Bonriki Inundation Vulnerability Assessment

Summary Report

Phoebe Mack

Australian Government

SPC Secretariat of the Pacific Community

Australian Aid

Bonriki Inundation Vulnerability Assessment (BIVA)

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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 Abreviations

3D	Three-dimensional
BIVA	Bonriki Inundation Vulnerability Assessment
GIS	Geographic information system
GoK	Government of Kiribati
MPWU	Ministry of Public Works and Utilities
PUB	Public Utilities Board
RTK	real-time kinematic

Executive Summary

The project

The Bonriki Inundation Vulnerability Assessment (BIVA) project is part of the Australian Government's Pacific–Australia Climate Change Science and Adaptation Planning Program, within the International Climate Change Adaptation Initiative. The BIVA project was developed by the Geoscience Division of the Secretariat of the Pacific Community in partnership with the Australian Government and the Government of the Republic of Kiribati. The project was undertaken over 22 months, from May 2013 to February 2015.

The BIVA project focused on Kiribati's National Water Reserve in Bonriki, South Tarawa, which is Bonriki's source of raw, fresh water. The project comprised three interlinked components: stakeholder engagement, groundwater investigations and analysis, and coastal investigations and analysis. It aimed to improve our understanding of the vulnerability of the Bonriki Water 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 government.

This report

This report synthesises key findings from each component of the project for use by water resource managers and policymakers in the future.

Key outcomes

The BIVA project has improved our understanding of the potential for wave overtopping at the Bonriki Water Reserve, and developed advanced numerical models to represent and investigate the impacts of saltwater intrusion on the freshwater resource. The project has helped us to understand how the freshwater lens recovers from a range of inundation, abstraction and climate scenarios.

The inundation and groundwater modelling has demonstrated that, although inundation of the Bonriki Water Reserve in an extreme event will significantly impact the lens, the probability of this extreme event occurring is relatively low (based on a 50-year intermediate–high climate change scenario and an extreme event with a 1% chance of occurring in any one year). The majority of modelled inundation events tend to be localised and confined to the coastal fringe, and the lens should recover after 2–5 years, depending on rainfall. The analysis has also shown that, although an extreme inundation event will impact the lens, threats from over-abstraction and low rainfall recharge are far more critical influences on its condition. However, the models did not consider morphological responses of the coast to climate change, climate variability and human activity over time, and the risk of inundation may increase in the future if coastal zone management plans are not implemented to ensure resilient shorelines.

The project has investigated the economic costs and benefits of potential management options in the event that the groundwater resource is too saline for distribution. The economic analysis considered using either desalination or large-scale rainwater harvesting to augment the Bonriki groundwater supply. In all scenarios modelled, desalination is the cheapest suitable option for backing up the Bonriki supply, while groundwater remains the cheapest source of water overall.

Future application

From the project analysis, it is clear that inundation impacts, although a threat, are not as significant as drought and abstraction impacts. For water resource managers and policymakers, this highlights the importance of:

- finalising, enacting and implementing the draft **South Tarawa Drought Response Plan**
- **continued monitoring** of the water resource via the existing borehole infrastructure, and the maintenance of this dataset by the Ministry of Public Works and Utilities
- continued monitoring of the abstraction volumes and salinity at individual galleries by the Public Utilities Board (PUB).

To inform future management, some specific operational scenarios of the PUB water supply system in Bonriki have been considered as part of the BIVA project analysis and in response to an inundation event. These include:

- **management of the infiltration gallery pumps** during an inundation event
- **reduction in abstraction** to reduce the likelihood of the freshwater lens salinity exceeding 1,500 µS/cm
- use of **alternative water supplies** to supplement the Bonriki groundwater source when the freshwater lens is impacted by inundation, abstraction and/or dry climate conditions.

The data collected and analysis undertaken as part of the BIVA project provide valuable information for **climate change adaptation planning and disaster risk management**, as well as **for integrated coastal zone management** for the Bonriki area. More specifically, information and tools that can be used for coastal zone management and disaster risk management include:

- inundation maps
- probabilistic hazard assessment
- land use and shoreline mapping
- participatory 3D mapping.

1. Introduction

1.1. Introduction

The Bonriki Inundation Vulnerability Assessment (BIVA) project comprised three interlinked components: stakeholder engagement, groundwater investigations and analysis, and coastal investigations and analysis. This report summarises the activities and outcomes of each component of the project so that they can be understood and used by water resource managers and policymakers in the future. Key conclusions from the technical work undertaken throughout the project are presented, and their implications are discussed with respect to:

- water resource management for the Bonriki Water Reserve
- operation and management decisions for the Public Utilities Board (PUB) water supply system in Bonriki
- disaster risk reduction and climate change adaptation planning.

