Bonriki Inundation Vulnerability Assessment

Economic analysis of water management options for impacts from inundation, climate variability and high abstraction rates, Bonriki water reserve, South Tarawa, Kiribati

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Acknowledgements

The BIVA project is part of the Australian Government's Pacific-Australia Climate Change Science and Adaptation Planning Program (PACCSAP), within the International Climate Change Adaptation Initiative. The project was developed by the Secretariat of the Pacific Community's (SPC) Geoscience Division (GSD) in partnership with the Australian Government and the Government of Kiribati (GoK).

Key GoK stakeholders that contributed to the implementation of the project were:

- Ministry of Public Works and Utilities (MPWU), in particular the Water Engineering Unit with the MPWU
- The Public Utilities Board (PUB), in particular the Water and Sanitation Division and the Customer Relations Division within the PUB
- The Office of the President, in particular the Disaster Management Office
- The Ministry of Environment, Lands and Agricultural Development (MELAD) Lands Division
- The Ministry of Fisheries and Marine Resources Development (MFMRD) Minerals Division
- Members of the Kiribati National Expert Group on climate change and disaster risk management (KNEG)

The Bonriki Village community members also played a key role in the implementation of the project. Community members participated in the school water science and mapping program, assisted with construction of new piezometers and data collection for the groundwater component, and shared their knowledge and experiences with regards to historical inundation events and coastal processes.

Key technical advisors involved with implementation of the project included:

- Flinders University, Adelaide, Australia
- University of Western Australia, Perth, Australia
- The University of Auckland, Auckland, New Zealand
- United Nations Educational, Scientific and Cultural Organization, Institute for Water Education (UNESCO-IHE), Delft, the Netherlands
- Technical advisors Tony Falkland and Ian White

List of Abbreviations

BIVA	Bonriki Inundation Vulnerability Assessment
PACCSAP	Pacific-Australia Climate Change Science and Adaptation Planning
kL	Kilolitre = 1,000 litres
LSRH	Large scale rainwater harvesting
PDaLo	Pacific Damage and Loss Information System
PUB	Public Utilities Board
SPC	Secretariat of the Pacific Community
TWMP	Tarawa Water Master Plan

Executive Summary

This analysis is produced as part of the Bonriki Inundation Vulnerability Assessment project, part of the Australian government's Pacific–Australia Climate Change Science and Adaptation Planning Program (PACCSAP), within the International Climate Change Adaptation Initiative. The Bonriki Inundation Vulnerability Assessment project aims to improve understanding of the vulnerability of the Bonriki freshwater reserve to coastal hazards and climate variability and change. Improving knowledge of risks to this freshwater resource will enable better adaptation planning by the Government of Kiribati. Seawater inundations of a certain magnitude are likely to impact the salinity of Bonriki groundwater lens (the main sources of government-provided water) and the consequent volume of potable water supplied to the population. In the case that the groundwater lens become too saline, it would be necessary to use alternative water sources to produce supplementary freshwater for the inhabitants of South Tarawa.

Objective

Specifically, this economic analysis focuses on two objectives:

- Provide a preliminary assessment of the costs and benefits of using either rainwater or reverse osmosis desalination to fully supplement the Bonriki groundwater, so that a target daily water volume (1,960 kL/day) can consistently be produced in the face of threats to the supply.
- Determine the costs of a seawater inundation threat to the Bonriki freshwater lens relative to other factors (rainfall and overabstraction) by using illustrative scenario analysis. In doing so, it is possible to determine the relative costs of natural versus human induced threats to groundwater and provide suggestions on the next steps for ensuring water supply at minimum cost in the future.

Results

Least-cost option to fully supplement government groundwater supply: Desalination

The two main options considered in this report as backup water sources for Bonriki are large-scale rainwater harvesting (LSRH) and desalination (which would able to provide 1,960 kL/day, if required). Cost estimates support previous studies such as the Tarawa Water Master Plan (White 2010a) in concluding that desalination is the more cost-efficient option for large-scale water production. The unit production cost (when using a zero discount rate) ranges between Australian dollar (AUD) 5.0/kL and AUD 5.3/kL, depending on the time frame of the analysis compared with the cost of LSRH, which ranges between AUD 9.4/kL and AUD 25.4/kL. In the 10-year analysis, desalination unit costs are approximately only 20% of those of LSRH.

Having compared the costs of producing the target 1,960 kL/day of water under different scenarios, it is possible to infer that:

- the effect of having a period of low rainfall versus a period of high rainfall is likely to be the most costly phenomenon;

- the effect of a seawater inundation event on the costs of providing water are smaller than the effects of rainfall and of abstracting at the 1,960 kL level;
- reducing abstraction after a seawater inundation event or during low rainfall periods produces cost *savings* by reducing the number of days where groundwater salinity is above the 1,500 µS/cm threshold; and
- only during high rainfall periods is the effect of a seawater inundation on production costs likely to be felt.

Because the climate model used in this analysis (Parris 2012) lies at the high end of the range in terms of sea-level rise predictions, the seawater inundation generated will also lie at the high end of predictions. Consequently, the finding here of this relatively ‘bad case' seawater inundation still being less of a threat than the other two factors, signals that the focus should indeed be on rainfall and overabstraction going forward. Because rainfall cannot be changed, the focus should lie on managing within the range of sustainable groundwater abstraction from Bonriki.

Additional findings

Groundwater remains the least-costly source

Although desalinated water is less costly than LSRH, it is still more costly than groundwater supplied from Bonriki and Buota. The estimated cost of groundwater (White 2010a) is AUD 3.60/kL, whereas the minimum expected cost for desalinated water is AUD 4.97/kL. In addition, desalination has far greater energy demands than groundwater abstraction and, given that energy is presently supplied via diesel combustion, desalination will produce more carbon emissions and increase Kiribati’s trade balance deficit through higher diesel imports. Consequently, it is clear that groundwater is still Kiribati’s least-costly water source and that protecting groundwater reserves from human pressures such as encroachment (White 2010a) should be a key focus in the future.

Household rainwater harvesting as additional private water source

Although household rainwater harvesting could not be relied on as a backup to groundwater and would be susceptible to extreme droughts, it is a relatively low-cost option for providing small volumes of extra water in order to reduce the stress on the Public Utilities Board (PUB) system during normal weather conditions. As discussed in the results section, if the normal 50% loss through distribution is assumed (Fraser Thomas Partners 2012; White 2010a), then the total cost of providing water to households via desalination is higher than that of small-scale household rainwater harvesting. This supports a recommendation of incentivising household rainwater harvesting in order to produce additional water, independently of the government (PUB) supplied system.

The results of this report are also supported by analysis in Rios Wilks (2015), where a lower target daily supply and average Bonriki abstraction rate of 1,700 kL/day is used in a similar analysis focusing on impacts of inundation and climate variability only.

1. Introduction

South Tarawa is the main atoll in the Republic of Kiribati, and is the government and economic centre. It is made up of many small islets joined to form a long, thin atoll with elevations less than 5 m of current sea level[1]. South Tarawa is the most densely populated atoll in Kiribati, and in 2010 was home to 50,182 people — 48.7% of the country's total population. Despite South Tarawa's limited resources, the population density is among the highest in the world; 3,184 per km^2 in 2010 (Republic of Kiribati 2012) and continues to rise due to inward migration from outer islands, which offer even fewer economic opportunities.

The geographical characteristics of South Tarawa coupled with it having one of the highest population densities in the world make water shortages an ever present threat for its inhabitants. Currently, the main government-provided water supply, administrated by the PUB, provides 2 hours of water every 48 hours to around two-thirds of the households in South Tarawa that use groundwater lenses as their water source.

1.1. Economy

The main source of government revenue is the sale of commercial fishing licences. The balance of trade has been negative since 1980, and has steadily increased over time. Copra, crude oil coconut, and other coconut products make up the main export in terms of value. Fish and sea products make up the majority of the remaining export value (Ministry of Statistics, pers. comm. 2013). Aside from fresh fish and the few local produce that can grow in Tarawa's soil, food is imported. The value of food imports is greater than any other import group, followed by machinery and transport equipment and mineral fuels.

Although there is one tuna processing factory that operates in Betio, there is little industry in South Tarawa. Two-thirds of the labour force is out of work or engaged in subsistence activities (Republic of Kiribati 2012). Subsistence fishing is particularly important. Currently, there is minimal agriculture in South Tarawa, the only nonsubsistence producer of vegetables is the Taiwanese Technical Mission farm, which educates communities in how to grow crops and supplies a few local shops with produce. Urban households typically grow only pawpaw (papaya) and breadfruit (KNSO and SPC 2012). The main industry in which the population is formally employed is the tertiary sector, which is public administration and services (KNSO and SPC 2012).

1.2. Climate change challenges

In addition to the challenges South Tarawa faces concerning population and resource limitations, the atoll is highly susceptible to impacts of climate change. As with most low lying atolls, sea-level rise is of great concern. Average sea-level rise around Kiribati has been on the order of 1–4 mm per year since 1993 (CSIRO 2011), gradually encroaching on shoreline properties. Two other natural hazard threats faced by Tarawa are drought and seawater inundations. Although Tarawa lies outside the

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[1] According to topographic survey data produced by the Secretariat of the Pacific Community in 2014.

cyclone belt, seawater inundations do occur and can be further exacerbated by El Niño–Southern Oscillation effects on the sea level (World Bank undated). Seawater inundations have been recorded for 2014 and 2002 in Tarawa, the former led to evacuation and 44 houses being damaged, the latter was estimated to cost around USD 50,000 (approx. 60,000 AUD) in damage (PDaLo 2013).

1.3. Dual threats to the water supply

Being a coral formation, land in Tarawa is porous and no surface water exists. Water comes instead from variety of sources, particularly rainwater harvesting or bores (groundwater from a freshwater lens) (Republic of Kiribati 2012). In the latter case, clean and treated groundwater relies heavily (although not entirely) on the Bonriki freshwater reserve (Republic of Kiribati 2012) which feeds into the government water supply system. The groundwater lens is an unconfined aquifer composed of coarse carbonate sands and underlain by reef limestone that make up the islet's substrates. Bonriki airport is located on the land above the Bonriki freshwater lens (Figure 1 and Figure 2).

Figure 1: *Bonriki area.*
Source: One World Nations Online, 2015

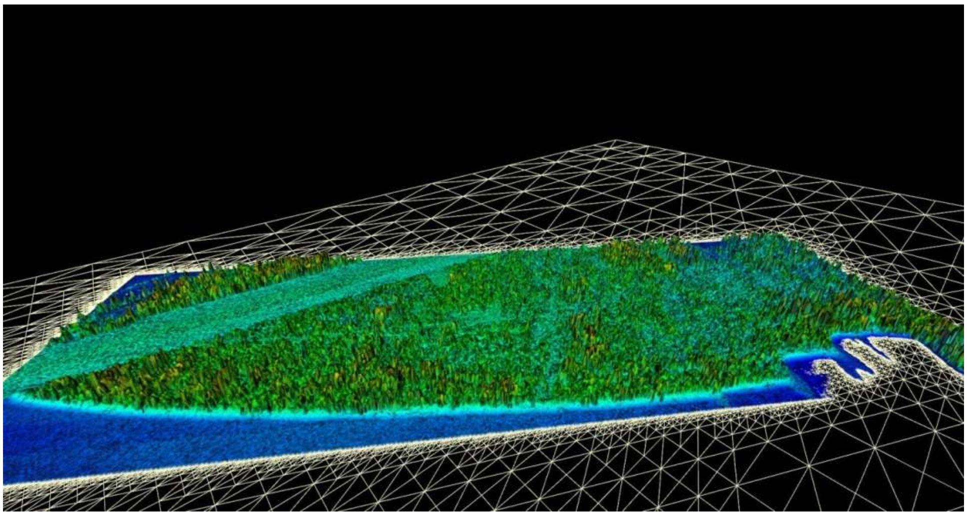

Figure 2: *Computer generated image of Bonriki freshwater reserve.*
Source: Damlamian, SPC 2014

Unfortunately for residents of Tarawa, groundwater presently cannot meet all demands for water. Moreover, the groundwater lenses are fragile and limited. Aside from human encroachment, aquifer geology and evapotranspiration, the risks that presently threaten ongoing supplies from groundwater include:

- **Salt water intrusion:** Intrusion arising from wave overtopping and seawater inundation along with over abstraction is expected to have implications for the volume of palatable freshwater that can be pumped out of Bonriki lenses to supply residents of South Tarawa.
- **Variations in rainfall:** Low rainfall and the consequent low recharge of lenses with freshwater are expected to put pressure on the supply of freshwater to South Tarawa's population (Bosserelle et al. 2015).
- **Overabstraction (exacerbated by water losses):** Accommodating the huge population pressure leads to high abstraction rates from Bonriki even during dry periods. White et al. (2008) noted that overabstraction poses a threat to freshwater lenses. Water loss through the public distribution system has also frequently been cited as a significant issue. All water produced from groundwater lenses is distributed via the PUB piping system but a large proportion of water is lost before it reaches consumers. These losses cause higher abstraction rates to be required in order to supply the population.

These key factors could cause the salinity of the Bonriki groundwater to surpass the 1,500 µS/cm salinity threshold limit for freshwater provided to the community from the public water supply system, at which point it is considered unpalatable.

1.4. Existing water initiatives

The National Adaptation Program of Action for Kiribati, 2007 has specific objectives for water resource adaptation:

- Maintain and conserve available good groundwater lenses.

- Gain users' confidence in the reliability of the distribution system and promote their willingness to pay, based on consumed quantity.
- Increase water storage and water resources to meet current demands and at times of serious droughts.
- Manage risks to water resources throughout the atolls.
- Assess impacts of urban water supplies on other natural resources, systems and subsistence activities.

Since 2007, the Tarawa Water Master Plan (TWMP) for Kiribati was produced by (2011a). The plan evaluates a variety of management options that address the supply and demand challenges for freshwater in the whole of Tarawa. The TWMP takes into account many different water sources and management options for Tarawa, making recommendations to the government on the most efficient overarching strategy for increasing the availability of freshwater on Tarawa. The report identifies that human factors are expected to produce the greatest threat to Tarawa's water supply over the next 15 years, while noting the high levels of water leakage within the present system:

> "…the most significant threat to the availability and quality of freshwater in South Tarawa is its ever-increasing population".
>
> "A major problem in meeting current water needs in South Tarawa is the estimated 50% losses of water from the reticulation [lens water distribution] system, and particularly from the domestic system. Reducing this excessive leakage and addressing the underlying causes should be highest priority. There is no point in introducing new water sources into South Tarawa if leakage rates are not reduced."

In addition to human-caused threats to the water supply, low rainfall and saltwater intrusion to freshwater sources is also expected to put pressure on the supply of freshwater to South Tarawa's population (Damlamian et al. 2015; Bosserelle et al. 2015).

1.5. Bonriki Inundation Vulnerability Assessment project background

The Bonriki Inundation Vulnerability Assessment (BIVA) project is part of the Australian government's Pacific–Australia Climate Change Science and Adaptation Planning Program (PACCSAP), within the International Climate Change Adaptation Initiative. The objectives of PACCSAP are to:

- improve scientific understanding of climate change in the Pacific;
- increase awareness of climate science, impacts and adaptation options; and
- improve adaptation planning to build resilience to climate change impacts.

