A Desktop Study of the Groundwater Resources of Cousine and Cousin Islands, Seychelles

FUNDED BY MSP GEF AND PREPARED FOR NATURE SEYCHELLES

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Disclaimer

This report is based on a desktop study and uses only available and existing information. The work does not represent itself as definitive guidance for the purposes of water resource management of Cousine or Cousin Islands. No site investigations were conducted nor any additional data collected with regard to the status of groundwater. It should be noted that the authors recommend that further investigations be undertaken of a more rigorous nature, and that the results of the current evaluation serve simply to summarise existing information, which is presently not adequate for forming the basis of any policy decision or water resource management plan for these islands. In particular, it should be noted that groundwater modelling is preliminary in nature, and based on very scant information, and therefore modelling results should not be considered as definitive or predictive.

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SUMMARY

The groundwater resources of Cousine and Cousin Islands has previously not been investigated, although these resources are accessed via bore pumping to support tourism, residents, and visitors to the islands, in terms of domestic use, drinking water, lawn irrigation and other anthropogenic requirements. It is also likely that groundwater plays an important role in the health of the highly valued ecosystems of these two islands, given the existence of springs and other surface water bodies that depend on groundwater influxes.

This report describes a desktop study of the groundwater resources of Cousine and Cousin Islands, and aims to address a number of issues, summarised as:

1. Describe general considerations of importance in the management of groundwater resources of Cousine and Cousin Islands
2. Collect and collate existing knowledge and data on the groundwater resources of Cousine and Cousin Islands
3. Within data availability constraints, development groundwater models of the islands to explore various water supply questions relating to mainly to the sustainability of groundwater extraction
4. Provide advice on water treatment options, hydrological monitoring, and areas of future investigation

The report provides an overview of the water resources of small islands. The existence of fresh groundwater on small islands is mostly controlled by island size and climate, but also topography, geology, vegetation and soil type. A review of existing guidelines on island water resources indicated that Cousin and Cousine Island are classified as “very small islands” in the typology of UNESCO (1991). Islands of size similar to Cousine and Cousin Islands are considered by the authors of the UNESCO (1991) guidelines to be unlikely to contain significant fresh groundwater resources, which are expected to occur as a very thin wedge overlying saline (seawater) groundwater. It is therefore somewhat surprising that fresh groundwater supplies are abstracted from both islands in non-trivial quantities.

The data collection phase of the study captured information relating to physiography, topography, climate, vegetation and land use, soils and geology, hydrogeology and groundwater use, and some groundwater quality observations. This information was used to develop conceptual models of the islands’ hydrogeology, and these served to develop computer models of the groundwater systems. The available dataset pertaining to the islands’ aquifers was considered to be deficient for the development of predictive management models, and further information needs to be obtained through field investigation, monitoring, sampling and analysis before reliable modelling results, sufficient to guide groundwater management decision, can be provided. Nonetheless, a groundwater modelling investigation was undertaken to assist in guiding management decisions and to demonstrate the capability of contemporary modelling methods for future studies.

The Cousine Island groundwater model is a state-of-the-art three-dimensional groundwater flow and seawater intrusion model, which is based on cutting-edge modelling software (i.e. the MODHMS code) and GIS-based modelling techniques (e.g. Groundwater Vistas software). The model simulates the density effects of seawater-freshwater interaction, and uses interpolated surfaces to explicitly represent the hydrostratigraphic units of sand and granite, of which the island is predominantly comprised. Models were developed that
simulate either long-term (548 years) or time-variant (i.e. climatic variations) conditions, and were used to evaluate both pumping and no pumping groundwater conditions. Simulations using the Cousine Island model demonstrated that pumping from several shallow bores is more likely to yield lower salinity groundwater than that obtained from a single deeper bore. This outcome is well aligned to “skimmer well” approaches adopted in similar settings of fresh groundwater overlying seawater. The Cousine Island study also demonstrated the potential for climatic variability in both water quality and watertable level, and showed that it is quite likely that a large variability in groundwater salinity could be expected from one year to the next. Simulations of well pumping, at rates similar to those historically recorded on Cousine Island, indicate that groundwater pumping has indeed induced a landward movement of saline groundwater towards the points of extraction. Further modelling is required to better optimise rates of extraction and sites of future bore construction.

The model of Cousin Island adopted an approach that was more closely aligned to the limited available information, and more routine methods were applied (e.g. MODFLOW and PMWIN software). A “single-layer” approach (i.e. two-dimensional) was adopted and only groundwater flow was modelled in the absence of salt-related density effects. The results of the Cousin Island modelling study also provided some indication of the benefit of using multiple points of shallow groundwater extraction, although the proximity to the shoreline also proved to be a critical consideration.

A review of water treatment options for the island water was discussed. It is clear that existing water chemistry and microbiological information are insufficient to properly plan an optimal water treatment strategy for each island. Further, more clarity of water use needs, in terms of quality and quantity, is required, especially for Cousin Island. A preliminary overview of water treatment options identified that such treatments as pH correction, filtration, reverse osmosis and/or disinfection could be considered to provide for improved water quality to users from Cousine Island, while it was not possible to predict specific water treatment works for Cousin Island with the current available information. However, it is recommended that proper analysis of water quality be undertaken before the purchase of water treatment infrastructure is further considered.

Finally, the report outlines a preliminary proposal for future investigation of the islands groundwater resources and water quality, aimed at completing the study predominantly through field investigations, thereby allowing for more reliable estimates of sustainable groundwater use and for the provision of more specific advice relating to water treatment options.
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1. **INTRODUCTION**

1.1 **BACKGROUND**

Many of the islands of the central Seychelles are recognised for their high conservation value, supporting rare endemic species of birds, reptiles, invertebrates and plants. Cousine Island of the central Seychelles has been the subject of extensive biodiversity restoration activities, and ongoing ecological monitoring provides the basis for continuing ecological management of the island’s terrestrial and marine habitats (Samways, 2000; Kelly and Samways, 2003; Gerlach and Canning, 2001). Similarly, the neighbouring Cousin Island has also been the focus of ecological restoration in efforts to improve the resilience of endemic species (e.g. Komdeur and Pels, 2005).

Invariably, the water resources of small islands have clear interrelationships with the environment, which are particularly susceptible to water resource development impacts due to the limited extent and fragility of both groundwater systems and island ecosystems (UNESCO, 1991). The caretakers of Cousine Island have identified the need to investigate the island hydrology and hydro-chemistry. Threats to the island’s water-dependent ecosystems may also need to consider climate change impacts in the longer term, given that precipitation and sea temperature changes are already evident, and that these are affecting physical and biological systems (Payet and Agricole, 2006). Projected demands for water resources are expected to soon exceed current supply infrastructure in the Seychelles (Payet and Agricole, 2006), and therefore the potential for sustainable groundwater abstraction needs to be assessed as an alternative and cheap source of fresh water.

The following investigation represents an initial desktop study into the water resources of Cousin and Cousine Islands to collect and summarise the existing literature relating to the islands’ hydrology/water resources, ecosystems, geology, climate and other related physiographic characteristics. Some simple calculations and basic interpretation to extend the existing understanding of the islands’ hydrology, as based on published information, will be carried out where possible. The desktop study will also outline methodological details of proposed subsequent studies, which are considered necessary to complete the investigation and respond to queries raised by the islands’ custodians (see Section 1.2). Subsequent investigations are expected to involve the strategic collection of field data to fill knowledge gaps identified in the current review.
1.2 AIMS OF THE STUDY

This study aims to:

1. Provide a general overview of the water resources of small islands of similar physiography to Cousine and Cousin Islands, including other similar islands of the Seychelles.
2. Review existing and relevant literature on Cousine and Cousin Islands.
3. Collect and collate existing information of relevance to the study.
4. Within data availability constraints, develop simplified instructional groundwater models of the islands to explore the following questions:
   - Characteristics of the islands’ groundwater resources
     a. What are the extent, distribution and volume of groundwater resources?
     b. What are the physical and chemical characteristics of groundwater, and how might it be affected by extraction, rainfall recharge and marine linkages?
     c. How is groundwater recharged?
     d. What is the link between the groundwater and the sea?
   - Sustainable groundwater extraction
     e. How much groundwater can be safely and sustainably withdrawn from the islands’ aquifers?
     f. What are the risks of seawater intrusion?
     g. Develop a predictive utility for exploring “if then” scenarios
   - Water treatment
     h. Provide advice on how to treat water for human consumption.
5. Develop a monitoring and data collection plan for Stage 2.
6. Develop a Stage 3 research plan
7. Establish knowledge gaps, and monitoring and sampling requirements of any future studies of the water resources of Cousin and Cousine Islands.
2. SITE DESCRIPTION – COUSINE AND COUSIN ISLANDS, SEYCHELLES

The following represents an overview of the existing relevant information for the islands of Cousine and Cousin, as obtained from an extensive literature review.

2.1 LOCATION

The Republic of Seychelles comprises 115 islands occupying an area of 455 km$^2$ and lying between 4°S and 11°S, and 45°E and 56°E in the Indian Ocean (Figure 1). Forty-one of the islands are granitic and lie within 90 km of the main island of Mahé, while the remaining islands are coralline (U.S. Department of Army, 1996; Seychelles Tourism Board, 2007). The locations of the granitic islands of Cousine (4°21’S, 55°39’E) and Cousin (4°20’S, 55°40’E) are shown in Figures 2 and 3.
2.2 CLIMATE

The tropical climate of Seychelles is characterised by high humidity and temperature, which is typically in the range 24°C-29°C (U.S. Army, 1996). The north-west monsoon brings high rainfall during November-March, with peak rainfall usually occurring in December-January. Rainfall tends to be higher on north-facing slopes due to the prevailing wind direction (Seychelles Meteorological Services, 2001). On the island of Mahe, mean annual rainfall varies from 1700 mm in the coastal areas to >3100mm on parts of the hilly interior (Government of Seychelles, 2004); evidence that altitude and aspect are important factors in the mean annual rainfall of granitic islands of the Seychelles (Walsh, 1984).

Rainfall data for Cousine Island for the period 1995-2006 were provided by the island’s research staff. The annual totals and seasonal variation (as monthly averages) are depicted in Figures 4 and 5, which also show values for La Passe, La Digue Island for the period 1950-
The average annual rainfall from La Digue Island records was 1906 mm, compared to 1715 mm per annum from the shorter duration of Cousine Island data. The average annual rainfall for Grand Anse (Praslin Island) was similar to that of La Digue Island, being 1916 mm from rainfall measurements during 1951-2003. Data for La Digue and Praslin Islands was taken from the UN report by Seychelles Government (2004).

Figure 4 – Annual rainfall (mm) for Cousine Island and La Digue Island (La Passe)

Figure 5 – Seasonal Rainfall (as monthly averages) for Cousine Island and La Passe on La Digue Island
Evaporation and evapotranspiration data for the Seychelles is limited in spatial extent. Published estimates, in terms of representative average monthly values, are given in Table 1. Published values of average annual evaporation include 5.3 mm/d (Seychelles Meteorological Services, 2001) and 5.4 mm/d (Shahin, 2002), and potential evapotranspiration (PE) estimates include 4.6 mm/d (Shahin, 2002) and 4.5 mm/d (Walsh, 1984).

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Sources of data: (1) Seychelles Meteorological Services (2001), (2) Potential evapotranspiration (P.E.) from Walsh (1984)

### 2.3 TOPOGRAPHY, VEGETATION AND LAND USE

The granitic islands of Cousine and Cousin are similar in area, being approximately 26 ha and 27 ha, respectively (Samways, 2000; Burger, 2005; Kelly and Samways, 2003; Currie et al., 2003). Cousine Island is about 1 km long and 400 m wide (Kelly and Samways, 2003), and Cousin Island is roughly isodiametric (TEMS, 2002). The maximum altitude of Cousine Island is 65 m above mean seal level or MSL (Lawrance and Samways, 2003), while Cousin Island reportedly rises to 69 m MSL (TEMS, 2002). The topography of Cousine Island was provided by the island’s researchers, and is shown in Figure 6. Surface contours for Cousin Island are given by Hill et al. (2002) and Fosberg (1983), and are shown in Figures 7 and 8.
Figure 6 – Cousine Island topography (source: Dr Dylan Evans and Ms San Marie Jolliffe, Cousine Island Ecology). Inset shows approximate location of boreholes (red dots), well (dark blue dot) and spring (light blue dots).
Figure 7 – Cousin Island topography according to Hill et al. (2002)
Quantitative measures of vegetation coverage on Cousin and Cousine Islands, in the form of NDVI (normalized difference vegetation index) or detailed classifications of satellite-based land cover data are presently not available (Seychelles Government, 2004; Seychelles National Climate Change Committee, 2002). Vegetation information is only available in the form of land-based surveys.

The low coastal plateau of Cousin Island, accounting for two-thirds of the island area, is covered with dense forest, dominated by *Pisonia grandis* (Nyctaginaceae) and including other large trees (e.g. *Ficus lutea*, *Ochrosia oppositifolia*, etc; Burger, 2005). *Pisonia* trees have an ability to thrive in the acidic guano-laden soils (for example, acidic groundwater was encountered on Cousine Island – see Section 2.9 “Preliminary Site Inspection”). The remainder of the island is granitic hill slopes, which is more sparsely vegetated with grass, ferns and woodland. Fosberg (1983) provides a map of the vegetation distribution of Cousin Island (not shown). Soils on Cousin occur very thinly or are absent. Granitic hillsides are generally soil-free (TEMS, 2002). The plateau previously supported a coconut plantation, which was removed when the island was purchased as a nature reserve in 1968 (Burger, 2005). The origin mor-humus (A) soil horizon was stripped during plantation development (TEMS, 2002).

Cousine Island supports four mostly undisturbed forest types (*Pisonia grandis* (Summerhayes), *P. grandis-Ficus* spp., *Ficus* spp., and *Euphorbia pyrifolia* (Summerhayes)-*Ficus* spp.), which cover 35% of the island (Kelly and Samways, 2003). Alien plants, including the bamboo *Bambus vulgaris* and cotton (*Gossypium* spp.) are being removed (Samways, 2000). Some grassland areas occur along the southeast and northern coasts, and mowed grass areas, bamboo thicket and secondary woodlands occupy small parts of the central and northern parts of the island (Lawrance and Samways, 2003).
Both Cousin and Cousine have fresh or salty marshes. Cousin’s small permanent marsh (<0.1 ha, see Figure 7) supports a population of endangered terrapins, and Cousine’s marsh is also small (<0.1 ha) (Gerlach and Canning, 2001).

2.4 GEOLOGY

There is only limited information on the geology of the granitic islands of Cousine and Cousin, although the regional geology of the Seychelles is well described (e.g. Baker, 1963; Baker and Miller, 1963; Braithwaite, 1984). The granitic islands of the Seychelles are of Pre-Cambrian age (Miller and Mudie, 1961), and are the peaks of the submarine Mascarene Plateau, which is thought to be either part of the original single continent of Gondwanaland, or the remnants of a microcontinent that existed up to about 50 millions years ago (U.S. Department of Army, 1996). The depth of the submarine platform is predominantly up to 65 m (Camoin et al., 2004).