This report synthesises key findings from each component, but does not repeat the technical detail provided in other reports. More comprehensive information on the data collection and analysis, and processes undertaken for each component of the project are contained in the following reports:

- for coastal data collection
  - Land use mapping (Raj et al. 2015a)
  - Topography survey (Begg et al. 2015)
  - Single beam survey (Kumar 2015)
  - Oceanographic assessment (Begg and Krüger 2015)
  - Shoreline change analysis (Raj et al. 2015b)
- for the coastal analysis component
  - Development of severe and extreme scenarios of wave and water level through statistical analysis and numerical modelling in Bonriki, Tarawa, Kiribati (Damlamian et al. 2015a)
  - Inundation modelling of Bonriki Islet, Tarawa, Kiribati (Damlamian et al. 2015b)
- for groundwater data collection and analysis
  - Atoll island hydrogeology and vulnerability to seawater intrusion: Literature review (Werner et al. 2015)
  - Groundwater field investigations, Bonriki Water Reserve, South Tarawa, Kiribati (Sinclair et al. 2015)
  - Assessment of sea level rise and inundation effects on the Bonriki freshwater lens, Tarawa Kiribati: Groundwater modelling report (Bosserelle et al. 2015)
- for the economic analysis
  - Economic analysis of water management options for impacts from inundation, climate variability and high abstraction rates, Bonriki Water Reserve, South Tarawa, Kiribati (Rios Wilks 2015a)
  - Economic analysis of water management options for impacts from inundation and climate variability under current abstraction rates, Bonriki Water Reserve, South Tarawa, Kiribati (Rios Wilks 2015b)
- for stakeholder engagement activities

- Report on Bonriki Inundation Vulnerability Assessment Project stakeholder engagement activities (Mack et al. 2015).

1.2. Report structure

This report has five sections.

- 'Project overview' summarises the BIVA project, including background and contextual information, and outlines the project objectives, outcomes and scope.
- 'Approach' summarises the methods used in each component of the project.
- 'Key outcomes' summarises key outcomes of the technical components of the project, including coastal, groundwater and economic analysis.
- 'Application of project findings' discusses the outcomes of the project in the context of water resource and infrastructure management in Bonriki, and disaster risk reduction and climate change adaptation planning.
- 'References' provides a detailed reference list, including all project reports on which this report is based.

1.3. Project Overview

1.3.1. Project background

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

- improve scientific understanding of climate change in the Pacific
- increase awareness of climate science, impacts and adaptation options
- 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 the Republic of Kiribati (GoK).

1.3.2. Project objective and outcomes

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

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;
- better data to inform a risk-based approach in the design, construction and protection of the Bonriki Water Reserve; and
- increased knowledge provided to GoK and the community of the risks associated with the impact of coastal hazards on freshwater resources in response to climate change, climate variability and sea level rise (SLR).

1.4. Site context

1.4.1. Location

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 Republic of Kiribati's National Water Reserve in Bonriki, South Tarawa. Bonriki is located on Tarawa atoll within the Gilbert group of islands in Western Kiribati. South Tarawa is the main urban area in Kiribati; the 2010 census recorded 50,182 people residing in South Tarawa from a population for Kiribati of more than 103,000 (KNSO and SPC 2012).

The Bonriki Water Reserve (Figure 1) is a fresh groundwater lens that is used as the primary raw water supply for the PUB reticulated system. PUB water is the primary source of potable water used by at least 67% of the population in South Tarawa (KNSO and SPC 2012). Key infrastructure, including the PUB Water Treatment Plant, Bonriki International Airport, and housing and community buildings, are also located on Bonriki above the freshwater lens, making it an important economic, social and cultural area for Kiribati.