The BIVA project was developed by the Geoscience Division of the Secretariat of the Pacific Community (SPC) in partnership with the Australian government and the Government of Kiribati (GoK).

1.5.1. Project objective and outcomes

The BIVA project aims to improve our understanding of the vulnerability of the Bonriki freshwater reserve to coastal hazards and climate variability and change. Improving our knowledge of risks to this freshwater resource will enable better adaptation planning by the GoK.

More specifically, the project has sought to use this knowledge to support adaptation planning through the following outcomes:

- Improved understanding and ability to model the role of reef systems in the dissipation of ocean surface waves and the generation of longer-period motions that contribute to coastal hazards.
- Improved understanding of freshwater lens systems in atoll environments with respect to seawater overtopping and infiltration, as well as current and future abstraction demands, recharge scenarios and land-use activities.
- Enhanced data to inform a risk-based approach in the design, construction and protection of the Bonriki water reserve.
- Increased knowledge provided to the GoK and the community of the risks associated with the impact of coastal hazards on freshwater resources in response to climate change, variability and sea-level rise.

1.5.2. Context

The Republic of Kiribati is located in the Central Pacific and comprises 33 atolls in three principal island groups. The islands are scattered within an area of about 5 million square kilometres. The BIVA project focuses on the Kiribati National Water Reserve of Bonriki. Bonriki is located on Tarawa atoll within the Gilbert group of islands in Western Kiribati (Figure 3). South Tarawa is the main urban area in Kiribati, with the 2010 census recording 50,182 people of the more than 103,058 total population (KNSO and SPC 2012). Impacts to the Bonriki water resource from climate change, inundation, abstraction and other anthropogenic influences have potential for severe impacts on people's livelihood of South Tarawa. The Bonriki water reserve is used as the primary raw water supply for the Public Utilities Board (PUB) reticulated water system. PUB water is the source of potable water use by at least 67% of the more than 50,182 people of South Tarawa (KNSO and SPC 2012). Key infrastructure including the PUB Water Treatment Plant and Bonriki International Airport and residential houses are also located on Bonriki, above the freshwater lens, making it an important economic, social and cultural area for the Republic of Kiribati.

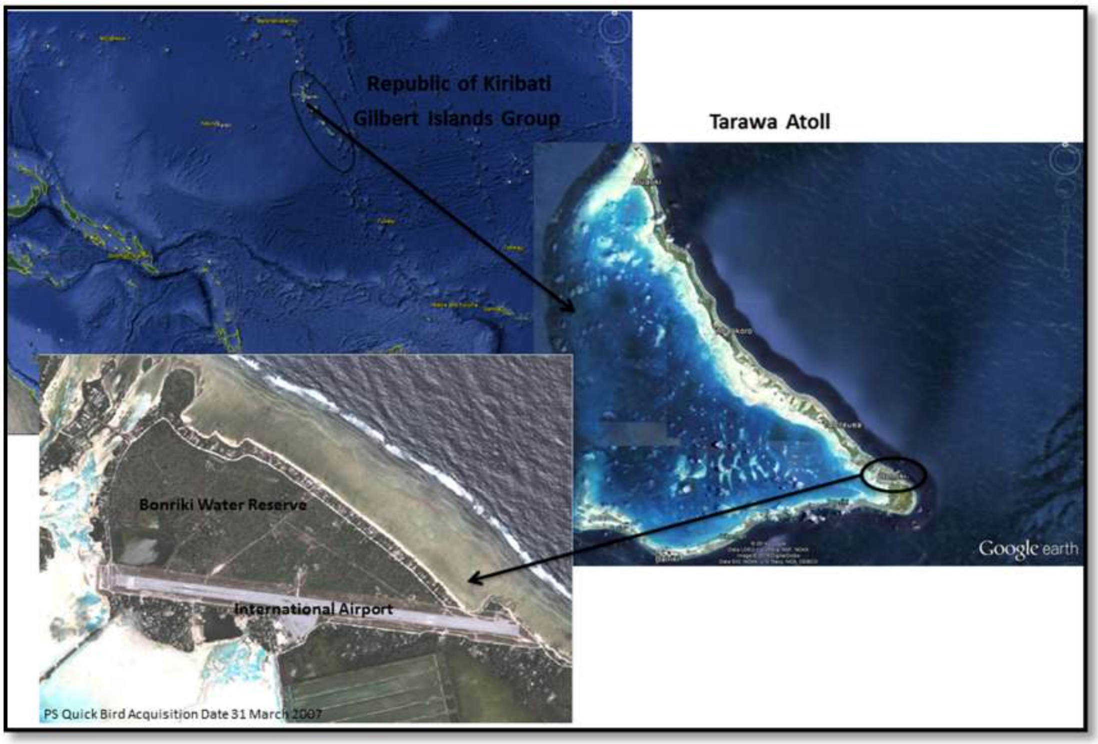

Figure 3. *Bonriki Water Reserve Location.*

1.5.3. Purpose of this report

Using a cost–benefit framework, this analysis:

- Provides a preliminary assessment of the costs and benefits of using either rainwater or reverse osmosis desalination to fully supplement the Bonriki groundwater, so that a target daily water volume can consistently be produced in the face of threats to the supply.
- Evaluates the potential cost to the government of a seawater inundation threat to the Bonriki freshwater lens relative to other threats (low rainfall and overabstraction) by using illustrative scenario analysis. In doing so it is possible to determine the relative significance of each of these threats to groundwater and provide suggestions on the next steps for ensuring water supply at minimum cost in the future.

As illustrated in Figure 4, the BIVA project consisted of three interlinked components: stakeholder engagement, groundwater investigations and analysis, and coastal investigations and analysis. This cost–benefit analysis component of the project has both been guided and supported by the technical groundwater and coastal components with information provided by stakeholders to inform the project and vice versa.

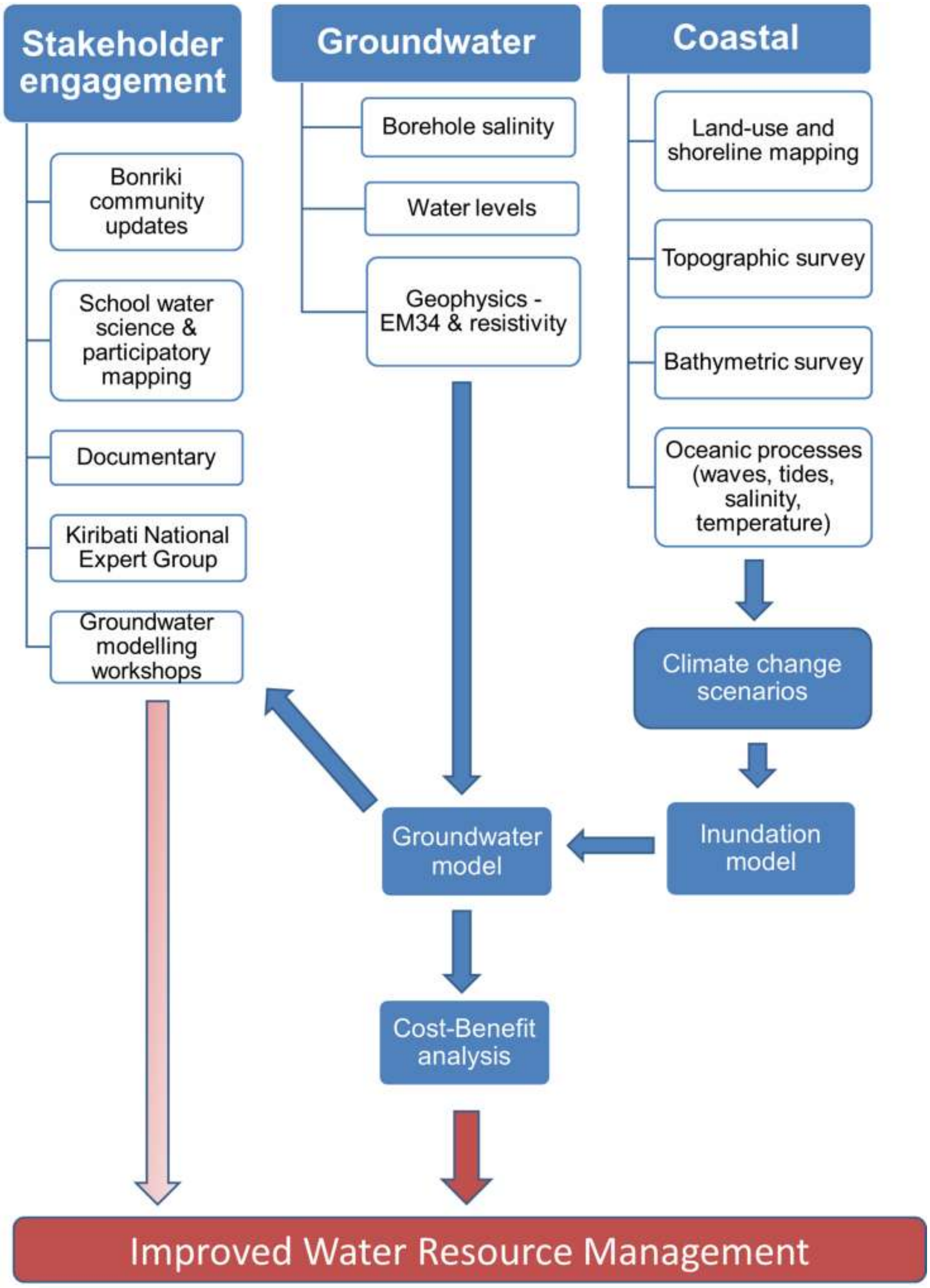

Figure 4: *Bonriki Inundation Vulnerability Assessment project components.*

1.5.4. Scope of this report

This analysis will provide information to the GoK on the potential costs, benefits and policy issues related to freshwater management options for Bonriki groundwater. The information will:

- inform public dialogue on the management of freshwater on Tarawa;
- identify data gaps needed to inform policy; and
- identify critical elements required to support policy development (enabling environment).

Section 2 provides data and background information on South Tarawa's water supply options; Section 3 explains the methodology used in the analysis; Section 4 provides the results; Section 5 discusses the implications of the results for future management; and Section 6 discusses the enabling environment for future water sources and further research required.

This report refers to the investigations and analysis undertaken as part of the groundwater and coastal components but does not seek to replicate the information within these. For detail on data collection and analysis, and processes undertaken as part of these components, refer to the other technical reports (Damlamian et al. 2015; Bosserelle et al. 2015) produced as part of the BIVA project.

2. Data and background information

2.1. Tarawa current water sources

There are four main sources of water in Kiribati: rainwater, piped water (freshwater lens), well water, and bottled or other water (Table 1).

Table 1: *Percent of households using each water source.*

Location	Rainwater	Pipe system (freshwater lens)	Well water	Bottled or other
South Tarawa	9 %	67 %	23 %	< 1 %
North Tarawa	1 %	2 %	97 %	< 1 %

Source: Calculated from the 2010 census report (KNSO 2010).

2.1.1. Private ground water and bottled water

White (2010a) rejects the notion of private groundwater wells as a source of safe drinking water around Tarawa because of their historically high frequency of contamination. The potential of private groundwater wells as a means to supplement water supplies is, therefore, not considered in this analysis. In the case of bottled water, statistics from the 2010 census (KNSO 2010) suggest that less than 1% of the population use bottled water. The low contribution of this source to water supplies is no doubt related to the high cost of this source, coupled with the large volumes of water required by the government to supply the population. Together, these factors render this source impractical for use as a backup to the Bonriki reserve and the potential for it is, therefore, not included in this analysis.

2.1.2. Household rain water harvesting

Although around 40% of households use rainwater as one of their freshwater sources, low roof catchment area capacity, large family sizes and frequent (approx. every seven years) droughts related to the El Niño–Southern Oscillation make this source unreliable (White 2010b). Consequently, Metutera (2002) and White (2010a) have recommended that household rainwater harvesting should be thought of as a supplemental water supply, rather than as a regular supply. No survey has yet been undertaken to record the current capacity for rainwater harvesting, making estimation of harvesting potential difficult. White (2011a) has estimated that, historically, the cost of household rainwater has been approximately AUD 8.2/kL. At first glance this seems high compared with the AUD 3.6/kL cost of production (abstraction) of water from the Bonriki reserves (White 2010a). Nevertheless, the cost of production from the groundwater lenses does not take into account the water lost though the distribution system before reaching households. Once these losses are taken into account, the cost of supplying water from Bonriki is actually higher per unit of water, rendering the cost of rainwater harvesting more competitive. The fact that household rainwater cannot produce all the necessary water does not mean that household rainwater harvesting should not be pursued. If properly maintained, rainwater harvesting systems using building roof areas have been estimated to be able to produce around 5 L/person/day for their inhabitants, with only a small risk of failure (White 2010a). This is enough to provide a third of the Sphere Standard (The Sphere Project 2014) total basic water need of a person[2].

Another potential reason for low rainwater harvesting levels is that groundwater is the traditional choice when making coconut toddy compared with rainwater (White 2010a) because the use of rainwater alters the taste unfavourably. This means that in some instances groundwater may be used even when clean rainwater is available, re-enforcing the need for quality groundwater. Despite those few instances where groundwater is preferred to rainwater, the value of rainwater as a safe source of water for normal drinking and cooking activities cannot be disregarded. In addition, the increasing salinity of ground water may ultimately result in changes in taste preference in the future.

2.1.3. Freshwater lenses

The Bonriki and Buota lenses feed the government-piped water system and supply approximately 67% of the households in South Tarawa according to the 2010 census. White (2010a) calculates the current unit cost of production for Bonriki and Buota to be AUD 3.60/kL. The water supply is managed by the PUB.

The water provided from Bonriki and Buota lens cannot supply all households in South Tarawa. Excess demand for water means that in 2005 over 40% of households used rain water and over 70% used wells as a source of water in South Tarawa. North Tarawa relies almost exclusively on open wells. Nevertheless, as discussed in White (2010a), previous studies have deemed household well water unsafe to use for bathing, cooking or drinking.

In addition to the ever greater demand on groundwater reserves from the population, coastal hazards such as wave overtopping, produce risks of seawater inundation and contamination. With average sea-level rise in Kiribati having been around 1–4 mm per year since 1993, and with further sea-level rise predicted over the next century (CSIRO 2011), and increasing demand for freshwater places additional stress on available groundwater, and saltwater intrusion is likely to become an ever greater threat to these vital water resources.

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[2] Between 7.5 L and 15 L of safe water per day

2.2. Alternative water sources

If Bonriki is unable to provide the target water volume after a seawater inundation or due to overabstraction, the PUB would be required to supplement the production.

White's (2010a) extensive assessment of other possible water sources provides an excellent source of information for choosing the least costly alternative water supply for use in this analysis. White (2010a) calculates the current unit cost of production for Bonriki to be AUD 3.60/kL, and notes that the Bonriki lens source is the cheapest source per unit because the installation costs have already been incurred, leaving only the operating and maintenance costs to fund. Metutera (2002) also shared this conclusion.

