regardless of usage. The monthly fee varies from $5 to $20 Tongan pa'anga per month. Therefore, a very small proportion of water users are actually paying for the amount of water they use. The lack of control on the extraction of water is a threat to the resource and represents a threat to water sustainability on Tongatapu.

2.7.4. WRS Salinity Monitoring Boreholes Database (SMB).

SMBs are specially constructed boreholes to measure groundwater salinity at different depths, and hence provide a measure of the fresh groundwater thickness at each borehole location. Measurement of groundwater thickness is crucial for understanding the sustainability of the groundwater resources in Tonga. There were initially 7 SMBs in Tongatapu monitored by TWB in 2002 and these were all located in and around the Mataki'eua-Tongamai Wellfield. There are now 18 SMBs now in Tongatapu with 4 in the Western District, 5 in the Eastern District and 11 in the central part (Figure 16).

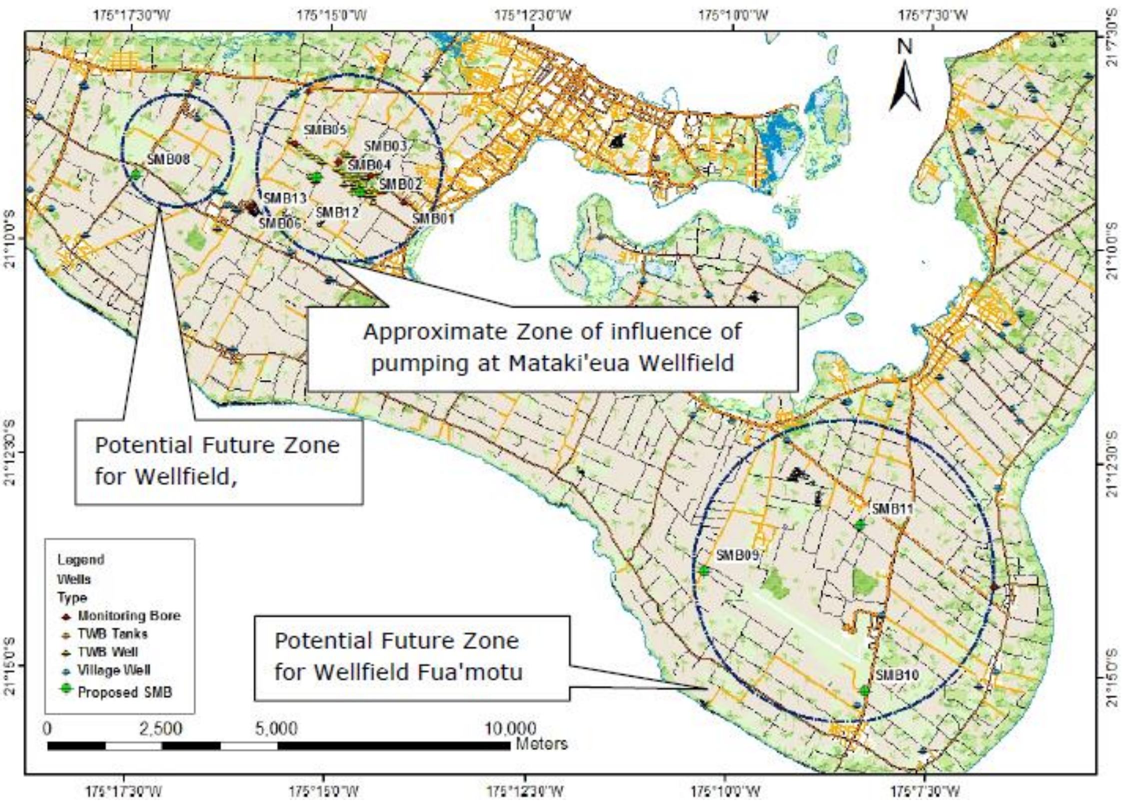

Figure 16: SMB locations at Central and Eastern District of Tongatapu.

2.7.5. Rainwater

Rainwater is the main source of drinking water and cooking for the population of Tonga with the 2016 Tonga Census reporting that 60% of the households of Tongatapu (18,005 households) rely on rainwater for drinking (Statistic Department Tonga, 2017). Rainwater is collected from rooftops and stored in household ferrocement, fibreglass or polythene tanks ranging in capacity from 1,000 litres (L) to 20,000 L. Almost every household in the urban and rural areas have at least one rainwater tank connected to the roof catchment through gutters and downpipes. Rainwater from tanks at community halls, churches and schools is commonly available for people with no rainwater storage facility. Harvesting rainwater is crucial for water security in Tonga and there are no limits imposed. Since rainfall varies during the year, storing rainwater during summer should be a priority for households to provide reserves for the drier conditions of summer. Investing in more rainwater storage tanks helps to secure access to rainwater all year round.

2.7.6. Others

Bottled water

While most of both urban and rural households of Tonga use rainwater for drinking, about 25% purchase bottled water (Lal, 2006). The use of bottled water is crucial in securing water needs in emergencies, especially those related to destructive cyclones. It also minimizes the risk of catching water borne diseases since the rainwater and groundwater sources are not always treated due to the limitations of treatment resources and lack of facilities. As noted earlier, the majority of tourists also use bottled water for drinking.

Desalination equipment

There is no portable desalination plant in the island of Tongatapu but there are several portable reverse osmosis units in reserve which are deployed in response to national emergencies, for example, to the Ha'apai Islands after damage by Cyclone Ian in 2014. Several agencies own a single unit with a capacity similar to the 18TS Portable desalination units distributed by Citor Desalinisation, Australia (Freshwater, 2012) at a unit cost of TOP$90,000.00 (approx. AUD$51,000). Those agencies include Tonga National Emergency Management Office (NEMO), His Majesty's Armed Forces (HMAF), Tonga Water Board (TWB) and the Tonga Red Cross Society.

2.8. Summary

This chapter has reviewed the natural environmental and institutional context to water supply and demand in Tongatapu. While the natural environmental factors are beyond the control of Tonga's water authorities, this chapter has noted some limitations in the infrastructure's framework that could be improved, and these may be relevant to future planning in the context of water sustainability.

3. Methods

3.1. Recharge estimation (Objective 1)

Recharge to groundwater was estimated using two methods. The first and more simplistic method used an empirical formula representing rainfall and recharge ratio where a reasonable estimate was determined using data from several limestone and coral islands in the South Pacific, including Tongatapu UNESCO (1991). The second method was estimated using a water balance approach as was used by White et al., (2009). This is a more accurate method where recharge is treated as the net inflow to groundwater after evapotranspiration losses have been subtracted from rainfall and it uses the computing software called WATBAL (WATer BALance) to determine the losses (Thornthwaite and Mather, 1955 & Kaczmarek, Z. 1993).

3.1.1. Method 1: Rainfall – recharge relationship (Objective 1a)

A simple empirical relationship (Fig, 15) was developed by UNESCO (1991) for correlating annual rainfall to recharge in various small low lying islands in the Pacific. A generalised rainfall-recharge relationship was derived based on the similarities of the prevailing conditions for these islands being, in particular, low lying with minor orographic differences and a relatively homogenous geology. As these conditions apply to Tongatapu, the UNESCO method was applied to the annual rainfall data for the island.

From this empirical relationship, UNESCO (1991) determined a recharge rate of 20-30% for Tongatapu giving an average annual recharge of 450 mm, based on total average rainfall of 1,700 mm. However, given the strong inter-annual variability of rainfall, the recharge amount will also vary considerably from year to year.

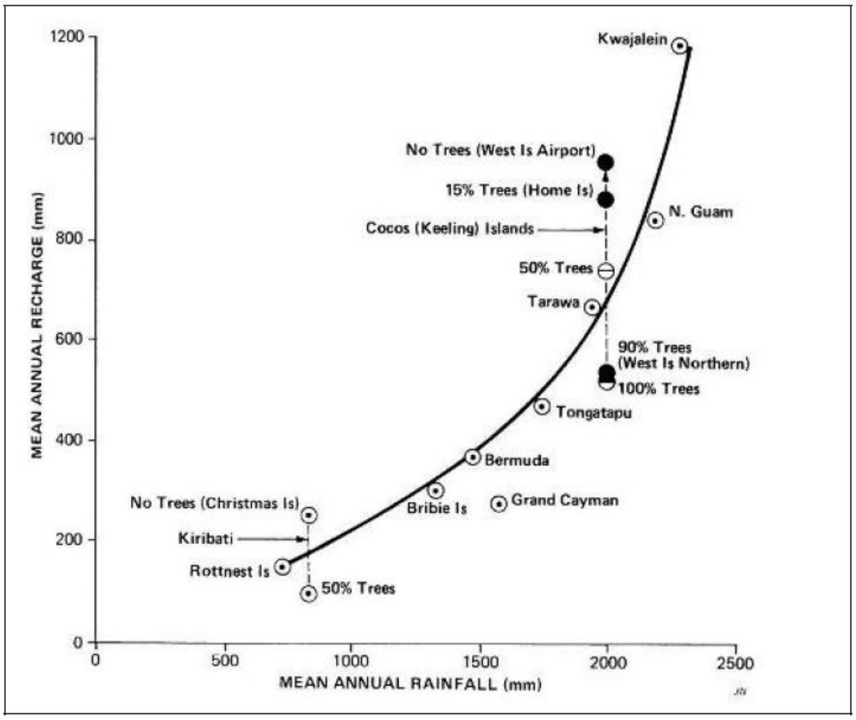

Figure 17: Relationship between annual rainfall and recharge for several islands (Falkland, 1992; UNESCO, 1991)

3.1.2. Method 2: Water balance using WATBAL (Objective 1b)

Description of WATBAL model

WATBAL is a model used to simulate the water balance above the groundwater table (White et al., 2009). Equation 1 below represents the main input variables which are precipitation (P, monthly or daily), monthly potential evapotranspiration (ET_{α}), and soil moisture-related content (V). These variables are measured in millimetres.

Equation. i $$R = P - ET_{\alpha} \pm \delta V$$

Figure 18 is a schematic representation of this equation and the processing sequence of the WATBAL model. Precipitation (P) is first intercepted by the vegetation cover (Interception storage, IS). When IS reaches maximum storage, the excess P then infiltrates the soil where it can be measured by the soil moisture content (SMC). When SMC reaches its maximum, any excess P recharges the groundwater. A possible further evaporative loss, transpiration from deep rooted vegetation (TL) is disregarded because of the thickness of the unsaturated zone including soil and underlying limestone which for Tongatapu ranges from around 1 m to 50 m.

The roots of trees on the island generally cannot penetrate to the depths of water table (White et al., 2009).

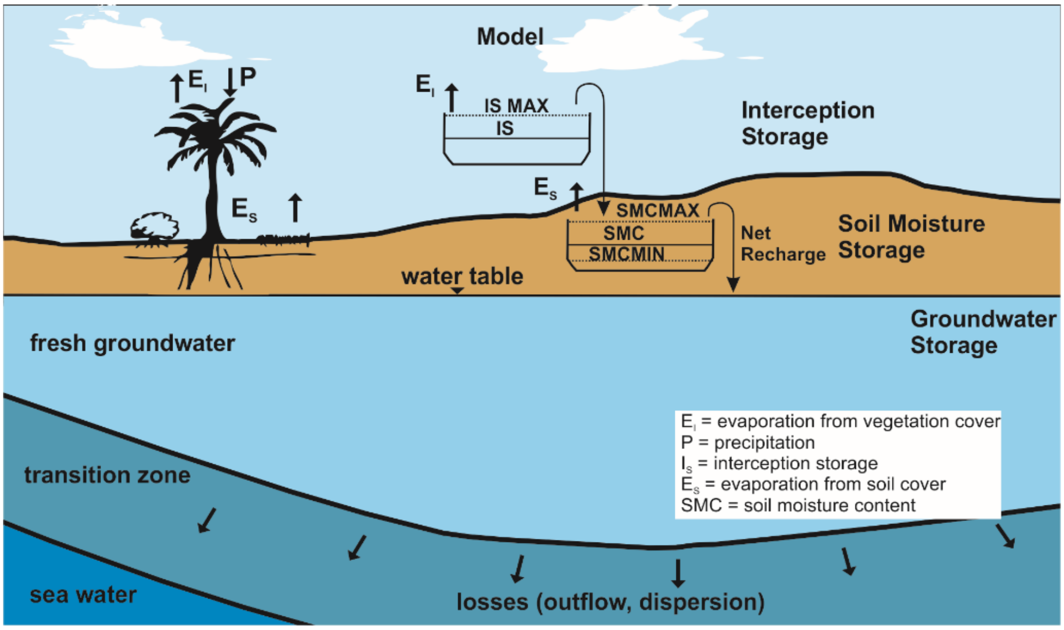

Figure 18: Flow diagram of the water balance model (WATBAL) for small islands. No surface runoff is included.

Daily rainfall data

The WATBAL model was previously used by White et al. (2009) to estimate historical groundwater recharge on Tongatapu for the period 1945-2006. They applied the model using monthly rainfall totals and acknowledged that more accurate estimates may be achieved by using daily rainfall inputs. The use of monthly rainfall data tends to underestimate the recharge when daily rainfall data is missing. An additional problem is non-linearity in the frequency and intensity of rainfall/recharge events, which is not captured in a monthly total. As a consequence, White et al (2009) recommended that future applications of WATBAL to Tongatapu should apply daily rainfall data. The current project follows this recommendation and builds on the work of White et al (2009) by applying WATBAL using daily rainfall data for the period January 1980 to December 2018. Records of rainfall from the Nuku'alofa station were used for this project and were obtained from the TMS.

There are two meteorological stations operating in Tongatapu: Nuku'alofa located within the Nuku'alofa CBD and the Fua'amotu station located at the TMS office near the airport. TMS measures a number of climate variables such as precipitation, temperature, wind speed, relative humidity, mean sea level pressure, evaporation and sunshine hours (Tonga Meteorological

Service, 2019). TMS provided daily records of the above variables for 1980-2018 which were used for this study.

Missing Rainfall Data Analysis

Daily rainfall data measured at the two TMS stations, used for the analysis of this project, extend from January 1980 to December 2018, a period of 39 years (468 months or 14,245 days). There were 211 missing days in total of which data were missing from both stations for 4 days and from only one station for 207 days. These missing data are problematic as the water balance model applied in this thesis requires continuous data. Therefore, a method for estimating these missing values was derived, based on comparison of the two sets of rainfall data, as described in the next paragraph.

The long-term ratio between the Fua'amotu (F) and the Nuku'alofa (N) daily total rainfall for 1980-2018 was F/N = 1.09. Previous measurements of the ratio were: ***a***. F/N = 1.092 using monthly data from 1980 to 1990; and ***b***. F/N = 1.116 using monthly rainfall data from January 1994-July 2007 (White et al., 2009). The similarity in these ratios indicates that daily values measured at the Nuku'alofa station can be used to estimate the daily values for the missing days in the Fua'amotu record and vice versa. This method of estimating the missing data is considered acceptable because the island is relatively flat and the distance between the two stations is relatively small. After estimating the missing data, a complete daily record for both stations were able to be processed in the WATBAL computing program.

Mean monthly potential evaporation

Evapotranspiration is the removal of water from the surface of the earth through the processes of evaporation and transpiration to the atmosphere. Thompson (1986) calculated monthly evapotranspiration values for Tongatapu (Table 2) by applying an unspecified version of the Penman equation (see below) to the Nuku'alofa meteorological dataset for 1983 – 1986. These monthly evapotranspiration values were subsequently used by White et al. (2009) for their water balance modelling as they argued that the underlying meteorological variables had not changed substantially for their period of application (1945-2006).

Month	Monthly (mm)	Days in month	Daily (mm)
Jan	164	31	5.29
Feb	137	28	4.89
Mar	139	31	4.48
Apr	108	30	3.60
May	89	31	2.87
Jun	77	30	2.56
Jul	85	31	2.74
Aug	96	31	3.09
Sep	116	30	3.86
Oct	144	31	4.64
Nov	152	30	5.06
Dec	154	31	4.96

Table 2: Thompson's evapotranspiration values which were used for the processing of the recharge values for this study.

The same assumption was used for this study. As an important aspect of the current research is to compare the daily-resolution water balance modelling approach to the monthly-resolution approach of White et al (2009), the decision was taken to apply the same evapotranspiration values (i.e. the Thompson values) after testing that the underlying meteorological variables had not shifted significantly, as was the case for White et al. (2009). However, it is important to point out that future water balance work should develop new evapotranspiration parameters by applying an appropriate version of the Penman model to the current Tongatapu meteorological data.

It is to be noted that there I attempted to calculate a new set of evapotranspiration values for Tongatapu using the more recent data (1980-2018). The attempt followed the Penman version mentioned above and yielded evapotranspiration values that were 30% higher than that of Thompson’s in 1986. It is assumed that the different evapotranspiration values were due to various weightings applied to the climate parameters of the Penman equation by Thompson (1986); however, the details of these weightings were not provided by Thompson (1986).