Few structural features are evident apart from jointing, and granites are considered anorogenic (lacking of tectonic disturbance) in character (Baker and Miller, 1963). Intrusion by basalts and olivine dolerites is evident; dykes are numerous on all islands, occurring as north-westerly swarms (van Straaten, 2002; Baker and Miller 1963).

The primary agro-mineral resources of the Seychelles are guano deposits and phosphatic sandstones, although most of the easily extractable guano has already been exported (van Straaten, 2002). Sandstones were formed by the leaching of guano, which converted the underlying sands to phosphatic sandstones and phosphatised reef rock (van Straaten, 2002). Seychelles’ soil types are described as either ferralitic soils or calcareous sandy soils (Food and Agricultural Organisation, 2007). The former are red soils originating from weathered granite and occurring over the slopes of mountains, while the latter exist on coastal plateaus.

The geology of Cousin and Cousine Islands is described by Baker (1963), as reproduced in Figure 9. On Cousin, the plateau calcareous deposits have combined with guano in the presence of *Pisonia* litter to form cemented phosphatic sandstones (Hill 2002, Hill et al., 2002). The soft phosphatic rock is described by Fosberg (1983) as a hard pan layer (possibly up to 1 m thick), but no information is available to determine what is below this (TEMS, 2002). A thin layer of soil comprising superficial sand and humus accumulations up to a few centimetres thick occurs over the Cousin plateau rock, although deeper alluvial deposits soils are found around marshes (Fosberg, 1983; Hill et al., 2002). The normal “mor” humus A-horizon was removed during the island’s conversion to a coconut plantation (TEMS, 2002; Fosberg, 1983).
2.5 HYDROGEOLOGY, GROUNDWATER USE AND WATER SUPPLY

The hydrogeology of the granitic Seychelles islands is somewhat unique, in that the Seychelles are the only mid-oceanic islands of granite, rather than basalt or coralline sediments (Payet et al., 2004). The Food and Agriculture Organisation (2007) indicated that groundwater resources are limited and often of high salinity and/or hardness. The groundwater associated with the raised reef-rock islands is generally too saline to be used (Baker, 1963). Seychelles’ granites are typically massive in nature and generally do not carry significant amounts of groundwater, although drilling has obtained minor groundwater resources from joints and fractures (Weaver, 2004). The calcareous sands of coastal plateaus can occur to thicknesses ranging from 14 to 25 m and are commonly high yielding and may represent good sources of freshwater (Weaver, 2004).

The first recorded groundwater investigations in the Seychelles were undertaken between 1970 and 1973, and focused on the coastal plateaux of Mahé, Praslin and La Digue; a brief history of groundwater exploration is given by the Seychelles National Climate Change Committee (2002). A groundwater study of the La Cour Plateau on Fregate Island undertaken by Weaver (2004) produced an estimated sustainable extraction of 35 m$^3$/d (pending construction of a harbour). It was recommended that pump intake elevations be restricted to 0.5 m MSL to avoid drawing the watertable below mean sea level, thereby limiting the risk of seawater intrusion.

Baker (1963) indicated that groundwater in the Seychelles is obtained from small springs, and from wells constructed at the inland portions of coastal plateaux on the smaller granitic islands. Baker (1963) also identifies the problem of saline water intake, and suggests the use of multiple wells (e.g. “skimming” wells; Asghar et al., 2002) to obtain groundwater supplies.

According to the SADC (South African Development Community) web site (www.sadcwscu.org.ls/programme/groundwater/prog_groundprog_list1.htm), the Water and Sewage Division of the Public Utilities Corporation (Seychelles Government) monitor...
groundwater systems on the main islands of Mahe, Praslin and La Digue, although no hydrogeological maps or databases are available. Reliable groundwater monitoring information was not available for either Cousin or Cousine Islands at the time of this study.

A description of the Cousin Island Research Station (TEMS, 2002) suggests that there is a freshwater aquifer below the central plateau of the island, and that groundwater springs are evident after heavy rainfall. Fosberg (1983) describes a drinking water well on Cousine Island, located in the central portion of an elongated depression that occurs at the north base of the granite hill, where it meets the phosphatic hard-pan layer. Results were provided relating to the pumping of groundwater from the “south borehole” on Cousine Island, and an average extraction rate of 23 kL/d occurred during the period August 2003 to April 2006. The average monthly rates of extraction are illustrated in Figure 10.

![Figure 10 – Average annual variation in pumping from Cousine Island’s “southern bore”](image)

Payet et al. (2004) report a deficit of 3,700 m$^3$/day between water supply and demand in the Seychelles in 1999. The main water management priority areas of the Seychelles Government (2004) focus on rectifying the present and future problems of sustainability in the water sector. Proposed actions include measures to reduce demand and increase conservation, and to increase potable water supply to the population (presently about 81,900). The total water withdrawal in the Seychelles in 2003 was 12.3 million m$^3$, of which 7% was used for agriculture (Food and Agriculture Organisation, 2007). It is noted that published estimates of nationwide water resources and use by the Seychelles Government (2004) are not in agreement with the values given by the Food and Agriculture Organisation (2007), although this discrepancy is of little relevance to the current study.

Small streams and rivers account for the majority of agricultural, domestic and industrial use, with surface water and groundwater abstraction in 2003 being 11.2 million m$^3$ and 0.3 million m$^3$, respectively (Food and Agriculture Organisation, 2007). Small dams have been built on Mahé since 1969 to enhance the reliability of water supplies. However, reservoir volumes are small and therefore susceptible to failure during prolonged drought when demand exceeds reservoir inflow (U.S. Department of Army, 1996). The majority of groundwater pumping in the Seychelles occurs on La Digue Island, where large changes in dry season watertable levels are reported and attributed to over-pumping (Payet et al., 2004). Potable water demand during dry periods is partly met through 1.0 million m$^3$/year of desalinated water from desalination plants on Mahe Island (2), Praslin Island, and La Digue Island (Food and Agriculture Organisation, 2007).
2.6 SURFACE HYDROLOGY AND CATCHMENT PROCESSES

The surface hydrology of the Seychelles’ granitic islands is characterised by very steep slopes (up to 1:4) containing numerous mostly ephemeral watercourses originating from central mountain ridges and flowing to the sea through choked “U”- and “V”-shaped catchments (Payet et al., 2004; Seychelles Ministry of Environment, 2007). The lateritic soils and the underlying rocks have a low water retention capacity, and as such, stream and river flows are characteristically episodic (Seychelles Ministry of Environment, 2007). The Seychelles Ministry of Environment estimate that only about 2% of rainfall actually enters the ground water for sustained infiltration into rivers and streams.

Stream flow data collection commenced on Mahe in 1960, using various triangular tin platted weirs in the major catchments, although several have been abandoned. The Seychelles Ministry of Environment describes the surface water monitoring of Seychelles streams, although no such monitoring has been undertaken within the study area, an expected position given the lack of surface water features.

On Cousin Island, a small seasonal rivulet directs runoff from the northern slope (TEMS, 2002). Channel erosion is evident on both Cousin and Cousine Islands (Fosberg, 1983). Some semi-permanent ponding occurs in depression on the north and east slopes of the Cousin Island hills and at the base of the hill, after prolonged rain.

2.7 TIDAL ASPECTS

Tidal data were obtained for Port Victoria, Seychelles. The average sea level from the data was 1.03 m (elevation datum unknown), and levels ranged from 0.2 m to 2.12 m for the period 2002-2007. The average tidal amplitude was 0.86 m.

2.8 PRELIMINARY SITE INSPECTION AND ADDITIONAL STUDY AREA DATA

A preliminary site inspection was undertaken by Flinders University student Anis Jacob during February 2007, and additional anecdotal comments have been provided by scientists from Cousine Island. The following results and anecdotal comments were subsequently compiled.

- Groundwater is taken mainly from the southern borehole of Cousine Island, in which there has been increases in electrical conductivity (EC) and chloride concentration, possibly due to seawater intrusion.
- In October 2001, measurements on Cousine Island indicated: the salinity of the southern borehole was high (the measurements provided are not consistent), and the water was acidic, with a pH of 3.2, while the northern borehole was less saline, but equally acidic, with a pH of 3.1. The low pH is attributed to guano deposits.
- On Cousine Island, groundwater is drawn from about 12 metres, from a borehole 15 metres deep.
• On Cousin Island, water is collected from a well about 5 metres deep, and then transferred to a reservoir higher up in the mountain. Cousin Island groundwater is used for most applications (including drinking if boiled), and is generally considered to be of better quality than that of Cousine Island.

• As at April 2006:
  o The extracted groundwater is reportedly used and then returned to the aquifer.
  o There is a marsh that forms behind the three buildings near the southern end of the island after considerable rainfall, and is located at 3-5 metres above sea level. It is reportedly influenced by the tide.
  o Drinking water is obtained from rainfall.

• Samples collected during the site visit produced the following water quality parameters:

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>South borehole, Depth 2.6 m</td>
<td>pH</td>
<td>3.09</td>
</tr>
<tr>
<td></td>
<td>EC (µS/cm)</td>
<td>1979</td>
</tr>
<tr>
<td></td>
<td>TDS (mg/L)</td>
<td>914</td>
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<tr>
<td>South borehole, Depth 20 m</td>
<td>pH</td>
<td>2.83</td>
</tr>
<tr>
<td></td>
<td>EC (µS/cm)</td>
<td>2100</td>
</tr>
<tr>
<td></td>
<td>TDS (mg/L)</td>
<td>947</td>
</tr>
<tr>
<td>North borehole, Depth 2.8 m</td>
<td>pH</td>
<td>3.28</td>
</tr>
<tr>
<td></td>
<td>EC (µS/cm)</td>
<td>1642</td>
</tr>
<tr>
<td></td>
<td>TDS (mg/L)</td>
<td>745</td>
</tr>
<tr>
<td>North borehole, Depth 10 m</td>
<td>pH</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td>EC (µS/cm)</td>
<td>1802</td>
</tr>
<tr>
<td></td>
<td>TDS (mg/L)</td>
<td>824</td>
</tr>
<tr>
<td>Source water</td>
<td>pH</td>
<td>2.64</td>
</tr>
<tr>
<td></td>
<td>EC (µS/cm)</td>
<td>1953</td>
</tr>
<tr>
<td></td>
<td>TDS (mg/L)</td>
<td>873</td>
</tr>
<tr>
<td>Water, beach dune, south borehole,</td>
<td>pH</td>
<td>7.28</td>
</tr>
<tr>
<td>Depth 3.5 m</td>
<td>EC (µS/cm)</td>
<td>1716</td>
</tr>
<tr>
<td></td>
<td>TDS (mg/L)</td>
<td>988</td>
</tr>
</tbody>
</table>

“Last Minute” Information: Cousine Island Wells

Information pertaining to Cousine Island bores and wells was provided at the “last minute”, on 7th November 2007 after a considerable amount of the modelling had already been completed. Fortunately and coincidentally, the position of bores in modelling activities, which assumed that the simulated “fresh groundwater” areas would be the most likely locations of bores, was actually quite similar to the true bore locations. Bore and well locations are given as an inset to Figure 6. The lateness of this information is the reason that some of the text of this report refers to an absence of information relating to bore locations.
3. AN OVERVIEW OF THE WATER RESOURCES OF SMALL ISLANDS

3.1 INTRODUCTION

This section is predominantly based on the Small Island Guidelines of UNESCO (1991). The following is provided as a general guide to the hydrology and water resources of very small islands. Given that the majority of this report is highly technical, it is hoped that this section provides some background for readers who may have limited hydrogeological understanding.

Freshwater can occur naturally on islands as both surface water and groundwater. Whether it occurs as surface water or groundwater, and in what quantities it occurs depend on many factors, including geology, topography, size of island, climate, vegetation and soil type, as given in UNESCO (1991):

- One of the most important factors influencing the hydrology of an island is climate, which drives the water balance of the island through changes in precipitation and evaporation.
- From a geological standpoint, freshwater quantities are influenced by the rock type of which the island is formed. In addition, soil characteristics can affect water resources and the water balance of islands by influencing surface runoff and evapotranspiration (i.e. evaporation and transpiration).
- Islands with steeper topography are more likely to have some surface water resources (e.g. streams and rivers) than those with flat topography.
- The size of an island is a very important factor since the likelihood of freshwater occurrence increases with increasing island size. This is because with increasing island size, the surface area (and therefore the total groundwater recharge) increases at a greater rate than the coastal length, which is the groundwater outflow boundary.
- Vegetation affects the hydrological cycle and therefore the water balance of the island by rainfall interception (e.g. rainfall caught and evaporated from canopies and leaf litter), transpiration, surface runoff and erosion.

These factors are described more broadly in the remainder of this section.

3.2 HYDROLOGICAL DEFINITIONS OF ISLANDS

Islands are commonly categorized from a hydrological standpoint by their size, whereby larger islands have similar geological features and problems as those found on continents, and smaller islands have their own characteristics and unique problems (Falkland, 1992). According to UNESCO (1991), small islands are those with an area not greater than 2000 km² or where the maximum width does not exceed 10 km. From a hydrologic perspective, a small island is considered to be one on which water resources are found in very limited supply and where special measures usually need to be implemented to develop and manage such resources (UNEP, 1998).

UNESCO (1991) define very small islands as those that have an area not greater than 100 km² or where the width is not greater than 3 km. Cousin and Cousine Islands are approximately 0.3 km² and therefore can be considered to be well within the category of
“Very Small Island”. These physiographical constraints mean that very limited options for the development of freshwater resources are likely to be available (UNESCO, 1991). From a hydrologic perspective, a very small island is considered to be one on which water resources development is even more limited than on a small island and where surface water resources are usually absent (UNEP, 1998).

3.3 IMPORTANT CONSIDERATIONS FOR SMALL-VERY SMALL ISLANDS

Small and very small islands have specific hydrological features that distinguish them from large islands and continents, for example, the impact of the sea is more pronounced on small and very small islands. Methods, techniques and approaches applied to characterizing the hydrology and water resources of large islands and continents cannot be applied to small and very small islands.

Problems of water availability on islands arise from difficult climatic conditions, such as capricious rainfall, low-storage geological conditions, or topographic features not suitable for the development of surface water resources (UNESCO, 1991). On most small and very small islands, permanent rivers and springs are scarce and occur only where rainfall is reasonably high and well distributed throughout the year, and where favourable geological and topographic conditions have developed (UNESCO, 1991). Groundwater is also usually in limited supply, and occurs as thin freshwater lenses overlying seawater. The seawater and freshwater are separated by a transition zone of thickness determined by both natural (e.g. permeability of the geological formation, tidal fluctuations) and artificial (e.g. man-induced extraction) influences (UNESCO, 1991). Extraction of freshwater from such lenses can easily induce saltwater intrusion and degrade freshwater quality if care is not taken in the design and operation of extraction facilities (UNEP, 1998).