One of the least costly alternatives suggested by White (2010a) is reverse osmosis desalination. Despite the potentially high unit production costs of running the desalination plant over short time spans, this source is put forward in this analysis as one of the least costly options open to the government. The government has also asked for rainwater to be assessed for its cost effectiveness.

2.2.1. Desalination

If the salinity of the water increases to a point where it renders groundwater unsuitable for consumption, it may become necessary to consider the use of reverse osmosis desalination of seawater, as concluded by the TWMP (White 2010a). Although desalination plants in the Pacific do not have a successful history (White 2010a), following the installation and operating of the plant in Nauru, it is possible that — if the operation and maintenance of the plant is contracted out to experienced international suppliers — reasonable service and maintenance might be sustained. An economic analysis of the value of this option would require information on the type of plant that would be most suitable and the cost the government would need to incur to implement and maintain it. White (2010a) recommends reverse osmosis desalination as one of the least costly ways to increase water supply; nevertheless, compared with groundwater, desalination is expensive. Although there is no cost breakdown by White (2010a), estimates vary between AUD 5.19/kL and AUD 21.79 /kL. This upper bound cost estimate is similar to the cost of small-scale desalination in Tuvalu, which produces 50 kL/day at a unit cost of around AUD 17/kL (Gerber et al. 2011). Metutera (2002) estimated that the costs (Table 2) involved in producing water from the reverse osmosis desalination plants first installed in Kiribati during the 1999 drought. The costs are based on PUB's reported costs during the first two years of operation.

Table 2: *Previous desalination experience.*

Description		AUD	Comment
Fixed costs	Implementation costs for two plants with a combined daily capacity of 110 kL	300,000	Includes purchase of plants, construction of the building housing the plant and of the saltwater intake well, and labour costs.
Variable costs	Electricity costs/kL	2.81	Must be magnified to account for the increase in real price level of energy since 2002.
	Labour costs/kL	1.84	-
	Replacement parts/kL	0.73	-
	Total variable costs/kL	5.38	-

Source: Metutera, 2002

More recently, Fraser Thomas Partners (2012) detailed the cost of reverse osmosis desalination in South Tarawa, reporting that the unit cost of water in their intervention scenario would be approximately AUD 4.50/kL, the long durable life of the units allows its cost estimate to sit at the lower end of White's cost rage. Although the full economic costs of desalination are not covered, this analysis of desalination potential on Tarawa specifically is the most detailed in terms of its attention to detail in the running of the plants and consequently it is used as the basis for desalination costs in this analysis. Using the cost break down in the Fraser Thomas Partners analysis appendix, it is possible to generate costs based on the scenarios and assumptions of this analysis. The Fraser Thomas Partners costs are altered to account for more recent energy price projections discussed below (OPEC 2013) and any differences in the volume of water required.

The Fraser Thomas Partners desalination units are built with an expected life of 30 years or more (if pumps, valves and chlorine units are replaced and the units are properly maintained by contracted engineers). All of these costs are also included in this analysis.

Harrison Grierson Consultants (2013) in their peer review[3] of Fraser Thomas Partners (2012), agree that reverse osmosis desalination is the least costly option and with the general technical aspects of reverse osmosis desalination assumed. Suggestions were made to use fewer, larger plants at a central site rather than the multiple plant setup evaluated by Fraser Thomas Partners in order to further reduce operating costs. It was also suggested that full contracted maintenance be budgeted for the lifetime of the plants in the case that the PUB is unable to manage the task. In addition, the environmental aspects of the implementation would also need to be evaluated. These suggestions and the implications for the cost of producing water are discussed in the sensitivity analysis section. Importantly, the review also noted that the costs associated with deconstruction and recycling of the old desalination plants after 30 years was not included in the Fraser Thomas Partners evaluation.

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[3] The peer review was produced for the use of the Pacific Infrastructure Advisory Centre only, and advises that only indicative costs can be inferred from the report. Nevertheless, omitting reference to the report and producing estimations based solely on the Fraser Thomas Partners report would be irresponsible. Consequently, its comments are discussed and used to check the robustness of results in the sensitivity analysis section.

Because of the significance of this omission, this analysis includes an extra 'disposal cost' in the baseline estimations.

2.3. Fuel and electricity costs

A high proportion of desalination costs are due to the high energy supply they demand. A Kiribati PUB report (Metutera 2002) finds that the electricity cost of supplying groundwater is only AUD 0.17/kL whereas that of running the desalination plants was AUD 2.81/kL. Energy costs have been found to make up between 30% and 60% of desalination production costs, with heat processes such as those used in reverse osmosis desalination needing more energy (Pacific Institute 2006). The PUB supplies energy to the grid through diesel fuel generators (Republic of Kiribati 2012) and it is likely that in Kiribati, energy costs will continue moving with the cost of crude oil. Information on the cost of importing fuel per barrel by Kiribati or the source of their imported fuel is not available, and consequently this analysis uses the Organization of the Petroleum Exporting Countries (OPEC) long-term oil price forecast (OPEC 2013). Their analysis of the demand and supply of world oil based on the OPEC reference basket lead to a prediction of a slight downward movement in real price of oil from USD 104/barrel in 2015 to USD 100/barrel in 2035. This amounts to a negligible annual price change; nevertheless, oil prices have recently fallen dramatically, indicating the volatile nature of this commodity price. Given the magnitude of uncertainty surrounding long-term oil prices, this analysis will assume a constant real energy price. Changes in fuel price are discussed in the sensitivity analysis.

2.3.1. Large scale rainwater harvesting

The second water supplementation option being considered in this analysis is rainwater harvesting. In order to make a fair comparison with the option of desalination, large scale harvesting (able to produce 1,700 kL/day when the salinity of Bonriki surpasses the limit) will be estimated. This would consist of purpose-built, large-scale rainwater harvesting as detailed in White (2011a). White (2011a), using a rainwater tank calculator estimated the size of catchment area and tank size required in order to reduce the risk of water supply failure to zero percent. A roof area of 100 ha and a tank volume of 600,000 kL would be needed in order to supply 2,000 kL per day. In addition, in order to be able to construct purpose-built catchments of this size, it is likely that the government would need to rent land from inhabitants or pay compensation to landowners, which would further increase the cost of this option. These additional costs are unquantified in this analysis but are summarised in Table 5 of the methodology section.

The magnitude of the required catchment area and storage capacity are due to the high degree of variability on rainfall on Tarawa. In order to deal with severe droughts, shown to be correlated with the El Niño–Southern Oscillation (White and Falkland 2009), it is necessary for the rainwater infrastructure to be able to capture and store sufficient amounts of water during normal rainfall times in order to provide enough water through drought periods. This characteristic makes reliable rainwater harvesting (able to consistently supply water through droughts) relatively expensive compared with harvesting in locations where rainfall is less varied.

2.4. The daily water production target

The daily water production target used in this analysis is 1,960 kL/day[4]. The analysis assumes that this volume is produced at all times via Bonriki supply, desalination or rainwater.

2.4.1. Putting the production target in the context of South Tarawa's population

The total demand for water on Tarawa is a function of the total population services and the quantity they are allocated per day. In Tarawa, the GoK has adopted an exponential growth rate model[5] for the expected future population of the atoll. Using this model with data from the last two censuses the mean annual percentage exponential growth rates for the period 2005 to 2010 is calculated and displayed in Table 3.

Table 3: *Kiribati population in 2005 and 2010, and the forecasted population for 2015.*

Region	Total population in 2005[6]	Total population in 2010[7]	Mean annual exponential growth rate		Total population forecast for 2015	
			Upper	**Lower**	**Upper**	**Lower**
South Tarawa	40,311	50,182	4.38%	2.15%	62,470	55,890
North Tarawa	5,678	6,102	1.44%		6,558	

These growth rates are very similar to those calculated independently by (White, 2010) and as reported in ADB (2014). In practice, growth rates of this level could not continue in perpetuity. This is because of land and resource constraints on Tarawa and the already existing high population density. Given this, a more realistic lower bound growth rate is also calculated. This lower growth rate assumes zero net inward migration to South Tarawa (the national growth rate is used).

At present, using the lower bound 2015 population forecast, the target water production is sufficient to supply South Tarawa's population with approximately 35 L/person/day of water only if 100% of the water produced reached consumers. In actual fact, the distribution system is expected to have around 50% losses (Fraser Thomas 2012; White 2010). Given an optimistic approximate water loss of 25% during the distribution process, the volume reaching consumers would be expected to be around 26 L/person/day. With an expected 50% loss, the supply may be only 18 L/person/day.

The approximate 18 L/person/day that the target volume is expected to supply using the 2015 population forecast and 50% water distribution losses, is below the 21 L/person/day that constitutes

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[4] On the order of magnitude of the abstraction rate for Bonriki between June 2008 to September 2012 (1,918 kL).

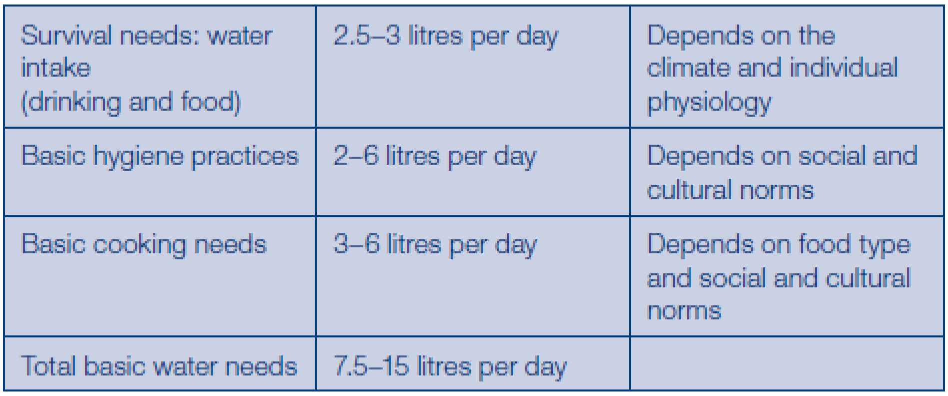
[5] Model is defined as: $P_t = P_0.e^{rt}$, where P_0 is population in the base year, P_t is the population t years after the base year, r is the growth rate, and e is Euler's number.

[6] Source: National Statistics Office, 2005

[8] Source: National Statistics Office and SPC, 2010

‘basic access’ to water under the World Health Organization standards (WHO 2006), but above the minimum (Table 4) global Sphere standard (The Sphere project 2014). The Sphere standard has calculated the average minimum daily requirement for water that enables populations to maintain health. Currently, the total basic water needs per person have been set at between 7.5 L and 15 L of safe water per day, depending on the environment in which the population lives. Given Tarawa’s location, which is almost directly over the equator, and its consequent climate, the maximum bound of 15 L/person/day could be used to represent the minimum water volume that should be provided to each inhabitant.

Table 4: *Total basic water needs according to the Sphere standard.*



Survival needs: water intake (drinking and food)	2.5–3 litres per day	Depends on the climate and individual physiology
Basic hygiene practices	2–6 litres per day	Depends on social and cultural norms
Basic cooking needs	3–6 litres per day	Depends on food type and social and cultural norms
Total basic water needs	7.5–15 litres per day	

Source: http://www.spherehandbook.org

Nevertheless, the target is still below the volume demanded by the population. White (2010a) estimated the average daily water demand per person to be 60 L/person/day based on survey information taken from Kiritimati Island villages and the village of Nonouti.

Looking to the future, even when using the lower growth rate and only a 25% loss of water during distribution, by 2036 the Bonriki freshwater reserve would be unable to provide the minimum global Sphere standard of 15 L/person/day.

3. Methodology

3.1. Analysis methodology

According to preliminary models generated by the BIVA project (Bosserelle et al. 2015), storm surges, variation in rainfall, and different abstraction rates all affect the volume of water available from the Bonriki groundwater reserve each year. In circumstances where Bonriki cannot supply water below the salinity threshold, other sources of water will be required. Although the Buota lens supplies approximately 15% of the total combined water provided to South Tarawa from PUB, the BIVA project focused on the Bonriki lens only and this analysis does the same (i.e. excludes Buota from the calculations).

Objective 1: Based on preliminary findings from BIVA groundwater models (see Annex 1), this analysis used a cost–benefit framework to estimate the most cost-effective way of providing additional water to supplement Bonriki's groundwater supply over the next 10, 20 and 50 years, taking into account the effect of seawater inundations and rainfall (the effects of which are captured in four illustrative scenarios, described in the next section).

Methodology: To determine the most cost-effective way of providing additional water, the analysis evaluates two water sources that could be used to supplement the groundwater supply; large-scale rainwater harvesting or reverse osmosis desalination. The analysis estimates the expected future cost of producing supplementary water via either desalination or rainwater so that the target water production (1,960 kL/day[8]) is always reached, under the four illustrative scenarios.

Objective 2: Determine the relative significance of each of these threats (seawater inundations, rainfall, and different abstraction rates) to groundwater and provide suggestions on the next steps for ensuring water supply at minimum cost in the future.

Methodology: Using the six illustrative scenarios, the analysis then evaluates the potential cost to the government of each threat by comparing the different costs of supplementing the Bonriki supply in each scenario.

3.1.1. Benefits and costs of water sources

The benefits of a maintained water supply are largely the same, regardless of the origin of the water (groundwater, large-scale rainwater or desalination). Benefits of the government producing sufficient supply for the population include cost savings from not having to import water from overseas or disruptions to the economy if the supply was to fall short.

On the other hand, costs vary between the two options, as indicated in Table 5. Costs marked in blue are unquantified in this analysis. Further work is required to determine these costs, but the expected impact of some of these unquantified costs is discussed in the sensitivity analysis.

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[8] On the order of magnitude of the abstraction rate for Bonriki between June 2008 and September 2012 (1,918 kL). It is the minimum volume of water that must be supplied to the population at any point in time in any analysis scenario.

Table 5: *Costs of water production options.*

	Large-scale rainwater harvesting	Desalination
Quantified	- Infrastructure and construction - Maintenance and labour	- Infrastructure and construction - Maintenance and labour
Not quantified	- Effect on supply of rainwater to groundwater lenses - Compensation to landowners/rent if private land required - Legal costs of negotiating the use of scarce land - Operational costs enforcing access rules to the resource, particularly if large-scale rainwater harvesting relies on a distributed system or approach. - Distribution costs via the Public Utilities Board system	- Environmental impacts - Importing fuel increases trade balance deficit - Sensitivity to fuel price fluctuations - Distribution costs via the Public Utilities Board system

3.1.2. Quantitative indicators

This analysis will estimate the net present value of total costs (net present cost, NPC) of producing water via rain capture or desalination in the representative scenarios used in this study. The NPC shows the cost of using either form of water supply over the period analysed, and is expressed in present day values. Costs per unit are also estimated, for ease of comparison with other water sources. Due to the range of discount rates used in the Pacific and the impact they can have on results, cost estimates are calculated using four different discount rates (10%, 8%, 3% and 0%, i.e. no discounting).

3.2. Modelling scenarios

The BIVA project has produced a wide range of seawater inundation scenarios under different wave height and water level predictions. As summarised in Annex 2, inundation scenarios consider the impact of predicted water level and wave heights occurring on sea levels predicted in 50 years (i.e. 2064), under three different greenhouse gas emission scenarios.