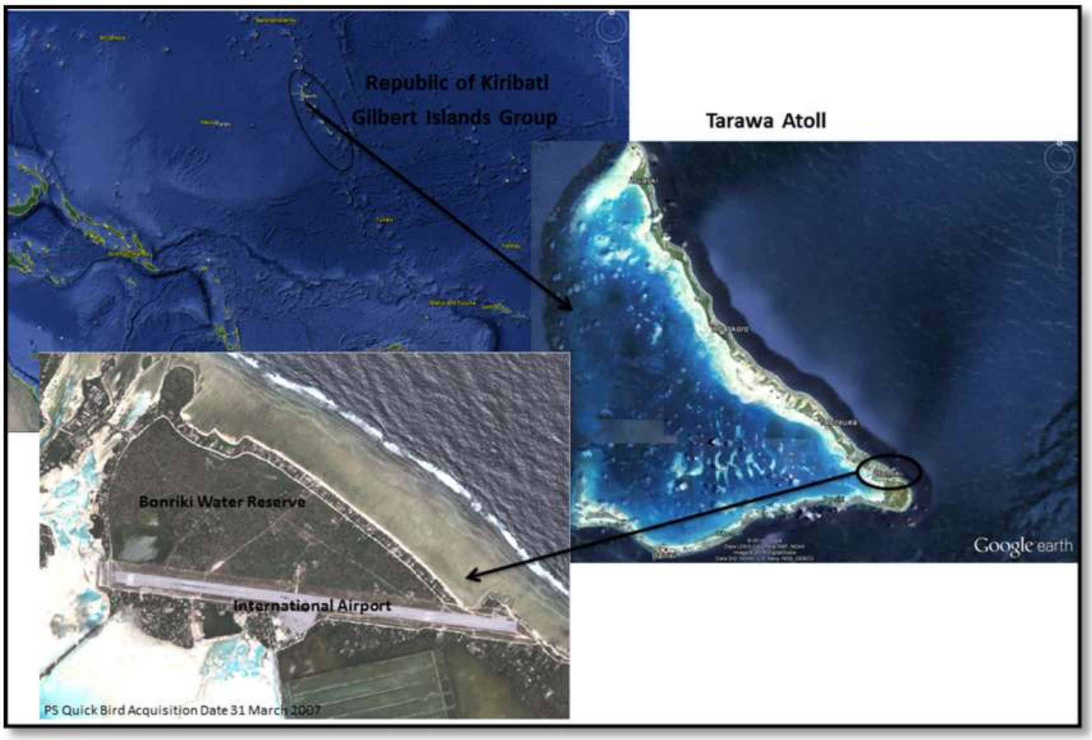


Figure 1: *Location of the Bonriki Water Reserve (source: Bosserelle et al. 2015).*

1.4.2. Threats to the Bonriki Water Reserve

During the 2005–2010 census period, Kiribati's population grew at a rate of 2.2% per year, while South Tarawa had an annual growth rate of 4.4% (KNSO and SPC 2012). This high rate of urban growth is linked to internal migration from outer islands and is a continuing trend. The resulting pressures from this growing population are reflected in Bonriki in encroachment of settlements onto the Bonriki Water Reserve, with resulting contamination of the underlying freshwater lens and pressure to abstract as much water as possible to supply the growing urban population. In addition to these anthropogenic pressures, the low-lying nature of the atoll, natural climate variability and impacts of climate change such as rising sea levels also put pressure on the Bonriki Water Reserve. These threats to Bonriki ultimately threaten the livelihood of the people of South Tarawa who rely on this resource as their primary water supply.

1.5. Project scope

The BIVA project was designed to investigate the impacts on the Bonriki Water Reserve of saltwater intrusion caused by seawater inundation and over-abstraction, combined with impacts from climate variability and SLR. To understand the impact of these threats, the BIVA project was undertaken through three interlinked components: stakeholder engagement, groundwater investigations and analysis, and coastal investigations and analysis (Figure 2). The groundwater and coastal components of the project involved extensive data collection to understand and characterise the coastal and hydrogeological processes of the study area. This information was then used to develop the climate scenarios, inundation model and numerical groundwater model. Outputs from the modelling were used as inputs for the economic analysis. Stakeholder engagement activities occurred in parallel with the technical investigations and analyses, and have both informed and been guided by these components of the project.

The project took place over 22 months, from May 2013 to February 2015, as a collaboration between GoK and SPC. Key GoK partners were the Ministry of Public Works and Utilities (MPWU) and PUB. Field work was undertaken in and around Bonriki Islet, and in the ocean and lagoon surrounding the study area. Data analysis and numerical modelling were undertaken by staff from SPC, with technical assistance from a range of specialist advisers.