Climate

As already mentioned the climate of an island is one of the major influences on the availability of the naturally occurring freshwater resources, since it affects the key input and output components of the water balance, which include precipitation and evaporation. These parameters greatly influence the water resources development on small and very small islands through its spatial and temporal distribution (UNESCO, 1991). Precipitation is far from constant because it is influenced by a range of weather conditions, such as, tropical cyclones, monsoons, El Nino-Southern Oscillation (ENSO) and Greenhouse Effect. These weather conditions can cause very wet and very dry periods. On some islands, periods of up to six months may elapse without significant rainfall (Falkland, 1992). Rainfall and climate of an island may also be greatly affected by its topography (e.g. in high islands, rainfall on the windward side is considerably higher than on the leeward side).

Geology and Morphology

Geology of small and very small islands greatly influences the occurrence and type of their water resources. This influence is mainly caused by the spatial distribution of rocks and soils of different permeability and porosity (UNEP, 1998). Islands with low permeability rocks are more suitable for surface water occurrence, whereas islands with high permeability rocks are more likely to have groundwater. Generally, availability of exploitable groundwater is
low when the permeability is low. Availability of exploitable groundwater is also limited in very high permeability formations, since mixing of freshwater and seawater is more likely.

Geomorphology is also an important factor, that is, size and shape of an island have great influence on groundwater occurrence. Larger and wider islands are more likely to have favourable conditions for freshwater occurrence than smaller narrower islands. The width and shape of an island are very important, since freshwater lens are more likely to occur on a circular and wider island than on an elongated and narrower island.

**Soil and Vegetation Coverage**

Soils play an important role in the hydrologic cycle by their influence on the surface runoff, evaporation and transpiration, and therefore affect water resources. Evapotranspiration and recharge are influenced by the soil water retention. Fine soils of high retention capacities enhance evapotranspiration and thus reduce the infiltration of precipitation. Coarse soils of low retention capacities allow quick infiltration of rainfall and therefore decrease evaporative losses.

The type and density of vegetation has a number of effects on the hydrological cycle and water occurrence. Vegetation slows surface runoff and therefore increases infiltration. It also intercepts part of the rainfall and causes transpiration, thus reducing recharge and, hence, decreasing the availability of groundwater resources.

**Groundwater Hydrology**

Groundwater occurs on small islands often in very limited quantities. However, it is the most important and reliable freshwater supply on small islands, especially very small islands, since surface water is not a common water resource on small islands and it is often completely absent from very small islands (UNESCO, 1991). Section 3.4 is intended to provide the reader with the basics of groundwater hydrology of small islands, concentrating on coastal aquifer conditions and freshwater lenses, which occur on many small and very small islands and are the main freshwater resources of small and very small islands.

**Saltwater Intrusion**

The coastal aquifers of small islands are, generally, fragile systems and can be severely contaminated by increased salinity due to saltwater intrusion, which is caused by excessive groundwater extraction from production wells.

Saltwater intrusion is a process that is caused by saltwater flowing inland in freshwater coastal aquifers. In a coastal aquifer, there is a direct contact between inland freshwater and marine saltwater, and this produces a transition zone between the two groundwater bodies (of different salinities) that takes the shape of a sloping interface. The interface extends downwards towards the bottom of the aquifer in the landward direction and adopts the form of a wedge resting on the aquifer floor (Figure 11). In a stable system, the interface is stationary and its position is a function of the groundwater hydraulic gradient causing freshwater flows from inland towards the sea (Saeed et al., 2002). Excessive groundwater pumping lowers the hydraulic potential in the fresh groundwater zone and the interface starts to move inland until a new hydraulic equilibrium is reached. This phenomenon is known as the saltwater (or seawater) intrusion.
The fresh groundwater and seawater are separated by a transition or mixing zone, as it is depicted in the above figure. The thickness of transition zone depends on both geological and hydraulic conditions, which include aquifer dispersivity, the heterogeneous nature of sediments and tidal fluctuations. In practice, it can be assumed as a sharp interface (i.e. no mixing) if it is thin in comparison with the freshwater thickness (UNESCO, 1991). This assumption is analogous to a membrane separation two immiscible fluids. However, in small islands, the transition zone represents a significant portion of the aquifer thickness and it usually cannot be neglected (UNESCO, 1991). The transition zone thickness, as well as the freshwater thickness, is not constant; they vary both spatially across islands and temporally due to climatic conditions and man-induced water extraction (UNESCO, 1991).

### 3.4 CHARACTERISATION OF FRESHWATER LENSES

The most abundant fresh groundwater resource in very small islands is in the form of a freshwater lens overlying the more dense seawater (Figure 12).
A number of factors influence the freshwater lens formation on an island, which includes the size and shape of the island, the recharge distribution and quantity, the permeability of sediments and tidal effects (Falkland, 1992). The transition zone between freshwater and seawater also exists. The freshwater resources of lenses are very susceptible to seawater intrusion through the process of saltwater up-coning and therefore must be very carefully managed to avoid overexploitation (Falkland, 1992). Saltwater up-coning is a process of saltwater intrusion that involves vertical saltwater movement under the influence of a pumping well. If the design and operation of pumping facilities are not selected carefully, the freshwater-saltwater interface will rise in the form of a cone under the operating well bottom and start impacting of bore water quality (Figure 13) (Saeed et al., 2002). The rising interface brings saline water with it and may eventually reach the well, forming a cusp-like form. In this case, degradation of well water quality occurs and requires the well to be shut down (Charlesworth et al., 2006).

Figure 13 - Saltwater up-coning beneath a well. (source: Aharmouch and Larabi, 2001)

**Calculating the Thickness of the Freshwater Lens**

All calculations and formulae in this section come from the Small Island Guidelines of UNESCO (1991).

Freshwater lenses are usually depicted with a highly exaggerated vertical scale (e.g. see Figure 14), which can lead to a misconception on the depth of a freshwater zone (Falkland, 1992). However, in reality, the freshwater lens thickness is often less than 10 m (Falkland, 1992). As mentioned before, the freshwater-saltwater transition zone can be taken as a sharp interface if its thickness is small when compared to the freshwater zone, and we adopt the sharp-interface assumption to allow for simplified calculations of the thickness of the freshwater zone to be made, as given below.
The following equation is used to calculate the freshwater head over mean sea level on a small circular island, with distance $r$ from the island’s centre. The total island recharge ($R_{Tot}$) can be compared to the discharge across the island coastline using Darcy’s Law, as:

$$R_{Tot} = 2\pi r^2 = 2\pi rK(1 + \alpha)h \frac{dh}{dr}$$  \hspace{1cm} (Equation 3.1)

Integrating and solving for the head $h$ gives:

$$h^2 = \frac{R(r_{max}^2 - r^2)}{2K(1 + \alpha)}$$  \hspace{1cm} (Equation 3.2)

where $R =$ recharge, (L/T)
$h =$ freshwater head over mean sea level, (L)
$K =$ hydraulic conductivity, (L/T)
$\alpha =$ specific weight ratio $= \gamma_f/(\gamma_s - \gamma_f)$, (non-dimensional)
$\gamma_f =$ specific weight of freshwater, (M/L$^2$/T$^2$)
$\gamma_s =$ specific weight of saltwater, (M/L$^2$/T$^2$) and
$r_{max} =$ effective island radius (L)

Similarly, $R_{Tot}$ can be computed for an elongated island (of width $a$) and combined with Darcy’s Law to determine $h$, as:

$$R_{Tot} = R\left(\frac{a}{2} - x\right) = K(1 + \alpha)h \frac{dh}{dx}$$  \hspace{1cm} (Equation 3.3)

where $x$ is the distance from the coast.
Integrating and solving for $h$ gives:

$$h^2 = \frac{R(ax - x^2)}{K(1 + \alpha)}$$  \hspace{1cm} (Equation 3.4)

Freshwater lens thickness is given by $\alpha h$, as can be seen in Figure 14. As UNESCO (1991) states, the above approximate formulation is acceptable when $R$ is moderate and the assumption of a sharp interface is reasonable.

As an example, using equation 3.2, we can calculate an approximate freshwater head above MSL (mean sea level) for a circular sand island of roughly the same size as Cousin Island. Using the recharge and $K$ values of sand from the Sections 4.2 and 4.3, we have $R$ is 0.0038 m/day and $K$ is 30 m/day. Also, using typical values of specific weight of freshwater and saltwater, we have that $\gamma_f$ is approximately 9.8 kN/m$^3$, $\gamma_s$ is approximately 10.1 kN/m$^3$, and $\alpha$ is 31.2. Finally, taking the effective radius $r_{\text{max}}$ to be 500 m, freshwater head at distance $r = 0$ m from the centre of the island (i.e. maximum lens thickness is at the centre of island) is $h = 0.7$ m MSL, and the maximum lens thickness, $\alpha h$, is 22 m. Obviously, these calculations don’t apply directly to Cousin Island because of the large proportion of granite of which the island is comprised.

Similarly, using equation 3.4, we can calculate an approximate freshwater head on an elongated sand island of about the same size as Cousine Island. Using the same recharge, $K$ and $\alpha$ values as in the previous example, and taking the width of the island to be 400 m, freshwater head at distance $x = 200$ m from the coast (i.e. at the centre of the island) is $h = 0.39$ m MSL, giving a maximum lens thickness, $\alpha h$, of 12 m. The above equations can also be used to show that the lens thickness is virtually proportional to the recharge, as demonstrated in Figure 15.
3.5 ALTERNATIVE FRESHWATER RESOURCES

It may be necessary to use artificial methods to provide a small island with freshwater when there are no sufficient freshwater resources due to the unfavourable geological, climatic and other conditions (Falkland, 1992). These include desalination, treatment of used water and importation of freshwater.

Desalination reduces the salt content of seawater and makes it suitable for drinking and other purposes. Since the seawater surrounds islands, desalination is a reasonable artificial method to employ, provided that the process is affordable and is within the community’s ability to operate it (UNESCO, 1991). Treatment of wastewater is a technically possible option, but since it includes sewage effluent and industrial discharges, its adoption is governed by the public health and aesthetic considerations and therefore may be problematic (UNESCO, 1991). Importation of freshwater to the small islands includes introduction of water through the submarine pipes when the island is close to the continent, and transporting water by ships when the island is more distant (UNESCO, 1991).
4. AN INSTRUCTIONAL GROUNDWATER FLOW AND SEAWATER INTRUSION MODEL OF COUSINE ISLAND

4.1 INTRODUCTION

In this section, an instructional groundwater model of Cousine Island is described. Due to a lack of hydrogeological, hydrological and hydro-chemical information for the island, a predictive management model is not able to be developed at this time. The model adopts somewhat hypothetical aquifer parameters and geometry, but is constrained by “best-guess” estimates, which are based predominantly on literature values.

It should be noted that the model developed for Cousine Island is a highly complex groundwater flow and transport model that accounts for the effects of salinity-induced density contrasts, plus considers the unsaturated part of the aquifer, albeit in a simplified manner (i.e. using “pseudo-soil functions”). The focus of the investigation is on the saturated part of the aquifer, rather than soil processes, and therefore simplifications of unsaturated processes are justified.

The development of models of this complexity would not normally be warranted for a study that is almost absent of hydrogeological field data, however, the objective of the modelling exercise is partly to demonstrate the application of this technology in assessing the groundwater resources and transport processes of the island. It is acknowledged that the complexity and detail of modelling is not reflective of data availability, and model predictions need to be viewed under strict precautionary principles. Three-dimensional (or at least quasi-three-dimensional) models of complete groundwater systems that incorporate density-dependent flow and transport processes are very uncommon, and only a few examples are evident in the literature, including MODHMS modelling by Werner and Gallagher (2006), and SEAWAT modelling by Schneider and Kruse (2005). Some of the more complex modelling presented in this report involves cutting-edge software and modelling techniques, and is likely to be unique in terms of setting, approach and detail.

4.2 CONCEPTUAL FRAMEWORK

Aquifer properties for the groundwater systems of both Cousin and Cousine Islands need to be assumed from published estimates, given the lack of field experimentation. In the case of water held in the granite parts of the islands, it is assumed that fractures account for the majority of the water holding and transmitting capacity. Groundwater hydraulic properties adopted for granite are the porous medium averages of fractured rock pathways; a common approach in the regional-scale assessment of fractured rock settings, and an appropriate assumption for this study, especially in light of the preliminary nature of the analysis and the lack of details relating to fracture aperture, spacing and connectivity.

The range of literature values for the representative hydraulic conductivity ($K$) of granite is large, e.g. $3.3 \times 10^{-6}$ m/s to $5.2 \times 10^{-5}$ m/s for weathered granite, $8 \times 10^{-9}$ m/s to $3 \times 10^{-3}$ m/s for fractured granite, and $3 \times 10^{-14}$ m/s to $2 \times 10^{-10}$ m/s for un-fractured, unweathered granite (Domenico and Schwartz, 1997). Further, there are issues of scale-dependency, i.e. representative hydraulic conductivity values are higher when considering larger scales, as highlighted by Martinez-Landa and Carrera (2005), who obtained granite hydraulic
conductivity values of about $10^{-12}$ m/s to $10^{-7}$ m/s (depending on the scale of measurement) from their study site.

The $K$ value for granite was assumed to be $10^{-3}$ m/d (or $1.16 \times 10^{-8}$ m/s) in this study. In the absence of any measurements, we adopt a sand $K$ of 30 m/d (or $3.47 \times 10^{-4}$ m/s); an estimate somewhat at the lower end of published values (e.g. Horn, 2006), because of the compacted/cemented nature of Cousine/Cousin sandy sediments. Specific yield ($S_y$; approximately equal to effective or “drainable” porosity) was taken as 0.30 for sand and 0.01 for granite. Porosity ($n$) values of 0.32 and 0.05 were used for sand and granite respectively (as indicated above, granite hydraulic parameters represent the voids due to fractures and joints).

Given the large relative differences in the hydraulic properties of the island sediments (i.e. a binary system of homogeneous and isotropic sand and granite aquifers), rainfall recharge to groundwater was also presumed to be highly spatially variable and contrasting between granite and sand values, with lower recharge occurring on areas of exposed granite and relatively higher recharge on sand. As an approximation, the groundwater recharge was assumed to be a direct proportion of rainfall, for example: $0.4P$ for sand, and $0.01P$ for granite (where $P$ is the rainfall); these being somewhat aligned with the assumed storage and permeability properties of each material, and with other studies of similar settings (e.g. Schneider and Kruse, 2005). Recharge rates used in this study for the exposed granite regions of the islands are constrained by the estimate of 2 % of rainfall discussed in Section 2.6. It should be noted that recharge estimates for mountainous granite aquifers are uncommon, and without any knowledge of the degree of fracturing, jointing and weathering of the islands’ exposed granite, it is very difficult to approximate hydraulic properties and recharge.

The recharge proportions of rainfall were approximated following a sensitivity analysis, as described in the “Modelling Results” sections. It is anticipated that the episodic nature of tropical rainfall events, combined with the steep topography are assumed to produce higher rates of runoff, and therefore lower rates of groundwater recharge (as a proportion of rainfall) into the granite compared to the sand areas. It should be noted that the estimation of recharge is actually a critical calculation in the investigation of the available groundwater resources of a closed system, and therefore it is highly recommended that further work be done to refine the estimate of recharge.