- Medium emission scenario (RP6) with sea level rise projection for 2064 (PACCSAP 2014).
- High emission scenario (RP8.5) with sea level rise projection for 2064 (PACCSAP 2014).
- Intermediate-high emission scenario from the US National Oceanic and Atmospheric Administration (Parris 2012.)

To provide an indication of the impacts on the salinity of the Bonriki freshwater lens resulting from inundation, four representative scenarios were developed for the groundwater model. They include consideration of two variables: extreme inundation impact versus no inundation; and wet (high) versus dry (low) rainfall conditions. The salinity of the water leaving the groundwater treatment plant via the trunk main is calculated from the groundwater model to allow comparison over time of the impacts on the groundwater supply in response to the different scenarios.

Abstraction variables considered for the Bonriki groundwater model include

- High abstraction: 1,960 kL/day (approximate Bonriki abstraction between 2008 and 2011).
- Approximate normal abstraction: 1,675 kL/day.
- Reduced abstraction for six years immediately post inundation, where those galleries that were directly inundated are switched off for six years, abstraction reduced to 690 kL/day for six years, before returning to abstraction levels prior to inundation.

Table 6: *Scenarios and groundwater impact.*

Scenario	Rainfall[9]	Seawater inundation	Abstraction rate (kL per day)	Number of days from the 6,208 days modeled and % of time that the water will be >1,500 µS/cm salinity limit
1	Wet (High)	No inundation	1,960	1,558, 25% of the time salinity is >1,500 µS/cm
2	Dry (Low)	No inundation	1,960	5,642, 91% of the time salinity is >1,500 µS/cm
3	Dry (Low)	No inundation	1,675	4,994, 80% of the time salinity is >1,500 µS/cm
4	Dry (Low)	Extreme inundation	1,960, reduced to 960 for 6 years after inundation	4,989, 80% of the time salinity is >1,500 µS/cm
5	Wet (High)	Extreme inundation	1,960	1,805 29% of the time salinity is >1,500 µS/cm
6	Dry (Low)	Extreme inundation	1,960	5,642, 91% of the time salinity is >1,500 µS/cm

The model was run for a period of 17 years (6,208 days) after the seawater intrusion event to determine the impact on the Bonriki freshwater lens and its recovery under different climatic conditions. Salinity estimates of the water leaving the trunk main at the groundwater treatment plant for six representative scenarios of inundation, rainfall and abstraction were produced (Table 6). Using these scenarios, the proportion of time that salinity of Bonriki is above the 1,500 µS/cm threshold was estimated.

3.3. Analysis of objective 1: Finding the least costly source of supplementary water

This part of the analysis looks at finding the least costly way to supplement the Bonriki water supply, either via reverse osmosis desalination or rainwater so that the daily target of 1,960 kL is produced at all times. When the Bonriki groundwater salinity is above the 1,500 µS/cm threshold, alternative sources (either rainwater or desalination) must supplement the supply to reach the target volume. Given the scenarios described above, the proportion of time that alternative sources are required and the volume of water they are required to produce, is calculated and displayed in Table 7. Proportions are based on the 17 years of analysis produced by Bosserelle et al. (2015). Because the

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[9] See Bosserelle et al. (2015) for rainfall assumptions.

economic evaluations span different time periods (50, 20 and 10 years), these proportions are used in order to calculate the number of days per year that Bonriki's salinity is above 1,500 µS/cm.

In other words, in each scenario it is assumed that the salinity patterns produced by Bosserelle et al. (2015) are repeated every 17 years. Using these groundwater model estimates, the proportion of time that salinity is above the threshold was used in 10, 20 and 50-year analyses and is displayed in Table 6.

It is important to note that in scenarios 3 and 4, whenever Bonriki's salinity is below the salinity threshold (able to produce potable water) but the abstraction rate is below 1,960 kL/day, alternative water sources (rainwater or desalination) must be used to top-up the groundwater. This ensures that 1,960 kL can be produced at all times under all scenarios. See Table 7 and Figure 5 for details.

Table 7: *Expected water requirements under the six scenarios.*

	Number of days from the 6,208 days that the water will be >1,500 µS/cm salinity limit	Proportion of time that salinity >1,500 µS/cm	Volume needed each of the days Bonriki salinity >1,500 µS/cm (kL)	Number of days from the 6,208 days that the water will <1,500 µS/cm and full 1,960 kL abstracted	Proportion of time that salinity <1,500 µS/cm and full 1,960 kL abstracted	Volume needed when Bonriki salinity <1,500 µS/cm and full 1,960 kL abstracted (kL)	Number of days that salinity <1,500 µS/cm but some pumps still turned off or abstraction is below 1,960 kL	Proportion of time that salinity <1,500 µS/cm but some pumps still turned off or abstraction is below 1,960 kL	Volume needed the days that salinity <1,500 µS/cm but some pumps still turned off or abstraction is below 1,960 kL
Scenario 1	1,558	0.25	1,959	4,650	0.75	0	0	0.00	0
Scenarios 2 and 6	5,642	0.91	1,959	566	0.09	0	0	0.00	0
Scenario 3	4,994	0.80	1,959	0	0.00	0	1,214	0.20	284
Scenario 4	4,989	0.80	1,959	967	0.16	0	252	0.04	999
Scenario 5	1,805	0.29	1,959	4,403	0.71	0	0	0.00	0

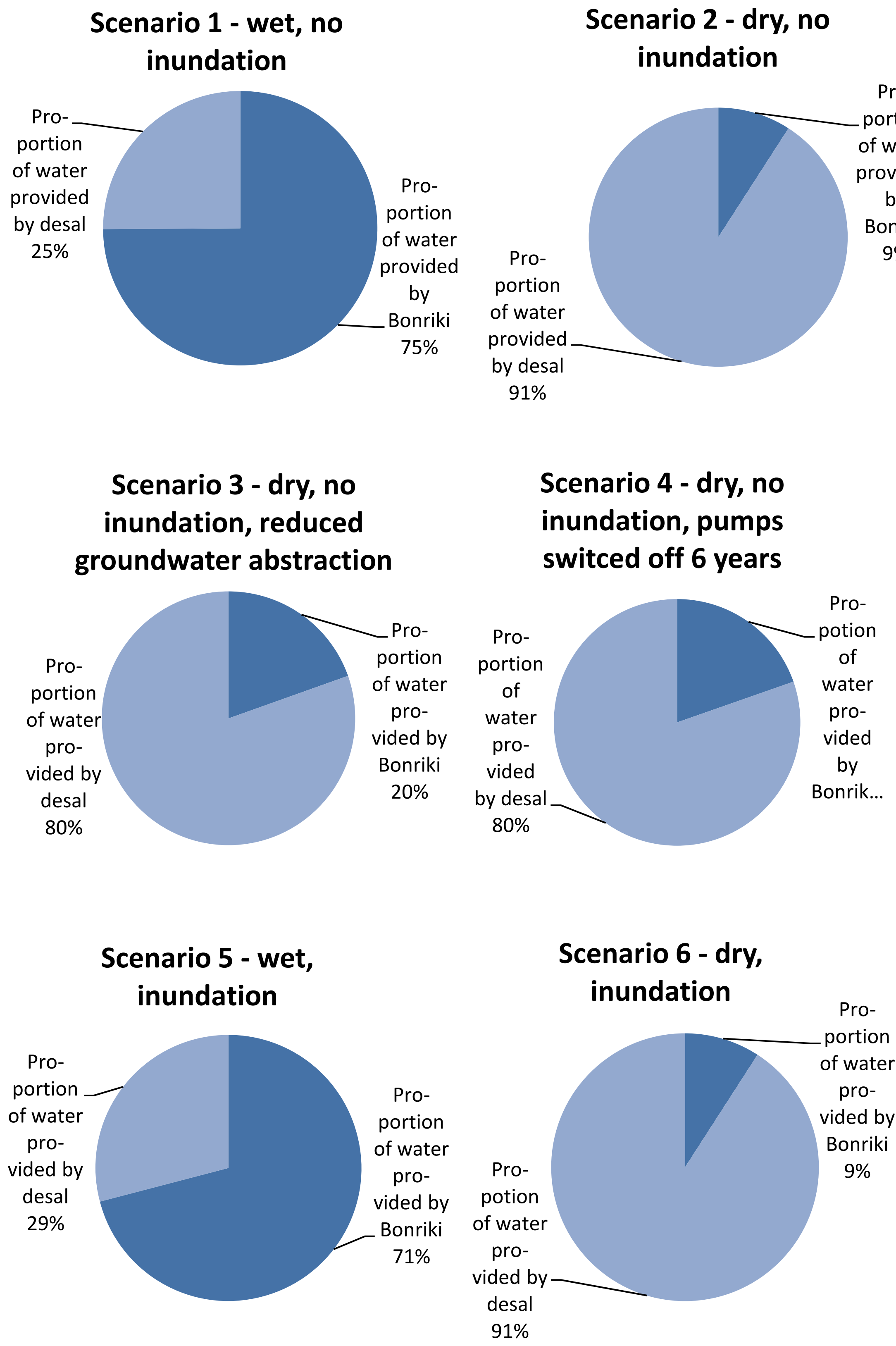

***Figure 5:** Expected water requirements under the six scenarios (total volumes over 6,208 days modelled).*

3.4. Analysis of objective 2: Evaluating the significance of threats to the groundwater supply

The cost of providing the water target in each scenario is estimated for the 17-year period modelled by the groundwater team. By comparing these costs of topping up the groundwater supply in different scenarios, it is possible to estimate the magnitude of the different threats in terms of the cost of producing the target water volume.

- **Cost of seawater inundation during high rainfall period:** The cost of seawater inundation can be estimated by calculating the cost of scenario 3 over the 17-year period minus the cost of scenario 1 over the 17-year period.
- **Cost of seawater inundation during low rainfall period:** The effect of seawater inundation on cost can be estimated by calculating the cost of scenario 4 over the 17-year period minus the cost of scenario 2 over the 17-year period.[10]
- **Cost saving by reducing abstraction during low rainfall period:** By comparing the cost in scenario 3 over the 17-year period to scenario 2 over the 17-year period, it is possible to estimate whether reducing Bonriki abstraction to 1,675 kL and making up the extra volume via alternative sources will produce a cost saving relative to continuing to abstract at the current level. When abstraction decreases, the cost savings (benefits) associated with this are included in the analysis.[11]
- **Cost saving by reducing abstraction after seawater inundation during low rainfall period:** By comparing the cost of scenario 4 over the 17-year period to scenario 6 over the 17-year period, it is possible to estimate whether reducing the abstraction rate after a seawater inundation and making up the extra volume via alternative sources will produce a cost saving relative to continuing to abstract as normal after a seawater inundation. When abstraction decreases, the cost savings (benefits) associated with this are included in the analysis.
- **Cost of reduced rainfall:** The effect of having a low rainfall period rather than a high rainfall period can be estimated by calculating the cost of scenario 2 over the 17-year period minus the cost of scenario 1 over the 17-year period.

3.5. Summary of analysis assumptions

All assumptions made in the analysis are summarised in the tables below (Tables 8 to 10). All values are in 2014 prices. The effects of changing assumptions are discussed in the sensitivity analysis section.

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[10] Even without undertaking any calculation, from the above table it is possible to see that the cost of a seawater inundation in dry conditions is zero. The inundation impact to salinity is so small compared with that of the rainfall that it has no additional effect on the number of days that Bonriki is above the 1,500 µS/cm salinity limit.

[11] White (2010a) states that the approximate cost of production via abstraction from Bonriki is AUD 3.60/ kL. When the volume abstracted decreases, the analysis reduces the total cost of abstraction accordingly.

Table 8: *Summary of general analysis assumptions.*

Analysis component	Assumption
Target water production	A target of 1,960 kL/day is used, estimated to be the approximate abstraction rate for Bonriki between 2008 and 2011. This is the volume of water that must be produced via either Bonriki, rainwater or desalination.
Seawater inundation impacts on Bonriki supply	The seawater inundation and groundwater models used to produce the data for this analysis (Damlamian et al. 2015; Bosserelle et al. 2015) have incorporated expected sea-level rise under different greenhouse gas emissions, for the next 50 years.
Water sources	Bonriki water reserve is the primary water source. When it is unable to provide 1,960 kL/day, one of the alternate sources is used to top-up water production to this amount.
Import prices (imported goods required for infrastructure construction)	No change in exchange rate is assumed (shadow exchange rate factor = 1). Fossil fuel prices (and consequently costs of transport) are held constant in real terms (OPEC 2013)
Local labour	Any costs incurred due to paying for local labour is adjusted to account for the 20 per cent income tax. A shadow wage rate of 90% is used to account for the loose labour market.
Social discount rate	Discount rates of 10, 8, 3 and zero per cent are employed for robustness.
Costs are calculated in real terms	It is assumed that the costs indicated in the cost breakdown in Fraser Thomas Partners (2012) analysis are in real, constant 2012 prices.

3.5.1. Large-scale rainwater harvesting

Table 9 details the assumptions made for large-scale rainwater harvesting. The required roof area and tank volume are from White (2011a) and are calculated based on the White and Falkland 2009 water model (runoff coefficient = 0.85, rainfall based on 1947–2008).

Table 9: *Large-scale rainwater harvesting assumptions.*

Analysis Component	Assumption
Cost of large-scale roof catchment area required (White 2011a)	107.8 million
Large water harvesting roof area life expectancy (maximum)	50 years
Cost of large-scale rainwater tanks per kL of storage (White 2011a)	AUD 108
Life expectancy of tanks and guttering (White 2010b)	20 years
Cost of installation, guttering and fittings as a percentage of tank costs (minimum estimate)	20%
Average annual salary of full time staff (Tanaea Facility, Government Ministry of Agriculture and Livestock)	AUD 4,600
Income tax (Fraser and Thomas Partners, 2012)	20%
Weekly wage of rainwater caretaker (20% income tax deducted)	AUD 71
Shadow wage used to account for loose labour market (high unemployment)	90%
Resilience of rainwater harvesting and desalination activities to natural hazards	It is assumed that the threat of sea level rise and seawater inundations be taken into account when deciding on the location of the constructed large scale water catchment and desalination plants.
Rainwater capture	As with the reports on which the rainwater infrastructure data for this analysis is based, the rainfall conditions are those used for the White and Falkland (2009) water model (runoff coefficient = 0.85, rainfall based on 1947–2008).

3.5.2. Desalination

Table 10 details the assumptions made for desalination. Values are based on Fraser and Thomas (2012) and Harrison Grierson Consultants (2013).

Table 10: *Desalination assumptions.*

Analysis Component	Assumption
Installation cost/daily kL capacity	AUD 5,117
Yearly running cost /daily kL capacity	AUD 1,122
Cost of replacement of pumps and valves every 15 years	AUD 2,084,864
Cost of replacement of clor units (Fraser Thomas partners, 2012) every 10 years	AUD 62,546
Life expectancy of plants	30 years
Disposal and recycling of desalination plants	An additional 100% of the implementation costs is added on the 30th year to account for the costs associated with disposal of the exhausted equipment

4. Results

4.1. General cost estimates (if rainwater or desalination was required to produce 1,960 kL every day) [12]

Before analysing the costs of water production under the six representative scenarios, general cost estimates for producing at least 1,960 kL of water per day via rainwater or desalinated water are calculated.