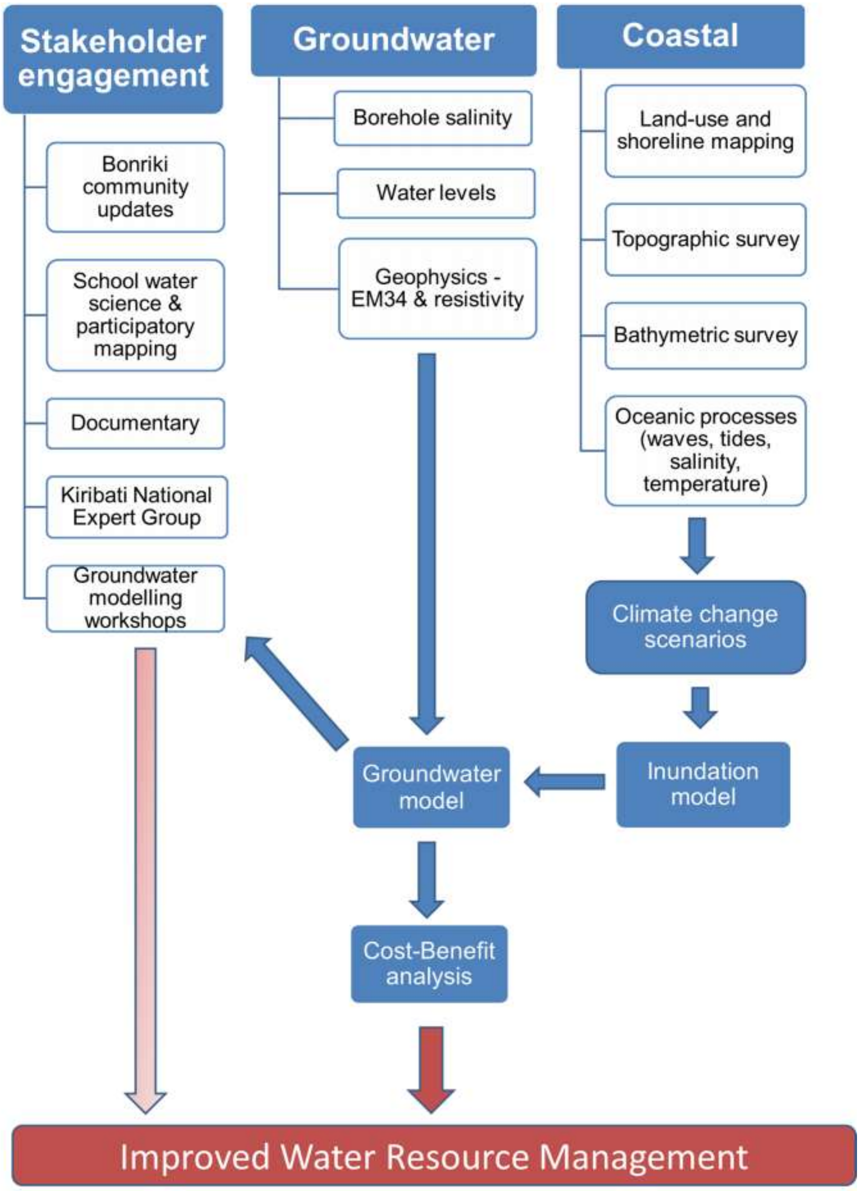


Figure 2: *Components of the Bonriki Inundation Vulnerability Assessment project.*

1.6. Outputs

Specific outputs from the groundwater, coastal and stakeholder engagement components of the BIVA project include:

- a GIS database of Bonriki and its surrounds, including
  - a detailed digital terrain model
  - 10-cm-resolution aerial photo imagery of the Bonriki Islet and coastal area, including production of a video flyover
  - mapping of historical changes in land use from 1943 to 2014
  - mapping of changes in the coastal shoreline from 1943 to 2014;
- high-resolution real-time kinematic (RTK) survey and bathymetric data of the study area for detailed topographical mapping and a digital elevation model;

- oceanographic data from around Bonriki and Tarawa atoll to characterise the oceanographic processes specific to the study area and to provide input into the numerical modelling;
- an evaluation of the probabilities of storm tide levels, extreme waves and associated water levels at Bonriki, to be used to develop 72 potential extreme scenarios to be modelled;
- numerical modelling and mapping of inundation extents across Bonriki from 72 possible extreme events, considering a range of sea level, tidal and swell scenarios;
- hydrological data to be used to characterise the physical aspects of the groundwater system in Bonriki and to understand factors influencing the freshwater resource;
- a numerical model of the Bonriki groundwater system to understand the impact on the freshwater lens of wave overtopping and its recovery under different inundation, abstraction and climate scenarios;
- an economic analysis that considered the feasibility of using alternative water sources (rainwater and desalination) to augment groundwater when the freshwater lens is stressed (as a result of inundation, climate or abstraction impacts);
- a documentary-style video to be used as a tool by GoK to increase knowledge and awareness within the community of the hazards to groundwater resources; and
- development and implementation of teaching resources on groundwater science and a participatory three-dimensional (3D) mapping programme to be used to develop awareness about water resource management and the interaction with land use activities.

2. Approach

This section provides an overview of the methods used in each component of the BIVA project. For comprehensive details, refer to the relevant technical reports.