Penman equation

The Penman equation shown below is assumed to have been used by Thompson (1986) and therefore to have generated the monthly evapotranspiration values used in this study (Table 2). The input variables are temperature, humidity, wind and sunshine hours available for Tonga from TMS, Nuku’alofa station.. These variables control the rates of evapotranspiration which is high during hot, sunny, low humidity and windy conditions. Evapotranspiration tends to be lowest in cool, cloudy, humid and less windy conditions.

Eq. ii.	$ETo = c\,[W.Rn + (1 - W).f(U).(ea - ed)]$

Where;

ETo	= Monthly Potential Evapotranspiration
C	= adjustment factor to compensate for the effect of day and night weather conditions
W	= temperature weighting factor
Rn	= net radiation in equivalent evaporation in mm/day
f(U)	= wind-related function
(ea-ed)	= difference between the saturation vapour pressure of the air, both in mbar

Interception by vegetation

The WATBAL model accounts for interception by vegetation by allowing for a vegetation interception storage (IS). Precipitation landing on the vegetation initially fills IS up to a maximum storage value (ISMAX) before excess water overflows and fall to the ground (soil). A daily ISMAX value of 1 mm (or 30 mm/month) was applied for predominantly grassed areas and a daily ISMAX value of 3 mm (90 mm/month) was applied for the areas covered by mostly trees. These were conservative approaches.

Soil moisture zone

The average thickness of the soil moisture zone (SMZ) was estimated to be 1,000 mm. The soil moisture content (SMC) can vary between the wilting point (WP), which is the minimum volume of water in the soil required for the growth of plants, and field capacity (FC), which is the maximum moisture content the soil can hold. The FC and WP values used in this study were 0.55 (55%) and 0.4 (40%), respectively. When the SMC is below the wilting point, plants tend to wilt and can die. When the SMC is at or below FC, there is no infiltration of water from the SMZ to the freshwater lens. When the SMC is more than FC, excess water infiltrates from the SMZ to the freshwater lens. An initial SMC of 500 mm is assumed for the soil, which is the approximate midpoint between the SMC at WP (i.e. 400 mm) and the SMC at FC (i.e. 550 mm).

Crop Factor

Vegetation is assigned a crop factor. Each type of plant has its evaporative potential compared with that of a 'reference crop'. In this study, separate values were assigned for the two types of vegetation: 0.8 for deep-rooted vegetation and 1.0 for shallow-rooted vegetation. The latter value was assigned because shallow-rooted vegetation evaporates at about the same rate as the reference crop while the deep rooted vegetation (e.g. coconut trees) potential evaporation rate is taken as 80% of that for the grassed land cover. The shallow rooted vegetation transpires more because it obtains its moisture requirement from the soil moisture zone while the deep rooted vegetation penetrates below the soil moisture zone but only by a small portion (Falkland, 1992).

Deep rooted vegetation ratio

The proportions covered by shallow and deep-rooted vegetation of the surface above the total freshwater lens area of Tongatapu were estimated from aerial photographs by Falkland (1992). These proportions were, respectively, 0.7 and 0.3 and have been used in this study.

3.2. Sustainable yield estimation

For freshwater lenses, the sustainable yield refers to the maximum amount of water that can be extracted before the remaining water is at risk of becoming saline. The salinity intrusion risk is significant in small island hydrogeology since the sustainable yield cannot be equal to the recharge because some of the recharge is required to maintain the freshwater lens and prevent from mixing entirely with the underlying salty sea water. Defining sustainable yield is crucial because the thin freshwater lens of Tongatapu overlies the denser and saltier underlying sea water. Saltwater intrusion occurs when the rate of pumping exceeds the rate of recharge from rainfall. Saltwater is continuously mixing with the freshwater within a transition zone due to the groundwater movement caused mainly by tides and natural dispersion processes. Excessive pumping of the fresh groundwater can cause the pumped water to become saline due to the upconing of the underlying saline water.

Sustainable yield of groundwater is controlled by the volume/thickness of freshwater above seawater, the average recharge rate at which rainwater infiltrates to the aquifer and the controlled-extraction rate by each pump. Thickness of the groundwater is determined by the ability of the aquifer to hold water. This retention capacity is controlled by the porosity of the rocks and the existence of caves. Recharge to groundwater is governed by the volume of rainfall, max storage capacity of vegetation, accumulated moisture content of the soils and the transpiring energy of the plant-roots.

The estimated sustainable yield for Tongatapu by Falkland (1992) was 52 ML/day or 106 mm/yr, or 20% of the groundwater recharge which was estimated as 528 mm/yr. For estimating sustainable yield in volumetric terms, a depth to volume conversion is necessary. The sustainable yield in megalitres was calculated by multiplying the sustainable yield in depth terms (mm) by the “effective recharge zone” of the island, which excludes salinity-prone areas within 500 m of the coastline and 100 m of the lagoon. The effective recharge zone therefore was 180 km^2, 70% of the island’s total surface area of 260 km^2. The 52 ML/day sustainable yield for the area where freshwater lens occurs, can be expressed on a per unit area basis in, as approximately 0.3 $ML/day/km^2$.

3.3. Groundwater extraction rate

The extraction rate of the groundwater resources from all wells and boreholes in Tongatapu is determined from the total pumping rate for all production pumps. Information about pumping rates from the village pumps was previously limited. The recent installation of 103 new flow meters combined with existing flow meters now provides a total of 126 village production pumps with flow meters in Tongatapu, This enable a more comprehensive measurement of extraction rates across the island. It is estimated that there are about 40 pumps that are still not fitted with flow meters. The new meter installations, completed in May 2019, were funded by the “Climate Resilience Sector Project” (CRSP) implemented by MEIDECC.

Flow meter data was obtained during a 5 week research trip to Tonga in April 2019. Two rounds of readings were conducted during the visit at all village wells or boreholes where meters were installed and at the boreholes in the Mataki’eua - Tongamai well field. Previous flow meter readings of were also retrieved from the WRS Groundwater Database during the visit. Measuring volumes of groundwater extracted is not only essential for overall water balance calculations but also for estimating leakage losses which is vital for the sustainable management of the groundwater resources. It is advised by the WRS that maximum pumping capacity for the pumps should be below 3 L/s although most of the pumps in Tonga have an average capacity of 2 L/s.

3.4. Climate prediction

3.4.1. Rainfall prediction for 2070-2099

Climate projections for the period 2070-2099 were examined using monthly-mean CMIP5 climate data under RCP 4.5 and RCP 8.5 scenarios and were compared to the historical simulations over the period 1975-2004. We use the ensemble mean of all 210 historical simulations and 107 RCP simulations. These two scenarios were specifically chosen because they are sufficient to represent the extreme (worst) and the average of the projected trends.

Averaging across all the models effectively removes internal variability, such as ENSO, and reflects the externally-forced climate response due to increases in greenhouse gases. As evident by the CMIP3 data processed by White et al. (2009), there is a large spread in climate predictions for Tongatapu with no clear change toward wetter or drier conditions. This is largely due to model deficiencies simulating ENSO events as well as the position and intensity of the SPCZ, both of which control the annual precipitation for Tongatapu.

The ensemble means of the historical simulations for 1975-2004 period simulated a 30-year climatological annual rainfall of 1,176 mm of rainfall over Tonga (the grid cell over 175.2W, 21.2S), more than 400 mm less than what is observed for Tongatapu at the latitude 21˚S. This is due to known biases in the CMIP5 models which produce a SPCZ that is too far north and parallel to the equator (the so-called "double Intertropical Convergence Zone", e.g. Brown et al. (2013)). Despite these issues, the CMIP5 models provide insight into the most likely changes in sub-tropical South Pacific rainfall in response to increased radiative forcing due to increasing greenhouse gases, and so to account for this bias, we choose a more northerly grid cell at 18°S along the same longitude to represent Tongatapu in the models. In the models, this grid cell is located along the poleward edge of the simulated SPCZ, identical to Tongatapu's actual location relative to the observed SPCZ, and it receives an average annual rainfall of 1,605 mm in the historical ensemble mean for the period 1975-2004, which is representative of the observed average annual rainfall at Tongatapu. Therefore, the simulated SPCZ modulates the climate of the grid cell 175.2W, 18S in a very similar way that the observed SPCZ modulates the real Tongatapu climate.

Future rainfall for Tongatapu is obtained by calculating the change in monthly-mean rainfall between the CMIP5 1975-2004 historical 30-year monthly climatologies and the 2070-2099 RCP4.5 and RCP8.5 30-year monthly climatologies. This projected "change" is then added to the observed 1975-2004 monthly rainfall; that is, the models are used to capture the projected change only, and the observed rainfall is used as a basis to determine the actual projected rainfall values used for further analysis.

Because the ensemble mean effectively removes inter-annual variability such as ENSO events, which significantly influence the Tongatapu climate, this study examines future recharge by adding the monthly changes in rainfall (that is, the RCP4.5 and RCP8.5 monthly climatologies compared to the historical 1975-2004 monthly climatologies) onto the observed 1975-2004 monthly rainfall. This method accounts for the projected change in monthly rainfall due to increasing greenhouse gases, while also retaining the large observed seasonal and inter-annual variability, including the impact of ENSO events.

3.4.2. Recharge prediction for 2070-2099

Evapotranspiration for 2070-2099

Evapotranspiration values for the processing of recharge for the 2070-2099 rainfall under the RCP 4.5 and 8.5 were estimated using 4 scenarios that are likely to occur in the future for the evapotranspiration given that the variables such as temperature are likely to increase. These estimates were;

i. Thompson's evapotranspiration values,
   Thompson's values increased by,
ii. 10%,
iii. 20%, and
iv. decreased by 10%.

The future projection for 2070-2099 showed that under RCP 4.5 and 8.5, annual-mean temperature increased by 1.0 ^{o}C and 2.5 ^{o}C, respectively, hence evapotranspiration will increase which means lesser recharge rate as percentage to rainfall.

4. Results

4.1. Recharge estimation (Objective 1)

4.1.1. Method 1: Rainfall – recharge relationship (Objective 1a)

Using the empirical rainfall-recharge trends across the Pacific reported by UNESCO (1991), the estimated range of recharge for Tongatapu is 25%-30% of rainfall. With an average annual rainfall of 1653 mm, the range of recharge for Tongatapu for the study interval therefore is 413 mm - 496 mm.

4.1.2. Method 2: Water balance using WATBAL (Objective 1b)

Evapotranspiration calculation and limitations

As explained in Section 3.1.2 '*Mean monthly potential evaporation*', it was necessary to undertake a comparison of the evapotranspiration between the values calculated in this study and those calculated by Thompson (1986) and adopted by previous investigations of Tonga's water balance's value. Figure 19 shows that the monthly evapotranspiration values calculated in this study are higher than Thompson's values, in most months by more than 25%, ranging from 9% in April to 48% in June.

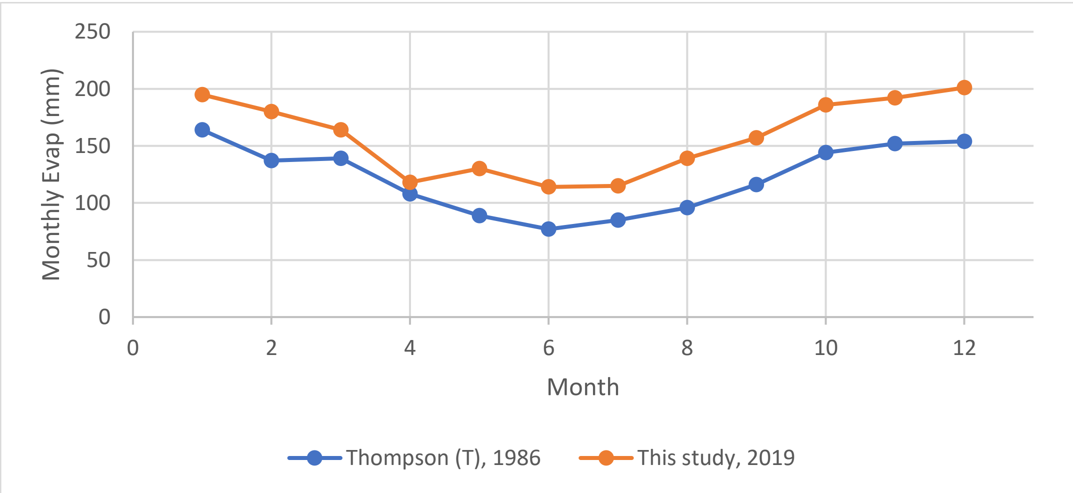

Figure 19: Differences between Thompson's monthly evapotranspiration values and those calculated in this study.

These differences could be due to differences between the underlying climate patterns of the two intervals: 1980-2018 for this study and presumed (as not specified) to be 1983-1986 for

Thompson's study. However, comparison of the variables [temperature (°C), relative humidity (%), wind speed (m/s) and sunshine hours (hr)] used for the calculation of evapotranspiration for this study and those assumed to be used by Thompson (1986) shows no significant differences between them (Figure 19-22).

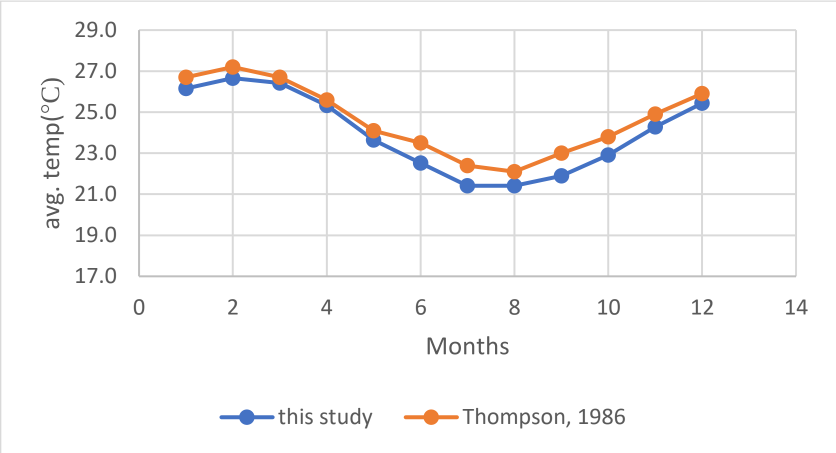

Figure 20: Comparison of monthly temperature means between the interval used by Thompson (1986) to calculate Evapotranspiration (1983-1986) and those used in this study (1980-2018).

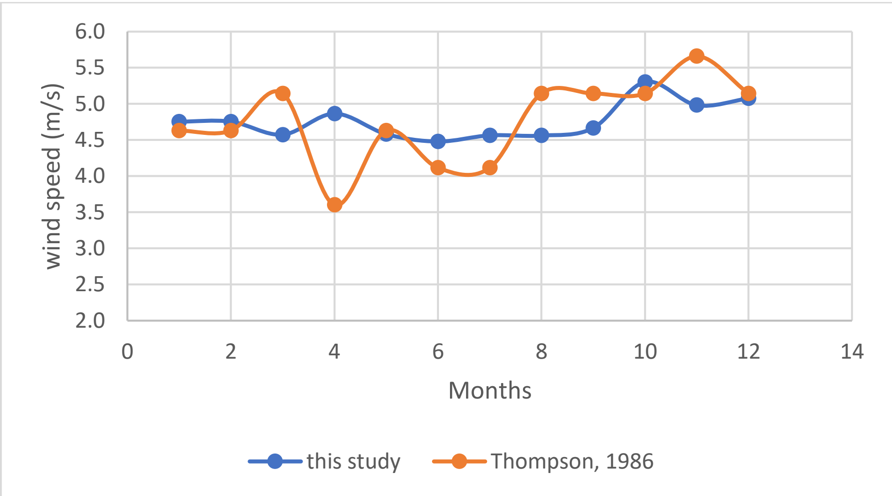

Figure 21: Comparison of monthly wind speed means Thompson (1986) to calculate Evapotranspiration (1983-1986) and those used in this study (1980-2018).

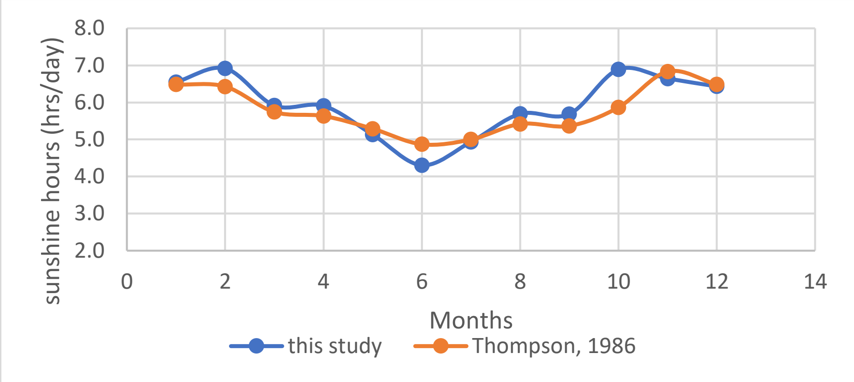

Figure 22: Comparison of monthly sunshine hour means.