These estimates show the costs of producing water from each source if they were required to produce at their maximum capacity every day. These estimates represent the standard costs of production from each water source, comparable with production costs found in the literature for studies evaluating the cost of producing additional water for Tarawa. As with the reports on which the rainwater infrastructure data for this analysis is based, rainfall conditions are those used for the White and Falkland (2009) water model (runoff coefficient = 0.85, rainfall based on 1947–2008).

Table 11 displays the NPC and the unit cost (cost per kL) of water produced from each source if production was required to take place for 50 years, 20 years or 10 years with the water from all sources being utilised. Estimates are shown for four discount rates (10%, 8%, 3% and 0%).

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[12] All cost estimates are indicative, preliminary cost estimates produced for the Secretariat of the Pacific Community, Pacific-Australia Climate Change Science and Adaptation Planning Bonriki Inundation Vulnerability Assessment project. In order to fully cost water sources, additional data and considerations must be addressed as described in Section 6.

Table 11: *General cost of production, in Australian dollars.*

	LSRH[13]	Desalination
Volume produced per day (kL)	**2,000**	**1,960**
50-year analysis		
NPC (10% discounting)	198,977,019	42,804,275
Average unit cost (10% discounting)	**5.45**	**1.20**
NPC (8% discounting)	205,979,623	50,825,792
Average unit cost (8% discounting)	**5.64**	**1.42**
NPC (3% discounting)	252,712,514	98,329,729
Average unit cost (3% discounting)	**6.92**	**2.75**
Total cost (no discounting)	341,532,362	182,865,195
Average unit cost (no discounting)	**9.35**	**5.11**
20-year analysis		
NPC (10% discounting)	185,678,250	36,896,195
Average unit cost (10% discounting)	**12.71**	**2.58**
NPC (8% discounting)	185,682,352	40,808,134
Average unit cost (8% discounting)	**12.71**	**2.85**
NPC (3% discounting)	185,697,986	55,869,940
Average unit cost (3% discounting)	**12.71**	**3.90**
Total cost (no discounting)	185,713,473	70,938,779
Average unit cost (no discounting)	**12.71**	**4.96**
10-year analysis		
NPC (10% discounting)	185,668,215	28,415,031
Average unit cost (10% discounting)	**25.42**	**3.97**
NPC (8% discounting)	185,669,578	29,860,265
Average unit cost (8% discounting)	**25.42**	**4.17**
NPC (3% discounting)	185,673,795	34,437,700
Average unit cost (3% discounting)	**25.42**	**4.81**
Total cost (no discounting)	185,680,353	38,061,944
Average unit cost (no discounting)	**25.42**	**5.32**

4.1.1. Comparing large-scale rainwater harvesting and desalination

The two main options considered in this report as 'backup water sources' for Bonriki are LSRH and desalination, both of which are able to provide 1,960 kL/day if required. The costs of these two options are shown in Table 11. Cost estimates support previous studies such as the TWMP (White 2010a) in concluding that desalination is the more cost-efficient option for large-scale water production. For example, as can be seen in Table 11, in the 50-year analysis the cost of desalination per unit ranges between AUD 1.2/kL (for a 10% discount rate) and AUD 5.1/kL (with no discounting).

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[13] Large-scale rainwater harvesting cost estimates represent the minimum expected cost of this option. Rental payments for land have not been included in the above estimates. Once rental payments are included, unit costs rise further to between AUD 10.1/kL and AUD 26.1/kL. Cost of rental payments for private land or hectare were at AUD 5,000/year in 2011 (White 2011a).

In comparison, the cost of LSRH ranges between AUD 5.5/kL and AUD 9.4/kL. In the 10-year analysis, desalination becomes even more appealing in comparison to LSRH, with unit costs approximately only 20% of those of LSRH. Figure 6 demonstrates the difference in magnitude of desalination and rainwater costs.

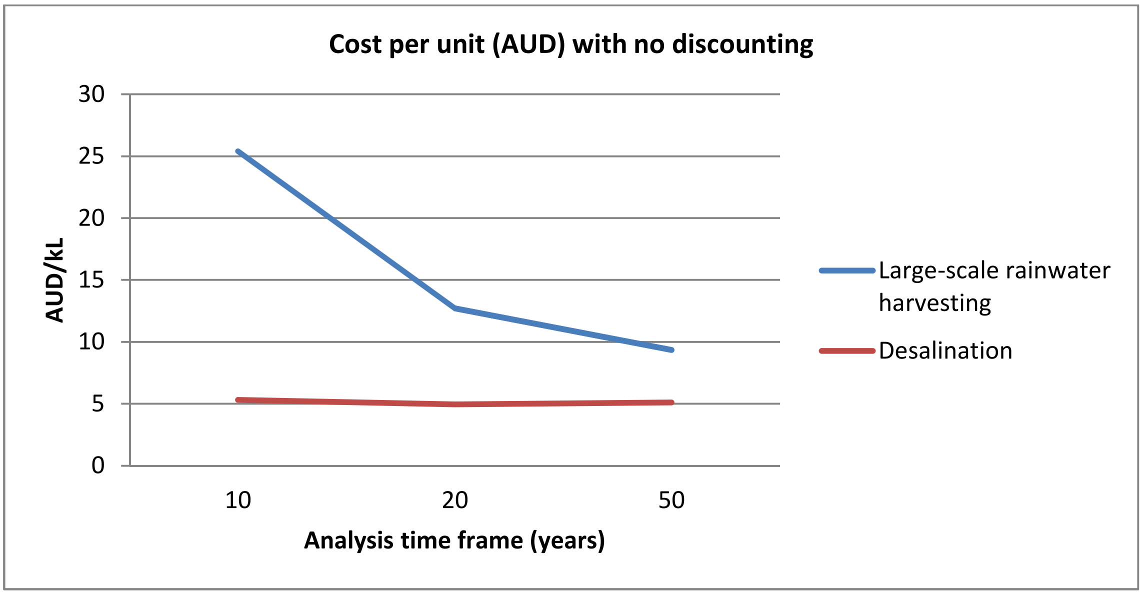

Figure 6: *Comparison of large-scale rainwater harvesting with desalination.*

Even if the large-scale rainwater harvesting roofing infrastructure was to last for 50 years before requiring replacement, the unit cost of rainwater is still about twice that of desalination.

4.1.2. Putting the least cost option (desalination) into perspective

Producing water via desalination versus groundwater

Although desalinated water is less costly than LSRH it is still more costly than groundwater supplied from Bonriki and Buota. The estimated cost of groundwater (White 2010a) is AUD 3.60/kL, whereas the minimum expected cost for desalinated water is AUD 4.97/kL. In addition, desalination has far greater energy demands than groundwater abstraction and, given that energy is presently supplied via diesel combustion, desalination will produce more carbon emissions and increase Kiribati's trade balance deficit through higher diesel imports. Consequently, it is clear that groundwater is still Kiribati's least costly water source and that protecting groundwater reserves from human pressures such as encroachment (White 2010a) should be a key focus in the future.

Supplying households via desalination versus small scale household rainwater harvesting

Desalination has been found to be the least costly option in this analysis for large-scale water *production*, but it is informative to ask how it compares with other, *smaller-scale* options, such as household rainwater harvesting in terms of the total cost of supplying water to consumers.

Although no survey has been undertaken to record the current capacity for rainwater harvesting, which makes the estimation of harvesting potential difficult, White (2011b) has estimated that historically, the cost of household rainwater has been approximately AUD 8.2/kL. Although private rainwater harvesting could never produce the full volume required to backup the PUB water supply, the use of existing suitable buildings has been recommended by previous reports (GWP 2012; White 2011a) and as a source of supplementary water (able to produce around 5 L/person/day in households with suitable roofs). Because of these recommendations, the estimated cost of private rainwater (White 2011b) is compared with the least costly option (desalination) found in this analysis.

From Table 11, the cost of desalination (using no discounting) ranges from AUD 4.97/kL to AUD 5.32/kL. Household rainwater harvesting is estimated to cost AUD 8.2/kL. Nevertheless, desalinated water would need to be distributed to households by the PUB, whereas household rainwater harvesting entails no distribution costs. Even if only 25% water loss was assumed via PUB distribution; in other words, to deliver three units of water four units must be produced, the true cost of actually producing and delivering desalinated water to households would be at least (AUD 4.97/kL / 3 X 4) = AUD 6.63/kL. If, following other reports (Fraser Thomas Partners 2012; White 2010), a 50% water loss via distribution is assumed (i.e. in order to deliver one unit of water to the household, two units must be produced), then the minimum cost of producing and delivering desalinated water to households would be (AUD 4.97/kL X 2) = AUD 9.94/kL. This actually makes the true cost of supplying desalinated water to households slightly more expensive than household rainwater harvesting.

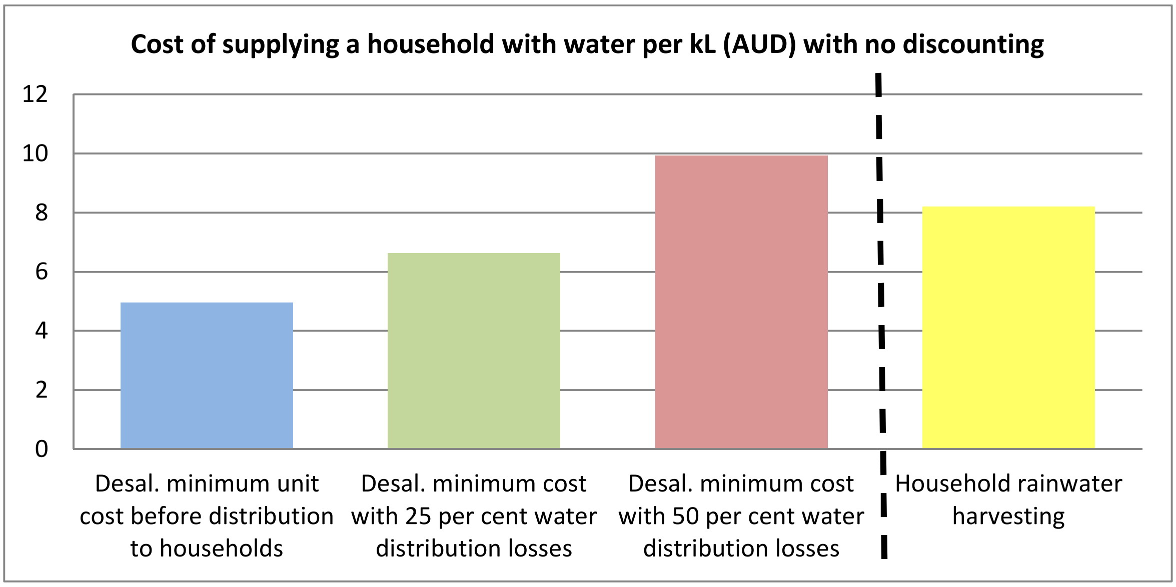

Figure 7: *Comparing desalination costs with household rainwater harvesting.*

As shown in Figure 7 above, if a 50% loss through distribution is assumed (Fraser Thomas Partners 2012; White 2010a), then the total cost of providing water to households via desalination (pink column) is higher than that of household rainwater harvesting (yellow column). This supports a recommendation of incentivising household rainwater harvesting in order to produce *supplementary* water. Although household rainwater harvesting could not be relied on as a backup to groundwater or during extreme droughts, it is a relatively low-cost option for providing extra water in order to reduce the stress on the PUB system during normal weather conditions.

One key difference between private rainwater harvesting and the PUB supplied water (Bonriki groundwater, LSRH and desalination), is that the production costs of private harvesting are usually incurred directly by households. This is briefly discussed in Section 6.

4.2. Results for objective 1: Least costly method of supplementation in illustrative scenarios

This section focuses on the two main water sources considered in this analysis as able to produce the large volumes of water (1,960 kL/day) required to act as backups to the Bonriki supply: LSRH and desalination.

Under each scenario, water produced from LSRH or desalination is only used at certain times of the year (i.e. the water they produce is only used when Bonriki's salinity is above 1,500 µS/cm). This makes the unit costs of production from rainwater or desalination much higher, the installation costs and many of the running costs must still be incurred even if not all of the water is used. Nevertheless, given that rainwater harvesting and desalination are being used as backups to ensure the target freshwater volume and quality is reached, it is necessary to have them in place throughout the 50 years of the analysis so that they can be employed when needed.

Table 12: *Cost of producing water from alternate sources under different scenarios, in Australian dollars.*

	Scenario 1	Scenarios 2 & 6	Scenario 3	Scenario 4	Scenario 5					
	LSRH	**Desal.**	**LSRH**	**Desal.**	**LSRH**	**Desal.**	**LSRH**	**Desal.**	**LSRH**	**Desal.**
50-year evaluation										
NPC (10% discounting)	198,977,019	26,256,304	198,977,019	40,726,485	198,977,019	39,205,985	198,977,019	38,978,665	198,977,019	27,131,459
Average unit cost (10% discounting)	**21.71**	**2.92**	**5.99**	**1.25**	**6.54**	**1.32**	**6.61**	**1.32**	**18.74**	**2.61**
NPC (8% discounting)	205,979,623	30,775,587	205,979,623	48,305,131	205,979,623	46,476,488	205,979,623	46,197,511	205,979,623	31,835,773
Average unit cost (8% discounting)	**22.47**	**3.43**	**6.21**	**1.49**	**6.77**	**1.56**	**6.84**	**1.57**	**19.40**	**3.06**
NPC (3% discounting)	252,712,514	58,094,700	252,712,514	93,256,388	252,712,514	89,652,800	252,712,514	89,075,836	252,712,514	60,221,276
Average unit cost (3% discounting)	**27.57**	**6.47**	**7.61**	**2.87**	**8.31**	**3.01**	**8.39**	**3.02**	**23.80**	**5.79**
Total cost (no discounting)	341,532,362	106,937,772	341,532,362	173,276,430	341,532,362	166,541,118	341,532,362	165,435,445	341,532,362	110,949,929
Average unit cost (no discounting)	**37.26**	**11.91**	**10.29**	**5.33**	**11.23**	**5.59**	**11.34**	**5.61**	**32.16**	**10.67**
20-year evaluation										
NPC (10% discounting)	185,678,250	22,688,377	185,678,250	35,113,501	185,678,250	33,802,504	185,678,250	33,608,765	185,678,250	23,439,847
Average unit cost (10% discounting)	**50.64**	**6.32**	**13.98**	**2.70**	**15.26**	**2.84**	**15.41**	**2.85**	**43.71**	**5.63**
NPC (8% discounting)	185,682,352	24,718,359	185,682,352	38,786,930	185,682,352	37,312,665	185,682,352	37,090,566	185,682,352	25,569,225
Average unit cost (8% discounting)	**50.64**	**6.88**	**13.98**	**2.98**	**15.26**	**3.13**	**15.41**	**3.14**	**43.71**	**6.15**
NPC (3% discounting)	185,697,986	32,607,468	185,697,986	52,938,674	185,697,986	50,846,637	185,697,986	50,515,283	185,697,986	33,837,098
Average unit cost (3% discounting)	**50.65**	**9.08**	**13.99**	**4.07**	**15.26**	**4.27**	**15.42**	**4.28**	**43.72**	**8.13**
Total cost (no discounting)	185,713,473	40,569,350	185,713,473	67,104,814	185,713,473	64,404,943	185,713,473	63,964,224	185,713,473	42,174,213
Average unit cost (no discounting)	**50.65**	**11.30**	**13.99**	**5.16**	**15.26**	**5.40**	**15.42**	**5.42**	**43.72**	**10.14**
10-year evaluation										
NPC (10% discounting)	185,668,215	18,168,329	185,668,215	27,136,020	185,668,215	26,161,373	185,668,215	26,029,220	185,668,215	18,710,694
Average unit cost (10% discounting)	**101.27**	**10.12**	**27.97**	**4.17**	**30.51**	**4.39**	**30.83**	**4.41**	**87.42**	**8.99**
NPC (8% discounting)	185,669,578	18,873,064	185,669,578	28,488,041	185,669,578	27,446,381	185,669,578	27,303,790	185,669,578	19,454,577
Average unit cost (8% discounting)	**101.28**	**10.51**	**27.97**	**4.38**	**30.51**	**4.60**	**30.83**	**4.63**	**87.42**	**9.35**
NPC (3% discounting)	185,673,795	21,114,077	185,673,795	32,771,251	185,673,795	31,518,669	185,673,795	31,343,006	185,673,795	21,819,102
Average unit cost (3% discounting)	**101.28**	**11.76**	**27.97**	**5.04**	**30.51**	**5.29**	**30.83**	**5.31**	**87.42**	**10.49**
Total cost (no discounting)	185,680,353	22,895,617	185,680,353	36,163,349	185,680,353	34,744,829	185,680,353	34,542,975	185,680,353	23,698,048
Average unit cost (no discounting)	**101.28**	**12.75**	**27.97**	**5.56**	**30.51**	**5.83**	**30.83**	**5.86**	**87.42**	**11.39**