Fresh water inputs to the aquifer system were assumed to occur solely through rainfall recharge, which is partly lost to evapotranspiration. Evapotranspiration was represented in models in two ways: firstly, as the difference between recharge rate ($R$) and rainfall ($P$), i.e. the deficit ($R - P$) was attributed to runoff, evapotranspiration from the soil zone, and rainfall interception (i.e. direct evaporation of rainfall from the forest canopy, under-storage and leaf litter). Secondly, groundwater losses to direct evaporation and evapotranspiration were accounted for using the EVT package of the modelling code, which simulates a loss of groundwater when the watertable approaches the ground surface. An evaporative loss of 5 mm/d was adopted when the watertable was at the ground surface, and this evaporative loss rate reduced linearly to zero for watertable levels at 1 m below the land surface. The potential rate (note that actual evapotranspiration losses are dependent on watertable depths) of evapotranspiration loss (i.e. 5 mm/d) remained constant in time in both steady-state and transient simulations, because of the low inter-annual seasonality of evaporation (see Table 1).
In order to simulate the island’s aquifers, both hydraulic properties and aquifer geometry are required. The geometry of the two hydrostratigraphic units of the island (comprising sand and granite) was ascertained from the island’s topography, and under the assumption that the granite surface extends below the sand and eventually tapers to an elevation of about 60 m below MSL (see Section 2.4). The elevation of the bottom of the “transmissive” portion of the granite was essentially guessed as -80 m MSL, but is not expected to be a significant factor given the lower permeability of granite sediments. The following assumptions were made:

- The granite surface generally follows the contours of the exposed granite hill, with some reduction in slope as it extends below the sand. Ultimately, it was assumed that the granite asymptotes to a level of -60 m MSL, following the suggestion by Camoin et al. (2004) that the Mascarene Plateau seldom exceeds 65 m depth.
- The bottom of the transmissive portion of the granite aquifer was assumed to be at -80 m MSL.
- Sand covers a portion of the island as illustrated by Baker (1963; Figure 9), and is underlain by the granite, which follows an assumed surface geometry (as described above), which was ultimately approximated by interpolation of the exposed granite topography.

The two surfaces representing the top of sand and the top of granite are shown in Figures 16a and 16b.

Figure 16a – The top surface of granite (purple) and sand (blue to tan) layers (×2 vertical exaggeration) on the north-eastern side of Cousine Island.
4.3 MODELLING METHODOLOGY

In this study, the modelling code MODHMS (HydroGeoLogic Inc., 2006) was used, and model files were developed and results extracted using a combination of project-specific FORTRAN codes developed by Dr Adrian Werner, plus the graphical user interface programs: Groundwater Vistas (ESI, 2004) and ViewHMS (Shareware by HydroGeoLogic Inc.). The reader is directed to the user manuals of the various computer programs for details on the functioning and underlying mathematics.

The hydrogeology of the island is simulated using a “grid” of rectangular prisms, each of which represents a block of homogeneous (i.e. uniform), isotropic (i.e. non-directional) aquifer material. A multi-layered approach was necessary, as distinct from a single-layer or vertically integrated model, to capture the expected vertical variability in flow, pressure head, salinity and water density. The model of Cousine Island comprises a finite-difference grid of 6 layers, 40 rows (rows are east-west) and 45 columns (columns are north-south) of 25 m by 25 m square cells. The total model grid therefore comprises 10,800 cells, although of these, only 3,803 are active (i.e. switched “on”) and the remainder are inactive. Each layer represents a “horizon” through the island, as illustrated conceptually in the figure below.
Layers are mostly horizontal, as shown in Figure 17, with some variation to the layer surfaces required to make sure that each model cell coincided with only sand or granite (because model cells are not able to represent composites of two different aquifer materials). This approach to the vertical discretisation of the groundwater domain follows recommendations by Werner and Gallagher (2006), who found that errors can be introduced if the vertical sub-division produces steeply undulating layers. The elevations of model layers, as shown in Figure 17, are given in the table below. Note that layer thicknesses were not uniform - the thinnest layers are those nearest mean sea level; that is, the zone of most importance in this study, while layers 1 and 6 represent parts of the aquifer that are of least interest (because the uppermost and lowermost parts of the aquifer are likely to be dry or saline), and are included using a coarser representation (i.e. a thicker layer). Each layer of model cells is of different extent in plan area, with layers 1 and 6 being of smallest and largest area extents, respectively. Figure 18 provides a plan view of each model layer.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Top of Layer (m MSL)</th>
<th>Bottom of Layer (m MSL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt;68.2</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>-5</td>
</tr>
<tr>
<td>4</td>
<td>-5</td>
<td>-10</td>
</tr>
<tr>
<td>5</td>
<td>-10</td>
<td>-20</td>
</tr>
<tr>
<td>6</td>
<td>-20</td>
<td>-80</td>
</tr>
</tbody>
</table>

The model adopts a “variably saturated” approach to the representation of the subterranean sand and granite materials. This way, individual model cells are able to “dry out” without the numerical problems commonly associated with de-saturation that arise using MODFLOW-based codes.
The ocean is represented as a constant water level of 0m MSL (i.e. tidal fluctuations are ignored). Constant head cells representing the ocean are assigned to the upper parts of the aquifers that are submerged, i.e. at the interface between the ocean and the sand/granite aquifers. Constant head cells are shown as diamond symbols in Figure 18. It simulations that incorporate seasonality (i.e. transient simulations), all aquifer “stresses” (e.g. pumping, recharge, etc) are averaged to monthly values; a common assumption in groundwater modelling studies because of the expected attenuation of the groundwater response to climatic drivers.

As with most studies involving seawater intrusion, the determination of an accurate initial or pre-development salinity condition is a challenging undertaking, and often approximated as the long-term (steady-state) condition in the absence of anthropogenic impacts (e.g. Bobba, 2002). Steady-state simulations (i.e. equilibrium or long-term modelling scenarios) are used in this study to both develop initial conditions for transient simulation (i.e. time-variant modelling scenarios that are inclusive of changes in climatic stresses), and also to “calibrate” groundwater recharge and examine possible flow and transport processes. Steady-state simulations are also used to evaluate the state of the system, both in the absence of, and inclusive of groundwater pumping, while transient simulations are used to explore possible seasonality in groundwater conditions. The recharge is designated as outlined above in Section 4.2, except in steady-state simulations, the average annual rainfall is used (i.e. 1715 mm/annum or 4.695 mm/day), rather than dynamic climatic drivers (as are adopted in transient simulations). Steady-state seawater intrusion simulations are achieved using MODHMS by simply running the model for a “long time”, and stopping the simulation when the salinity and hydraulic condition of the aquifers no longer vary significantly in time. Steady-state simulations were created by running the model for 200,000 days (548 years) with constant stresses on the system. It is worth noting that each steady-state simulation required between 16 and 30 hours of run time on an Intel® Core™ Duo Processor (2.13 GHz), and therefore, model run-times were somewhat of a limiting factor in the investigation.

Steady-state simulations were used to explore the effects of the assuming different recharge (R) values on the salinity and head condition of the aquifers, and several different R combinations were evaluated, including: 0.2P for sand and 0.005P for granite, 0.4P for sand and 0.01P for granite, 0.6P for sand and 0.015P for granite, and 0.8P for sand and 0.02P for granite (where P is the rainfall). This sensitivity analysis of R was used to adopt the final R combination (i.e. as used in simulations of groundwater pumping) by comparing steady-state salinity contours to anecdotal evidence (albeit unsubstantiated) of the extent of groundwater salinity on Cousine Island.

“Predictive” or “instructive” transient simulations (note that these are instructive rather than predictive because of a lack of constraint on model hydraulic parameters) adopted a simulation time period of 40 years, and used historical rainfall in the form of monthly averages (from Cousine Island data – see Figures 4 and 5) to provide the temporal variability in aquifer stresses due to climatic variation. The initial condition was adopted from the steady-state simulation with the corresponding recharge rate (see the following section).
Figure 18 – Model layers. Diamonds represent specified head ocean boundary conditions. Green cells represent sand, while yellow cells represent granite.
4.4 MODELLING RESULTS – STEADY-STATE SIMULATIONS

“Steady-state” simulations were not strictly steady-state per se, but were in fact long-term simulations of 200,000 days (548 years) duration; a necessary undertaking because of the numerical difficulties of obtaining steady-state solutions to the variably saturated, density-dependent problem. Henceforth in this report, the term “steady-state” is used for long-term, constant-stress simulations, which may or may not have actually reached steady-state (i.e. equilibrium) conditions. The results of steady-state simulations are defined in terms of groundwater levels, fluxes and salinity distributions, and these vary in three-dimensions, and therefore, given the large amount of model output data, only a selection of the results from the various simulations is presented.

In the first instance, four “steady-state” (i.e. long-term) simulations were generated to evaluate the influence of different groundwater recharge rates on salinity and watertable distributions. Groundwater pumping was neglected, because an indication of the “natural” state of the system was required (i.e. to adopt as the initial condition in transient simulation). Models runs included:

- Steady-state simulation 1 (SSS1) - 0.2P for sand and 0.005P for granite
- Steady-state simulation 2 (SSS2) - 0.4P for sand and 0.01P for granite
- Steady-state simulation 3 (SSS3) - 0.6P for sand and 0.015P for granite
- Steady-state simulation 4 (SSS4) - 0.8P for sand and 0.02P for granite

A complete set of simulation results, including hydraulic heads, concentrations, flow directions and water budgets for all 6 layers, is given in Appendix C for SSS3. Appendix C also provides a more complete description of the various model outputs. Interpretation of the modelling and a selection of results for SSS1 to SSS4 are given in the following.

SSS1

The case SSS1 involved the lowest rate of recharge, and therefore, it is expected that this simulation will produce the smallest available fresh groundwater on Cousine Island, in terms of watertable height and extent of salinisation. The water budget for the simulation is given in Table 4. Note that modelling scenarios SSS1 to SSS4 do not include any groundwater pumping.

The water budget for SSS1 involves 106.4 kL/d of total island recharge, of which about 9% is lost to direct evapotranspiration of groundwater (other evapotranspiration losses are accounted for by the difference between rainfall: P and recharge). The other 91% of groundwater discharges to the sea in the SSS1 case. The re-circulation of seawater is apparent in transects of model-generated velocities (results not shown), and is also demonstrated in the large influx of seawater to the island, which is subsequently returned to the ocean through re-circulation; a well-established phenomenon in seawater-freshwater interface settings.
Table 4 – Water balance fluxes at the end of simulation (in m$^3$/d or kL/d) for SSS1

<table>
<thead>
<tr>
<th>Water balance component</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
<th>Layer 6</th>
<th>Entire Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recharge (IN)</td>
<td>2.96</td>
<td>45.5</td>
<td>58.0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>106.4</td>
</tr>
<tr>
<td>Inflow from layer above (IN)</td>
<td>0.00</td>
<td>2.96</td>
<td>48.0</td>
<td>124.4</td>
<td>291.3</td>
<td>1.84</td>
<td>-</td>
</tr>
<tr>
<td>Inflow from layer below (IN)</td>
<td>0.00</td>
<td>0.47</td>
<td>420.6</td>
<td>326.7</td>
<td>1.76</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>Inflow of seawater (IN)</td>
<td>0.00</td>
<td>0.00</td>
<td>111.2</td>
<td>264.4</td>
<td>36.7</td>
<td>0.01</td>
<td>412.3</td>
</tr>
<tr>
<td>Discharge to layer above (OUT)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.47</td>
<td>420.6</td>
<td>326.7</td>
<td>1.76</td>
<td>-</td>
</tr>
<tr>
<td>Discharge to layer below (OUT)</td>
<td>2.96</td>
<td>48.0</td>
<td>124.4</td>
<td>291.3</td>
<td>1.84</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>Groundwater discharge to the ocean (OUT)</td>
<td>0.00</td>
<td>0.00</td>
<td>504.3</td>
<td>3.51</td>
<td>1.30</td>
<td>0.10</td>
<td>509.2</td>
</tr>
<tr>
<td>Evapotranspiration of groundwater (OUT)</td>
<td>0.00</td>
<td>0.96</td>
<td>8.83</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>9.78</td>
</tr>
<tr>
<td>Change in stored groundwater</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

An image of some of the results is given in Figure 19 for Layer 4. Layer 4 represents aquifer material between elevations of -15 m MSL to -2.5 m MSL, and therefore is likely to be indicative of the water quality and hydraulic conditions that are presently encountered by bores on the island. Figure 19 presents a three-dimensional representation of the watertable, velocity vectors and salinity distribution in Layer 4, and shows the northern side of the island. In the absence of geographical landmarks, it is difficult to interpret the results shown in Figure 19, and therefore, the more traditional contours of salinity are provided in Figure 20 (for Layer 4 only).

Comparison between Figure 20 and the geology of the area (i.e. Figure 18) highlight that within Layer 4, none of the sand areas contained deep potable groundwater. This result is further demonstrated in the complete set of salinity predictions (i.e. for all layers) given in Appendix A, which shows that fresh groundwater is simulated only in Layers 1 and 2 (note that Layers 1 and 2 are predominantly above mean sea level; layer elevations are listed in Table C1). As this is not the observed situation, it is most likely that the recharge rates adopted in SSS1 (relative to the assumed $K$ and to a lesser degree to storage parameters) are lower than are actually occurring on Cousine Island.
Figure 19 – A sample of the results, in terms of velocity vectors, hydraulic heads and concentrations in Layer 4 of the model, from the case: SSS1

Figure 20 – Relative salinity contours (e.g. 1.0 is seawater or 50,000 µS/cm, 0.03 is equivalent to 1,500 µS/cm) from Layer 4 of the case: SSS1
The maximum height of the hydraulic head in the model case SSS1 occurred in the granitic centre of the island (as expected) and reached elevations of 4.1 m MSL in Layer 4, 4.2 m MSL in Layer 3, 4.4 m MSL in Layer 2 and 5.8 m MSL in Layer 1. The vertical gradient in heads, whereby higher heads are predicted in the upper layers is an expected outcome in a system where the sole source of fresh groundwater is through rainfall recharge at the land surface, which subsequently travels downward and laterally (under hydraulic gradients) to the lower layers, eventually to the sea.

It was noted that the seawater-freshwater distribution in Layer 6 (i.e. the lower granite layer) changed at an extremely slow rate during the 548-year simulation; an outcome of the low assumed $K$ value. It is quite likely that the salinity distribution in this lower layer had not reached an equilibrium state; however longer duration simulations were not undertaken due to constraints on model run times, which exceeded 25 hours for some of the 548-year simulations. The small rates of groundwater transfer between Layer 6 and the overlying Layer 5 were small, and therefore the non-equilibrium state of Layer 6 is not expected to influence the results significantly, although further modelling to ascertain the steady-state condition of the system is warranted.