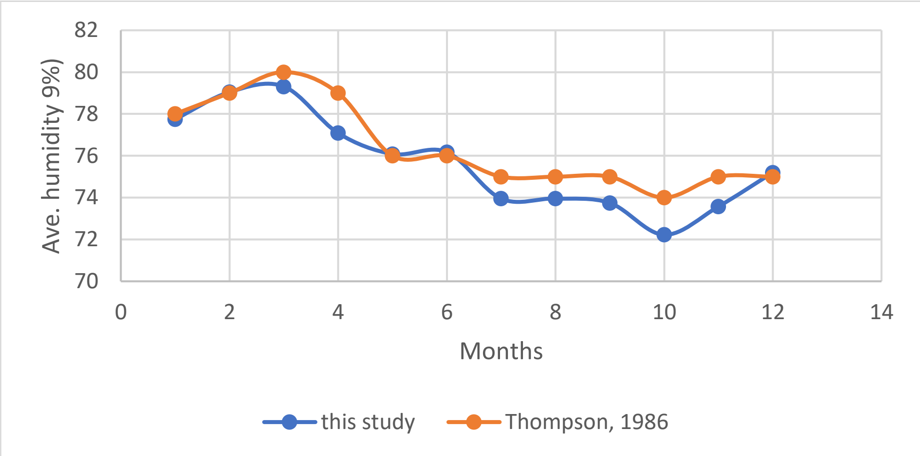

Figure 23: Comparison of monthly humidity means.

The above comparisons show that the differences in derived evapotranspiration cannot be explained by the different intervals of study. The differences remain unexplained, although as alluded to earlier, it is likely due to weighting of parameters in the Penman equation, which were not specified by Thompson (1986). A comparison of the two recharges is presented in Figure 24. It shows that using the evapotranspiration calculated in this study, the recharge values decreased by 8% from the recharge values estimated using the Thompson's values.

Despite the differences in evapotranspiration, this study proceeded with Thompson's evapotranspiration values to run the recharge estimation to the groundwater of Tongatapu using the WATBAL computing system as described above at Section 3.1.2 '*Mean monthly potential evaporation*'. This allowed for a direct comparison between WATBAL recharge estimations using monthly (i.e., White et al. (2009)) and daily resolution rainfall inputs. Nevertheless, it is important to point out that as the evapotranspiration rates for 1980-2018 calculated in this study are considerably higher than those applied to WATBAL, the actual recharge estimations are likely to be lower than described below.

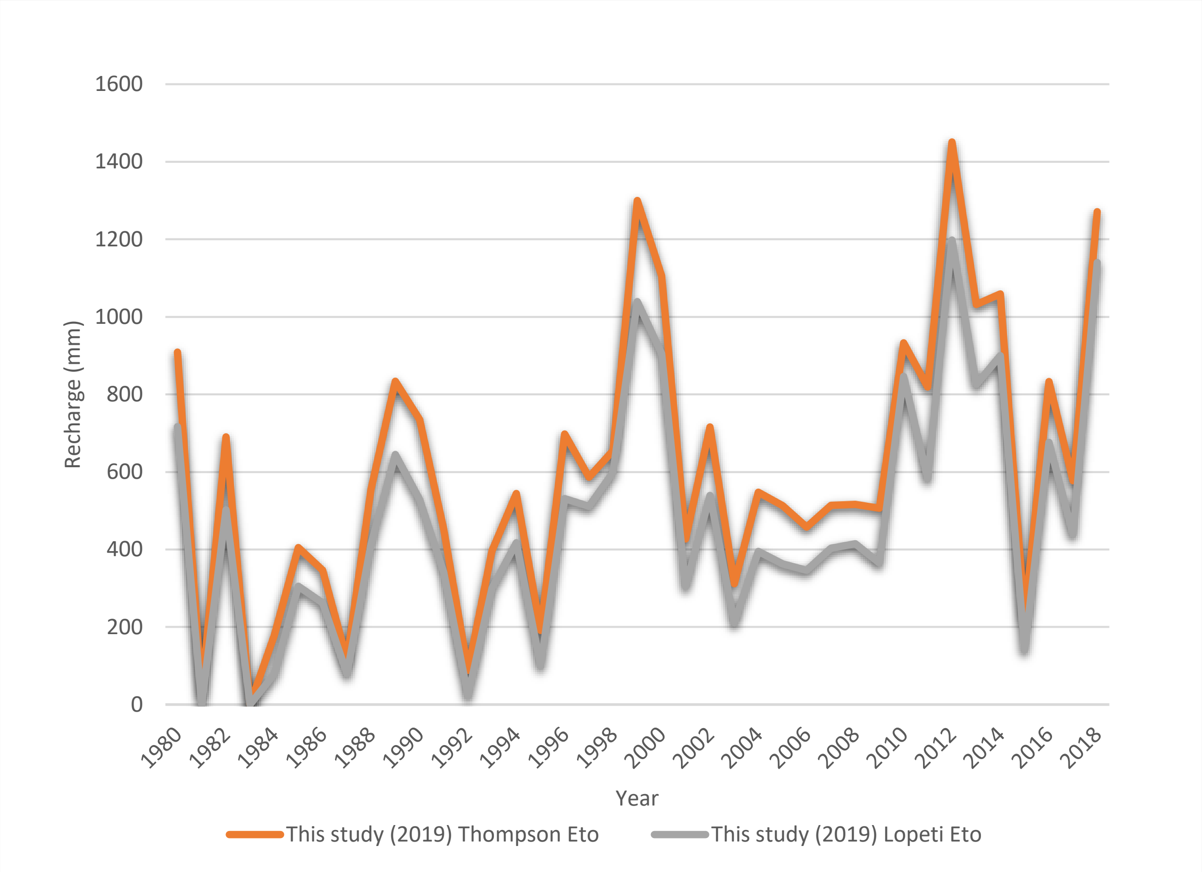

Figure 24: Comparison of daily recharge estimated using evapotransipiration values determined by Thompson (1986) and in this study.

Rainfall-recharge relationship using WATBAL

Using the monthly evapotranspiration values estimated by Thompson (1986), the WATBAL model was applied to the Tongatapu daily meteorological data for 1980-2018 (Figure 25) to determine recharge values for that interval. Maximum evapotranspiration occurs during the Summer season (October-March), when rainfall is highest, however, from October to December rainfall is slightly below evapotranspiration on average.

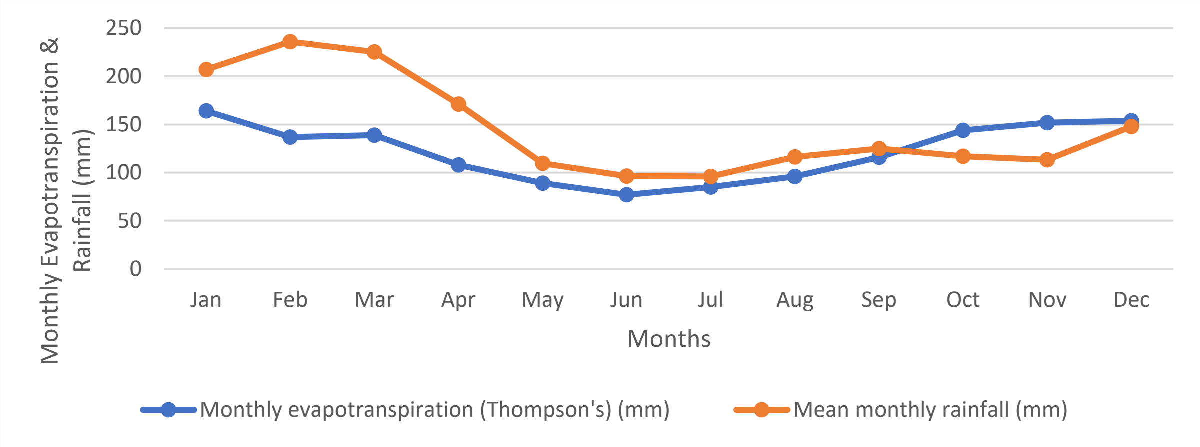

Figure 25: Average monthly rainfall (1980-2019) (red) vs the Thompson's evapotranspiration values (blue).

Turning to comparison between model simulations using daily and monthly rainfall resolution, Figure 24 shows that estimated groundwater recharge was on average 8% higher with a range of variability between 4% to 13%, when based on daily rainfall input (Figure 26, red) than when using monthly rainfall input (Figure 26, *black*). The re-run recharge from Figure 26 was the duplication of the White et al., 2009 recharge investigation using the monthly resolution approach for the period 1980-2018.

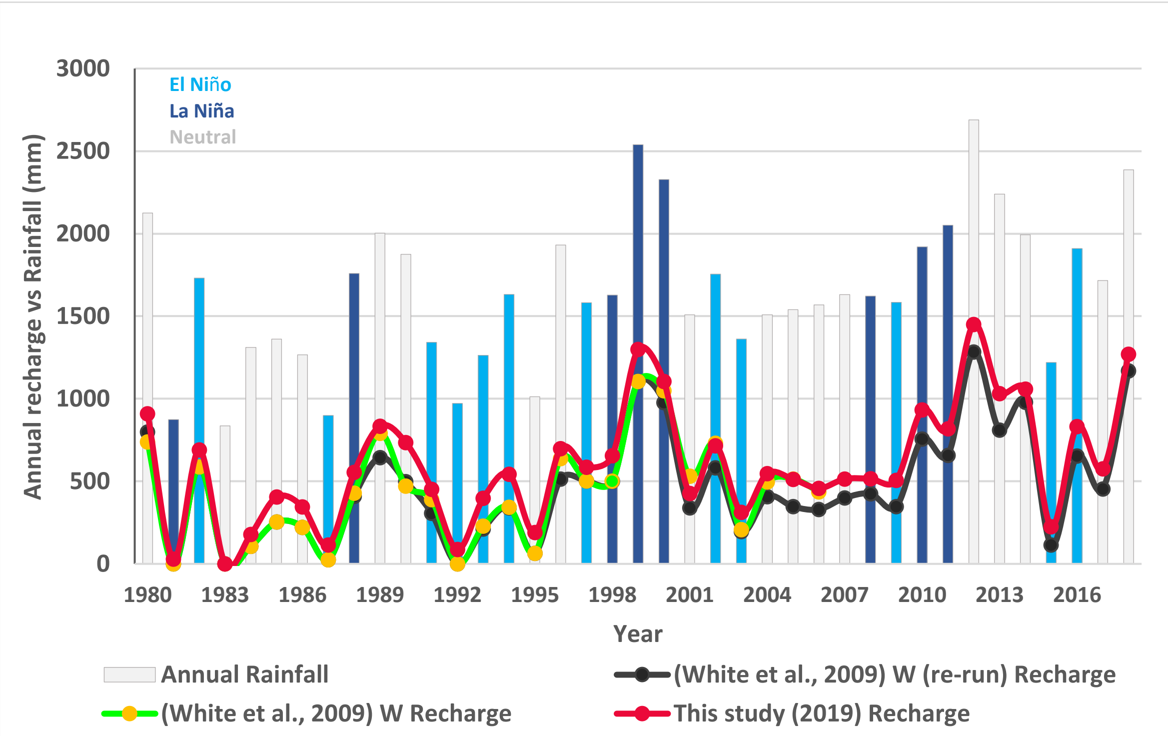

Figure 26: Annual rainfall and recharge volume for Tongatapu from 1980-2018. Recharge values of White et al. (2009) were determined from monthly rainfall totals for the interval (1945-2007). The re-run (black curve) was determined in this study by applying the same methodology of White et al (2009) for the interval (1980-2018). This study (red curve) is the trend of recharge using daily rainfall as input for WATBAL. All trends used Thompson's evapotranspiration values.

These results also indicate that Tongatapu received an annual average recharge of 36% of the average annual rainfall (1653 mm) from 1980-2018 (Figure 26)(recharge file from WATBAL on Annex A), above the range that has previously reported by UNESCO (1991; Figure 17) for Tongatapu. Prolonged El Niño years is a threat to groundwater where recharge could be extremely cut off and hence fresh groundwater may become scarce in prone areas near coast.

A strong relationship between annual recharge and rainfall is also evident from Figure 26 as is the role of ENSO in inter-annual variability in recharge. For example, there was near-zero recharge in the strong El Niño years of 1981 and 1983 and peak recharge in La Niña years 1989, 1999, 2000 and 2012 (Figure 26). These results demonstrate that both rainfall and recharge are highly sensitive to ENSO. Figure 27 shows that the highest recharge as percentage of rainfall occurred in 2012 with the highest rainfall over the 39-year period of 2,690 mm with a recharge-rainfall ratio of 54%. The lowest recharge-rainfall ratio (0%) occurred in 1983 with an annual rainfall of 836 mm and 0 mm recharge.

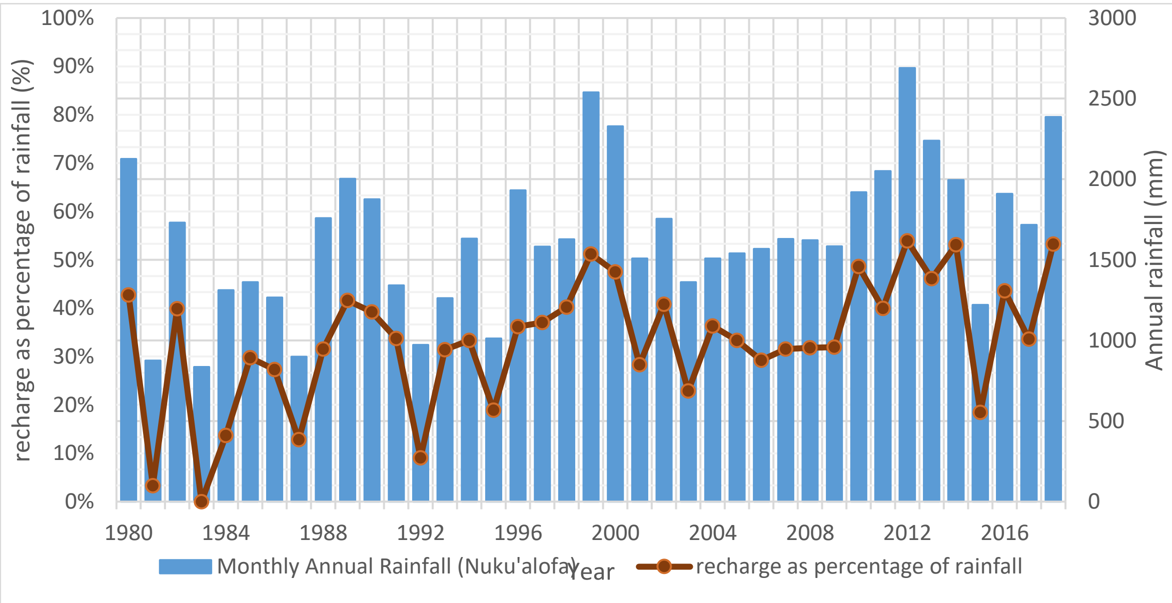

Figure 27: Annual recharge as percentage of annual rainfall simulated by the Watbal model.

Similarly, to these inter-annual patterns, a strong relationship between recharge and precipitation is evident at the monthly scale. Figure 28 & Figure 29 shows that highest recharge volumes occur in the months of February and March, at the end of the Summer/wet season. The lowest recharge volumes occur during the months of October and November, at the end of the Winter/dry season). As shown by Figure *23*, evapotranspiration is higher than the average monthly rainfall (1980-2018) which explains why October-December receives relatively less recharge than August and September (Figure 28) meaning that August and September are important recharge months due to seasonal variability in the amount of evapotranspiration occurring.