2.1. Stakeholder engagement

The following activities were undertaken as part of the stakeholder engagement component of the BIVA project:

- community surveys to assess coastal hazard concerns, following the January and March 2014 inundation events;
- progress updates to the stakeholder technical advisory body: the Kiribati National Expert Group on Climate Change and Disaster Risk Reduction;
- capacity-building activities to develop skills on topographic and bathymetric survey methods, groundwater modelling and groundwater field investigations within key GoK agencies;[1]
- consultation and engagement with key implementation agencies – MPWU and PUB;
- a presentation to multistakeholder advisory groups on results of technical assessments and management options;

[1] Ministry of Public Works and Utilities; Public Utilities Board; Ministry of Environment, Lands and Agricultural Development – Lands Division; and Ministry of Fisheries and Marine Resources Development – Minerals Division

- community outreach – community participation in project data collection activities and presentation of technical results to community leaders;
- school outreach – groundwater science activities and participatory 3D mapping activities with local school students; and
- a project documentary on groundwater science, water conservation and the vulnerability of the groundwater lens to impacts from anthropogenic and natural hazards.

2.2. Land surveys

Comprehensive elevation information for the reef and the land surface was needed for modelling inundation and groundwater. These data were collected through a number of surveys, including:

- topographic surveys using
  - RTK positioning. RTK provides centimetre accuracy and is significantly faster than conventional land survey techniques, particularly where a large number of survey points are required
  - a drone-like instrument – an unmanned aircraft system – to capture high-resolution aerial imagery at 10-cm resolution; and
- a bathymetric survey using a single beam echo sounder to map 176 line kilometres of the ocean and lagoon seabed surrounding Bonriki Islet.

The data collected from the surveys were combined to develop a seamless digital terrain model (DTM) of the site. The DTM was required as an input for the inundation modelling, and the detailed elevation data of monitoring bores were used to determine flow directions, and to understand impacts from recharge and abstraction for the groundwater modelling.

2.1. Coastal investigations

2.1.1. Oceanographic data

Oceanographic data were acquired from the lagoon and reef environment surrounding Bonriki over 14 months, with a major exercise in December 2013. Data on current speed and direction, directional waves, water temperature and water levels due to tides were collected, to characterise the ocean current and wave regimes occurring around Bonriki and impacting the groundwater system. The data were used in the numerical inundation modelling.

2.1.2. Inundation scenarios

Coastal inundation is a constant threat to low-lying islands such as Tarawa. The primary forces driving inundation on Tarawa are waves generated from wave set-up[2] and run-up[3] on the reef side as open ocean waves propagate over the reef and onto the land. Other factors influencing

[2] The rise of water level on the reef flat due to wave breaking
[3] The rush of wave water up a slope or structure

inundation in Tarawa are elevated mean sea levels due to El Niño and La Niña events, high tide and storm surge,[4] particularly on the lagoon side.

To understand the co-occurrence of water levels and waves, and their potential as a contributing factor to coastal inundation, a joint probability analysis was undertaken. Three combinations of extreme water levels and waves were chosen from the computed return intervals of 20-, 50- and 100-year events. The resultant nine datasets were combined with three climate change SLR projections[5] and current sea level conditions. This method of selecting scenarios was applied to the computed offshore (ocean-side) conditions and to the lagoon-side conditions (i.e. 36 scenarios each). The combined 72 scenarios modelled for potential coastal inundation are shown in Table 1 and Table 2.

Table 1: *Offshore inundation scenarios with a range of water levels and wave heights for 20-, 50- and 100-year return intervals.*

	ID	NO SLR Scenario		ID	SC1 +22cm		ID	SC2 +28cm		ID	SC3 +49cm	
		WL	Hs		WL	Hs		WL	Hs		WL	Hs
20 yrs	1	1.35	3.02	4	1.57	3.02	7	1.63	3.02	10	1.84	3.02
	2	2.01	2.57	5	2.23	2.57	8	2.29	2.57	11	2.5	2.57
	3	2.41	2.03	6	2.63	2.03	9	2.69	2.03	12	2.9	2.03
50 yrs	13	1.36	3.26	16	1.58	3.26	19	1.64	3.26	22	1.85	3.26
	14	2.05	2.8	17	2.27	2.8	20	2.33	2.8	23	2.54	2.8
	15	2.52	2	18	2.74	2	21	2.8	2	24	3.01	2
100 yrs	25	1.38	3.43	28	1.6	3.43	31	1.66	3.43	34	1.87	3.43
	26	2.08	3	29	2.3	3	32	2.36	3	35	2.57	3
	27	2.56	1.969	30	2.78	1.969	33	2.84	1.969	36	3.05	1.969