SSS2

Case SSS2 adopted a higher groundwater recharge rate compared to SSS1, in which the results indicated that a higher rate of recharge was necessary to produce indicative salinity distributions. The water budget for the SSS2 simulation is given in Table 5.

<table>
<thead>
<tr>
<th>Water balance component</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
<th>Layer 6</th>
<th>Entire Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recharge (IN)</td>
<td>5.93</td>
<td>91.1</td>
<td>115.9</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>212.9</td>
</tr>
<tr>
<td>Inflow from layer above (IN)</td>
<td>0.00</td>
<td>5.93</td>
<td>95.5</td>
<td>178.2</td>
<td>420.0</td>
<td>3.62</td>
<td>-</td>
</tr>
<tr>
<td>Inflow from layer below (IN)</td>
<td>0.00</td>
<td>0.71</td>
<td>593.7</td>
<td>460.4</td>
<td>3.16</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>Inflow of seawater (IN)</td>
<td>0.00</td>
<td>0.00</td>
<td>154.9</td>
<td>371.5</td>
<td>52.5</td>
<td>&lt;0.01</td>
<td>578.9</td>
</tr>
<tr>
<td>Discharge to layer above (OUT)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.71</td>
<td>593.7</td>
<td>460.4</td>
<td>3.16</td>
<td>-</td>
</tr>
<tr>
<td>Discharge to layer below (OUT)</td>
<td>5.93</td>
<td>95.5</td>
<td>178.2</td>
<td>410.0</td>
<td>3.62</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>Groundwater discharge to the ocean (OUT)</td>
<td>0.00</td>
<td>0.00</td>
<td>771.3</td>
<td>6.43</td>
<td>1.61</td>
<td>0.47</td>
<td>779.8</td>
</tr>
<tr>
<td>Evapotranspiration of groundwater (OUT)</td>
<td>0.00</td>
<td>2.19</td>
<td>9.94</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>12.1</td>
</tr>
<tr>
<td>Change in stored groundwater</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

As expected, the SSS2 total recharge rate (213 kL/d) was approximately twice the rate of SSS1. The higher rate of recharge produced an increased evapotranspiration loss, which was about 6% of recharge – a smaller proportion of rainfall compared to case SSS1. In general, the higher rate of recharge produced greater re-circulation (of seawater) fluxes.

A 3D image is produced for the conditions occurring in Layer 4 for case SSS2 – similar to that developed for case SSS1 (Figure 19), as shown in Figure 21. The vertical scales (i.e. elevation) of Figures 19 and 21 are identical, to give a perspective of the relative difference in the watertable mound between the two simulations. The difference between the landward
extents of seawater intrusion between the two cases is difficult to ascertain by comparing Figures 19 and 21, and therefore, as previously, predictions of salinity distributions in all layers is provided (see Appendix B).

Figure 21 – Velocity vectors, hydraulic heads and concentrations in Layer 4 of the model, from the case: SSS2.

It is worth noting that a TDS greater than 800 mg/L (approximately 1350 µS/cm) is described as “poor”, and greater than 1000 mg/L (approximately 1700 µS/cm) is described as “unacceptable” in the Australian Drinking Water Guidelines (NHMRC, 2004). The 0.03 relative salinity iso-chlor (contour), which is equivalent to about 1500 µS/cm, is adopted in this report as indicative of the limit of potable water within the aquifer systems. While there are larger areas of <1500 µS/cm in the sand aquifer for Case SSS2 compared to Case SSS1, most importantly in Layers 3 and 4 (Figures A3, A4, B3, B4 of Appendices A and B) from which groundwater pumping is likely to occur, the availability of fresh groundwater appears to be overly limited in both cases (SSS1 and SSS2) compared to anecdotal evidence and from groundwater abstraction information (see Sections 2.5 and 2.8). Therefore, the rate of groundwater recharge required by the model is higher than that applied in Case SSS2 (note that the estimate of recharge is intimately linked to the adopted $K$ values, which are rough approximations from textbook ranges).

The maximum height of the hydraulic heads in the model case SSS2 reached elevations of 7.1 m MSL in Layer 4, 7.3 m MSL in Layer 3, 7.6 m MSL in Layer 2 and 10.5 m MSL in Layer 1. Differences in the height of the groundwater mounds in Cases SSS1 and SSS2 are evident in the comparison of Figures 19 and 21.
SSS3

The results of Case SSS2 indicated that a higher rate of recharge was necessary in the model to re-produce the expected saltwater-freshwater distribution. Therefore, Case SSS3 was generated and run. In order to gain an enhanced appreciation of the model output and predicted state of Cousine Island’s aquifers, a complete set of results are provided in Appendices C and D for this model scenario.

The water budget for Case SSS3 is given in Table C2 (Appendix C). Of the SSS3 total recharge rate of 319 kL/d, only 4.5% was utilised as direct groundwater evapotranspiration. The results indicate a general trend of greater re-circulation of seawater (i.e. higher fluxes of boundary inflow and discharge to the sea) generated by higher recharge rates.

A 3D image is again produced for the Layer 4 conditions for case SSS3 (Figure 22). The vertical scale of Figure 22 is again the same as previous 3D results (Figures 19 and 21). In order to illustrate the greater availability of fresh groundwater in upper parts of the aquifer, a 3D image of model predictions for Layer 3 is given in Figure 23, which illustrates the higher watertable conditions and lower salinity of Layer 3 compared to Layer 4. The salinity distributions in all layers are given in Appendix D. Comparison between Figures B3, B4, D3 and D4 indicate that some fresh groundwater is present in the sand aquifer (i.e. albeit only in Layer 3) in Case SSS3, whereas in Case SSS2 only very minor amounts of fresh groundwater are predicted to occur (i.e. in sand aquifers in either Layers 3 or 4).

Figure 22 – Velocity vectors, hydraulic heads and concentrations in Layer 4 of the model, from the case: SSS3.
Figure 23 – Velocity vectors, hydraulic heads and concentrations in Layer 3 of the model, from the case: SSS3.

The maximum height of the hydraulic heads in the model case SSS3 reached elevations of 9.7 m MSL in Layer 4, 10.0 m MSL in Layer 3, 10.4 m MSL in Layer 2 and 14.4 m MSL in Layer 1. It is worth noting that by the 1:40 Ghyben-Herzberg “rule-of-thumb”, these watertable elevations indicate large depths of freshwater with the granite body; this being substantiated by the large amount of freshwater in Layer 6 of the model (see Figure C2), which is bounded by a lower surface of -80 m MSL.

Velocity vectors from Case SSS3 are given for all model layers in Figure C3. The following interpretations are made of the results of Figure C3 (in combination with the water budget values of Table C2):

- The vast majority of groundwater discharge to the sea occurs through the boundary conditions of Layer 3, due to the density-driven re-circulation effect, whereby fresh groundwater discharges over the top of a slower moving saltwater body.
- Large rates of groundwater flux, being discharge from the shallow upper regions of the sand aquifer to lower parts of the sand aquifer are evident in Layer 2, and appear to be synonymous with gravity drainage of sand aquifer groundwater following the shape of the underlying granite surface.
- A large upward transfer of groundwater occurs from Layer 4 to Layer 3, induced by convective fluxes and the density-related circulation patterns, whereby fresh groundwater from lower in the aquifer is forced upwards over the more dense body of saltwater. This convergence of deeper fresh groundwater and upper aquifer fresh groundwater discharging at the ocean through the upper portion of the sand aquifer is an important process in terms of managing the access to fresh groundwater reserves. That is, it supports the general practice of obtaining groundwater from multiple shallow bore “spears”, rather than from a small number of deeper bores, as discharging fresh groundwater occurs predominantly in the upper aquifer, while more
“stagnant” groundwater that acts to stabilise the position of the saltwater-freshwater interface, occurs in the lower parts of the aquifer.

Appendix C (Figures C4 and C5) shows a series of transects through the island illustrating cross-sections of groundwater salinity. This perspective of the predicted salinity from Case SSS3 highlights a number of important processes that occur in the model, namely:

- A thin wedge of freshwater overlying saline groundwater is simulated in the sand aquifer, and is most distinct in Rows 18 and 24, and Columns 19 and 24 of the model. The presence of this thin freshwater lens is a significant phenomenon in terms of accessing fresh groundwater resources, and leads to the conclusion that shallow spears may be necessary to access this water.
- The high hydraulic heads of the granite aquifer that appear within the centre of the island cause the saltwater-freshwater interface in the lower parts of the aquifer (i.e. in the deep granite aquifer) to extend seaward in some places (e.g. Row 29, and Columns 19 and 24), to the point that freshwater trapped in granite underlies more saline water in the sand aquifer. It should be noted that a somewhat simplified representation of seawater intrusion dynamics are adopted for the lower granitic realms of the system, however the general patterns of salinity are in accordance with similar studies of multi-layered systems (e.g. Werner, 2004). It is also worth mentioning that the system may not be in steady-state, particularly the granite aquifer, and that the actual equilibrium position of the freshwater-saltwater interface may be different to that shown in Figure C5.

While the results of Case SSS3 show some similarities to anecdotal evidence of the state of the Cousine Island aquifer, a higher rate of recharge was tested to further explore the potential aquifer condition and the related flow and transport processes.

### SSS4

Case SSS4 represents a very high rate of recharge in the sand aquifers, but this rate may be plausible if runoff from the granite hill occurs, and adds to the recharge of the sand aquifer. Presently, there is no information or conceptual understanding of surface runoff processes on the island, and therefore it is not possible to approximate the actual rate of recharge using surface water balance approaches, e.g. \( R = P - RO - E - I \), where \( R \) is recharge, \( P \) is rainfall, \( RO \) is surface runoff, \( E \) is evapotranspiration from the soil zone, and \( I \) is vegetation canopy interception loss. The groundwater model water budget for the SSS4 simulation is given in Table 6.
## Table 6 – Water balance fluxes at the end of simulation (in m$^3$/d or kL/d) for SSS4

<table>
<thead>
<tr>
<th>Water balance component</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
<th>Layer 6</th>
<th>Entire Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recharge (IN)</td>
<td>11.9</td>
<td>182.1</td>
<td>231.8</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>425.8</td>
</tr>
<tr>
<td>Inflow from layer above (IN)</td>
<td>0.00</td>
<td>11.9</td>
<td>190.3</td>
<td>294.4</td>
<td>565.0</td>
<td>6.77</td>
<td>-</td>
</tr>
<tr>
<td>Inflow from layer below (IN)</td>
<td>0.00</td>
<td>1.28</td>
<td>863.2</td>
<td>636.7</td>
<td>5.47</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>Inflow of seawater (IN)</td>
<td>0.00</td>
<td>0.00</td>
<td>209.3</td>
<td>509.5</td>
<td>75.1</td>
<td>&lt;0.01</td>
<td>800.8</td>
</tr>
<tr>
<td>Discharge to layer above (OUT)</td>
<td>0.00</td>
<td>0.00</td>
<td>1.28</td>
<td>863.2</td>
<td>636.2</td>
<td>5.47</td>
<td>-</td>
</tr>
<tr>
<td>Discharge to layer below (OUT)</td>
<td>11.9</td>
<td>190.3</td>
<td>294.4</td>
<td>565.0</td>
<td>6.77</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>Groundwater discharge to the ocean (OUT)</td>
<td>0.00</td>
<td>0.00</td>
<td>1187</td>
<td>12.4</td>
<td>2.08</td>
<td>1.30</td>
<td>1209</td>
</tr>
<tr>
<td>Evapotranspiration of groundwater (OUT)</td>
<td>0.00</td>
<td>4.95</td>
<td>12.7</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>17.6</td>
</tr>
<tr>
<td>Change in stored groundwater</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

In Case SSS4, direct groundwater evapotranspiration increased slightly compared to previous cases, but reduces relative to rainfall recharge to 4.1%. The same general pattern of groundwater fluxes occurred in all four cases, with the magnitude of fluxes related (non-linearly) to the rate of groundwater recharge.

3D images of the results from Layers 4 and 3 are provided in Figures 24 and 25, respectively for Case SSS4 and salinity distributions for all layers are illustrated in Appendix E. With this high rate of groundwater recharge, the amount of fresh groundwater persisting in sand aquifers in the lower parts of the aquifer (i.e. Layer 4 to 6, and to a less degree Layer 3) is still quite marginal, although according to the model results there is a pocket of fresh groundwater occurring in Layer 3 near the central part of the island, i.e. at the most inland extent of the sand deposits. Hydraulic heads in Case SSS4 reached elevations of 12.1 m MSL in Layer 4, 12.4 m MSL in Layer 3, 13.0 m MSL in Layer 2 and 17.9 m MSL in Layer 1.
Figure 24 – Velocity vectors, hydraulic heads and concentrations in Layer 4 of the model, from the case: SSS4.

Figure 25 – Velocity vectors, hydraulic heads and concentrations in Layer 3 of the model, from the case: SSS4.
Interpretation of the Results of SSS1 to SSS4

The lack of field observation data makes calibration of the model impossible, and the selection of such parameters as hydraulic conductivity $K$, recharge $R$ and solute transport parameters of porosity and dispersion coefficients were based almost entirely on literature values. In general, the availability of deep freshwater in sand aquifers on the island was of limited extent, even in the highest recharge case SSS4. Further manipulation of model parameters in the absence of field data (e.g. such as watertable and groundwater salinity observations, or aquifer hydraulic properties from pump tests) was not considered a worthwhile pursuit. However, it is conceivable that adopting different hydraulic parameters, e.g. more transmissive aquifer properties for granite, in the conceptualisation would have provided reasoning to use higher granite recharge rates, and would likely have led to a larger overall freshwater lens. Future investigations should explore alternative hydraulic property combinations (based on field analyses) for the island’s sand and granite aquifers.

The model simulations described in this report are not sufficiently constrained by field data to provide absolute salinity and watertable predictions because of the limitations mentioned above. Model results should be interpreted to provide an indication of the relative impacts of different pumping scenarios, and aim to afford the managers of the island reasoning for adopting future groundwater management practices and for the construction of any additional groundwater pumping infrastructure.

While the aim of the model runs SSS1 to SSS4 was to “calibrate” aquifer recharge, it was not possible to provide sufficient comparison between simulation results and field observations because of the uncertainties of reported groundwater measurements. In the absence of a proper field sampling campaign, the recharge adopted in the modelling case SSS3 was used arbitrarily in pumping simulations. “Steady-state” model simulations (i.e. using constant aquifer stresses of recharge and pumping) were used to evaluate two different pumping scenarios, as:

1. A single “deep aquifer” bore pumping at the average rate of abstraction from metered data described in Section 2.5.
2. Six “shallow aquifer” bores, each pumping at one-sixth the rate of abstraction used in (1).

At the time of development of these models, the precise location of existing pumping bore/s on Cousine Island was unfortunately not clear, although email liaisons with the island’s staff provided a better indication of this post-modelling, and the actual bore locations are given in Figure 6. In the absence of this information, the locations of bores were based on likely best locations, as illustrated in Figure 26.
Figure 26 – The locations of modelled groundwater bores for the two simulations: SSS5 and SSS6.