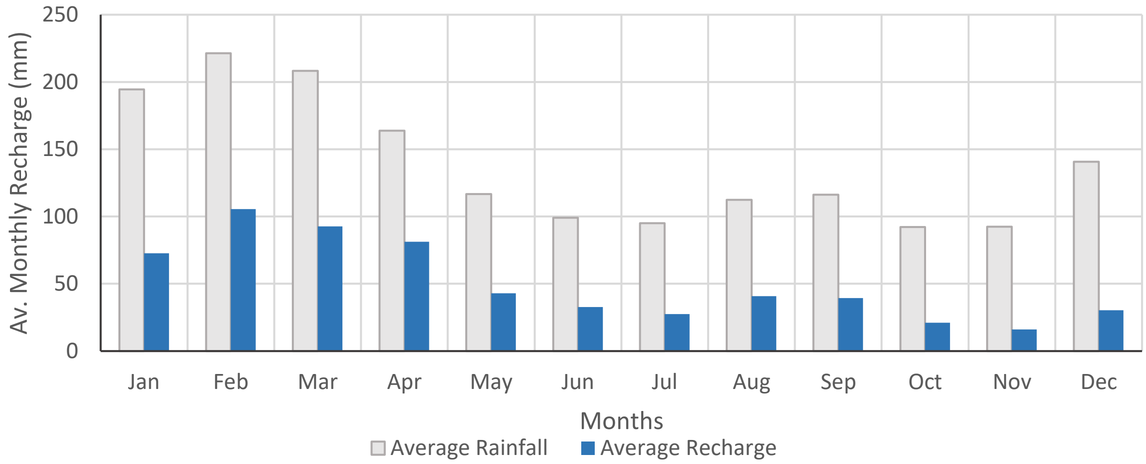

Figure 28: Monthly recharge averages vs rainfall averages for Tongatapu, 1980-2018

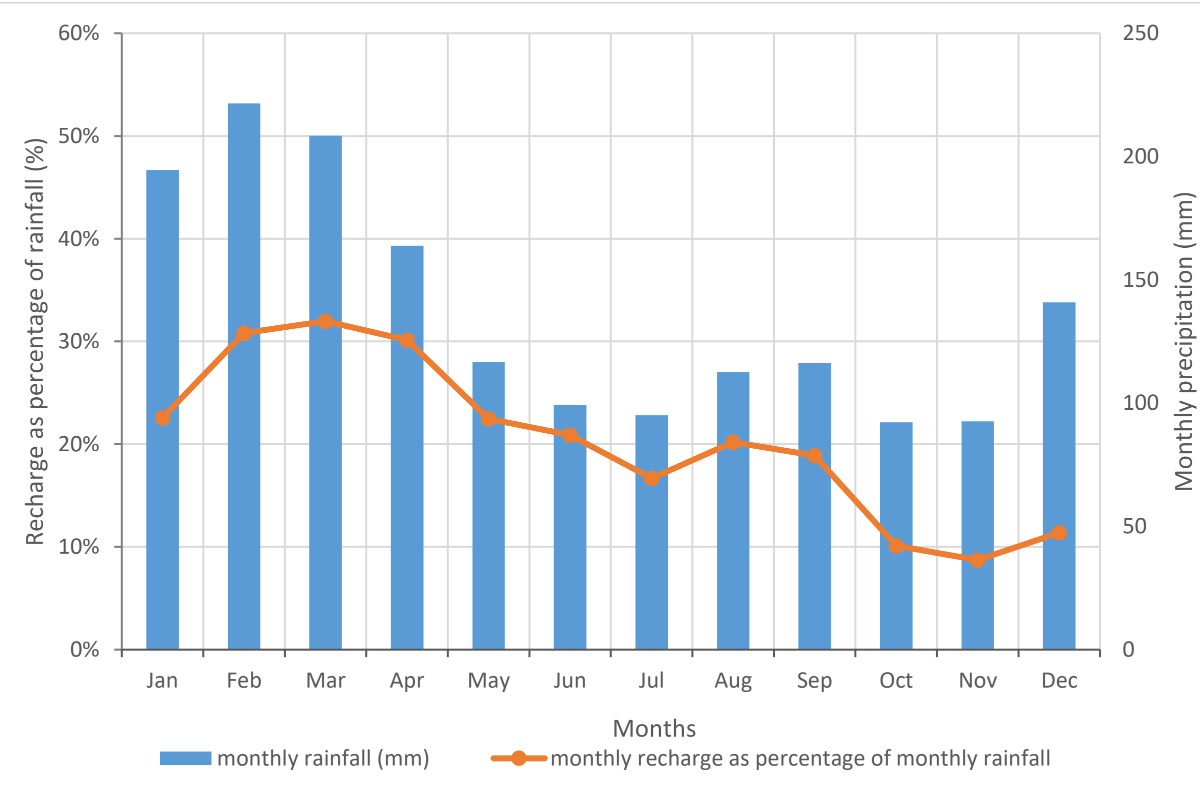

Figure 29: Monthly recharge as percentage of monthly rainfall, 1980-2018.

Figure 29, showing the monthly recharge rate as a percentage of rainfall, also illustrates the marked seasonality of recharge on Tongatapu. The recharge rate peaks in the interval February-March and then declines throughout most of the remainder of the annual cycle, apart from a minor rise in August and September. The important role of temperature is evident in Figure 29 as during the cooler months of August and September a larger percentage of recharge occurs than during the warmer month of December, despite higher rainfall in December.

4.2. Flow rate measurement (Objective 2)

There are altogether 180 pumps recorded in the WRS database for all Tongatapu, although only 103 of these pumps are operating. These pumps operate at community wells; the number of privately-owned wells is unknown. Water extraction rates determined from the currently operating pumps are presented in Table 3. For the rural areas, 61 pumps were operating at an average rate of 2.2 L/s each extracting a total of 12 ML/day of water from the aquifer while at the urban (Mataki'eua-Tongamai wellfield), 42 pumps were pumping water from the wells at an average rate of 4.5 L/s each extracting 16 ML/day of water from the aquifer. The average pumping rate for the whole island of Tongatapu is estimated at 28 ML/day. It is assumed that all pumps at Tongatapu are pumping water continuously 24 hrs a day.

Water Supply	No. of pumps	No. pumps operating	Average pumping rate		Max pumping rate	
			(L/s)	(ML/day);	(L/s)	(ML/day)
Urban (Mataki'eua-Tongamai Wellfield)	52	42	190	16	233	20
Rural	128	61	137	12	326	28
Total	180	103	327	28	559	48

Table 3: Pumping rate for urban and rural wells.

Historically, the number of pumps and hence the pumping rate at the Tongamai-Mataki'eua wellfield has increased progressively. The rate of increase has accelerated recently, from 8 ML/day in 2007 to 16 ML/day by 2019, with an additional 10 pumps installed in the wellfield during this period. If this rate of increase continues, by 2099, a total of ~65 ML/day will be extracted from the urban wellfield alone.

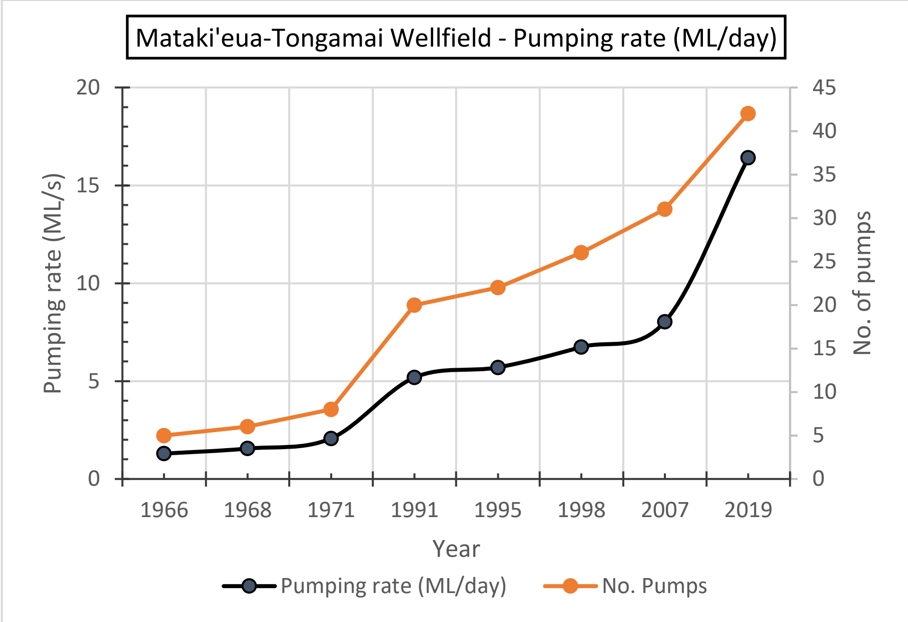

Figure 30: Current extraction rate at the Mataki'eua-Tongamai Wellfield.

4.3. Rainfall and recharge projection (Objective 3)

Rainfall Projections

The CMIP5 average annual rainfall projections for 2070-2099 are 1473 mm for RCP 4.5 and 1681 mm for RCP 8.5 (Figure 31, large middle circle). These projection averages are 7% lower (RCP4.5) and 6% higher (RCP8.5) than the observed average (1582) for 1975-2004 (Figure 31). The range of wettest to driest years (Figure 29, smaller high and low circles) shows a slight decrease for RCP4.5 due to the lower rainfall values during the wettest years, while the range is expected to significantly increase for RCP8.5 with an increase in maximum possible rainfall but the driest years remain near the same as current levels. Therefore, though annual rainfall is expected to increase for RCP8.5, year-to-year variability is also likely to increase.

Figure 32 shows the monthly average rainfall projections for 2070-2099 compared with the observed monthly averages for 1975-2004. This window was used simply because the CMIP5 “historical” climate model simulations end in 2004. The historical simulations, which are forced by observationally-constrained, time-varying greenhouse gases (as well as all external forcings, e.g., volcanic eruptions) provide the best base-period of modern climate to compare future projections, and the aim is to compare future projections (e.g., "RCP4.5" and "RCP8.5") of 30-year climatological rainfall at the end of this century with the most recent 30-year period in the historical simulations. Therefore we are limited in using 1975-2004 as the most recent

30-year climatology period to compare future projections Both future scenarios show a decrease in rainfall during August and September. Outside of these months (Figure 32), the RCP4.5 scenario results in lower monthly rainfall totals while RCP8.5 results in higher monthly rainfall totals.

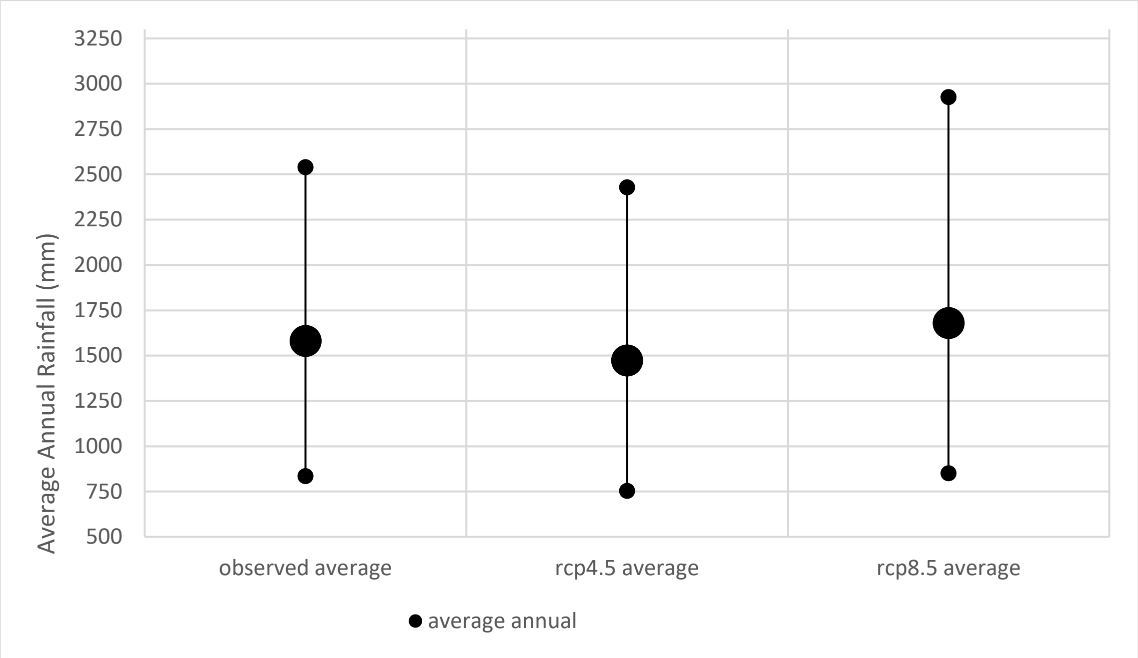

Figure 31: Observed average annual rainfall (1975-2004) vs the RCP projections for 2070-2099 with the maximum and minimum for each time period.

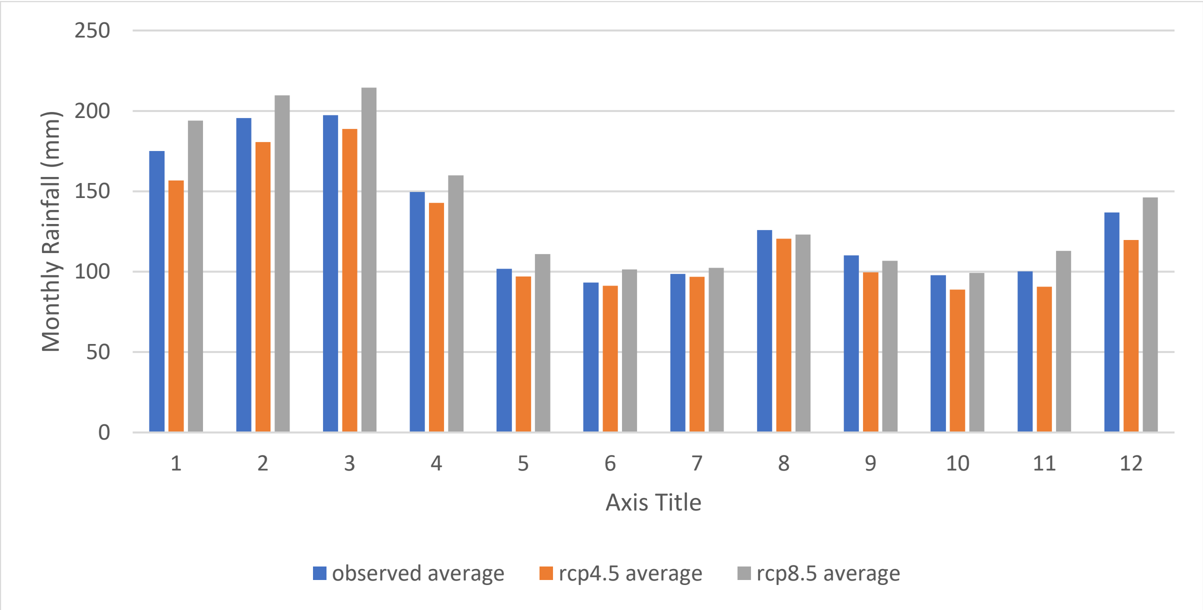

Figure 32: The monthly averages between the observed average (1975-2004) and the future RCP scenarios for 2070-2099.

Recharge Projections

Watbal was applied to the CMIP climate projections using 4 scenarios for evapotranspiration that were considered to reasonably cover the range of uncertainty surrounding the future applicability of Thompson's (1986) monthly values (see 3.4.2).

This range of uncertainty for RCP 4.5 (2070-2099) is depicted in Figure 33 which shows the estimated recharge volume for each of the 4 scenarios. The average recharge rate (volume of recharge as a percentage of rainfall) across the 4 scenarios is 23%. For the higher temperature – higher evapotranspiration scenario (Figure 33, green-Thompson's evapotranspiration increased by 20%), recharge rate falls consistently below 19% of the annual rainfall. For the (unlikely) lower temperature-lower evapotranspiration scenario (Figure 33, yellow - Thompson's evapotranspiration decreased by 20%), the recharge rate increases to an average of ~28% of the annual rainfall. The overall range of recharge as a percentage of rainfall for the RCP 4.5 for 2070 is between 19% and 28% both of which are less than the current recharge-rainfall rate of 36%.

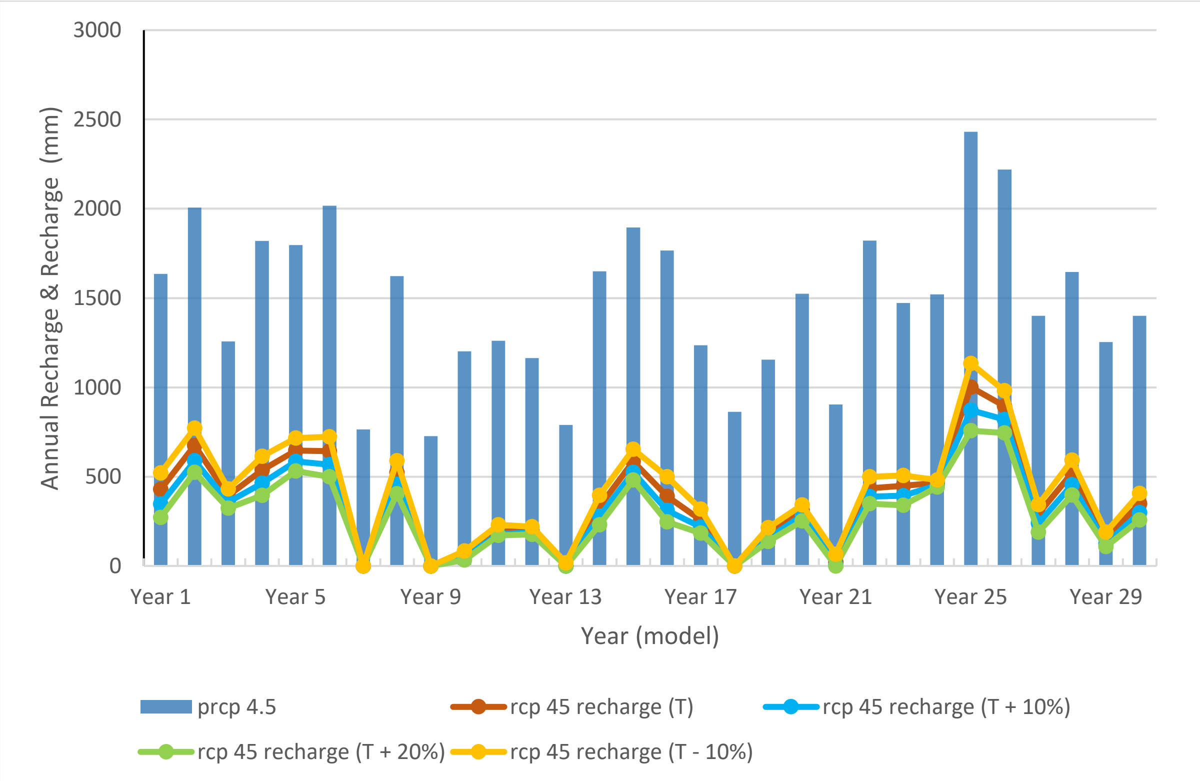

Figure 33: RCP 4.5 recharge estimates. Year 1 to Year 30 represent 2070-2099 for the future projections.