4.2.1. Comparison of large-scale rainwater harvesting to desalination

As expected, Table 12 demonstrates that desalination is always the least costly way of producing the larger volumes of water, which are required for South Tarawa. This is due to: 1) the general cost of desalination being lower (as found in the previous section); and 2) the fact that rainwater production costs cannot be reduced during the times that water is not needed (i.e. when Bonriki's salinity is below the 1,500 µS/cm threshold and able to produce 1,960 kL/day). On the other hand, desalination production can be reduced and plants can be turned off or run at lower capacity. In calculating desalination cost estimates it was assumed that all variable costs of production (such as electricity) would be proportional to the volume produced. When less water is required, production can vary accordingly.

4.3. Results for objective 2: Comparison of costs of different threats

As discussed in Section 3, by comparing the costs of producing water in different scenarios it is possible to understand the likely effects of variables on production costs. For ease of comparison, estimations use no discounting and are calculated for 17-year time periods (Table 13).

Table 13: *Scenario comparisons.*

Scenario	1	2 and 6	3	4	5
Cost of producing desalinated water over 17 years (in AUD)	37,448,727	61,330,644	58,898,875	58,502,737	38,893,103
Cost savings from decreased groundwater abstraction over 17 years (in AUD)	0	0	1,241,194	906,293	0
Total cost over 17 years (in AUD)	37,448,727	61,330,644	57,657,681	57,596,444	38,893,103

4.3.1. Cost of seawater inundation during high rainfall period

The effect of a seawater inundation during a high rainfall period can be estimated by calculating the cost of scenario 5 over the 17 years of simulation minus the cost of scenario 1 over the 17 years of simulation. Seawater inundation would increase the proportion of time that Bonriki's salinity is above the threshold and the number of days that alternative sources must be used. The total cost of seawater inundation during high rainfall times is estimated to be AUD 1,444,376 for the 17 years of simulation.

4.3.2. Cost of seawater inundation during low rainfall period

The effect of seawater inundation during a low rainfall period can be estimated by calculating the cost of scenario 6 over the 17 years of simulation minus the cost of scenario 2 over the 17 years of simulation. The total cost of seawater inundation during low rainfall times is estimated to be zero over the 17 years of simulation. This is because the effect of rainfall is so much larger than the effect of seawater inundations on Bonriki's salinity that the simulations predict that during dry conditions there would be no difference in the number of days that Bonriki's salinity is above the 1,500 µS/cm threshold with or without a seawater inundation.

4.3.3. Benefit of reducing abstraction during low rainfall period

By comparing the cost in scenario 3 to scenario 2 over the 17 years of simulation, it is possible to estimate whether reducing abstraction from Bonriki to 1,675 kL/day and making up the extra volume via alternative sources will produce a cost saving relative to abstracting at 1,960 kL/day. The total cost saving (benefit) of reducing abstraction from Bonriki from 1,960 kL/day to 1,675 kL/day and sourcing the additional water from an alternate source, such as desalination, during low rainfall periods is estimated to be AUD 3,672,963 for the 17 years of simulation.

4.3.4. Benefit of reducing abstraction after seawater inundation during low rainfall period

By comparing the NPC of scenario 4 to scenario 6 over the 17 years of simulation, it is possible to estimate whether reducing the abstraction rate after a seawater inundation and making up the extra volume via alternative sources will produce a cost saving relative to continuing to abstract at the high rate after a seawater inundation. The total cost saving (benefit) of reducing abstraction after a seawater inundation during low rainfall periods is estimated to be AUD 3,734,200 for the 17 years of simulation.

4.3.5. Cost of reduced rainfall

The effect of having a low rainfall period rather than a high rainfall period can be estimated by comparing the cost in scenario 2 to scenario 1. The total cost of a period of low rainfall compared with a period of high rainfall in this model is estimated to be AUD 23,881,917 for the 17 years of simulation.

4.3.6. Conclusions from scenario comparisons

Having compared the costs of producing 1,960 kL/day of water under different scenarios, it is possible to infer that:

- the effect of having a period of low rainfall versus a period of high rainfall is the most costly phenomenon based on this model;
- the effect of a seawater inundation on the costs of providing water are smaller than the effects of rainfall and of abstracting at higher rates longer term;
- only during high rainfall periods is the effect of a seawater inundation on production costs likely to be felt; and
- reducing abstraction after a seawater inundation or during low rainfall periods produces cost savings.

Findings 1 and 3 are also supported in (Rios Wilks 2015), which analyses the cost of rainfall variation and seawater inundation at a lower abstraction rate (1,700 kL).

Because the inundation scenarios used in this analysis are based on sea-level rise predictions at the high end of the range (Parris 2012), the seawater inundation generated will also lie at the high end of predictions. Consequently, the finding here of this relatively 'bad case' seawater inundation still being less of a threat than the other two factors, signals that the focus should indeed be on rainfall and overabstraction going forward. Because rainfall cannot be changed, the focus should be on managing within the range of sustainable groundwater abstraction from Bonriki.

4.4. Sensitivity analysis

In this section, the assumptions and uncertainties of the analysis are discussed in order to check the level of robustness of the results.

4.4.1. Desalination

Cost assumptions

From the Fraser Thomas Partners (2012) cost break-down, it is not possible to tell whether ongoing costs are in real or nominal terms. Because the analysis they conducted was termed an 'economic analysis' it is assumed that these are real costs (at 2012 prices). If this is not the case, then the cost estimations in this analysis will have slightly overestimated the cost of desalination water production. Nevertheless, this would not change the ranking of desalination as the least costly method of supplementing groundwater.

The peer review (Harrison Grierson Consultants 2013) made some valid comments on the robustness of the Fraser and Thomas financial analysis. Aside from the cost of disposing and recycling the plants after their 30-year lifespan comes to an end (which has already been accounted for in the main calculations and results discussed in Section 4 of this report), the peer review also noted some other factors that may impact the cost of desalinated water production.

- Significant cost savings associated with using fewer, larger plants at a central site.
- Concern about cost of importing plants in 40-foot containers when the current port capacity is 20-foot containers. To account for this, port handling fees were increased by 70% in Harrison Grierson Consultants (2013), and even with this increase the review concluded that there would be significant cost savings associated with using fewer, larger plants at a central site.
- Risks associated with leaving day-to-day operations of the plants to the PUB were highlighted in the peer review. It was suggested that the supply of items requiring constant replacement and the preparation of the 'multimedia and calcite beds' should be provided by the contracted maintenance. Nevertheless, it was noted that this would likely only increase running costs marginally while providing benefits of reduced risks to the water supply operations from fluctuations government budgets.

Overall, once the three comments above are taken into account, there is likely to be a reduction in costs relative to those in the results section if fewer larger desalination plants were used as detailed in Harrison Grierson Consultants (2013). This lends further support to the cost-effectiveness of pursuing desalination rather than purpose-built, large-scale rainwater catchment structures when large volumes of production are required.

Historical desalination estimates

Desalination costs were also estimated using data from Metutera (2002). The unit costs were significantly higher than those estimated in the main estimates as shown in Table 14. All costs are in AUD. The Metutera (2002)-based cost estimates are higher because aside from the inefficiency of using multiple small units for large-scale production, these older plants require more frequent replacement given their six-year life expectancy. Nevertheless, these second, higher desalination costs were still lower than those of using large-scale rainwater harvesting, confirming that desalination is likely to be less costly than LSRH as a method of supplementing groundwater.

Table 14: *Comparison of main desalination cost estimates with those based on Metutera (2002).*

	Desalination (main estimates)	**Desalination (Metutera 2002)**
Volume produced per day (kL)	**1,960**	**2,000**
50-year evaluation		
NPC (10% discounting)	42,804,275	73,293,190
Average unit cost (10% discounting)	**1.20**	**2.01**
NPC (8% discounting)	50,825,792	88,038,822
Average unit cost (8% discounting)	**1.42**	**2.41**
NPC (3% discounting)	98,329,729	173,465,076
Average unit cost (3% discounting)	**2.75**	**4.75**
Total cost (no discounting)	182,865,195	325,418,416
Average unit cost (no discounting)	**5.11**	**8.91**
20-year evaluation		
NPC (10% discounting)	36,896,195	63,678,572
Average unit cost (10% discounting)	**2.58**	**4.36**
NPC (8% discounting)	40,808,134	71,679,656
Average unit cost (8% discounting)	**2.85**	**4.91**
NPC (3% discounting)	55,869,940	102,393,878
Average unit cost (3% discounting)	**3.90**	**7.01**
Total cost (no discounting)	70,938,779	133,059,900
Average unit cost (no discounting)	**4.96**	**9.11**
10-year evaluation		
NPC (10% discounting)	28,415,031	46,505,633
Average unit cost (10% discounting)	**3.97**	**6.37**
NPC (8% discounting)	29,860,265	49,520,876
Average unit cost (8% discounting)	**4.17**	**6.78**
NPC (3% discounting)	34,437,700	59,034,343
Average unit cost (3% discounting)	**4.81**	**8.08**
Total cost (no discounting)	38,061,944	66,529,950
Average unit cost (no discounting)	**5.32**	**9.11**

Fuel price

Given the predictions of OPEC (2013), this analysis has assumed a constant real price of fuel. Nevertheless, fuel price predictions are susceptible to high degrees of error, and changes in fuel price would translate into changes in desalination production costs. Nevertheless, an increase of fuel costs of around 500% would be required to make desalination as costly as LSRH, which is considered unlikely. Any decrease in fuel costs would make desalination even more cost efficient compared with LSRH. Additionally, if energy was to be supplied via an alternate technology, such as solar power, and the energy could be produced more cheaply than by fossil fuel combustion, then the cost of desalination would also decrease.

Environmental aspects

As suggested in Harrison Grierson Consultants (2013), before finalising the design of desalination operations, experts should evaluate:

- the sustainable volume that may be abstracted from the saltwater boreholes to mitigate over abstraction;
- any impact on coastal processes (e.g. movement of sediment) that may occur from the use of infiltration galleries; and
- any effect that the brine discharge may have on biodiversity and marine life.

Approximately 42% of the seawater volume processed by the desalination plants is emitted as freshwater for use by the population; the remaining 58% will be returned to the ocean in the form of a brine solution that includes the backwash water. Not only will the brine have an increased salt content, it could also contain chemicals used in the treatment process such as anti-scalant and sodium meta-bisulphite. The TWMP (White 2010a) highlights the fact that the brine solution should be discharged into the ocean during outgoing tides to reduce the probability of brine coming into contact with the shoreline.

The possibility of environmental costs of desalination should be considered if this option is to be pursued; in particular, to the surrounding marine life (on which much of the population depends) and the planned disposal of membrane modules into local landfills. An environmental impact assessment would need to be undertaken in order to determine any environmental implications so that these could be added to the costs of using desalinated water supplies in a full economic analysis. It is expected that the environmental impact assessment would need to be undertaken externally.

It is challenging to quantify environmental factors but any environmental effects caused by desalination would increase costs. If the environmental effects were expected to be significant, then the design of this option would need to be modified in order to reduce the impact on the environment to a negligible level.

4.4.2. Rainwater

Cost assumptions

In the analysis, the maximum life expectancy of the roof infrastructure (50 years) is assumed. Likewise, the minimum cost of installation of harvesting infrastructure is assumed. A shorter life expectance or higher installation costs would make LSRH an even more expensive option relative to desalination. Additionally, any rental payments to landowners which may be required were also excluded from the analysis and would increase the cost of LSRH compared with desalination. Consequently, none of these elements would affect the ranking of desalination as less costly than LSRH.

Capture rate

The reports on which the rainwater infrastructure and catchment data for this analysis is based use the assumptions from the White and Falkland (2009) water model. A key variable in this model is the runoff coefficient which is set at 0.85. Kinrade et al. (2014), when estimating the volume of rainwater harvesting potential in Tuvalu, used a run-off coefficient of 0.65 to 0.72 in the first year of analysis which was then decreased over time to reflect the poor quality of maintenance. As it is so vital that maintenance be carried out, this analysis has included the cost of employing a dedicated maintenance officer in order to allow the coefficient to remain at 0.85 throughout the life of the harvesting infrastructure. Previous analysis (GWP Consultants 2010; Kinrade et al. 2014) have suggested that a lack of maintenance is one of the main reasons for low capture rates. In the case that maintenance was for some reason not carried out, the run-off coefficient in this analysis would decrease and the cost of rainwater would increase. The cost of LSRH (already the most expensive option) would increase even further.

Environmental aspects

Rainwater harvesting is unlikely to have a negative impact on the environment although if rainwater run-off was previously feeding into a groundwater lens then it may be possible that the lens volume would be reduced. If large-scale rainwater harvesting was to be pursued then an analysis of any risks to groundwater in the area would need to be undertaken.

4.4.3. General assumptions

Changes in the water production target

The 1,960 kL target was chosen because it is expected to be on the order of magnitude of current groundwater abstracted from Bonriki by the PUB. Abstraction rates have been known to vary over time, and if the target water volume was to change, then total production costs also would change. Nevertheless, unless there is a dramatic change in the target volume, unit production costs can be expected to remain similar. Consequently, small changes in the production target are not expected to change the cost-effectiveness ranking of desalination compared with LSRH or any of the key results of this analysis.

These findings are supported by Rios Wilks (2015), who analysed the cost of supplementation when the supply target and daily abstraction rate from Bonriki is 1,700 kL.