**SSS5: Groundwater Pumping Case 1**

The first pumping scenario was case SSS5, which adopted SSS3 stresses plus a deep bore as sited in Figure 26. The bore is assumed to be able to access groundwater over the entire sand thickness, i.e. 3 m MSL down to -3.7 m MSL at the bore site. The SSS5 water budget is given in Table 7.

<table>
<thead>
<tr>
<th>Water balance component</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
<th>Layer 6</th>
<th>Entire Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recharge (IN)</td>
<td>8.89</td>
<td>136.6</td>
<td>173.9</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>319.3</td>
</tr>
<tr>
<td>Inflow from layer above (IN)</td>
<td>0.00</td>
<td>8.89</td>
<td>131.0</td>
<td>219.9</td>
<td>480.6</td>
<td>5.30</td>
<td>-</td>
</tr>
<tr>
<td>Inflow from layer below (IN)</td>
<td>0.00</td>
<td>0.99</td>
<td>706.2</td>
<td>541.8</td>
<td>4.40</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>Inflow of seawater (IN)</td>
<td>0.00</td>
<td>0.00</td>
<td>179.7</td>
<td>434.8</td>
<td>63.9</td>
<td>&lt;0.01</td>
<td>678.5</td>
</tr>
<tr>
<td>Discharge to layer above (OUT)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.99</td>
<td>706.2</td>
<td>541.8</td>
<td>4.40</td>
<td>-</td>
</tr>
<tr>
<td>Discharge to layer below (OUT)</td>
<td>8.89</td>
<td>131.0</td>
<td>219.9</td>
<td>480.6</td>
<td>5.30</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>Groundwater discharge</td>
<td>0.00</td>
<td>0.00</td>
<td>947.9</td>
<td>9.77</td>
<td>1.88</td>
<td>0.90</td>
<td>960.4</td>
</tr>
<tr>
<td>to the ocean (OUT)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evapotranspiration of</td>
<td>0.00</td>
<td>3.47</td>
<td>11.0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>14.5</td>
</tr>
<tr>
<td>groundwater (OUT)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumping (OUT)</td>
<td>0.00</td>
<td>0.00</td>
<td>23.0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>23.0</td>
</tr>
<tr>
<td>Change in stored</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>groundwater</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Groundwater abstraction is shown to occur entirely from layer 3, because the layers above (layers 1 and 2) are made to become unsaturated by the bore pumping or are inactive. Overall, the water budget figures for SSS5 are very similar to SSS3, which is an identical situation.
except SSS3 has no groundwater pumping. According to the model, groundwater pumping has an insignificant impact on direct evapotranspiration of groundwater. It should be noted that no account has been made of the increased recharge that might occur in the form of returned flow of pumped groundwater to the aquifer; a conservative assumption. Overall, the simulated pumping appears to have only a minor effect on the island’s overall water budget, at least for the assumed hydraulic parameters and aquifer stresses.

The results from the model’s layers 3 and 4 are again given in 3D (Figures 27 and 28). The influence of the pumping bore is clear from comparisons between Figure 22 and Figure 27, and between Figure 23 and Figure 28. Differences between SSS3 and SSS5 were determined exactly, and are illustrated for layer 3 in Figure 29. The pumping bore produced a maximum watertable drawdown of 230 mm in the aquifer adjacent to the well; this being considered a relatively minor hydraulic impact. It should be noted that well drawdown in the model does not account for well losses, and therefore any future comparisons with measured values of water levels in pumping bores need to account for this.

The salinity of the aquifer at some 25 metres seaward of the bore increased by 0.116 (in salinity units relative to seawater) or an EC increase equal to 5,800 µS/cm greater than the “no-pumping” EC of <100 µS/cm. The increase in groundwater salinity caused by groundwater pumping is shown in Figure 29, as is the extent of the cone of depression around the bore. The groundwater being pumped from the well was a mixture of fresh and saline groundwater occurring in the vicinity of the well, and was predicted to be about 1900 µS/cm.

The predicted value for pumped groundwater salinity of EC 1900 µS/cm is similar to reported well salinity values (see Section 2.8, Table 2), a somewhat surprising outcome given the arbitrary nature of selected parameters. The similarity between this value and that observed at the study site provide some indication of the model’s appropriateness, at least in general terms, as an approximate representation of flow and transport processes occurring on the island.
Figure 27 – Velocity vectors, hydraulic heads and concentrations in Layer 4 of the model, from the case: SSS5. The area of impact of the pumping bore is shown as the green circle.

Figure 28 – Velocity vectors, hydraulic heads and concentrations in Layer 3 of the model, from the case: SSS5. The area of impact of the pumping bore is shown as the green circle.
Figure 29 – The net effect of the single deep borehole simulated in case SSS5, given in plan (top image) and in side perspective (bottom image) for model layer 3. As previously, colours represent salinity, the surface shape represents the hydraulic head condition, and velocity vectors are shown, although the data presented here represents the difference between cases SSS5 and SSS3 (i.e. the impact of groundwater pumping).

**SSS6: Groundwater Pumping Case 2**

An alternative approach to that of SSS5 for groundwater extraction from Cousine Island, involving a different bore field arrangement was tested using the model. Following recommendations by various authors that shallow groundwater pumping is a preferred and more effective approach to fresh groundwater extraction (rather than deeper groundwater pumping) under small island conditions (e.g. UNESCO, 1991), the model was used to test the scenario whereby several shallow bores are installed and operated. Six shallow bores were situated as shown in Figure 26. Each of the bores is assumed to have a capacity to extract groundwater of up to 4 kL/d, and pumping is limited such that the watertable can not be drawn down below an elevation of 0 m MSL (groundwater pumping is thus taken from model layer 2). Therefore, a potential extraction rate (in total) of 24 kL/d is assigned, but actual
Pumping rates, as limited by drawdown constraints, can only be determined through model simulation. As with SSS5, SSS6 adopts aquifer recharge from case SSS3. The resulting SSS6 water budget is given in Table 8.

Table 8 – Water balance fluxes at the end of simulation (in m$^3$/d or kL/d) for SSS6

<table>
<thead>
<tr>
<th>Water balance component</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
<th>Layer 6</th>
<th>Entire Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recharge (IN)</td>
<td>8.89</td>
<td>136.6</td>
<td>173.9</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>319.3</td>
</tr>
<tr>
<td>Inflow from layer above (IN)</td>
<td>0.00</td>
<td>8.89</td>
<td>122.9</td>
<td>217.7</td>
<td>478.7</td>
<td>5.30</td>
<td>-</td>
</tr>
<tr>
<td>Inflow from layer below (IN)</td>
<td>0.00</td>
<td>4.87</td>
<td>701.9</td>
<td>539.5</td>
<td>4.40</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>Inflow of seawater (IN)</td>
<td>0.00</td>
<td>0.00</td>
<td>178.9</td>
<td>433.3</td>
<td>63.5</td>
<td>&lt;0.01</td>
<td>675.7</td>
</tr>
<tr>
<td>Discharge to layer above (OUT)</td>
<td>0.00</td>
<td>0.00</td>
<td>4.87</td>
<td>701.9</td>
<td>539.5</td>
<td>4.40</td>
<td>-</td>
</tr>
<tr>
<td>Discharge to layer below (OUT)</td>
<td>8.89</td>
<td>122.9</td>
<td>217.7</td>
<td>478.7</td>
<td>5.30</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>Groundwater discharge to the ocean (OUT)</td>
<td>0.00</td>
<td>0.00</td>
<td>944.1</td>
<td>9.78</td>
<td>1.88</td>
<td>0.90</td>
<td>956.6</td>
</tr>
<tr>
<td>Evapotranspiration of groundwater (OUT)</td>
<td>0.00</td>
<td>3.47</td>
<td>11.0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>14.5</td>
</tr>
<tr>
<td>Pumping (OUT)</td>
<td>0.00</td>
<td>24.0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>24.0</td>
</tr>
<tr>
<td>Change in stored groundwater</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

Pumping rates used in the model were not constrained by the imposed limit of drawdown of 0 m MSL, and the entire potential pumping rate of 24 kL/d was withdrawn from the aquifer. The water budget results show that SSS6 involved a slightly smaller discharge of groundwater to the ocean compared to case SSS5, but as with SSS5, the evapotranspiration loss is virtually unaffected by pumping. Again, simulated pumping appears to have only a minor effect on the island’s overall water budget, at least for the assumed hydraulic parameters and aquifer stresses. The “net effect” images, as given in Figure 29 for SSS5, are re-produced for SSS6 and are illustrated in Figure 30.

The maximum watertable drawdown induced by the 6 shallow bores in SSS6 was about 80 mm, considerably less than the single-bore case of SSS5 (230 mm drawdown), as expected because the rate of pumping from individual bores was less in the SSS6 case. Table 9 (Section 4.5) lists the model-simulated watertable drawdown and bore salinity for each of the SSS6 bores. The average EC of extracted groundwater in the SSS6 case (i.e. equivalent to the expected EC of a mixture of groundwater from all 6 bores) was 1400 µS/cm, as compared to the pumped groundwater EC of 1900 µS/cm from the single-bore case.
Figure 30 – The net effect of six shallow boreholes simulated in case SSS6, given in plan (top image) and in side perspective (bottom image). As previously, colours represent salinity, the surface shape represents the hydraulic head condition, and velocity vectors are shown, although the data presented here represents the difference between cases SSS6 and SSS3 (i.e. the impact of groundwater pumping).
4.5 MODELLING RESULTS – TRANSIENT SIMULATIONS

“Transient” simulations adopt time-variant recharge, which is based on historical rainfall records (with some in-filling of missing data by using average values). Transient simulations are used in this study to explore the possible impacts that seasonality in aquifer stresses has on the groundwater and salinity condition, thereby extending the results of steady-state simulations, which ignore seasonality. A time period of 40 years is adopted (Jan 1967 to Dec 2006). Initial head and concentration conditions are taken as the final aquifer conditions from the steady-state case SSS3, and rainfall recharge is assumed to be $0.6P$ for sand and $0.015P$ for granite, where $P$ is the rainfall rate averaged to a monthly time-step.

Two transient simulations are reported here, as:

- Transient simulation 1 (TS3) – A transient version of SSS3 (i.e. no pumping).
- Transient simulation 2 (TS6) – A transient version of SSS6 (i.e. 6 shallow bores)

In order to gauge the effects of recharge seasonality, hydrographs (hydraulic head versus time) and salinographs (EC versus time) were extracted from the model at 6 locations, namely the sites of the 6 shallow bores. Bore identification is provided in Figure 31.

The results of TS3 and TS6, in terms of head and concentration values at the six sites shown above, are summarised in Table 9, which also contains the results at these sites as obtained from the corresponding steady-state simulations. Statistics are based on the temporal variability over the 40-year period of simulation. The predicted seasonality in head and concentration is demonstrated by the Well 3 results as illustrated in Figure 32.
Table 9 – Predicted salinity and head statistics at 6 well sites (see Figure 31) from the cases: TS3, TS6, SSS3 and SSS6

<table>
<thead>
<tr>
<th>Salinity and Head Statistics</th>
<th>Well 1</th>
<th>Well 2</th>
<th>Well 3</th>
<th>Well 4</th>
<th>Well 5</th>
<th>Well 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSS3 – Final EC (µS/cm)</td>
<td>100</td>
<td>50</td>
<td>40</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>30</td>
</tr>
<tr>
<td>SSS6 – Final EC (µS/cm)</td>
<td>2400</td>
<td>1700</td>
<td>2100</td>
<td>40</td>
<td>280</td>
<td>1600</td>
</tr>
<tr>
<td>TS3 – Average EC (µS/cm)</td>
<td>140</td>
<td>70</td>
<td>50</td>
<td>&lt;10</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>TS3 – Maximum EC (µS/cm)</td>
<td>220</td>
<td>120</td>
<td>90</td>
<td>&lt;10</td>
<td>20</td>
<td>70</td>
</tr>
<tr>
<td>TS6 – Average EC (µS/cm)</td>
<td>1000</td>
<td>640</td>
<td>850</td>
<td>20</td>
<td>140</td>
<td>720</td>
</tr>
<tr>
<td>TS6 – Maximum EC (µS/cm)</td>
<td>3500</td>
<td>2800</td>
<td>4200</td>
<td>150</td>
<td>990</td>
<td>2900</td>
</tr>
<tr>
<td>SSS3 – Final Head (m MSL)</td>
<td>0.26</td>
<td>0.28</td>
<td>0.28</td>
<td>0.34</td>
<td>0.30</td>
<td>0.27</td>
</tr>
<tr>
<td>SSS6 – Final Head (m MSL)</td>
<td>0.23</td>
<td>0.22</td>
<td>0.22</td>
<td>0.26</td>
<td>0.23</td>
<td>0.21</td>
</tr>
<tr>
<td>TS3 – Average Head (m MSL)</td>
<td>0.27</td>
<td>0.29</td>
<td>0.30</td>
<td>0.36</td>
<td>0.31</td>
<td>0.28</td>
</tr>
<tr>
<td>TS3 – Minimum Head (m MSL)</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.21</td>
<td>0.20</td>
<td>0.19</td>
</tr>
<tr>
<td>TS6 – Average Head (m MSL)</td>
<td>0.24</td>
<td>0.23</td>
<td>0.24</td>
<td>0.28</td>
<td>0.25</td>
<td>0.22</td>
</tr>
<tr>
<td>TS6 – Minimum Head (m MSL)</td>
<td>0.17</td>
<td>0.13</td>
<td>0.13</td>
<td>0.12</td>
<td>0.13</td>
<td>0.13</td>
</tr>
</tbody>
</table>

The modelling results listed in Table 9 allow for a comparison of the aquifer head and salinity for no-pumping versus pumping cases, under both seasonal and constant climatic conditions. Pumping under the assumption of constant climatic conditions provides an under-estimation of the maximum EC that is predicted to occur under seasonally variations in rainfall recharge. For example, while fresh groundwater occurs in the model at the site of well 6 with no pumping (i.e. 30 µS/cm in the constant climate case and up to 70 µS/cm in the seasonal climate case), the groundwater EC in the well during pumping is estimated to rise to 1600 µS/cm in the absence of climatic variation, and up to 2900 µS/cm with seasonal rainfall recharge.

The temporal variability in simulated groundwater levels is illustrated in Figure 32 (A) for the well 3 site. A seasonal fluctuation is apparent, plus an longer-term response to the annual rainfall (i.e. wet and dry years), although the amplitude of seasonal watertable fluctuation seems relatively consistent and small, being in the order of 0.15 m to 0.30 m. Pumping produces a fairly constant drop in groundwater head, as expected given that the pumping rate was constant. A more realistic simulation would have involved the use of temporally variant pumping, which would have incorporated the worsening influence of high pumping during periods of low rainfall. This analysis is warranted in any subsequent studies that use field-based hydrogeological information from the island.