The average recharge ratio for each of the 4 evapotranspiration scenarios for RCP 8.5 was estimated at 27% of the average annual rainfall of 1681 mm (Figure 34). In a scenario where the evapotranspiration value (Thompson's) increases by 20%, recharge rate falls to a 22% low. On the other hand, where Thompson's evapotranspiration decreases by 10%, recharge reaches 33% of rainfall.

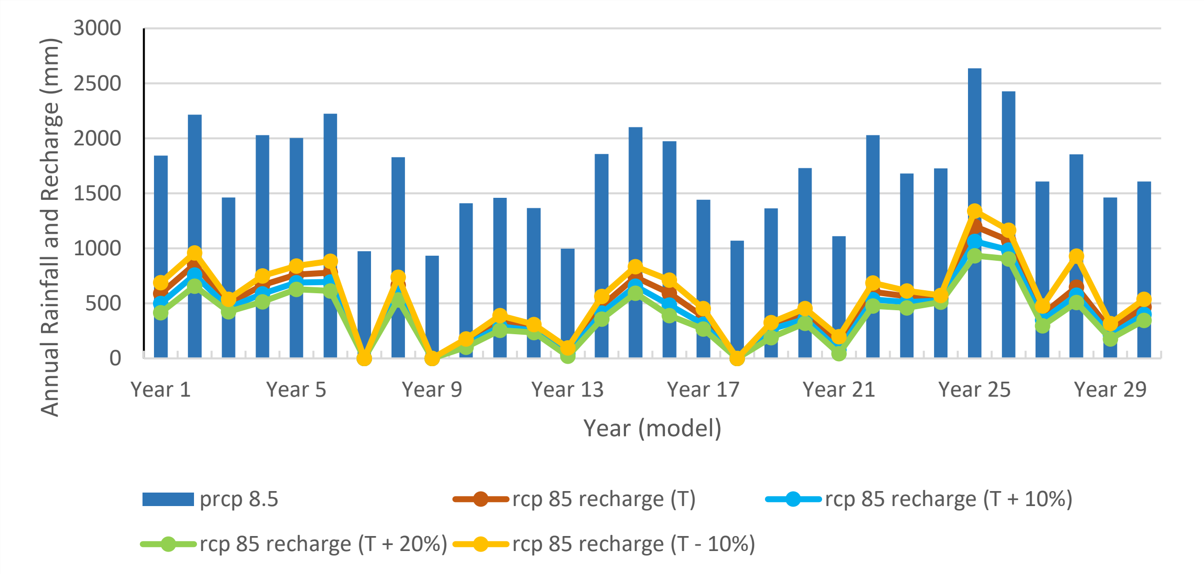

Figure 34: RCP 8.5 recharge estimates for RCP 4.5. Year 1 to Year 30 represents 2070-2099 in the future projections.

Recharge rates for both future RCP scenarios with all the applied evapotranspiration scenarios, are below the current recharge to rainfall rate. The implications of these findings numbers are considered in the discussion chapter.

Climate variable changes

Under RCP 4.5 & 8.5, temperature increases by 1.1 °C and 2.4 °C (Table 4) and there are also slight increases relative humidity and wind speed. As discussed previously, rainfall is expected to decrease by 109.8 mm under the RCP 4.5 and increase by 98.5 mm under RCP 8.5.

	CHANGE	
CLIMATE VARIABLES	RCP4.5	RCP8.5
TEMPERATURE (°C)	1.10	2.42
RELATIVE HUMIDITY (%)	0.15	0.10
WIND SPEED (M/S)	0.3	1.1
PRCP (MM)	-109.8	98.5

Table 4: Annual-average changes in temperature (°C), wind speed (m/s), relative humidity (%), and total precipitation (mm per year) from the modelled climatology of 1975-2004 versus 2070-2099.

4.4. Sustainable yield estimation

Table 5 describes the various scenarios of recharge volume estimated for 2070-2099 that are subsequently depicted in Table 6 along with other derived parameters of interest to this study.

PARAMETERS	DESCRIPTION
1980-2018 + T	Thompson’s evapotranspiration values applied to the rainfall for the current and future projections.
2070-2099 + [T+10%]	Thompson’s evapotranspiration values increased by 10%, applied to the 2070-2099 projection.
2070-2099 + [T-10%]	Thompson’s evapotranspiration values decreased by 10%, applied to the 2070-2099 projection.
recharge value (mm/yr)	Recharge estimation from WATBAL
effective recharge area (km^2)	Area within the Tongatapu landmass where recharge to groundwater is deemed fresh and less saline (500 m from the coast and 100 m from the lagoon - 70% of the total land area). This area is assumed to remain constant for the projected interval.
recharge volume (ML/yr)	Effective recharge area (km^2) * recharge value (km) [MegaLitre/yr]
recharge volume (ML/day)	Recharge volume (ML/yr)/365 days
average recharge rate (%)	Recharge to rainfall percentage
sustainable value (mm/yr)	30% of recharge rate

Table 5: Description table of the parameters shown in Table 6.

The current sustainable yield is projected to decrease in the year 2070-2099 for both the 4.5 and 8.4 RCP scenarios with varying evapotranspiration. This decrease in sustainable yield is independent of the effective recharge zone and how it would change by the end of the century. Such changes are unknown but are likely to result in a reduced effective recharge zone due to saline intrusion accompanying projected sea level rise. Under all scenarios of evapotranspiration, the future projections for RCP 4.5 and 8.5 show a lower sustainable volume than the current sustainable volume.

Parameters	1980-2018 + T	2070-2099 + T		2070-2099 + [T + 10%]		2070-2099 + [T + 20%]		2070-2099 + [T - 10%]	
RCP		4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
average precipitation (mm)	1653	1473	1681	1473	1681	1473	1681	1473	1681
recharge value (mm/yr)	595	364	480	320	424	282	373	418	552
effective recharge area (km2)	180	180	180	180	180	180	180	180	180
recharge value (km/yr)	0.000595	0.00036	0.00048	0.00032	0.000424	0.000282	0.000373	0.000418	0.000552
recharge volume (ML/yr)	107,100	65,520	86,400	57,600	76,320	50,760	67,140	75,240	99,360
average recharge rate	36%	25%	29%	22%	25%	19%	22%	28%	33%
recharge volume (ML/day)	293	180	237	158	209	139	184	206	272
sustainable value (mm/yr)	179	109	144	96	127	85	112	125	166
sustainable volume (ML/day)	88	54	71	47	63	42	55	62	82
current extraction rate (ML/day)	28	28	28	28	28	28	28	28	28
difference (sust. yield – current extrct. rate)	60	26	43	19	35	14	27	34	54

Table 6: Calculation of sustainable yield from the recharge for 1980-2018 with Thompson's ETo (T), 2070-2099 with T, and T increased 10%, T increased 20% and T decreased by 10% for the 2 RCP scenarios.

5. Discussion

5.1. Recharge estimation (Objective 1)

5.1.1. Method 2: Water balance using WATBAL (Objective 1b)

Evapotranspiration calculation and limitations

The monthly evapotranspiration that was formulated using the Penman equation initially for this project (1980-2018) was, on average, 30% higher (Figure 19) than Thompson's (1983-1986; assumed) values, despite the similarity between the two periods of the various climate variables used to calculate evapotranspiration (and assumed to be used by Thompson) (Figure 19-22). The marked difference between evapotranspiration values calculated (it is assumed) by the same process with similar input variables remains unknown but may be due to different albeit unspecified weighing factors used by Thompson (1986) for the different climate variables. Clearly future water balance studies for Tongatapu should be based on evapotranspiration values determined using a specified version of the Penman equation applied to climate variables measured for the period of interest. For this study, however, Thompson's evapotranspiration values were applied, to allow for the direct comparison between recharge estimation at daily (this study) and monthly (White et al., 2009) resolutions

Monthly vs daily simulation of recharge

An important motivation for this study was to evaluate whether applying daily rainfall input data to Watbal would improve upon the estimates of recharge for Tongatapu that were previously made using monthly rainfall input. This study has shown that after comparing the monthly and daily produced recharge (Figure 26), the daily resolution model data yielded estimated recharge values that where ~8% higher than those of the monthly processed recharge resolution model with a variability between 0% and 15% for the year 1980-2018 (Figure 26). Additionally, the overall recharge rate as percentage of rainfall for this study was 36% compared to 28% derived by White et al. (2009).

It is important to evaluate this result as it suggests that more freshwater is available to the people of Tongatapu than was previously thought. The reason for the differences between the monthly simulation and the daily simulations arise from their different thresholds for Interception Storage capacity and Soil Moisture Zone capacity (Table 7), both of which must be exceeded for aquifer recharge to take place. As a consequence, the daily simulation will initiate aquifer recharge after 153 mm of rainfall , whereas, the monthly cumulative rainfall must exceed 240 mm for Watbal to initiate aquifer recharge.is that with daily simulation, there is more chance that the rainfall can fill the SMZ on a daily basis (3mm IS) and become recharge than there is when monthly rainfall data and larger SMZ (90mm IS) is used. This scenario is not unusual for Tonga's subtropical oceanic setting where rainfall variability is highly seasonal and amplified by the ENSO cycle.

For example, as shown in Table 7, in the month of April 1994, 166 mm of rain fell on the 19th, when the interception store (IS) and SMZ were completely dry. With the daily model, the IS (3 mm) was filled and the remaining 163 mm passed to the SMZ. Once Field capacity (150 mm) was reached, recharge (GWR) commenced, giving a surplus of ~13 mm. With the monthly model, with IS threshold = 90 mm, there was no recharge. So, for that month, the daily model gave ~7% recharge, and the monthly model 0%. This example shows not only that the daily resolution model is a more accurate simulation of GWR. This work suggests that recharge has been underestimated in the past for Tongatapu by ~8%.

	Daily Simulation	Monthly Simulation
Rainfall (mm)	166	166
IS threshold (mm)	3	90
SMZ threshold (mm)	150	150
GWR (mm)	13	0

Table 7: Comparison of recharge estimation for April 1994 when the entire monthly rainfall fell in one event.

Rainfall and recharge relationship

A strong relationship between annual recharge and annual rainfall is evident in Figure 26. Variability in recharge shows a close correspondence to the amount of rain that falls throughout the year. Because ENSO cycles play a major role in the amount of rainfall that falls in the Tongatapu region, they are also an important factor in the amount of recharge that infiltrates to the groundwater. Recharge to groundwater is excessive during the La Niña years and lesser during the El Niño years. Strong El Niño years are those years with recharge below 20% of the precipitation (1981, 1983 & 1992) (Figure 26).

Short term predictions of the ENSO phase from the Climate Prediction Centre/CNEP could help feed the prediction of recharge for Tongatapu using the consolidated SST Outlook (NINO 3.4) with major emphasis on the outlook probability (NOAA, 2020).

Seasonal recharge patterns and the importance of Evapotranspiration

More than 70% of annual rainfall occurs in the Summer season (November-April). Figure 29 shows that recharge is more than 30% of the monthly rainfall during the months of February, March and April, but falls below 15% between October, and December. The variability of the monthly ratio is important in determining the degree to which evapotranspiration impacts on monthly recharge. For example, December rainfall is higher than September rainfall, yet December has a lower recharge rate (Figure 29). This can be explained by the drop in temperature during August and September (to 23 ^{o}C, Figure 8) decreasing the amount of evapotranspiration from the surface while in December, temperature averages at 27 ^{o}C.

Thus, an increase in rainfall does not always mean increase in recharge. This evapotranspiration factor is crucial especially in relation to future scenarios where increased temperatures will very likely increase the amount of water loss due to evapotranspiration, and hence decrease recharge rate. This observation further underpins the importance for future water balance studies in Tonga to utilise evapotranspiration inputs derived from contemporaneous climate data.

Recharge and freshwater thickness relationship

Tongatapu aquifer has an average of 10 m of freshwater thickness for the whole island. Freshwater thickness is higher in the east side of the island then on the west side due to the thinner soil cover at the eastern district (Figure 35). The response of increased recharge during the La Niña years is clearly evident in the freshwater thickness of the groundwater as measured from the SMBs around Tongatapu. For the La Niña years 1998, 1999 and 2000, the freshwater thickness gradually increased at all SMBs from SMB 1 to SMB 7 by 2 m of freshwater and then then started decreasing by 2001 (Figure 36). For the La Niña years of 2010 and 2011 and 2012; SMB 2, SMB 3, SMB 4 and SMB 5 all show increased freshwater thickness by an average of ~3 m. There is a gap in the record of freshwater thickness from 2002 until 2010 and this was due to a halt in the monitoring of the SMBs.

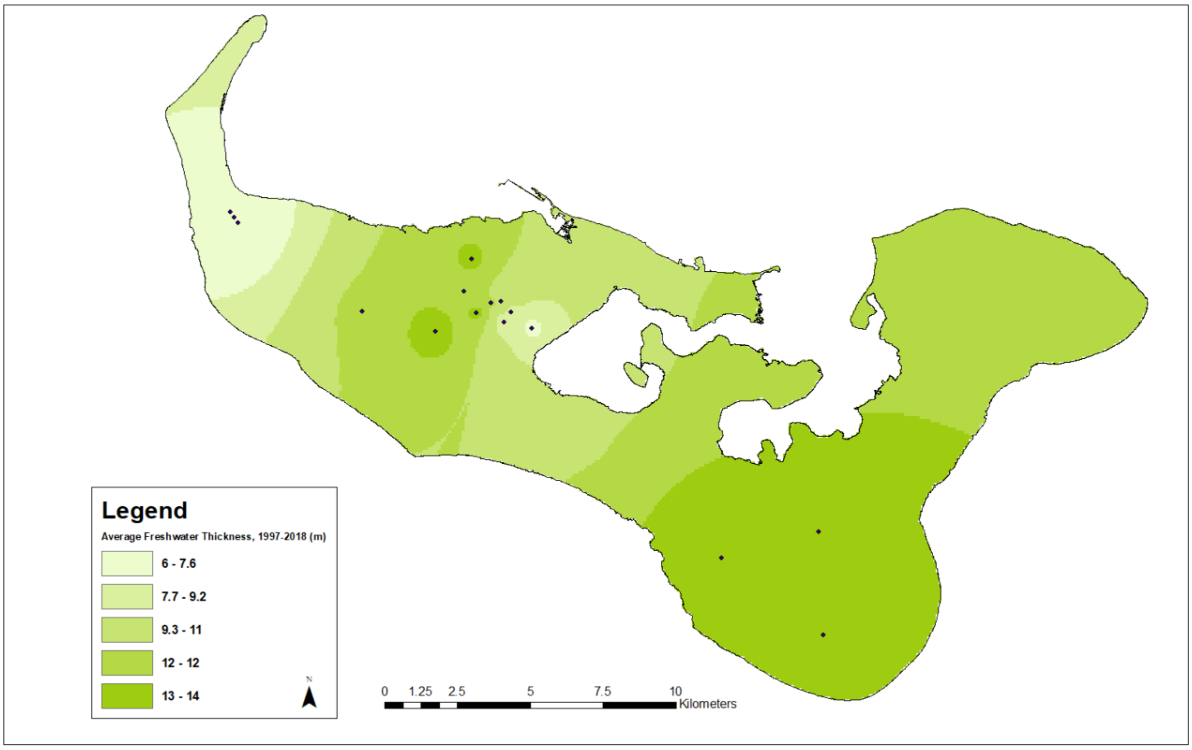

Figure 35: Average freshwater thickness for Tongatapu (1997-2018((data retrieved fromt the SMBs).