Discount rate

As shown in Table 11, whichever discount rate is used, desalination is always less costly than LSRH.

5. Key findings and implications

5.1. Key findings

5.1.1. Objective 1: Least cost option suitable to backup Bonriki supply

As shown in Table 11, producing water via desalination is much more cost efficient than LSRH. This finding remains the same, regardless of the discount rate, large changes in fuel prices, increased costs from outsourcing parts of the desalination production, and maintenance process to external contractors, and changes in abstraction rates.

5.1.2. Objective 2: Threats to sustainable water supply: Lessons from scenario comparisons

- The effect of having a period of low rainfall versus a period of high rainfall seems to be the most costly.
- Reducing abstraction after a seawater inundation or during low rainfall periods produces cost savings by reducing the number of days where groundwater salinity is above the 1,500 µS/cm threshold.
- The effect of seawater inundation on the costs of providing water are smaller than the effects of rainfall and of continuing to abstract at the rate of 1,960 kL, and its effects are only likely to be felt during high rainfall periods.

The seawater inundation generated for this analysis lies at the high end of predictions (extreme inundation). Consequently, the finding here that this relatively ‘bad case’ seawater inundation still being less of a threat than the other two factors, signals that focus should indeed be on the other two factors going forward. As rainfall cannot be changed*, future focus should be on managing within the range of sustainable groundwater abstraction from Bonriki.*

5.1.3. Additional findings

Groundwater remains the least costly source

Although desalinated water is less costly than LSRH it is still more costly than groundwater supplied from Bonriki and Buota. The estimated cost of groundwater (White 2010a) is AUD 3.60/kL, whereas the minimum expected cost for desalinated water is AUD 4.97/kL. In addition, desalination has far greater energy demands than groundwater abstraction and, given that energy is presently supplied via diesel combustion, desalination will produce more carbon emissions and increase Kiribati's trade balance deficit through higher diesel imports. Consequently, it is clear that groundwater is still Kiribati's least costly water source and that protecting groundwater reserves from human pressures such as encroachment (White 2010a) should be a key focus in the future.

Household rainwater harvesting as additional private water source

Although household rainwater harvesting could not be relied on as a backup to groundwater and would be susceptible to extreme droughts, it is a relatively low-cost option for providing small volumes of extra water in order to reduce the stress on the PUB system during normal weather conditions. As discussed in the results section, if normal 50% losses through distribution are assumed (Fraser Thomas Partners 2012; White 2010a), then the total cost of providing water to households via desalination is higher than that of small-scale household rainwater harvesting. This supports a recommendation of incentivising household rainwater harvesting in order to produce additional water, independently of the government (PUB) supplied system.

5.2. Implications for future management

5.2.1. Sustainable abstraction

Although the low cost of Bonriki abstraction compared with desalination (and LSRH) might lead to the conclusion that increased abstraction would lower PUB costs, it is likely that it would actually increase costs overall. This is because increasing abstraction would also increase the number of days that salinity is above the threshold, and consequently increases the water that must be produced via alternative means. In fact, lowering the abstraction rate even more than that of the illustrative scenario 3 (1,675 kL) could result in overall cost savings for the government. Lowering the abstraction rate lowers the proportion of the year in which groundwater salinity is above 1,500 µS/cm, by lowering the number of days in which desalination would be required to produce the full 1,960 kL. Minimising costs is a question of balance; if it were possible to lower the abstraction rate from Bonriki just enough so that the salinity is never above the threshold (while supplementing Bonriki with desalination on a smaller scale to make up the remaining water volume), it may be possible to achieve further cost reductions.

For example, if it were possible to stop salinity surpassing 1,500 µS/cm by limiting abstraction to, say, 1,000 kL, desalination could be used constantly to produce the remaining 959 kL/day. Because groundwater salinity would be kept below the threshold, desalination would never need to produce the full 1,960 kL and a single 1,000 kL unit could be installed (such as suggested in Harrison Grierson Consultants 2013), vastly reducing the cost of desalination infrastructure.

On the other hand, if abstraction remains high at 1,960 kL, there will be times in which desalination infrastructure is not used (the full 1,960 kL can be produced from Bonriki) and times at which salinity surpasses the threshold and all water must be supplied by desalination. The large variability in water required via desalination means that more plants would need to be installed, but that they would be left unused during the times when Bonriki can produce the full 1,960 kL. This waste in resources would be removed if a balance was found and abstraction and desalination each produced a share of the 1,960 kL required, so that salinity remained below the threshold. Consequently, it is recommended that future research determine a sustainable abstraction rate for Bonriki (which sustains salinity below the threshold for each of the possible threat scenarios Bonriki could face), so that an economic analysis can identify whether it is indeed less costly to decrease abstraction to this rate and use desalination as a constant source alongside.

5.2.2. Small-scale water supplementation

As discussed in the results section, if the normal 50% loss through distribution is assumed (Fraser Thomas Partners 2012; White 2010a), then the total cost of providing water to households via desalination is higher than that of small-scale household rainwater harvesting. This supports a recommendation of incentivising household rainwater harvesting in order to produce supplementary water. Nevertheless, household rainwater harvesting could not be relied on as a backup to groundwater or during extreme droughts. It is simply a relatively low-cost option for providing extra water in order to reduce the stress on the PUB system during normal weather conditions.

Although private household systems can only supplement water requirements (producing around 5 L/person/day for household), any increase in water supply should be considered by the government. Even if it is not a ‘silver bullet’ answer to South Tarawa’s water scarcity challenge, every bit of extra water that can be viably produced at low cost will help in improving the standard of living and reduce pressure on the PUB.

5.2.3. Wider perspective on challenges

This analysis has focused on the most cost effective way of ensuring that the government can produce the target water volume over the next 50 years, taking into consideration the threat of seawater inundation and the current abstraction rate. Nevertheless, it is necessary to put this objective in perspective. Even if it is assumed that 1) the PUB distribution system is renovated (reducing water loss to 25%); 2) there will be zero net inward migration to Tarawa; and 3) the current rate of 1,960 kL can continue to be supplied each day, within 30 years this would no longer be sufficient to provide the Sphere Standard Basic of 15 L/person/day in South Tarawa.

For this reason, in order to ensure that the government can provide a minimum volume of water to the population, it must also focus on protecting existing water resources. A policy of just increasing water supply via human-made freshwater (i.e. desalination) in line with population could simply increase incentive for inward migration to South Tarawa and add to social costs through further strain on sanitation infrastructure, food and land resources.

Water conservation and resource protection requires behavioural changes. Unfortunately, these are complex and slow to change, sometimes taking many years for behavioural change initiatives to take effect. This, among the many other challenges associated with behavioural changes often forces it to the bottom of the list of priorities for policy-makers who are likely to be confronted with the short-term costs and challenges but who will not be around to see the long-term benefits. This also reduces the incentive of short-term initiatives (two to five years) to use funds for water management projects versus quick fix infrastructure projects. Nevertheless, as project evaluation and accountability become more important and the focus turns to longer-term outcomes and sustainability, these other root-causes of scarcity will need to be tackled alongside supply initiatives.

6. Enabling environment and future work required

6.1. Financing: Who pays?

Both of the large-scale supplementation options considered in the main analysis (LSRH and desalination) were designed to be the responsibility of the government PUB, just as Bonriki groundwater currently is. The LSRH would use purpose-built, government-constructed roof catchments, and desalination would also be controlled by the PUB. Nevertheless, due to large production costs, it is likely that whichever of the water production options is implemented, the government will be unable to cover all financial costs. Consequently, the government would need to rely on external assistance in order to progress these options.

6.2. Environmental assessments

As suggested in Harrison Grierson Consultants (2013), before finalising the design of desalination operations, experts should evaluate:

- the sustainable volume that may be abstracted from the saltwater boreholes to mitigate over abstraction;
- any impact on the coastal processes (e.g. movement of sediment) that may occur from the use of infiltration galleries;
- and any effect that the brine discharge may have on biodiversity and marine life.

6.3. Running of desalination plants

The day-to-day operation of the plants would be conducted by the PUB, and would include managing the chemical inputs and changing certain filters (as detailed in Harrison Grierson Consultants 2013). In order to ensure the smooth operation of the plants it is recommended that technicians be trained by desalination unit suppliers. In addition, to avoid the loss of these skills from the country it may be necessary to tie the training scholarships to contracts with the PUB, which would require the newly trained engineers to work for a certain number of years for the PUB and to pass on their skills to other elected staff through formal training sessions. Not only will this ensure that local capacity is increased, it will also reduce the risk of skills being lost over time as workers move on. If desalination suppliers are not confident that the PUB has sufficient capacity to operate the plants, it would be necessary to factor in the cost of contracting full-time technicians from elsewhere.

6.4. Water distribution

The water supplied through the options assessed would need to be distributed to consumers. The current PUB distribution system is likely to be the least costly and disruptive system but it is recommended that renovations take place beforehand (Fraser Thomas Partners 2012; White 2010a).

The PUB distribution system pumps groundwater from Bonriki and Buota to the population. Although in 2013 the average groundwater abstraction from these lenses was 1,960 kL/day, a large proportion of this water is reported to be 'lost' due to pipe system leakage. Metutera (2002) and the PUB conducted a village survey in Nanikaai village, South Tarawa and found that from just one of the many connection points on the distribution system alone (the household tap connection to the pipes), around 25–40% of the water supply was being lost. The more recent TWMP reported at least 50% loss due to leakage from the piping system (White 2010a). The 2012 economic analysis of desalination (Fraser Thomas Partners 2012) suggested that 67% of the water is lost. Although some of the water 'lost' is, in reality, still reaching users through illegal connections to the piping system, there is no information on what percentage of this 'lost' water is used.

Given the existing water constraints that Tarawa currently faces, and the high existing water losses from the distribution system, it is of vital importance to renovate the existing distribution system before the government proceeds with other interventions. Without improvements, the losses will continue to increase the cost of water produced and distributed. Without renovations, the cost of water produced by desalination that has been estimated in this report would need to be doubled to account for these large (approximately 50%) losses in order to represent full costs to the government in supplying water to consumers.

A recent report by Fraser Thomas Partners (2012) has estimated the cost of renovating the existing system in order to reduce leakage to 25% to around AUD 5 million. Based on this figure it is possible to calculate the approximate recuperation period here. If costs were indeed AUD 5 million, maintenance per year was 5% of this, and the volume of water distributed via the system was 1,960 kL, then benefits would outweigh the costs of renovation within 50 years, even if an 8% discount rate is used (benefit to cost ratio = 1.06). If more water was to be distributed through the system or if discount rates were reduced then the benefits would outweigh costs in less time. Harrison Grierson Consultants Limited (2013) noted that the time scale suggested in Fraser Thomas Partners (2012) is likely to be overly optimistic, and renovations could take more time and consequently cost more. If renovation costs were 50% more (AUD 7.5 million), maintenance was 5% of this, and an 8% discount rate is used, around 3,000 kL would need to be distributed through the system per day in order for benefits to outweigh costs over 50 years.

6.5. Supply sustainability, protection and community ownership

The renovations discussed above (which include meter installation) would also allow the government to pursue demand management and cost recovery mechanisms if it chooses to. At present, those with water pipe connections have no financial incentive to limit water wastage (a flat connection fee of AUD 15 is paid per month by households) and those who cannot afford this fee must use another household's water, rainwater or resort to unsafe household wells. If the government wishes to sustainably provide water for its population in the future it must consider pursuing a mechanism to incentivise more water conservation. Upgrading the PUB distribution system and installing meters will be a prerequisite for this.

Sustainability of groundwater supplies in terms of community ownership and acceptance is also important. Community discussions and participatory approaches allow communities to generate their own solutions to problems, increasing community participation and the long-term success of initiatives, but in some cases this type of discussion is made difficult for the government. The traditional values held by families regarding land and groundwater as private family property makes government involvement in water supply, especially through groundwater, a controversial issue. Many families believe compensation should be paid for the use of their land and groundwater, hampering the protection of natural reserves and the government's ability to restrict settlement on reserve land. Regardless of which party holds the property rights, it will be possible to reach a given level of conservation and reduction in settlement provided enough compensation is paid. The more rights that are held by the government, the less compensation they would be required to pay.

Part of minimising the cost to the PUB in providing the (presently subsidised) water to consumers is to incentivise responsible management at the household level.

Education and public awareness: In order to further aid the government in addressing water supply pressures it is recommended that action be taken to alert the population to the risks faced and the importance of responsible water use and of the merits of capturing household rainwater. Practices such as only using valuable, safe water for drinking, basic hygiene practices and basic cooking needs could be enforced. Schools and church groups could be used as channels through which to promote good water management.

Education can also be used to improve health and sanitation. Teaching the benefits of safe water sourcing, treating water before consumption, and maintaining water tanks to reduce contamination are likely to have large long-term benefits through decreased health costs. The recent Asian Development Bank report on the costs of poor water and sanitation practices in South Tarawa highlight the gains that could be made in this area (ADB 2014). If the public is informed of the high quality of rainwater relative to other supplies, their perceptions of rainwater versus groundwater may also change.

Although education and awareness initiatives are costly in the short term and the benefits likely to be reaped in future years, the government will be compelled to address demand management going forward if a sustainable equilibrium is to be met.

Drought alerts: In times of drought, alerts can be provided via private rainwater tank levels as well as through government disseminated alerts. Private conservation alerts could be introduced when rainwater infrastructure is installed. For example, if government water authorities draw a ‘red line’ level on household tanks to indicate the number of days water supply left given the household size and daily demand, households will be able to check their water stock. When the water level passes below the ‘red alert line' the household would be prompted to go into a stricter water conservation mode.

Reinstating traditional water values: As discussed in White (2007), water has always been valued highly at the family level (Talu et al. 1979). Consequently, it has been suggested that the recent government policy of supplying water through the PUB has removed the responsibility from households that would previously have identified careful use of water. Although by law households are supposed to pay for water from the PUB, many pipes have been reported to be tampered with and it is highly conceivable that water is siphoned off without any payments being made to the PUB. In addition, those that do make payments for water to the PUB actually have an *increased* incentive to use water, as they are making fixed sum payments that do not increase with their water use. Unfortunately, now that responsibility for water management has been transferred to the government, it is difficult to reinstate water conservation practices without financial-based interventions (such as reducing subsidies on PUB water). Why would household A employ extra time and energy using water more responsibly if household B next door (who is benefiting from household A's efforts via increased water security) does not bother to do the same? In order to reinstate traditional household values of responsible water use, policies must be undertaken by the government.

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Government-assisted purchases: Recently households have been offered loans by the government to assist them in setting up private rainwater harvesting infrastructure. Aside from the increased affordability to the government, this scheme seems preferable to directly subsidising development because buyers still appreciate the full value of the equipment. Unless households contribute to the implementation of the infrastructure and its cost, it is unlikely that full care and maintenance of the resource will be taken. Proper maintenance is of vital importance to the functioning of the systems. Without it, the reliability and cost effectiveness of rainwater decreases. This form of self provision of the infrastructure, with help from the government if required, is likely to be the optimal method of ensuring the infrastructure is cared for. White (2010b) also notes that community level competitions and prizes can motivate better maintenance.