Groundwater salinity shows a markedly more pronounced response to seasonality and to pumping than head levels, as demonstrated in Figure 32 (B). At well site 3, there is very little seasonal variation in salinity under conditions of no groundwater pumping. However, pumping causes a significant increase in salinity, which is shown to vary greatly, i.e. from <500 µS/cm to >4000 µS/cm in individual years, depending on seasonal rainfall totals.
Figure 32 – Predicted seasonality in head (A) and salinity (B) at well 3 from the transient simulations: TS3 (blue lines) and TS6 (pink and red lines).
4.6 DISCUSSION AND CONCLUSIONS

Seawater intrusion models, incorporating density-dependent groundwater flow and salt transport were developed for Cousine Island using the code MODHMS (HydroGeoLogic Inc., 2006). Initially, four steady-state simulations were run to explore the likely rates of groundwater recharge that match the assumed aquifer parameters. It should be noted that the selection of model parameters was a paradigm of non-uniqueness, whereby recharge values were dependent on the adopted \( K \) and specific yield \( \text{S} \); a common issue for modelling projects that are poorly constrained by field measurements and aquifer testing. It was decided to adopt rainfall recharge rates of \( 0.6P \) for sand and \( 0.015P \) for granite (\( P \) is the average rainfall of 4.695 mm/d), based on the predicted distribution of fresh groundwater, although the groundwater condition is not well understood, and therefore the calibration of recharge was somewhat arbitrary.

Following the selection of aquifer recharge from the four steady-state simulations, two additional steady-state simulations (SSS5 and SSS6) were completed with different approaches to groundwater pumping, i.e. a single borehole pumping a 23 kL/d (the average of metered use from the “southern borehole” on the island; Figure 10), and six bores each pumping at 4 kL/d. The first case was aligned to the current situation on the island, while the second case was meant to represent a possible adjustment to groundwater abstraction, whereby a “skimmer well” approach is assumed and fresh groundwater is tapped from the upper part of the aquifer. The six wells were each limited to a watertable drawdown of mean sea level (0 m MSL), although none of the wells reached this lower limit of head.

The two steady-state pumping cases were compared in terms of salinity in the aquifer, salinity in abstracted bore water, and hydraulic head. The second case, involving six shallow bores had clearly a lower impact on the aquifer, with a maximum drawdown of only 80 mm, compared to 230 mm for the single bore simulation. In the single bore case, groundwater of EC 1900 \( \mu \text{S/cm} \) was predicted, while in the six bore case, the groundwater EC in bores ranged from 40 \( \mu \text{S/cm} \) in well 4, to 2400 \( \mu \text{S/cm} \) in well 1, and averaged about 1400 \( \mu \text{S/cm} \). Clearly, the multiple, shallow borehole scenario provided a better outcome for water supply, as demonstrated by the lower salinity. It would likely be possible to optimise the abstraction from wells in a real situation with this available infrastructure, to reduce the average salinity even further. It may also be possible to re-locate wells to make better use of the distribution network for obtaining lower salinity groundwater. Well optimisation was not tested using the model, because of the limited field measurements and the resulting high uncertainty in modelling predictions.

The steady-state simulations neglected seasonal changes, which were expected to have an influence on the year-to-year groundwater condition, given the close proximity of seawater to any pumping bores. Therefore, two additional simulations were completed that adopted 40 years of monthly average monthly rainfall (some months of missing data were in-filled using averages). These transient simulations (TS3 and TS6) were based on the two steady-state simulations (SSS3 and SSS6) in which no pumping and six-bore pumping were adopted. The aims of the transient simulations were to predict the seasonal variability in “natural” groundwater salinity and head, and compare these to the pumping-induced seasonal variability.

Transient simulations produced slightly higher average groundwater EC values than the equivalent steady-state simulations. Surprisingly, the average watertable level in transient
simulations was higher than the steady-state equivalent case, thereby demonstrating the non-linear relationship between average head and average salinity for the complex transport processes predicted for the Cousine Island aquifer. The maximum EC for the no-pumping transient case was roughly double the average EC, but still within the range of recommended drinking water levels.

The watertable conditions and salinities from the transient bore-pumping case were significantly different to the corresponding steady-state scenario. The mean groundwater salinity from the transient case was unexpectedly lower than the steady-state predictions, but the maximum-in-time EC from transient cases was considerably higher than steady-state estimation. This means that the bore salinity in dry years is likely to be much higher than in wet years, and this effect is illustrated in Figure 32, which provides model output for well 3 for both pumping and no-pumping cases. It is worth noting that despite minimum bore water levels being all higher than 0.1 m MSL, seawater intrusion was still predicted to impact of bores, which demonstrates the importance of considering the density effects when managing fresh groundwater resources in the vicinity of seawater boundaries.
5. **AN INSTRUCTIONAL GROUNDWATER MODEL OF COUSIN ISLAND**

The development of a conceptual hydrogeological model of Cousin Island, of sufficient detail to build a complex seawater intrusion model (as was undertaken for Cousine Island) is precluded by a lack of field data and monitoring evidence. In addition to the same limitations of data paucity as per the Cousine Island dataset, the information for Cousin Island also lacks any information relating to watertable levels, groundwater pumping rates, salinity distribution, and accurate and recent topographical information. Therefore, only a highly simplified modelling exercise is undertaken, as described below.

5.1 **CONCEPTUAL FRAMEWORK**

Aquifer properties \((K, S_p, \text{and porosity or } n)\) and aquifer recharge \((R)\) were made identical to the Cousine Island, i.e. \(K = 10^{-3} \text{ m/d}\) for granite and 30 m/d for sand, \(S_p = 0.01\) for granite and 0.30 for sand, \(n = 0.05\) for granite and 0.32 for sand, and \(R = 0.015P\) for granite and 0.6\(P\) for sand (where \(P\) is rainfall). Given that only small direct evapotranspiration (EVT) totals were obtained from the Cousine Island study, and also in light of the approximate nature of the Cousin Island study, the EVT component of the water balance was neglected.

The island was assumed to comprise a binary system of hydrostratigraphic units, similar to the Cousine Island study, however in the Cousin Island analysis, each hydrostratigraphic unit was vertically integrated and modelled as a single-layer representation. The distribution of sand and granite was defined according to the mapping and interpretation work of Baker (1963), as shown in Figure 9. The model layout and distribution of hydrostratigraphic units are shown in Figure 33.

![Figure 33 – Layout of a simplified groundwater flow model of Cousin Island. Dark blue lines represent the fixed head boundary condition, the light blue area represents granite and the green area represents sand.](image-url)
5.2 MODELLING METHODOLOGY

The modelling of Cousin Island uses the industry-standard MODFLOW code (McDonald and Harbaugh, 1988; Version MODFLOW96), and density effects and solute transport are neglected to obtain an approximation of the watertable mound within the island. The graphical user interface PMWIN (Chiang and Kinzelbach, 1996) was used to construct the model.

The Cousin Island model grid comprises 34 rows by 32 columns of 25 m by 25 m cells, although 646 of these cells are actually “active”, while the remainder are beyond the land bounds of the island and are designated as “inactive”. Simplified aquifer geometry is assumed in the absence of reliable topographical information, with sand areas being assigned a surface elevation of 5 m MSL and granite areas are at 15 m MSL. The bottom of aquifer is taken as -80 m MSL in granite areas and -20 m MSL in sand areas, in the absence of hydrogeological field measurements or drilling. The ocean is represented as 0 m MSL, and there is no correction for seawater density on the effective freshwater head along the coastline, and therefore groundwater levels are conceptually equal to the height about the coastline head (which may be higher than 0 m MSL due to density and tidal effects).

Only steady-state simulations are undertaken due to the simplistic nature of the analysis, and three different pumping scenarios were tested, with rates and bore locations selected somewhat arbitrarily. For the analysis of seawater intrusion, the Ghyben-Herzberg 1:40 rule-of-thumb is adopted – i.e. that the seawater-freshwater interface is at a depth below MSL of 40 times the watertable height (above MSL); a highly idealised simplification, but considered necessary in the absence of sufficient field data.

5.3 MODELLING RESULTS

In the case of Cousin Island simulations, steady-state results were strictly equilibrium values (as compared to the “long-term” results from the Cousine Island study). A comparison between simulations of 200,000 days duration and steady-state runs indicated that there were essentially insignificant differences in the hydraulic heads of these two predictions. The prediction of heads and groundwater velocities from the “no pumping” case is given in Figure 34. The water budget for this model run is relatively straightforward, with 670 kL/d entering the system as recharge, and the same amount discharging via the ocean boundary (due to the assumption of equilibrium conditions).

Two different well placement scenarios were adopted in simulations aimed at exploring the drawdown under a total pumping rate of 24 kL/d (similar to the Cousine Island study). The new water budget with groundwater pumping is simply: 670 kL/d recharge, 24 kL/d pumping and 646 kL/d groundwater discharge to the sea. The layout of the wells is illustrated in Figure 35. The head and velocity contours under the different pumping stresses are illustrated in Figure 36, while the watertable drawdown contours for the two cases are shown in Figure 37.
Figure 34 – Results of the “no pumping” simulation of an idealised representation of Cousin Island.

Figure 35 – Positions of wells for the two “pumping” scenarios. The pink cell represents the case of single bore pumping at 24 kL/d, while the red cells represent the case of three wells each pumping at 8 kL/d.
5.4 DISCUSSION AND CONCLUSIONS

The results of the “no pumping” modelling of a highly simplified representation of Cousin Island indicated that a watertable height of mostly <100mm above sea level may be occurring in the sand aquifer of the island. By the Ghyben-Herzberg 1:40 rule-of-thumb, this would equate to an seawater-freshwater interface at only 4 m below MSL, although this calculation is a very approximate guide. Watertable drawdown in the case of the three bores was a maximum of 22 mm, while the single-bore simulation produced a steady-state well drawdown of 37 mm. While these seem like minor impacts, the small “freeboard” or height above MSL of the “natural” watertable condition may be very small, and therefore, such pumping rates may well result in significant changes in the groundwater salinity.
It is worth noting that while the single bore case produces the largest watertable drawdown at the site of pumping, the extent of the cone of depression, as defined by the 0.004 m contour in Figure 37, is larger in the three well case. In the absence of monitoring information or hydrogeological field data, further interpretation of the results is highly speculative, contains significant uncertainty and is likely not warranted given time and resources constraints.
6. WATER TREATMENT CONSIDERATIONS

6.1 INTRODUCTION

This section describes some basic water treatment options available for the islands. It should be noted that existing water chemistry and microbiological data are insufficient to design an optimal water treatment strategy, however some basic treatment options are discussed. Furthermore, this section details the array of water quality parameters (physical, chemical and microbiological) required to better design a tailored water treatment process for each island.

6.2 WATER TREATMENT

If the raw water quality is high with respect to turbidity and microbiological contaminants, the water may be suitable for consumption with only pH correction, reverse osmosis (assuming EC is consistently high) and disinfection as the only treatment steps. If not, additional treatment options may be required, as discussed below.

pH Correction

Desired pH range for potable water is 7 -7.5, with a target of 7.2. pH correction can be achieved using lime which is cheap and readily available. If pH is variable, an online pH controller may be required. Treatment involves dosing slaked lime or hydrated lime to raise the pH, which can also precipitate calcium and remove magnesium from hard water (AWWA, 1999). Water hardness in terms of calcium and magnesium concentrations should also be characterised.

Filtration: Removal of Turbidity and Suspended Solids

For aesthetics, water with a turbidity less than 5.0 NTU (Nephelometric Turbidity Units) is acceptable to consumers, however because of its microbiological effects (i.e. capacity to protect pathogens from disinfection, and exert a high chlorine demand) turbidity should not exceed 1.0 NTU (WHO, 1996). Turbidity less than 0.15 NTU is desired. The authors recommend that turbidity and suspended solid (SS) concentrations of the raw water should be closely monitored. If the turbidity and SS concentrations are high, filtration in the form of slow sand filtration and/or microfiltration is recommended.

Microfiltration involves filtering water through a fine hollow fibre filter membrane which remove suspended solids, colour, inorganic and biological particles >2µm in size. Entrapped solids can be removed using pulses of air and/or employing a backwashing function (AWWA, 1999). Microfiltration is reliable and cost effective, however the disadvantage is that the process can not withstand waters high in turbidity (AWWA, 1999). If SS or turbidity concentrations are high, addition of a coagulant coupled with sand filtration maybe required upstream. Slow sand filtration is well suited to part-time operation and small scale systems, and may be a substitute to microfiltration (AWWA, 1999). Several types of media and grain sizes are available depending on the application and desired product-water quality. It should
be noted that if some form of filtration is employed, a waste stream will be produced, which may need to be treated and disposed off.

**Reverse Osmosis**

Total dissolved solids (TDS) concentrations and electrical conductivity (EC) affects the palatability of drinking water and therefore need to be closely monitored (WHO, 1996). TDS <300 mg/L is desired however <1000 mg/L is acceptable to consumers (WHO, 1996). EC should be <800 µs/cm. If TDS and EC values exceed these limits, RO may be required to remove salts from the raw water. Many commercial packages size reverse osmosis (RO) plants of various classifications and configurations are available. RO have a broad span of treatment capabilities, which include pathogen removal. Filtration may be required upstream of the RO plant if SS and turbidity concentrations are high.

**Microbial Load and Disinfection**

The water source and delivery infrastructure must be free of faecal contamination from either surface water (e.g. surface run-off and waste infiltration) or sub-surface sources (e.g. seepage from septic tanks). All waste disposal systems on the islands must be characterised in terms of mode(s) of disposal and treatment and proximity to the potable water supply.

The authors strongly recommend that the microbial load of the raw water as determined using indicator organisms (total coliforms, thermotolerant coliforms and *E.coli* count) be closely monitored (see Section 6.3). These microbial indicators highlight either the potential for faecal pollution or that such pollution has occurred (WHO, 1996). If the microbiological load of the raw water is high (i.e. >0 CFU per 100 ml; WHO, 1996) filtration followed by disinfection is highly recommended (note: CFU - Colony Forming Units).

Two options for disinfection are readily available:

1. **Chlorine disinfection:**
   Treatment usually involves doing calcium- or sodium-hypochlorite to maintain a free chlorine concentration within the order of 0.2 – 1.0 mg Cl₂/L (AWWA, 1999; WHO, 1996). A free chlorine residual of at least 0.5 mg/L after a minimum contact time of 30 minutes is usually required (AWWA, 1999). Hypochlorite dosing is relatively cheap and provides a residual disinfectant to protect against the regrowth of pathogens within the distribution infrastructure (AWWA, 1999). The disadvantage is that disinfection can be difficult to control if the raw water experiences intermittent changes SS, inorganic nitrogen, and dissolved organic carbon concentrations. In addition, chlorine disinfection requires the storage of potentially dangerous chemicals onsite.