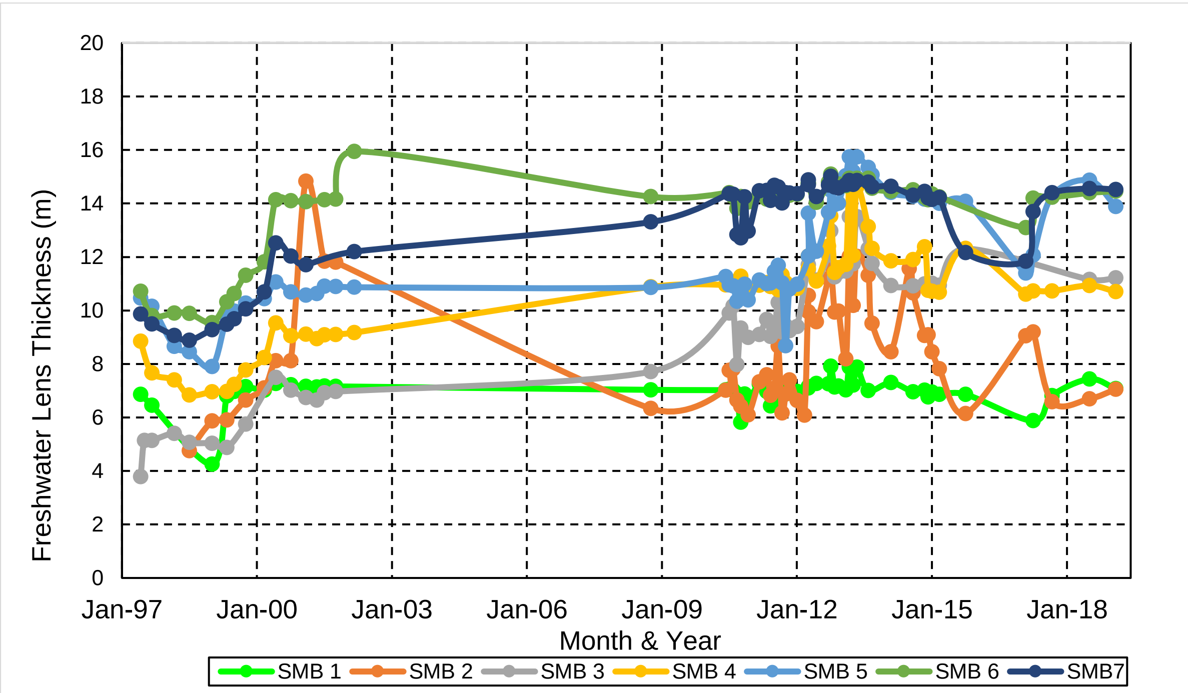

Figure 36: Freshwater Lens Thickness Variations at SMB's 1-7, June 1997 - Feb 2019. Freshwater conductivity range (100-2500 µS/cm).

5.2. Extraction rate & sustainable yield estimation

Compared to a sustainable yield of 52 ML/day, estimated by White et al. (2009), this study estimated a sustainable yield of 88 ML/day for Tongatapu, arising from a higher recharge rate for the period 1980-2018 (Table 6). This current sustainable yield is well above the current extraction rate (28 ML/day). Out of the 180 community pumps existing, 103 pumps were operating with an average pumping rate of 3.40 L/s, extracted 28 million litres of water every day from the Tongatapu groundwater aquifer. If the 77 currently non-operational pumps are factored in at a constant rate of 3.40 L/s, the overall extraction rate for Tongatapu would increase by 20 ML/day to 48 ML/day. Given that the wells measured for this study consists only of community/public wells, while the number of private wells is unknown, it is likely that the rate of extraction could be higher than the current estimated rate.

These calculations suggest that an additional 143 pumps (i.e. 326 in total), pumping continuously a rate of 3.40 L/s could be accommodated by the 180 km^2 effective recharge zone before the rate becomes unsustainable. With 326 pumps operating at current rates, a volume of 5,000 L/ha/day could be extracted safely without affecting the groundwater aquifer. To minimize upconing of saltier sea water from beneath the freshwater, the pumps should be at a minimum 0.5 km to 1 km spacing of each other. The effective recharge area for Tongatapu is vulnerable to enormous decline due to impending sea level rise.

The current recharge rate (36%) of annual mean-rainfall is the highest recharge rate over the two RCP scenarios for the future projection of recharge rates. Under RCP 4.5 with a decrease of annual mean-rainfall by 109 m by 2070, recharge rate averaged at 23% for the various evapotranspiration scenarios. Under RCP 8.5, the recharge rate averaged at 27% of the annual mean-rainfall.

The recent abrupt increase in the pumping rate from the Tongamai-Mataki’eua well field is concerning given that if this rate continues, by 2099 a total of 60 ML/day will be extracted from the urban wellfield. With the future projection of recharge (Table 6), this rate plus the extraction rate from the rural villages would exceed the sustainable yield for both RCP 4.5 and 8.5. The major threat to the urban water supply is the upconing of sea water due to excessive pumping while there is a 50% loss for unaccounted water due primarily to leakage.

5.3. Climate and recharge projections

5.3.1. Rainfall and recharge projections for 2070-2099

Although the future scenarios projected a higher average annual rainfall for Tongatapu under RCP 8.5, the recharge values estimated were lower than the current sustainable yield which is 30% of the recharge rate to rainfall (Table 6). This is attributed to the projected change in seasonality of rainfall and that is

Table 6 also shows that the sustainable yields for the future scenarios are 50% lower than the current sustainable yield but nevertheless remain sustainable under current extraction rates and assuming no change to the effective recharge area. However, with the current rate of extraction increasing progressively (Table 3) along with significant leakages in water supply, the future for the groundwater resources for Tongatapu is potentially not secure. This is concerning given that demand for water is likely to increase from agriculture, tourism, population growth and infrastructure as has been the case in the past decade.

An additional threat is posed by the prospect of future sea level rise which is very likely to reduce the effective recharge area (currently 180 km^2) due to saline intrusion. It is projected that for the period 2081-2100, global mean sea level is likely (medium confident) to be 0.36-0.71 m for RCP 4.5 and 0.52-0.98 m for RCP 8.5 (IPCC, 2018). A 1 m rise in sea level is disastrous for the island of Tongatapu which has an average elevation of 3 m above mean sea level.

The tiny population of Tonga has little influence on the future climate of the planet, although, as this study has shown, they are likely to suffer severe consequences from climate change. Nevertheless, there are actions that can be taken to mitigate these consequences for Tonga’s water supply. Such factors include controlling the volume of water extracted from the water lenses by controlling pumping rates and the number of pumps operating, resolving leakages from the reticulation system of both urban and rural areas, applying tight regulations to the commercial usage of groundwater as in bottling treated water and, last but not least, closely monitoring the use of groundwater for irrigation in agriculture and farming.

6. Conclusion

Tongatapu is blessed with reliable rainfall through both dry and wet season. There are natural and anthropogenic that poses potential risk for the resources and its sustainability. The investigation of these risks therefore is crucial for the monitoring and reporting on the security of water for Tongatapu.

The investigations of this study focused on the effects of varying climatic conditions on the sustainable yield of the groundwater. Assessment of the extent of the impact of past, present and future climate change on the groundwater were the primary focus of this research.

6.1. Recharge estimation

In order to estimate the groundwater balance for Tongatapu, hence sustainable yield, groundwater recharge must be estimated. The conclusions regarding recharge are made;

- The empirical relationship between rainfall and recharge yielded a range of 413 mm – 496 mm for the 25-30% of rainfall between 1980-2018.
- The daily resolution approach, from this study, of estimating recharge to groundwater estimated a higher recharge rate than the monthly resolution approach by 8%. That is, this study estimated a 36% annual recharge to groundwater during the period of 1980-2018 with an estimation of 595 mm from an annual average precipitation of 1653 mm while White et al. (2009) estimated a 28% for the same period with an estimation of 470 mm of recharge.
- Rainfall and recharge are sensitive to the ENSO cycles evident by the near-zero recharge in the strong El Niño years of 1981 and 1983 and peak recharge in La Niña years 1989, 1999, 2000 and 2012. Close monitor of groundwater recharge from the ENSO predictions should
- Sensitivity of recharge to the ENSO is also evident in the increase in the freshwater thickness measured at the SMBs where there was a 3 m increase in thickness during the strong La Niña years of 2010 and 2011.
- August and September are important recharge months with lesser rainfall than December. This is enforced by the increased evapotranspiration during the end of the year as the Summer season attract higher temperatures hence more water loss due to evaporation.

6.2. Extraction rate & Sustainable yield estimation

Information for the current extraction for the whole island of Tongatapu was made available by the recent installation of flow meters in all community wells of Tongatapu. Measuring of the volume extracted is essential for estimating how much is being used by human but also for estimating leakage loss and therefore vital for the sustainable management of the resources. The comparison of sustainable yield to extraction rate is crucial for estimating how much more the aquifer can withstand without damaging its sustainability. Here are conclusions from the investigations of the extraction rate in comparison to the sustainable yield for the aquifer;

- An estimate of the sustainable groundwater yield for Tongatapu has been derived assuming a 20% of groundwater recharge of 36% from the 1563 mm annual rainfall for the period 1980-2018. This estimation resulted in a current sustainable yield of 88 ML/day.
- A total extraction rate of 28 ML/day is estimated from the 103 pumps currently operating in Tongatapu where 16 ML/day is extracted from the urban wellfield (Mataki'eua-Tongamai) and 12 ML/day is extracted from the production boreholes of the rural villages.
- The current extraction rate extracts up 27% of the current sustainable yield (88 ML/day), however other implication such as distancing the pumps from each other and reducing the concentration of pumps at a specific lot would be advantageous as to reduce upconing of saltier water.
- Altogether if all the 180 pumps were operating at an average of 3.4 L/s, and additional 20 ML/day will be added to the current extraction rate, increasing it to 48 ML/day for the whole of Tonga.
- It should be noted that the current extraction rate would be higher if the privately-owned production pumps are metered and monitored.

6.3. Climate and recharge projections

- Despite the overall increase in annual precipitation with RCP8.5, there is a slight decrease in annual recharge compared to the current recharge rate, and this is attributed to the reduction in rainfall during August and September which are critical recharge months.

- Under RCP 4.5 with a decrease of annual mean-rainfall by 109 m by 2070, recharge rate averaged at 23% for the various evapotranspiration scenarios. Under RCP 8.5, the recharge rate averaged at 27% of the annual mean-rainfall.
- With the current global sea level rise projection of ~1 m by 2100 under RCP 8.5, it is likely that the effective recharge area for Tongatapu will be reduced as the landmass of the island of Tongatapu shrinks.
- Increase demand for tourism, agriculture and population growth are threats to the sustainability of the groundwater given that recharge rates are lower than the current recharge rate.

6.4. Recommendations

Here are recommendations for each discussion made above for future work.

Recharge estimation

- It is recommended that a more recent calculation of the evapotranspiration for Tongatapu is made in order to be more consistent with the processing of recent rainfall data, and also as an update of the Thompson's evapotranspiration values from 1986, as the climate is shifting in a rapid rate.
- Re-evaluate the extent of the effective recharge area by stimulating the movement of the transition zone between sea water and freshwater in regards of the island's landmass.

Extraction rate measurement

- All public and private groundwater pump in Tongatapu should be metered and licensed by the WRS of the MLNR. This would allow for a more accurate estimation of the extraction volume for the entire island.
- Future investment on the urban water supply should be allocated to fixing the leakage issue where the risk of upconing of saltwater is a threat where 50% of the 14 ML of water extracted each day is unaccounted for. This means, installation of pumps near the wellfield should be put on halt while more resources are allocated to the fixing of the reticulation system distributing water to the urban household.

Rainfall projections

- Better stimulate the extent of the extremes of the SPCZ variability to capture the actual amount of rainfall that is projected to fall in the Tongatapu region.
- Increase the accuracy of projecting seasonal rainfall where the climate variables especially, temperature, controls how much is being made available for recharge to groundwater in term of evapotranspiration.

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Annex A: Groundwater recharge – from Watbal

```
        Water Balance Program to compute Recharge to Groundwater
        using DAILY RAINFALL and AVERAGE MONTHLY EVAPORATION data

        - allows for interception losses
        - assumes linear relation between evapotranspiration
          ratio (EA/ET) and soil moisture content
---------------------------------------------------------------------------
RAINFALL & EVAPORATION DATA USED IN WATER BALANCE
-------------------------------------------------
 Name of Daily Rainfall File :  NFRN8018.TXT
 Title of Rainfall Data      :  Daily Rainfall Data, Nukualofa, Tongatapu,1980-2018

 Name of Monthly Evap File   :  TBUEVA1B.TXT
 Title of Evaporation        :  Average monthly (daily) PENMAN ET(1986)

 No.of Years of Rain Record  :  39
 First Year of Rain Record   :  1980
 Last Year of Rain Record    :  2018
---------------------------------------------------------------------------
INPUT SOIL AND VEGETATION PARAMETERS
------------------------------------

Interception Store Capacity (ISMAX) in mm =                 3
Initial Interception Store Level (IIS) in mm =              3
Soil Moisture Zone Thickness(SMZ) in mm =                 1000
Field Capacity(FC)=                                       .55
Wilting Point(WP)=                                        .4
Initial Soil Moisture Content(ISMC) in mm =               500
Deep Rooted Vegetation(eg Coconut Trees) Ratio(DRVR)=     .3
Ratio of these roots reaching water table(DRWT)=          0
Crop Factor for Deep Rooted Vegetation(CROPFD)=           .8
Crop Factor for Shallow Rooted Vegetation(CROPFS)=        1
Linear Relation of Ea/Et(actual/potential evap) ratio to SMC
---------------------------------------------------------------------------
```

Explanations for the column headings in the listings below:

```
RAIN          monthly rainfall (addition of daily values)
ET            monthly potential evaporation
EI            monthly interception loss
SMC1          soil moisture content at start of month
ES            monthly evaporation from soil moisture store
XCESS         rainfall minus evaporation losses above (EI + ES)
AVSMDEF       average soil moisture deficit for the month
SMC2          soil moisture content at end of month
GWR           gross recharge to freshwater lens
TL            transpiration due to deep-rooted vegetation
EA            sum of all evaporation losses (EI + ES + TL)
NETR          net recharge to freshwater lens (GWR - TL)
```

YEAR 1980

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
139	164	34	500	90	18	42	504	13	0	125	13	+0.10
123	142	29	504	75	18	47	521	1	0	104	1	+0.01
291	139	37	521	79	175	26	529	168	0	115	168	+0.58
267	108	29	529	66	172	15	529	171	0	96	171	+0.64
45	89	22	529	49	-26	35	504	0	0	71	0	+0.00
111	77	21	504	41	49	37	537	16	0	61	16	+0.15
144	85	18	537	58	68	13	543	62	0	76	62	+0.43
161	96	30	543	58	73	10	531	84	0	88	84	+0.53
189	116	39	531	67	83	10	535	79	0	106	79	+0.42
399	144	22	535	94	283	27	526	293	0	116	293	+0.73
114	152	23	526	94	-3	35	523	0	0	117	0	+0.00
143	154	19	523	102	22	30	524	21	0	121	21	+0.14
2126	1466	322		873				909	0	1195	909	+0.43

YEAR 1981

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
60	164	25	524	88	-53	49	472	0	0	113	0	+0.00
98	137	32	472	63	4	56	476	0	0	94	0	+0.00
118	139	37	476	49	32	73	508	0	0	86	0	+0.00
72	108	18	508	61	-7	42	500	0	0	79	0	+0.00
102	89	23	500	45	35	44	535	0	0	67	0	+0.00
94	77	23	535	46	25	16	531	29	0	69	29	+0.31
23	85	15	531	48	-40	40	491	0	0	64	0	+0.00
56	96	25	491	40	-8	61	483	0	0	64	0	+0.00
66	116	11	483	52	3	71	486	0	0	63	0	+0.00
54	144	12	486	63	-22	73	464	0	0	75	0	+0.00
90	152	16	464	53	21	87	485	0	0	69	0	+0.00
40	154	28	485	50	-37	88	448	0	0	78	0	+0.00
874	1461	263		658				29	0	921	29	+0.03

YEAR 1982

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
386	164	71	448	73	243	22	550	141	0	143	141	+0.36
238	137	56	550	72	109	6	528	130	0	129	130	+0.55
253	139	42	528	84	127	14	526	129	0	126	129	+0.51
136	108	31	526	65	39	15	544	21	0	96	21	+0.16
241	89	36	544	47	158	9	550	152	0	83	152	+0.63
58	77	28	550	44	-13	8	529	7	0	72	7	+0.12
87	85	15	529	57	15	20	526	18	0	72	18	+0.20
149	96	37	526	45	68	30	539	55	0	81	55	+0.37
75	116	13	539	76	-14	31	489	36	0	89	36	+0.48
34	144	9	489	60	-35	79	454	0	0	69	0	+0.00
19	152	12	454	33	-26	113	427	0	0	45	0	+0.00
57	154	16	427	38	3	107	430	0	0	54	0	+0.00
1731	1461	365		694				690	0	1059	690	+0.40