6.6. Replicability

Findings indicate that desalination would be more cost effective than LSRH under Tarawa's rainfall conditions. The high variation in rainfall requires large capture areas and tank storage capacity to be employed in order to ensure that the water supply does not fail during droughts. This finding is likely to apply to other locations which experience high volatility in the annual rainfall and have limited groundwater capacity to rely on. The importance of rainwater harvesting maintenance, which was discussed in this report, has already been highlighted in previous studies for Tarawa (GWP Consultants 2010; White 2010) and a gutter maintenance programme has also been recommended as the basis for future water security in Tuvalu (Kinrade et al. 2014).

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Annexes

Annex 1: Preliminary findings of the Bonriki Inundation Vulnerability Assessment groundwater models

The preliminary Bonriki Inundation Vulnerability Assessment (BIVA) groundwater models indicate:

- that current abstraction is causing an increasing trend in salinity;
- abstraction and the rainfall recharge are the most critical components influencing the lens and salinisation impacts;
- impact from abstraction is greater than sea-level rise impacts over the next 50 years;
- the area of salinity impact from inundation is restricted to the area that is inundated;
- recovery from inundation takes about two to six years, depending on rainfall; and
- recovery from abstraction impacts is longer than from inundation impacts.

Given these findings, the BIVA project economic analysis focuses on six representative scenarios and the expected number of days that salinity is above the 1,500 µS/cm threshold in each.

Annex 2: BIVA inundation modelling

Table A2 briefly describes the categories of inundation extents to the Bonriki water reserve that were identified under different wave height, water levels and sea-level rise probabilities and scenarios used in the BIVA project. For more detailed information please see Bosserelle et al. (2015) and Damlamian et al. (2015).

Table A2: *Seawater inundation extents and impact on groundwater.*

Inundation extents to Bonriki water reserve	Expected inundation impact on Bonriki groundwater?	Used in this analysis?	Greenhouse gas emission scenario and sea-level rise projection for 2064 reference
No inundation	No	Yes	No sea-level rise
Minimal inundation	No	No	No sea-level rise
Moderate inundation	Yes	No	Medium emission scenario (RP6) with sea-level rise projection for 2064 (PACCSAP 2014)
Severe inundation	Yes	No	High emission scenario (RP8.5) with sea-level rise projection for 2064 (PACCSAP 2014)
Extreme inundation	Yes	Yes	Intermediate-high emission scenario from the US National Oceanic and Atmospheric Administration (Parris 2012)

Annex 3: Scenario impact on salinity

The following details and figures are provided by the Bonriki Inundation Vulnerability Assessment groundwater models for Bonriki. The figures show the estimated salinity (µS/cm) at the trunk main for their 17 years of simulation.

Scenario 1: Wet conditions, 1,960 kL/day abstraction. Green line shows the no inundation scenario under wet conditions. During the 6,208 day (17 years) modelling period, salinity is expected to be higher than 1,500 µS/cm for 1,558 days (approximately 4 years), less than 25% of the time.

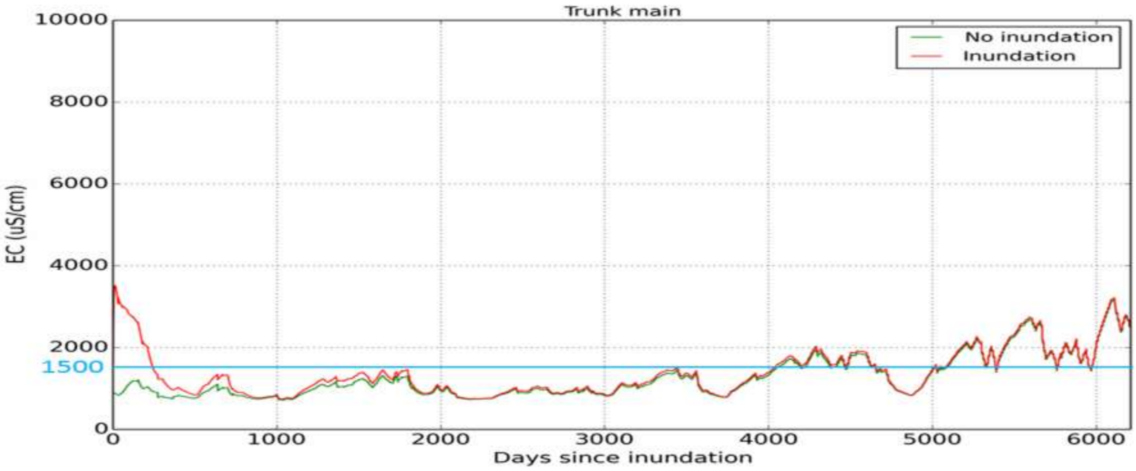

Figure A3a: *Bonriki salinity under scenario 1.*

Scenarios 2 and 6: Dry conditions, 1,960 kL/day abstraction. Green line shows the no inundation scenario for dry conditions. During the 6,208 (17 years) modelling period salinity is higher than 1,500 µS/cm for 5,642 days (approximately 15 and half years), 91% of the time. It is important to note that under no inundation and inundation scenarios (red and green lines in this plot), the number of days that salinity will be > 1,500 µS/cm is the same (i.e. under dry conditions with or without inundation the same amount of water is required).

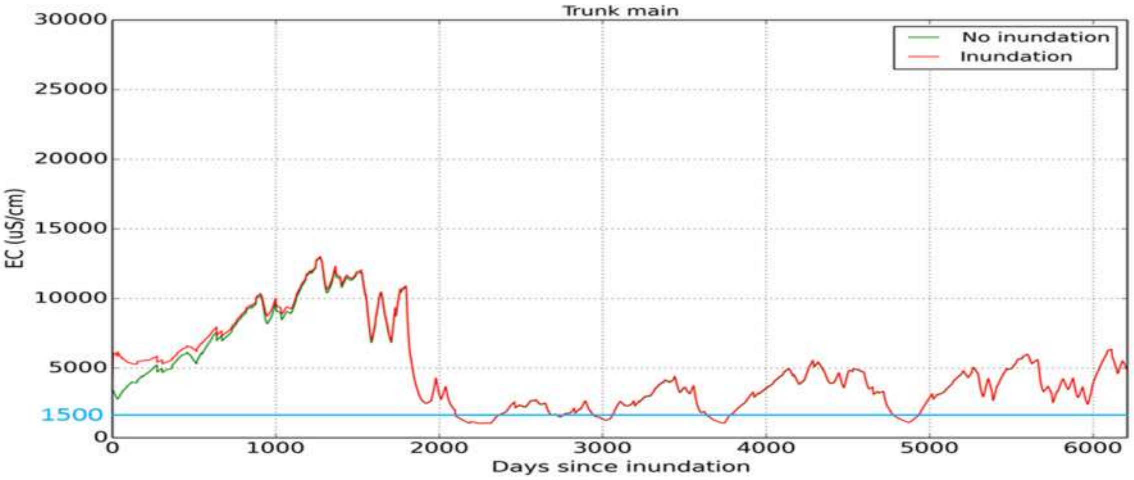

Figure A3b: *Bonriki salinity under scenarios 2 and 6.*

Scenario 3: Dry conditions, and reduced abstraction. Red line shows the no inundation scenario for dry conditions under a reduced abstraction (1,675 kL/day). During the 6,208 day (17 years) modelling period salinity is higher than 1,500 µS/cm for 4,994 days (approximately 13 and half years), 80% of the time.

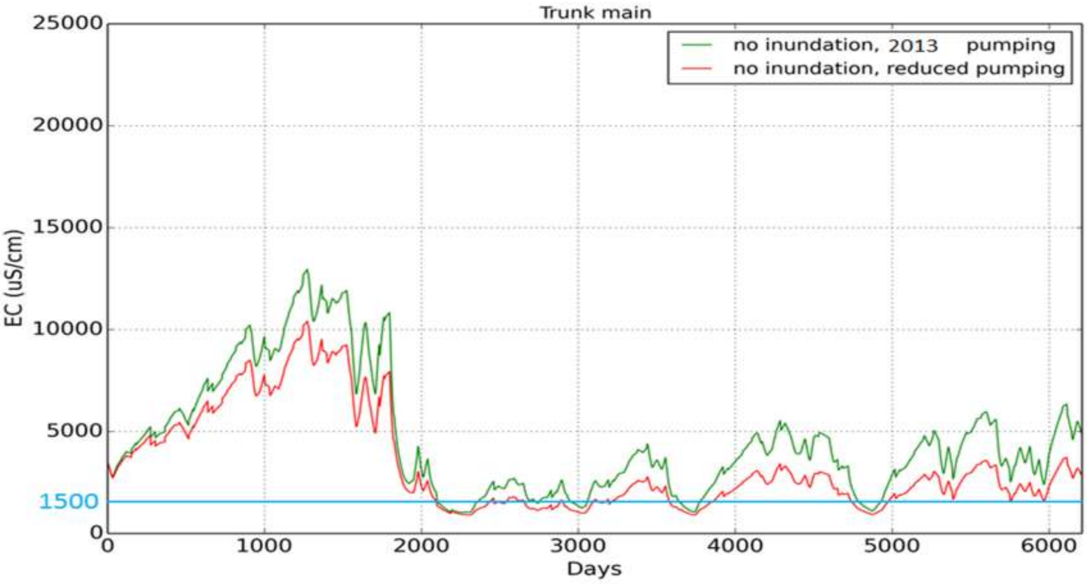

Figure A3c: *Bonriki salinity under scenario 3.*

Scenario 4: Dry conditions and the inundated galleries are switched off immediately after inundation for a period of six years (2,190 days). Blue line shows the inundation scenario for dry conditions and reduced abstraction with the inundated galleries switched off for a period of six years (2,190 days). During the 6,208 day (17 years) modelling period, salinity is higher than 1,500 µS/cm for 4,989 days (approximately 13 and half years), 80% of the time. Note that while salinities are higher than 1,500 µS/cm they are significantly less in response to the reduced pumping than either reduced abstraction or maintaining abstraction at the 1,960 kL rate.

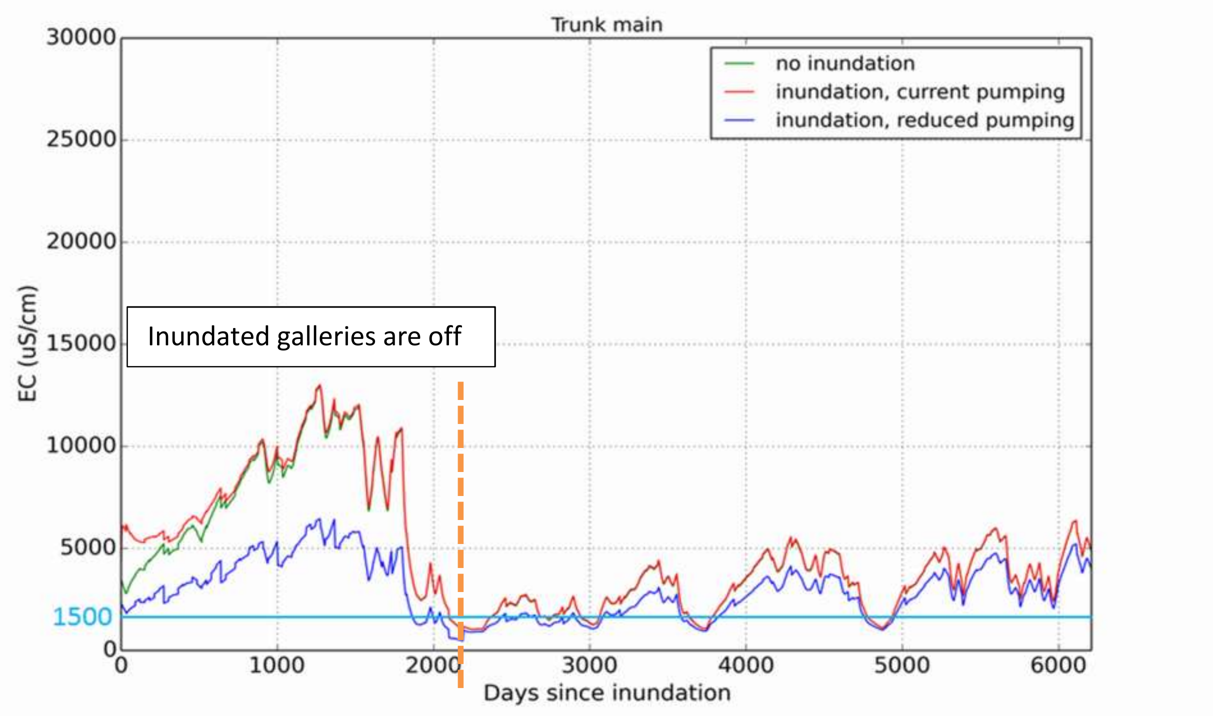

Figure A3d: *Bonriki salinity under scenario 4.*

Scenario 5: Wet conditions, 1,960 kL/day abstraction. Red line shows the inundation scenario under wet conditions. During the 6,208 day (17 years) modelling period, salinity is expected to be higher than 1,500 µS/cm for 1,805 days (approximately 5 years), 29% of the time.

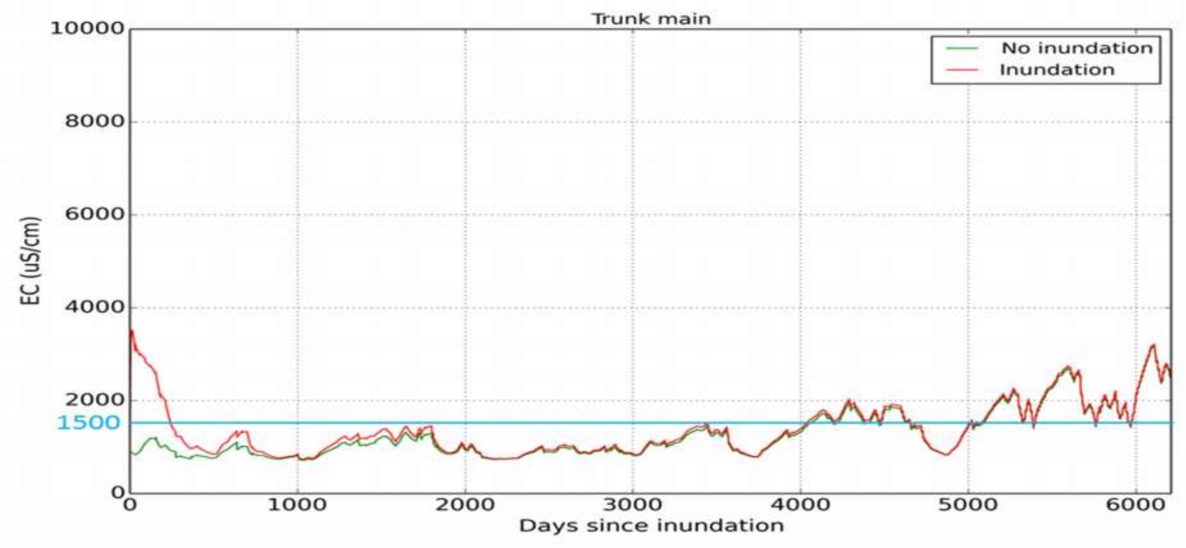

Figure A3e: *Bonriki salinity under scenario 5.*