Hs = wave height; SC = scenario; SLR = sea level rise; WL = water level

[4] The rise of sea level due to wind stress and low atmospheric pressure

[5] Sea level rise scenarios for 2064 from the Intergovernmental Panel on Climate Change under representative concentration pathway (RCP) 6 (0.22 m) and RCP8.5 (0.28 m), and under the intermediate–high scenario from the National Oceanic and Atmospheric Administration (0.49 m) (Parris et al. 2012)

Table 2: *Lagoon-side inundation scenarios with a range of water levels and wave heights for 20-, 50- and 100-year return intervals.*

	ID	NO SLR Scenario		ID	SC1 +22cm		ID	SC2 +28cm		ID	SC3 +49cm	
		WL	Hs		WL	Hs		WL	Hs		WL	Hs
20 yrs	1	2	0.84	4	2.22	0.84	7	2.28	0.84	10	2.49	0.84
	2	2.44	0.65	5	2.66	0.65	8	2.72	0.65	11	2.93	0.65
	3	2.66	0	6	2.88	0	9	2.94	0	12	3.15	0
50 yrs	13	2.08	0.93	16	2.3	0.93	19	2.36	0.93	22	2.57	0.93
	14	2.48	0.716	17	2.7	0.716	20	2.76	0.716	23	2.97	0.716
	15	2.71	0	18	2.93	0	21	2.99	0	24	3.2	0
100 yrs	25	2.11	0.99	28	2.33	0.99	31	2.39	0.99	34	2.6	0.99
	26	2.52	0.766	29	2.74	0.766	32	2.8	0.766	35	3.01	0.766
	27	2.75	0	30	2.97	0	33	3.03	0	36	3.24	0

Hs = wave height; SC = scenario; SLR = sea level rise; WL = water level

2.1.3. Inundation modelling

The final component of the Bonriki probabilistic inundation risk assessment was the development of an inundation model. The inundation model combines the outcomes from the topographic and bathymetric surveys with the oceanographic data to analyse the effects of the 72 scenarios described in 'Inundation modelling' under 'Key outcomes'. The outputs from the inundation modelling were then used as inputs to the numerical groundwater modelling (see 'Groundwater investigations' under 'Key outcomes').

The open-source model XBeach was used for this analysis, which included a new process-based and time-dependent 2DH (depth-averaged) model of the nearshore and coast. The model was calibrated using oceanographic data collected as part of the BIVA project and information from a field survey undertaken following the March 2014 inundation event (described in Chapter 3, 'Key Outcomes', section 3.3 'Coastal investigations'). Modelling parameters were calibrated by comparing modelled wave height, wave set-up and infragravity wave on the reef flat with measured data. The output of the model was then validated against the described inundation extent from the March 2014 survey. The validation provided good correlation with the observations on the ground and therefore confidence in the modelled results.

2.2. Groundwater investigations

2.2.1. Groundwater field investigations

To characterise the physical attributes of the groundwater system in Bonriki, and to determine factors influencing the development and behaviour of the freshwater lens, hydrological data were collected. Information collected included topographic data, geological data, recharge responses and time-varying data such as rainfall, groundwater levels, and quality and abstraction rates. Data collated included a combination of new and historical information. Methods used for the collection of new data included:

- monitoring of multilevel boreholes to determine salinity at fixed depths in the groundwater profile and interpolate the freshwater lens thickness. Bacteriological sampling was also undertaken at boreholes to assess baseline contamination;
- geophysical surveys using Geonics EM-34 electromagnetic survey and electrical resistivity profiling techniques, to improve the conceptual understanding of the Bonriki groundwater system, and determine the shape and extent of the freshwater lens;
- installation of new piezometers to measure groundwater levels;
- installation of downhole loggers – 'CTD divers' – in piezometers to collect continuous time-series data on water level, electrical conductivity and temperature from ten selected wells for 3–6 months. These data were useful to understand the tidal influence on the freshwater lens, and to observe the recharge response from rainfall events and the dispersivity of salt in the freshwater lens; and
- installation of new flow meters and review of historical metered abstraction data from the pumping stations located across Bonriki.

2.2.2. Groundwater modelling

To understand the response of the Bonriki groundwater system to a range of inundation, climate and abstraction scenarios, a 3D numerical groundwater model was developed, using the SEAWAT programme. The Bonriki study area was represented through a 9.52 km^2 model grid and 36 vertical layers of increasing thickness with depth from the surface. Each cell within the model was attributed with specific hydraulic parameters to represent the aquifer properties. The upper layers were assigned values for recharge, abstraction and inundation, depending on the scenario being modelled and the location being represented.