YEAR 1983

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
37	164	9	430	19	9	130	439	0	0	28	0	+0.00
102	137	22	439	45	35	88	474	0	0	67	0	+0.00
73	139	30	474	50	-7	78	467	0	0	79	0	+0.00
9	108	9	467	31	-31	100	436	0	0	40	0	+0.00
26	89	16	436	16	-6	115	430	0	0	32	0	+0.00
69	77	23	430	12	33	114	463	0	0	35	0	+0.00
118	85	25	463	29	64	73	527	0	0	55	0	+0.00
66	96	18	527	55	-7	38	520	0	0	73	0	+0.00
41	116	16	520	63	-39	47	481	0	0	80	0	+0.00
108	144	21	481	61	27	72	507	0	0	81	0	+0.00
24	152	7	507	73	-57	69	451	0	0	80	0	+0.00
165	154	22	451	91	52	42	502	0	0	113	0	+0.00
836	1461	218		546				0	0	764	0	+0.00

YEAR 1984

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
222	164	40	502	103	80	18	508	74	0	143	74	+0.33
217	142	44	508	77	96	25	550	54	0	121	54	+0.25
71	139	24	550	89	-42	26	493	15	0	113	15	+0.21
126	108	35	493	50	40	40	533	0	0	86	0	+0.00
26	89	21	533	48	-42	40	491	0	0	68	0	+0.00
75	77	25	491	36	14	39	505	0	0	61	0	+0.00
69	85	9	505	47	13	52	518	0	0	56	0	+0.00
41	96	20	518	50	-29	43	489	0	0	70	0	+0.00
142	116	29	489	51	62	57	550	1	0	80	1	+0.01
64	144	21	550	87	-43	38	481	25	0	108	25	+0.40
80	152	25	481	53	2	84	483	0	0	78	0	+0.00
177	154	38	483	88	51	29	525	9	0	126	9	+0.05
1311	1466	330		780				179	0	1110	179	+0.14

YEAR 1985

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
97	164	18	525	102	-23	39	502	0	0	120	0	+0.00
162	137	25	502	73	64	45	544	22	0	98	22	+0.14
212	139	46	544	79	88	13	504	127	0	124	127	+0.60
54	108	26	504	53	-25	45	479	0	0	79	0	+0.00
102	89	28	479	45	29	35	508	0	0	73	0	+0.00
140	77	19	508	42	79	34	536	51	0	61	51	+0.37
56	85	22	536	49	-15	28	521	0	0	71	0	+0.00
27	96	11	521	51	-35	54	486	0	0	62	0	+0.00
28	116	9	486	47	-28	80	458	0	0	56	0	+0.00
53	144	19	458	43	-9	96	449	0	0	62	0	+0.00
2	152	2	449	30	-30	118	419	0	0	32	0	+0.00
429	154	38	419	90	300	26	515	204	0	129	204	+0.48
1362	1461	264		703				405	0	966	405	+0.30

YEAR 1986

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
12	164	8	515	73	-68	76	447	0	0	80	0	+0.00
69	137	20	447	47	2	87	449	0	0	67	0	+0.00
113	139	42	449	34	37	94	486	0	0	76	0	+0.00
285	108	35	486	58	193	25	511	168	0	92	168	+0.59
118	89	23	511	52	44	25	508	47	0	74	47	+0.40
214	77	38	508	33	143	13	550	101	0	71	101	+0.47
62	85	26	550	51	-15	13	532	3	0	77	3	+0.05
98	96	31	532	54	13	19	545	0	0	85	0	+0.00
16	116	16	545	68	-68	42	477	0	0	84	0	+0.00
57	144	14	477	50	-6	90	471	0	0	63	0	+0.00
25	152	15	471	44	-34	100	437	0	0	58	0	+0.00
199	154	22	437	78	99	57	508	27	0	100	27	+0.14
1267	1461	288		640				346	0	928	346	+0.27

YEAR 1987

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
57	164	18	508	80	-41	62	467	0	0	99	0	+0.00
204	137	25	467	65	114	55	520	61	0	90	61	+0.30
169	139	28	520	80	60	34	527	53	0	109	53	+0.32
17	108	14	527	58	-54	51	472	0	0	72	0	+0.00
85	89	36	472	31	18	58	490	0	0	67	0	+0.00
35	77	26	490	25	-17	71	473	0	0	52	0	+0.00
54	85	10	473	38	6	70	479	0	0	48	0	+0.00
17	96	11	479	35	-29	85	450	0	0	45	0	+0.00
23	116	8	450	26	-10	113	440	0	0	33	0	+0.00
40	144	8	440	35	-3	110	437	0	0	43	0	+0.00
41	152	20	437	24	-3	121	434	0	0	44	0	+0.00
157	154	24	434	65	68	70	502	0	0	89	0	+0.00
899	1461	228		562				115	0	790	115	+0.13

YEAR 1988

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
280	164	41	502	93	146	30	550	98	0	134	98	+0.35
242	142	41	550	89	111	9	524	138	0	130	138	+0.57
114	139	28	524	85	1	29	523	2	0	113	2	+0.02
215	108	46	523	54	114	11	547	90	0	100	90	+0.42
69	89	31	547	50	-12	14	535	0	0	81	0	+0.00
31	77	17	535	46	-32	26	503	0	0	63	0	+0.00
102	85	19	503	47	37	37	529	10	0	66	10	+0.10
46	96	18	529	58	-30	31	499	0	0	76	0	+0.00
313	116	26	499	66	221	36	545	175	0	92	175	+0.56
114	144	18	545	100	-5	24	499	41	0	118	41	+0.36
26	152	8	499	59	-41	85	457	0	0	67	0	+0.00
209	154	54	457	62	92	50	550	0	0	116	0	+0.00
1759	1466	348		809				555	0	1157	555	+0.32

YEAR 1989

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
140	164	32	550	94	14	37	550	14	0	126	14	+0.10
583	137	47	550	81	455	7	550	455	0	128	455	+0.78
168	139	36	550	78	54	30	550	54	0	114	54	+0.32
153	108	39	550	61	53	8	525	78	0	100	78	+0.51
212	89	50	525	31	131	18	550	106	0	81	106	+0.50
47	77	28	550	42	-23	14	525	2	0	70	2	+0.05
130	85	21	525	55	54	13	532	47	0	76	47	+0.36
52	96	21	532	59	-27	25	505	0	0	79	0	+0.00
93	116	21	505	71	1	32	507	0	0	92	0	+0.00
140	144	25	507	93	22	26	526	2	0	119	2	+0.02
173	152	37	526	91	45	25	520	51	0	128	51	+0.29
111	154	18	520	96	-3	37	492	25	0	114	25	+0.23
2003	1461	375		852				834	0	1227	834	+0.42

YEAR 1990

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
216	164	41	492	88	87	35	492	87	0	129	87	+0.40
58	137	32	492	53	-28	68	464	0	0	85	0	+0.00
116	139	44	464	51	21	65	485	0	0	95	0	+0.00
120	108	27	485	58	35	36	514	6	0	85	6	+0.05
227	89	33	514	48	146	16	529	131	0	81	131	+0.58
104	77	30	529	40	33	13	531	32	0	70	32	+0.31
194	85	26	531	49	120	16	538	112	0	74	112	+0.58
192	96	26	538	56	110	21	547	100	0	82	100	+0.52
173	116	26	547	77	70	14	540	77	0	103	77	+0.45
25	144	10	540	88	-73	44	467	0	0	98	0	+0.00
223	152	17	467	44	162	97	546	83	0	61	83	+0.37
229	154	20	546	104	105	26	545	106	0	124	106	+0.46
1875	1461	331		755				735	0	1086	735	+0.39

YEAR 1991

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
322	164	37	545	108	178	15	550	173	0	144	173	+0.54
244	137	34	550	90	120	10	520	151	0	124	151	+0.62
164	139	36	520	83	44	22	504	60	0	119	60	+0.37
109	108	27	504	58	24	37	528	0	0	85	0	+0.00
42	89	12	528	59	-29	28	499	0	0	71	0	+0.00
98	77	17	499	47	34	25	513	20	0	63	20	+0.21
26	85	19	513	40	-33	54	480	0	0	59	0	+0.00
166	96	22	480	54	90	37	522	49	0	76	49	+0.29
53	116	24	522	65	-35	37	487	0	0	88	0	+0.00
80	144	18	487	71	-8	61	478	0	0	88	0	+0.00
24	152	13	478	50	-39	94	440	0	0	62	0	+0.00
15	154	11	440	25	-21	123	418	0	0	36	0	+0.00
1342	1461	269		747				453	0	1016	453	+0.34

YEAR 1992

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
42	164	20	418	19	3	128	421	0	0	40	0	+0.00
68	142	15	421	25	27	118	448	0	0	40	0	+0.00
39	139	28	448	29	-18	108	431	0	0	57	0	+0.00
68	108	18	431	21	28	113	459	0	0	39	0	+0.00
33	89	14	459	29	-10	87	449	0	0	43	0	+0.00
32	77	18	449	17	-3	104	445	0	0	35	0	+0.00
115	85	24	445	22	69	92	515	0	0	46	0	+0.00
160	96	20	515	58	82	29	544	53	0	78	53	+0.33
57	116	19	544	72	-34	34	511	0	0	91	0	+0.00
134	144	29	511	93	12	22	512	10	0	122	10	+0.08
43	152	21	512	70	-48	65	464	0	0	91	0	+0.00
181	154	23	464	76	83	57	521	25	0	98	25	+0.14
972	1466	249		532				88	0	781	88	+0.09

YEAR 1993

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
37	164	18	521	84	-65	57	456	0	0	102	0	+0.00
95	137	24	456	41	31	94	487	0	0	64	0	+0.00
227	139	30	487	83	114	29	524	77	0	113	77	+0.34
85	108	34	524	58	-8	23	505	11	0	93	11	+0.12
135	89	28	505	50	57	20	513	49	0	78	49	+0.36
27	77	21	513	34	-29	53	485	0	0	56	0	+0.00
63	85	23	485	36	4	56	488	0	0	59	0	+0.00
341	96	28	488	54	259	24	540	207	0	82	207	+0.61
103	116	21	540	74	8	26	495	53	0	95	53	+0.51
37	144	18	495	57	-39	77	456	0	0	76	0	+0.00
45	152	11	456	47	-14	97	443	0	0	58	0	+0.00
69	154	23	443	42	4	99	447	0	0	65	0	+0.00
1263	1461	280		661				397	0	941	397	+0.31

YEAR 1994

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
225	164	31	447	56	137	83	550	34	0	87	34	+0.15
85	137	34	550	87	-37	14	508	5	0	122	5	+0.06
51	139	23	508	64	-36	62	472	0	0	87	0	+0.00
285	108	29	472	47	210	59	523	159	0	75	159	+0.56
145	89	18	523	56	71	25	504	91	0	74	91	+0.63
158	77	12	504	50	95	26	502	96	0	63	96	+0.61
211	85	30	502	41	139	30	549	93	0	72	93	+0.44
49	96	18	549	64	-33	19	516	0	0	82	0	+0.00
75	116	16	516	67	-7	45	508	0	0	83	0	+0.00
8	144	5	508	64	-62	77	447	0	0	69	0	+0.00
197	152	42	447	32	123	102	550	20	0	73	20	+0.10
145	154	31	550	103	10	17	515	46	0	134	46	+0.31
1632	1461	290		731				544	0	1021	544	+0.33

YEAR 1995

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
69	164	24	515	71	-27	68	488	0	0	96	0	+0.00
211	137	33	488	66	113	48	548	53	0	99	53	+0.25
184	139	36	548	89	59	13	546	61	0	125	61	+0.33
73	108	19	546	69	-15	24	498	33	0	88	33	+0.45
48	89	23	498	35	-10	67	488	0	0	58	0	+0.00
139	77	23	488	48	68	12	533	23	0	71	23	+0.16
101	85	19	533	56	26	14	537	22	0	76	22	+0.21
25	96	17	537	56	-49	36	489	0	0	73	0	+0.00
38	116	19	489	48	-29	72	460	0	0	67	0	+0.00
23	144	18	460	33	-28	108	432	0	0	51	0	+0.00
81	152	19	432	42	20	99	451	0	0	62	0	+0.00
21	154	13	451	33	-24	113	427	0	0	45	0	+0.00
1012	1461	263		647				191	0	910	191	+0.19

YEAR 1996

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
344	164	41	427	83	221	46	533	114	0	124	114	+0.33
87	142	32	533	83	-28	31	505	0	0	115	0	+0.00
411	139	38	505	84	289	19	536	258	0	122	258	+0.63
70	108	29	536	59	-18	31	518	0	0	88	0	+0.00
166	89	30	518	50	86	13	528	77	0	80	77	+0.46
163	77	30	528	39	94	19	542	79	0	69	79	+0.49
29	85	15	542	54	-40	24	502	0	0	69	0	+0.00
80	96	16	502	60	4	32	494	13	0	76	13	+0.16
69	116	22	494	56	-9	57	485	0	0	78	0	+0.00
233	144	28	485	67	139	60	535	89	0	94	89	+0.38
68	152	9	535	95	-36	43	466	33	0	105	33	+0.48
210	154	37	466	54	120	72	550	36	0	90	36	+0.17
1931	1466	325		785				698	0	1109	698	+0.36

YEAR 1997

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
256	164	40	550	95	121	28	550	121	0	135	121	+0.47
405	137	46	550	77	282	13	550	282	0	123	282	+0.70
218	139	36	550	87	94	12	504	141	0	124	141	+0.64
161	108	38	504	54	68	25	536	37	0	93	37	+0.23
68	89	33	536	48	-13	14	523	0	0	81	0	+0.00
18	77	10	523	45	-37	41	486	0	0	55	0	+0.00
50	85	18	486	33	-0	72	486	0	0	51	0	+0.00
126	96	28	486	52	46	32	526	6	0	80	6	+0.05
74	116	28	526	66	-21	30	505	0	0	95	0	+0.00
103	144	28	505	60	15	67	520	0	0	88	0	+0.00
37	152	16	520	78	-57	60	463	0	0	93	0	+0.00
65	154	29	463	49	-13	87	450	0	0	78	0	+0.00
1582	1461	350		745				586	0	1095	586	+0.37

YEAR 1998

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
16	164	13	450	33	-29	116	421	0	0	45	0	+0.00
90	137	35	421	15	40	127	461	0	0	50	0	+0.00
483	139	41	461	74	368	29	498	331	0	115	331	+0.69
34	108	21	498	44	-31	69	466	0	0	66	0	+0.00
72	89	29	466	25	19	84	485	0	0	54	0	+0.00
76	77	32	485	25	19	62	504	0	0	56	0	+0.00
41	85	27	504	35	-20	55	484	0	0	62	0	+0.00
32	96	26	484	30	-24	81	460	0	0	57	0	+0.00
103	116	22	460	61	20	50	480	0	0	83	0	+0.00
52	144	16	480	54	-18	83	462	0	0	70	0	+0.00
207	152	31	462	85	90	34	498	54	0	116	54	+0.26
421	154	36	498	64	321	59	549	270	0	100	270	+0.64
1628	1461	329		544				655	0	874	655	+0.40

YEAR 1999

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
153	164	42	549	92	19	31	538	31	0	134	31	+0.20
410	137	51	538	77	281	7	525	294	0	128	294	+0.72
152	139	47	525	77	28	17	539	15	0	124	15	+0.10
300	108	45	539	58	198	4	535	201	0	103	201	+0.67
80	89	26	535	51	3	21	507	32	0	77	32	+0.40
148	77	19	507	40	88	39	550	44	0	59	44	+0.30
134	85	27	550	48	59	18	548	61	0	76	61	+0.46
205	96	28	548	60	116	9	531	133	0	89	133	+0.65
148	116	23	531	74	52	24	500	82	0	97	82	+0.56
344	144	41	500	80	224	25	533	191	0	121	191	+0.56
276	152	45	533	95	137	10	541	128	0	139	128	+0.47
189	154	33	541	101	55	17	508	87	0	134	87	+0.46
2539	1461	428		852				1300	0	1280	1300	+0.51

YEAR 2000

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
336	164	58	508	93	186	12	545	149	0	150	149	+0.44
310	142	46	545	81	182	13	507	221	0	128	221	+0.71
348	139	41	507	80	227	21	550	184	0	120	184	+0.53
323	108	42	550	57	224	9	520	254	0	99	254	+0.79
98	89	32	520	48	18	18	533	6	0	80	6	+0.06
90	77	25	533	41	24	22	548	9	0	66	9	+0.09
236	85	27	548	52	157	7	525	181	0	78	181	+0.77
81	96	22	525	59	0	24	525	0	0	81	0	+0.00
97	116	26	525	65	6	35	532	0	0	90	0	+0.00
99	144	12	532	98	-10	32	492	29	0	109	29	+0.30
67	152	21	492	65	-20	71	471	0	0	87	0	+0.00
243	154	37	471	92	115	25	514	72	0	128	72	+0.30
2328	1466	387		830				1105	0	1218	1105	+0.47