2. **U.V. disinfection:**
   U.V. radiation using U.V. lamps can be a chemical free alternative to chlorine, which are relatively compact in size and have low maintenance requirements. Operationally, they are simple requiring a cleaning program to periodically remove biological and chemical fouling material from the lamps (AWWA, 1999). The disadvantage of U.V. radiation is that they offer no residual and disinfection becomes compromised during periods of high turbidity.
6.3 WATER QUALITY ANALYSES

It was not possible to predict specific water treatment works for each island with the current available information, and therefore the authors recommend that a more detailed and rigorous analysis of water quality be undertaken to better design a tailored water treatment process for each island. The array of water quality parameters which are to be closely monitored are listed in Tables 10 and 11. Those listed in Table 10 are essential water quality parameters, which must be monitored. Routine monitoring of microbiological parameters are strongly recommended during:

- before and after significant rainstorm events;
- before, during and after periods of human occupancy.

Parameters listed in Table 11 are desired water quality indicators which should be monitored, however not necessarily as often to those listed in Table 10. Monitoring of *Giardia* and *Cryptosporidium* are strongly recommended if there is evidence of faecal contamination caused by animals including amphibians, birds, and mammals, particularly after rain storm events. The frequency of sampling in a necessary water quality monitoring program is difficult to prescribe given limited knowledge of contamination hazards and risks, but a preliminary guide might be once or twice a week for 3 to 4 months initially.

<table>
<thead>
<tr>
<th>Table 10 – Essential water quality parameters</th>
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<tbody>
<tr>
<td><strong>Physiochemical</strong></td>
</tr>
<tr>
<td>Turbidity</td>
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<tr>
<td>Suspended solids</td>
</tr>
<tr>
<td>pH</td>
</tr>
<tr>
<td>Nitrate-Nitrogen</td>
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<tr>
<td>Phosphorous (total and soluble)</td>
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<tr>
<td>Calcium</td>
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<td>Magnesium</td>
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<tr>
<td>Electrical conductivity</td>
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<tr>
<td>Total dissolved solids</td>
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<tr>
<td>Metals</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 11 – Desired water quality parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physiochemical</strong></td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>Ammonia- Nitrogen</td>
</tr>
<tr>
<td>Nitrite- Nitrogen</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
</tr>
<tr>
<td>Manganese (total and soluble)</td>
</tr>
<tr>
<td>Iron (total and soluble)</td>
</tr>
<tr>
<td>Dissolved organic carbon</td>
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<tr>
<td>Redox potential</td>
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</table>
6.4 CONCLUSIONS

A general review of water treatment options for the island water was discussed. It is clear that existing water chemistry and micro-biological information are insufficient to properly plan an optimal water treatment strategy for each island. Further, more clarity of water use needs, in terms of quality and quantity, is required, especially for Cousin Island. A preliminary overview of water treatment options identified that such treatments as pH correction, filtration, reverse osmosis and/or disinfection could be considered to provide for improved water quality to users from Cousine Island. Further information is required to predict specific water treatment works for Cousin Island. The authors recommend that more detailed and rigorous analysis of water quality be undertaken before the purchase of water treatment infrastructure is further considered.
7. **RECOMMENDATIONS**

Recommendations arising from this investigation are sub-divided into: 1. Data deficiencies and knowledge gaps, 2. Future modelling investigations, 3. Island groundwater management, 4. Water treatment

7.1 **DATA DEFICIENCIES AND KNOWLEDGE GAPS**

The compilation of the existing data and literature on the groundwater resources of Cousin and Cousine Islands indicated that there are major deficiencies in available information, as would be required to manage the hydrology and salinity of these resources, and to ensure the sustainability of groundwater extraction. Certainly, there is insufficient information to develop a conceptual model of the island of enough detail to warrant the construction of predictive groundwater management models of the aquifers. Therefore it is recommended that a field investigation be undertaken to enhance the limited available hydrogeological dataset. Required measurements and testing include, but are not limited to: aquifer hydraulic properties (including depths of sediments), groundwater extraction rates, bore construction details (depth of bore, bore lining material, points of groundwater inflow), watertable levels, groundwater salinity measurements, water chemistry, surface processes such as overland flow, wetland hydrology, evapotranspiration rates, topography of Cousin Island, and soil morphology and hydraulic properties. The specifics of a proposed field reconnaissance program are outlined in Section 8 of this report.

Groundwater investigation (i.e. episodic, single-study-based analysis) needs to be complemented with regular monitoring (i.e. ongoing measurement) for a combination of reasons. Monitoring is expected to: 1. Control the influence of pumping on the water resource by monitoring trends in water quality and water levels in observation wells, and in response to different pumping rates; 2. Provide insight into the trends and behaviour of the islands’ aquifers in response to climatic and anthropogenic stresses, thereby allowing for an improved characterisation the islands’ hydrogeology; 3. Identify any long-term trends in the state of the system, such as gradual water quality deterioration, climate change influences, and pumping-based impacts.

In addition to traditional hydrogeological data gathering, it is also deemed necessary to explore the following areas of limited knowledge/understanding: the effect of tides on the shoreline boundary condition and the groundwater and salinity dynamics, and the potential for climate change to influence available groundwater resources. A number of other studies would also provide useful insight for the management and understanding of the groundwater resources. For example, given the low pH of the groundwater in some locations, an investigation of the role of soil hydro-chemistry on the groundwater quality is also warranted. Further, the dependence of wetland/marsh persistence on groundwater discharge (i.e. surface water-groundwater interaction) would allow a better approximation of the islands’ water budgets, and therefore of the available fresh water. An interpretation of the dependence of the island’s ecology on groundwater is also considered to be necessary, in order to manage groundwater extraction such that impacts on the key species of the islands are minimised. It is likely that these latter two recommendations are inherently linked, as ecological health may be dependent on surface water persistence.
7.2 FUTURE MODELLING INVESTIGATIONS

Groundwater modelling activities were constrained by the lack of available field data for the two sites. It is suggested that subsequent to a field sampling and monitoring campaign, and data collation and re-conceptualisation of the islands’ aquifers, the modelling described in this report be extended as follows:

1. A revision to the parameters of models, including aquifer geometry, hydraulic properties, recharge, pumping, geology, initial salinity conditions and evapotranspiration following completion of a revised conceptual model.

2. Modelling is required to test two alternative conceptual hypotheses for the hydrology of the islands, these being: (a) that rainfall runoff from relatively impermeable granite areas causes high sand aquifer recharge, or (b) recharge into fractured granite is significantly higher than that assumed for this study.

3. A revised conceptual model of surface runoff and wetland-groundwater interaction is also required to develop comprehensive conceptual models.

4. The influence of tidal sea level fluctuations on both the groundwater system (water table levels and salinity) and the boundary condition representing the shoreline needs to be undertaken to ascertain whether density-corrected mean sea level is an appropriate approximation for the shoreline boundary condition.

5. Modelling could be used, in combination with estimates of likely sea level rise associated climate-change, to determine the long-term viability of groundwater abstraction.

6. Models that capture the seasonal variation and temporal variability in evapotranspiration are warranted to determine whether this effect is significant.

7. Future modelling should also include the variability of groundwater pumping (confirmation and re-organisation of existing pumping data are required), which was assumed to be constant in the present study.

8. Following hydrodynamic calibration, modelling could be used to optimise groundwater pumping rate and bore location through a more comprehensive set of simulations.

9. A three-dimensional seawater intrusion model for Cousin Island, similar to that developed for Cousine Island is warranted once an appropriate conceptualisation can be achieved. Data shortfalls for Cousin Island are greater than that for Cousine Island.

A number of recommendations for future modelling resulted through the modelling activities, in terms of take-home messages for future methodologies, and these included:

1. Climatic variability is a critical consideration in obtaining a more realistic estimation of possible groundwater abstraction rates and the best location of bores.

2. The length of time required to achieve steady-state conditions in the granite aquifer was extremely long, and possibly of longer duration than the time-scales used in this study.

3. Modelling indicated that high sand recharge rates were necessary to reproduce observations of groundwater salinity, although this outcome is dependent on the assumed geology. It is quite likely that rainfall runoff from relatively impermeable granite areas contribute to these apparently high rates of sand recharge and some account of this is probably necessary in future modelling activities, because “textbook” recharge rates seemed to under-estimate sand recharge.

4. The combined modelling approach of MODHMS, Groundwater Vistas, PMWIN and project-specific software proved an effective approach to model development. The final model was extremely robust and virtually free of numerical error, although run-
times were significant and proved to be a limiting factor in sensitivity analyses by reducing the number of possible combinations that could be explored.

7.3 ISLAND GROUNDWATER MANAGEMENT

Recommendations for the management of groundwater on Cousine and Cousin Islands adopt a precautionary principle due to the theoretical nature (i.e. limited available field data) of this study. Further, modelling is not sufficient constrained to be used to make explicit recommendations for bore construction or pumping rates. However, a number of recommendations can be made, based on the data collection and conceptualisation efforts, and on instructional groundwater modelling:

1. Management of the island’s groundwater resources requires the collection of monitoring data, in terms of watertable levels and salinity, to periodically evaluate the condition of the resource and trends in any water quality degradation. It is suggested that groundwater be managed as a finite resource, whereby pumping is restricted during certain periods and if monitoring identifies worrying trends. Monitoring should include the measurement of pumping bore salinities, but also salinities and water levels from observation bores (i.e. piezometers).

2. The present location of the main pumping bore on Cousine Island is probably optimally situated, although further analysis is required to confirm this.

3. The abstraction of groundwater from both Cousine and Cousin Islands should occur from the sand aquifers (i.e. because groundwater abstraction from the granite aquifers likely requires excessively heavy machinery in the form of a drilling rig) at locations most distant from the shoreline. Also, groundwater pumping is best undertaken from shallow in the aquifer, and also from several sites rather than a single bore.

4. The modelling of Cousine Island indicated the 23 kL/d was close to the upper limit of possible groundwater extraction, although it needs to be stressed that predictions were based on “textbook” model parameters, and therefore large uncertainty is associated with this value of 23 kL/d.

5. Groundwater pumping during years of below-average rainfall may need to be reduced in accordance with increasing salinity.

6. Modelling simulations indicated that seawater intrusion impacts were reversible – although the geochemistry of the system is not considered, and it may be case that sodium-rich seawater has almost irreversible impacts on soils and vegetation, despite modelling predictions of reversible seawater intrusion behaviour.

7. The study has not considered the potential for “artificial” or at least targeted groundwater recharge, as might be induced through the disposal of wastewater, and the potential benefits of this in regards to limiting seawater intrusion impacts. The application of wastewater to minimise seawater intrusion impacts has been practiced in similar systems, although the risk of microbiological contamination would need to be managed.
7.4 WATER TREATMENT

There is a need to characterise water quality on Cousine and Cousin Island, including water chemistry and microbiology. Only preliminary recommendations in relation to the sort of water treatment infrastructure that might be available and applicable to the situation on Cousine Island are possible at the present time, and options are discussed in Section 6. There is insufficient understanding of the water use needs and water quality of Cousin Island to be able to make a judgment of recommendation regarding water treatment.
8. **FUTURE WORK**

Future work on characterising the groundwater resources of Cousine and Cousin Islands, and on optimising groundwater extraction, needs to focus on addressing knowledge gaps and on revising and extending the analysis described in this report. Options for completing some or all of this work could include an investigation through a one-year Honours project based at Flinders University, at which there are presently final-year undergraduate student/s within the Bachelor of Science Environmental Science) degree who are citizens of the Seychelles and have expressed an interest in the project. The engagement of Honours students to extend this work is contingent on the acceptance of appropriate students into the Honours degree, and also on these students obtaining financial support to complete this study.

Future work has been sub-divided into the topics: field work and groundwater modelling, and these are described below.

### 8.1 FIELD WORK

The following field work is suggested as a necessary precursor to developing sustainable strategies to groundwater resources management for Cousine and Cousin Islands.

1. **Piezometer (observation bores) installation for watertable monitoring and water quality assessment** – Piezometers should be installed in strategic locations to monitor groundwater levels and groundwater salinity, as the first priority of subsequent investigations. Piezometers should be installed using best-practice guidelines, and may be able to be installed “by hand”; an approach that would result in minimal environmental impact.

2. **The installation of a piezometer network would allow for a watertable monitoring program, designed to both characterise groundwater trends and to develop an understanding of the watertable response to groundwater pumping.** Further, piezometer measurements will allow for the estimation of aquifer hydraulic properties, through bore pumping tests, slug tests, and other field testing methods.

3. **Stratigraphic sequencing** – The installation of piezometers and any new production bores will allow for an assessment of sediment thicknesses, and will also facilitate geological descriptions of the stratigraphy.

4. **Water quality assessment** – Characterisation of groundwater quality at sites of groundwater extraction and groundwater monitoring is required to both enhance the conceptual understanding of groundwater flow and transport processes, but also to properly design water treatment options. Microbiological water quality indicators need to be measured and hydro-chemical analyses should be conducted to evaluate the concentrations of dissolved ions. The sampling campaign should include a fairly broad assessment of groundwater salinity, including a few multiple-depth measurements, to assist in constraining numerical modelling predictions of seawater intrusion.

5. **Groundwater pumping volumes** – An enhanced understanding of the operation of existing groundwater infrastructure on both islands is required to improve this aspect of the current conceptual model.

6. **Hydraulic properties determination** – Bore testing, using both pumping bores and piezometers (where installed) will allow for deterministic analysis of the islands’ groundwater resources.
7. Catchment and soil processes: Overland flow and recharge estimation – Some assessment of the catchment processes is required to distinguish the two different conceptual models hypothesised for the island’s hydrology as described in Section 7.2 above. Also, an evaluation of the hydro-chemistry of overland flow and interflow (lateral soil water movement) will allow for a more optimal design of new bore locations, by avoiding areas down-gradient of low pH runoff.

8. Survey of surface water bodies and approximation of wetland-groundwater interaction – A survey of surface water features, including springs and wetlands, plus an interpretation of the groundwater-dependency of these features is necessary to account for surface water-groundwater interaction in groundwater modelling activities.

9. Topography of Cousin Island – Additional ground surface levels need to be obtained for Cousin Island so that the geometry of stratigraphic units can be interpolated.

It is expected that a full costing of the necessary field work will be produced if these activities are deemed warranted and are commissioned. As a preliminary estimate, it is expected that field work will require some 3-5 weeks of effort, and will require funding for equipment (e.g. water level and salinity loggers), water quality testing and associated consumables, bore construction materials, and other field-based materials (not including flights, accommodation and meals for field staff) in the order of $AUS10,000 to $AUS15,000 (€EUR6,000 to €EUR9,000). It is likely that ongoing monitoring of field sites will be necessary subsequent to the field investigation, and occasional assistance from island staff may be required for this.

8.2 GROUNDWATER MODELLING REVISIONS

Recommendations for future modelling work are given in Section 7.2 above. It should be noted that the work described in this report will allow for significantly shorter model development effort for future activities, given that part of the modelling process involved the establishment of a modelling methodology, including de-bugging of software input files. The principle reason for revising the modelling in the future relates to the re-conceptualisation that is anticipated to arise from a field-based data collection campaign.

Modelling revisions are also expected to be a mostly inexpensive undertaking (with the exception of time resources), because the majority of modelling software has already been purchased. It is proposed that future efforts involve the engagement of student projects rather than consultancy-type projects, to reduce labour costs.
9. **REFERENCES**