The model was calibrated by comparing the modelled output with measured groundwater salinity. The historical time-series record of salinity measured at the infiltration galleries (abstraction points) and the combined salinity within the trunk main[6] were critical for the calibration.

Significant challenges were faced during this analysis because of gaps, uncertainties and irregularities in the historical abstraction data. Even after being calibrated, the model had a tendency to overestimate the salinity of the abstracted water compared with measured values.

Flow meters were tested during the final stage of the BIVA project[7] and highlighted possible inaccuracies in the meter readings. To investigate the impact of reduced abstraction on the historical salinities, the model was run with the historical abstraction reduced by 15%, and the modelled results were compared with the observed historical salinities in the gallery[8] and the trunk main.

[6] The large diameter pipeline conveying water abstracted from the galleries to the treatment plant
[7] Testing was undertaken as part of leakage detection work for the Kiribati Adaptation Project (KAPIII). The information was provided to the BIVA project team after the calibration phase of the groundwater modelling had already been completed. Time limits restricted further refinement of the model.
[8] The groundwater pumping station, designed to abstract fresh water near the surface of the groundwater lens over a large area, to reduce the potential for saline water located deeper in the groundwater system to be drawn up through the pumps

Reducing abstraction by 15% significantly improved the match between the measured and modelled values of the trunk main salinities. However, without further certainty in the measured flow rates (refer to Sinclair et al. 2015), it was considered unwarranted to use the lower flow rates merely because they provided a better match to the salinities, and the available measured pump rates were used without modification.

Six inundation scenarios were modelled, with a range of permutations (e.g. wet and dry within each), as summarised in Table 3. The variables adjusted between scenarios were as follows.

- ***Abstraction*** – to look at the possible measures that could be taken during an inundation event, a scenario was used in which pumping galleries were overtopped by sea water, and were switched off immediately following the inundation event and remained off for a set period of time (based on the maximum recovery time for the individual galleries).
- ***Climate*** – the wet scenarios were based on the rainfall data from 1990 to 1993, and the dry scenarios were based on the rainfall data from 1998 to 2000. The average annual rainfall for 1990 to 1993 was 3,790 mm, compared with 607 mm for 1998 to 2000. The average net recharge for the wet and dry conditions was 2,039 mm/year and 102 mm/year, respectively.
- ***Inundation*** – two cases from the inundation categories 'moderate' and 'extreme' (refer to Table 4) were selected to simulate the effects of inundation on the groundwater system. These represent minor and significant overtopping of the lens. No flooding of the groundwater pumping galleries occurs in the moderate event, whereas a significant number of the pumping galleries are flooded in the extreme event. These scenarios were compared with a 'no inundation' scenario to quantify the effects of inundation.
- ***Sea level*** – before running the inundation scenarios, SLR was simulated so that the starting point of the inundation scenario in 2064 was 0.51 m higher than in 2014. This SLR scenario is based on the intermediate–high emissions scenario from the National Oceanic and Atmospheric Administration (Parris et al. 2012), and is often used for engineering designs. No difference was observed in salinities between the SLR and no SLR scenarios.

The inundation events were modelled to occur in 2064. The 50-year period leading up to the overtopping was simulated by using the historical recharge conditions from 1964 to 2013. These 49 years were complemented by either a dry (1990) or a wet (1998) year to make up the 50 years and to take into account the possibility of the inundation occurring during dry or wet periods. The model cells that were inundated were assigned a water level that depended on the depth of inundation and a high initial salt concentration. The first 17 years following inundation were simulated for dry and wet conditions under the current pumping regime of 1,700 m^3/d.

***Table 3:** Modelled scenarios for the groundwater model.*

Variable		Scenario						
		SLR vs no SLR, no inundation		SLR, moderate inundation, DSWC	SLR, extreme inundation, DSWC	SLR, extreme inundation, SWC	SLR, extreme inundation, DSWC and SWC, inundated wells turned off	SLR, extreme inundation, DSWC, increased abstraction, and inundated wells turned off
Inundation	No inundation	✓	✓					
	Moderate inundation			✓				
	Extreme inundation				✓	✓	✓	✓
Climate	Wet	✓	✓	✓	✓	✓	✓	✓
	Dry	✓	✓	✓	✓	✓	✓	✓
Sea level rise	None	✓						
	0.2365 m			✓				
	0.5065 m		✓		✓	✓	✓	✓
Abstraction	Inundated wells turned off						✓	
	Inundated wells remain on			✓	✓	✓		
	2,000 m^3/d							✓
Initial concentrations	Diluted sea water			✓	✓		✓	✓
	Sea water					✓	✓	

DSWC = diluted seawater concentrations; SLR = sea level rise; SWC = seawater concentrations

2.3. Economic analysis

The findings of the numerical groundwater modelling demonstrated that groundwater supplies will be insufficient to meet community needs at particular times or under various scenarios, such as when recharge is low, which increases salinity of the abstracted water supplies above the threshold of 1,500 µS/cm. During these times, water supplementation is needed.