YEAR 2001

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
329	164	45	514	89	195	26	529	180	0	134	180	+0.55
229	137	47	529	79	103	10	546	85	0	126	85	+0.37
149	139	42	546	72	35	32	550	31	0	114	31	+0.21
170	108	27	550	69	74	15	541	83	0	96	83	+0.49
25	89	12	541	58	-45	30	496	0	0	70	0	+0.00
127	77	29	496	40	58	20	530	24	0	69	24	+0.19
69	85	27	530	49	-6	16	518	5	0	76	5	+0.07
98	96	20	518	58	19	27	519	19	0	79	19	+0.19
103	116	28	519	61	15	40	534	0	0	89	0	+0.00
20	144	14	534	77	-71	56	463	0	0	90	0	+0.00
68	152	23	463	39	6	102	469	0	0	62	0	+0.00
123	154	34	469	63	26	68	495	0	0	96	0	+0.00
1509	1461	347		753				427	0	1101	427	+0.28

YEAR 2002

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
79	164	31	495	58	-9	81	485	0	0	89	0	+0.00
430	137	46	485	80	305	11	550	240	0	126	240	+0.56
197	139	43	550	86	68	7	530	88	0	129	88	+0.45
218	108	48	530	49	121	17	509	142	0	97	142	+0.65
75	89	27	509	43	6	42	515	0	0	70	0	+0.00
63	77	27	515	36	0	37	515	0	0	63	0	+0.00
231	85	39	515	41	150	8	543	122	0	80	122	+0.53
154	96	34	543	54	67	12	550	60	0	88	60	+0.39
143	116	38	550	69	36	7	521	65	0	107	65	+0.45
37	144	20	521	70	-53	60	468	0	0	89	0	+0.00
79	152	15	468	55	9	86	478	0	0	70	0	+0.00
48	154	16	478	63	-31	76	447	0	0	79	0	+0.00
1755	1461	383		704				716	0	1087	716	+0.41

YEAR 2003

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
306	164	32	447	91	183	40	531	99	0	123	99	+0.32
16	137	16	531	70	-70	56	461	0	0	87	0	+0.00
207	139	44	461	79	83	18	514	30	0	124	30	+0.15
92	108	32	514	59	1	26	515	0	0	91	0	+0.00
55	89	19	515	47	-11	42	504	0	0	66	0	+0.00
44	77	16	504	37	-10	54	494	0	0	53	0	+0.00
109	85	32	494	37	40	38	534	0	0	70	0	+0.00
265	96	23	534	62	180	15	531	183	0	85	183	+0.69
72	116	21	531	68	-18	36	513	0	0	90	0	+0.00
40	144	16	513	71	-47	61	467	0	0	87	0	+0.00
27	152	10	467	46	-29	99	438	0	0	56	0	+0.00
128	154	30	438	45	53	91	491	0	0	76	0	+0.00
1362	1461	293		714				312	0	1007	312	+0.23

YEAR 2004

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
103	164	26	491	69	8	71	499	0	0	94	0	+0.00
124	142	33	499	74	17	42	516	0	0	107	0	+0.00
251	139	49	516	72	130	22	544	102	0	120	102	+0.41
41	108	26	544	63	-48	24	495	0	0	89	0	+0.00
69	89	24	495	37	7	58	502	0	0	62	0	+0.00
145	77	28	502	40	78	23	541	39	0	67	39	+0.27
118	85	24	541	53	41	11	534	48	0	77	48	+0.41
251	96	38	534	52	162	8	547	149	0	90	149	+0.59
288	116	28	547	76	184	12	521	211	0	104	211	+0.73
26	144	15	521	69	-58	65	462	0	0	84	0	+0.00
41	152	13	462	50	-23	92	440	0	0	63	0	+0.00
53	154	15	440	35	3	110	442	0	0	50	0	+0.00
1509	1466	318		691				548	0	1008	548	+0.36

YEAR 2005

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
148	164	33	442	38	76	102	519	0	0	71	0	+0.00
15	137	15	519	64	-64	66	455	0	0	79	0	+0.00
128	139	33	455	60	36	64	491	0	0	92	0	+0.00
293	108	43	491	52	199	21	537	152	0	94	152	+0.52
195	89	27	537	52	116	14	514	140	0	79	140	+0.72
150	77	18	514	47	85	26	516	83	0	65	83	+0.55
143	85	27	516	50	67	15	540	42	0	77	42	+0.29
102	96	24	540	58	21	22	548	13	0	82	13	+0.13
118	116	28	548	75	14	14	529	33	0	103	33	+0.28
145	144	20	529	91	34	33	513	50	0	111	50	+0.35
65	152	10	513	75	-21	66	492	0	0	86	0	+0.00
38	154	15	492	62	-39	79	454	0	0	77	0	+0.00
1540	1461	292		724				513	0	1016	513	+0.33

YEAR 2006

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
325	164	35	454	53	237	80	545	145	0	88	145	+0.45
260	137	26	545	92	142	18	550	138	0	118	138	+0.53
199	139	55	550	75	70	6	521	99	0	130	99	+0.49
120	108	25	521	62	33	28	527	27	0	87	27	+0.22
39	89	19	527	51	-32	32	495	0	0	71	0	+0.00
170	77	21	495	46	103	21	550	48	0	67	48	+0.28
55	85	25	550	50	-19	21	531	0	0	75	0	+0.00
46	96	17	531	59	-31	31	500	0	0	77	0	+0.00
108	116	21	500	63	24	45	524	0	0	84	0	+0.00
75	144	23	524	92	-39	28	483	2	0	114	2	+0.02
72	152	24	483	49	-0	90	483	0	0	72	0	+0.00
98	154	24	483	67	7	68	490	0	0	92	0	+0.00
1568	1461	316		759				458	0	1074	458	+0.29

YEAR 2007

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
32	164	17	490	61	-47	83	442	0	0	79	0	+0.00
129	137	43	442	49	37	69	480	0	0	92	0	+0.00
241	139	48	480	66	127	37	549	58	0	114	58	+0.24
243	108	46	549	56	140	6	537	152	0	102	152	+0.63
276	89	42	537	42	191	6	542	186	0	84	186	+0.67
16	77	8	542	53	-45	26	497	0	0	61	0	+0.00
145	85	20	497	54	71	19	549	19	0	74	19	+0.13
139	96	26	549	59	54	16	513	90	0	85	90	+0.65
111	116	23	513	58	30	49	540	3	0	81	3	+0.02
117	144	31	540	85	0	30	534	6	0	116	6	+0.05
92	152	24	534	96	-29	29	506	0	0	121	0	+0.00
91	154	34	506	69	-12	59	494	0	0	103	0	+0.00
1630	1461	364		748				514	0	1111	514	+0.32

YEAR 2008

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
131	164	42	494	89	-1	34	493	0	0	131	0	+0.00
352	142	43	493	79	230	24	537	187	0	122	187	+0.53
312	139	51	537	71	189	21	539	187	0	123	187	+0.60
64	108	26	539	65	-27	23	512	0	0	92	0	+0.00
221	89	38	512	45	137	8	525	124	0	83	124	+0.56
46	77	18	525	46	-17	27	508	0	0	64	0	+0.00
19	85	9	508	42	-32	63	476	0	0	51	0	+0.00
18	96	8	476	35	-25	86	451	0	0	43	0	+0.00
152	116	32	451	54	66	48	516	0	0	87	0	+0.00
46	144	16	516	76	-46	55	470	0	0	92	0	+0.00
181	152	42	470	73	67	48	518	19	0	115	19	+0.10
79	154	20	518	89	-31	44	488	0	0	110	0	+0.00
1622	1466	345		766				516	0	1112	516	+0.32

YEAR 2009

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
348	164	60	488	87	201	17	546	143	0	147	143	+0.41
74	137	25	546	82	-33	33	512	0	0	107	0	+0.00
36	139	19	512	63	-46	66	466	0	0	82	0	+0.00
128	108	36	466	50	42	44	508	0	0	86	0	+0.00
104	89	31	508	42	31	36	540	0	0	73	0	+0.00
60	77	21	540	47	-7	17	532	0	0	68	0	+0.00
132	85	25	532	53	54	10	530	57	0	78	57	+0.43
81	96	22	530	63	-4	14	524	1	0	85	1	+0.01
357	116	28	524	73	256	17	513	267	0	101	267	+0.75
52	144	19	513	77	-44	50	469	0	0	96	0	+0.00
40	152	22	469	48	-29	91	440	0	0	69	0	+0.00
172	154	9	440	73	89	72	490	39	0	83	39	+0.22
1584	1461	316		759				506	0	1075	506	+0.32

YEAR 2010

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
96	164	27	490	56	13	84	503	0	0	83	0	+0.00
238	137	21	503	80	137	42	503	137	0	101	137	+0.58
140	139	38	503	80	23	24	524	1	0	118	1	+0.01
691	108	56	524	48	587	5	550	562	0	104	562	+0.81
220	89	22	550	59	139	10	537	152	0	81	152	+0.69
10	77	10	537	47	-47	39	490	0	0	57	0	+0.00
40	85	16	490	36	-12	68	478	0	0	52	0	+0.00
40	96	22	478	30	-12	85	466	0	0	52	0	+0.00
47	116	13	466	41	-8	86	458	0	0	55	0	+0.00
107	144	30	458	53	24	79	482	0	0	83	0	+0.00
117	152	28	482	48	41	88	523	0	0	76	0	+0.00
175	154	23	523	96	55	33	496	82	0	120	82	+0.47
1920	1461	306		674				933	0	981	933	+0.49

YEAR 2011

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
424	164	50	496	91	283	19	524	255	0	141	255	+0.60
190	137	42	524	82	66	13	533	57	0	124	57	+0.30
190	139	44	533	82	64	13	532	65	0	126	65	+0.34
125	108	31	532	62	31	18	504	59	0	94	59	+0.47
142	89	32	504	45	64	26	547	21	0	77	21	+0.15
153	77	33	547	39	80	7	544	84	0	72	84	+0.55
168	85	28	544	49	90	12	548	87	0	77	87	+0.52
77	96	30	548	57	-10	11	519	18	0	87	18	+0.24
183	116	30	519	68	85	23	541	64	0	98	64	+0.35
61	144	19	541	91	-49	33	478	14	0	110	14	+0.22
217	152	19	478	81	116	55	499	96	0	100	96	+0.44
123	154	34	499	69	21	55	519	0	0	103	0	+0.00
2051	1461	392		818				819	0	1209	819	+0.40

YEAR 2012

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
467	164	49	519	96	323	17	550	292	0	144	292	+0.62
628	142	50	550	81	496	9	542	504	0	131	504	+0.80
115	139	41	542	80	-6	21	517	19	0	121	19	+0.17
265	108	40	517	62	164	7	538	143	0	101	143	+0.54
91	89	45	538	38	8	12	537	9	0	83	9	+0.10
197	77	22	537	47	129	16	525	141	0	68	141	+0.71
45	85	18	525	44	-17	47	508	0	0	62	0	+0.00
137	96	26	508	58	53	18	533	28	0	84	28	+0.20
346	116	41	533	64	241	13	550	224	0	105	224	+0.65
82	144	21	550	90	-29	35	521	0	0	111	0	+0.00
164	152	16	521	102	46	31	502	65	0	118	65	+0.40
153	154	28	502	75	50	57	525	27	0	103	27	+0.17
2690	1466	396		836				1451	0	1233	1451	+0.54

YEAR 2013

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
303	164	45	525	101	157	15	536	147	0	146	147	+0.48
288	137	53	536	64	171	28	546	161	0	116	161	+0.56
531	139	53	546	74	404	11	546	403	0	127	403	+0.76
92	108	17	546	66	10	36	550	6	0	82	6	+0.07
57	89	22	550	58	-23	13	521	6	0	80	6	+0.11
77	77	20	521	46	12	23	517	15	0	66	15	+0.20
80	85	25	517	43	12	35	529	0	0	68	0	+0.00
128	96	26	529	56	46	24	550	25	0	81	25	+0.20
116	116	16	550	76	24	28	490	84	0	92	84	+0.73
161	144	20	490	84	57	44	486	60	0	104	60	+0.37
173	152	22	486	70	81	65	525	43	0	92	43	+0.25
234	154	49	525	85	99	19	544	80	0	134	80	+0.34
2239	1461	367		822				1032	0	1189	1032	+0.46

YEAR 2014

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
421	164	60	544	93	268	7	550	262	0	153	262	+0.62
179	137	43	550	79	57	17	550	57	0	122	57	+0.32
507	139	53	550	78	376	6	541	385	0	131	385	+0.76
133	108	18	541	71	43	21	497	88	0	90	88	+0.66
228	89	25	497	53	150	20	541	106	0	78	106	+0.47
144	77	28	541	44	73	8	537	77	0	72	77	+0.53
159	85	41	537	39	79	9	534	82	0	80	82	+0.52
15	96	10	534	58	-52	42	481	0	0	68	0	+0.00
33	116	8	481	41	-16	91	465	0	0	49	0	+0.00
136	144	17	465	56	62	81	526	1	0	74	1	+0.01
14	152	10	526	77	-73	64	453	0	0	87	0	+0.00
24	154	19	453	32	-27	113	426	0	0	51	0	+0.00
1994	1461	332		721				1059	0	1053	1059	+0.53

YEAR 2015

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
96	164	34	426	42	20	100	445	0	0	76	0	+0.00
229	137	46	445	70	114	33	541	18	0	115	18	+0.08
194	139	31	541	92	71	15	527	85	0	123	85	+0.44
30	108	17	527	59	-46	47	481	0	0	76	0	+0.00
76	89	20	481	30	25	80	506	0	0	50	0	+0.00
87	77	25	506	38	24	35	530	0	0	63	0	+0.00
30	85	21	530	46	-37	33	493	0	0	67	0	+0.00
252	96	30	493	51	170	24	542	122	0	81	122	+0.48
54	116	21	542	72	-39	31	503	0	0	93	0	+0.00
10	144	5	503	64	-58	76	445	0	0	68	0	+0.00
120	152	25	445	61	34	75	479	0	0	86	0	+0.00
43	154	18	479	57	-32	83	447	0	0	75	0	+0.00
1220	1461	293		681				225	0	974	225	+0.18

YEAR 2016

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
55	164	33	447	37	-15	105	432	0	0	70	0	+0.00
352	142	35	432	60	257	64	504	186	0	94	186	+0.53
133	139	29	504	80	24	35	517	10	0	109	10	+0.07
238	108	36	517	58	145	21	503	160	0	94	160	+0.67
181	89	40	503	43	99	12	531	70	0	83	70	+0.39
233	77	23	531	46	163	13	531	163	0	70	163	+0.70
24	85	21	531	44	-41	40	490	0	0	65	0	+0.00
314	96	44	490	44	227	16	532	185	0	87	185	+0.59
9	116	4	532	68	-64	52	468	0	0	73	0	+0.00
84	144	20	468	57	7	77	475	0	0	77	0	+0.00
149	152	14	475	91	43	45	483	35	0	105	35	+0.24
139	154	22	483	91	25	40	484	25	0	114	25	+0.18
1910	1466	321		720				833	0	1040	833	+0.44

YEAR 2017

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
31	164	17	484	53	-40	93	444	0	0	71	0	+0.00
417	137	54	444	65	298	23	531	211	0	119	211	+0.51
269	139	28	531	95	145	13	530	146	0	123	146	+0.54
37	108	15	530	65	-43	38	487	0	0	80	0	+0.00
245	89	32	487	32	182	52	547	121	0	63	121	+0.50
36	77	13	547	53	-31	17	516	0	0	67	0	+0.00
76	85	23	516	49	4	28	520	0	0	71	0	+0.00
72	96	21	520	53	-2	37	519	0	0	75	0	+0.00
210	116	18	519	81	111	19	543	87	0	99	87	+0.41
127	144	17	543	91	19	37	550	12	0	108	12	+0.09
95	152	39	550	85	-28	32	522	0	0	123	0	+0.00
101	154	33	522	80	-11	45	511	0	0	113	0	+0.00
1716	1461	310		802				577	0	1112	577	+0.34

YEAR 2018

RAIN (mm)	ET (mm)	EI (mm)	SMC1 (mm)	ES (mm)	XCESS (mm)	AVSMDEF (mm)	SMC2 (mm)	GWR (mm)	TL (mm)	EA (mm)	NETR (mm)	RECHARGE RATIO
447	164	49	511	101	296	10	545	262	0	150	262	+0.59
390	137	42	545	84	264	9	541	268	0	125	268	+0.69
356	139	38	541	82	236	19	550	228	0	120	228	+0.64
444	108	35	550	65	344	8	528	366	0	100	366	+0.83
110	89	27	528	49	33	22	508	53	0	76	53	+0.48
183	77	24	508	46	113	15	527	94	0	70	94	+0.52
16	85	9	527	49	-42	47	485	0	0	58	0	+0.00
29	96	16	485	35	-22	81	462	0	0	51	0	+0.00
112	116	23	462	49	40	68	502	0	0	73	0	+0.00
69	144	24	502	73	-29	53	473	0	0	97	0	+0.00
36	152	10	473	53	-27	91	446	0	0	63	0	+0.00
196	154	56	446	44	96	72	541	0	0	101	0	+0.00
2386	1461	354		731				1271	0	1084	1271	+0.53

39 YEAR AVERAGES

1653	1462	322		727				603	0	1049	603	+0.36