An economic analysis assessed the cost-effectiveness of two possible water sources to supplement groundwater in South Tarawa: large-scale rainwater harvesting or desalinated water.

The analysis considered the costs of topping up groundwater supplies to 1,700 kL per day (approximately the current abstraction rate from the Bonriki lens) and a higher abstraction rate of 1,960 kL per day (which is similar to the abstraction rate for Bonriki between June 2008 and September 2012). Both abstraction rate scenarios were analysed because the results of the groundwater modelling indicate that the freshwater lens is more strongly influenced by abstraction than by inundation (refer to 'Groundwater investigations' under 'Key outcomes').

3. Key Outcomes

This section provides an overview of the key outcomes from each component of the BIVA project.

3.1. Stakeholder engagement

3.1.1. Government stakeholder engagement

The focus of engagement with GoK stakeholders was to share knowledge and results from the oceanographic and hydrogeological modelling and data collection activities undertaken for the project. The project has successfully met this objective through the briefing of multistakeholder groups, including the Kiribati National Expert Group, and development of a strong partnership with the implementing agencies MPWU and PUB. In addition, efforts were made to develop the technical capacity of GoK staff in the areas of:

- topographic and bathymetric survey techniques
- groundwater geophysical survey methods
- numerical groundwater modelling and hydrogeology.

3.1.2. Bonriki community engagement

The project has contributed to knowledge and awareness in the community of groundwater resource management, with a particular focus on the importance of the Bonriki Water Reserve and the PUB water supply assets. This awareness has been developed directly through community participation in the field investigation and data collection components of the project, and through a range of presentations, including at community meetings and through the educational, documentary-style video. Indirectly, awareness has been raised through the participation of the Bareaumai Primary School Class 3 students in the BIVA water science programme. The interaction with school students provided a good entry point into the broader community, and the potential to develop knowledge and awareness in both young leaders in the community and, indirectly, in their peers, families and broader community networks.

Two significant king tide inundation events occurred during the project, including the highest water level measured in more than 20 years. Following these inundation events, surveys were conducted. Through the information and assistance of community members, the data collected provided valuable information that was used to validate the numerical inundation model.

3.2. Land surveys

3.2.1. Survey

The BIVA project required detailed and comprehensive elevation information for the reef and the land surface for inundation and groundwater modelling. This information provides important context relating to land use and changes to the coastline over time. For this component of the project, a large topographic and bathymetric dataset on Bonriki and its surrounds was developed. Outputs from the surveys were:

- a detailed digital terrain model
- 10-cm-resolution aerial photo imagery of the Bonriki Islet and coastal area, including production of a video flyover
- mapping of historical changes in land use from 1943 to 2014
- mapping of the changes in the coastal shoreline from 1943 to 2014
- high-accuracy elevation data specific to the groundwater monitoring bores.

3.2.2. Land use and shoreline mapping

Available historical aerial imagery of the Bonriki study area from 1943, and new high-resolution imagery captured during the project were analysed to understand the extent of changes to the coastline and land area, the changes to land use over time, and the coastal processes occurring in the study area and their possible effect on the Bonriki freshwater lens. Findings from the analysis are listed below.

- In different areas along the Bonriki coastline, both advancement and retreat of the shoreline have occurred. Over the past 30 years, erosion has been the dominant process on the ocean side, while accretion has dominated on the lagoon side (see Figure 3). The opposite trend was observed between 1943 and 1984. The recent erosion trend can be attributed to increasing population and development, leading to encroachment onto the active beach, which is resulting in interruptions to longshore sediment transport.
- Since 1984, in some areas, the coastline has been subject to an alarming average erosion rate of 0.6 m/year, with a maximum erosion rate of more than 1 m/year. Erosion is exacerbated in some areas by beach sand mining, and improvised or ad hoc seawalls.

- Vegetation coverage across the water reserve increased from 1998 to 2003, and then slowly declined from 2003 to 2014.[9]
- The number of buildings in Bonriki identified from the high-resolution imagery collected in 2014 (approximately 1,400) is approximately double that identified in the 1998 imagery (approximately 700).[10] This highlights the rapid population growth in South Tarawa, including in Bonriki.

[9] The analysis has some intrinsic inaccuracies due to the quality of historical imagery; however, general trends can be observed.
[10] Numbers quoted cannot be relied on and show general trends only.

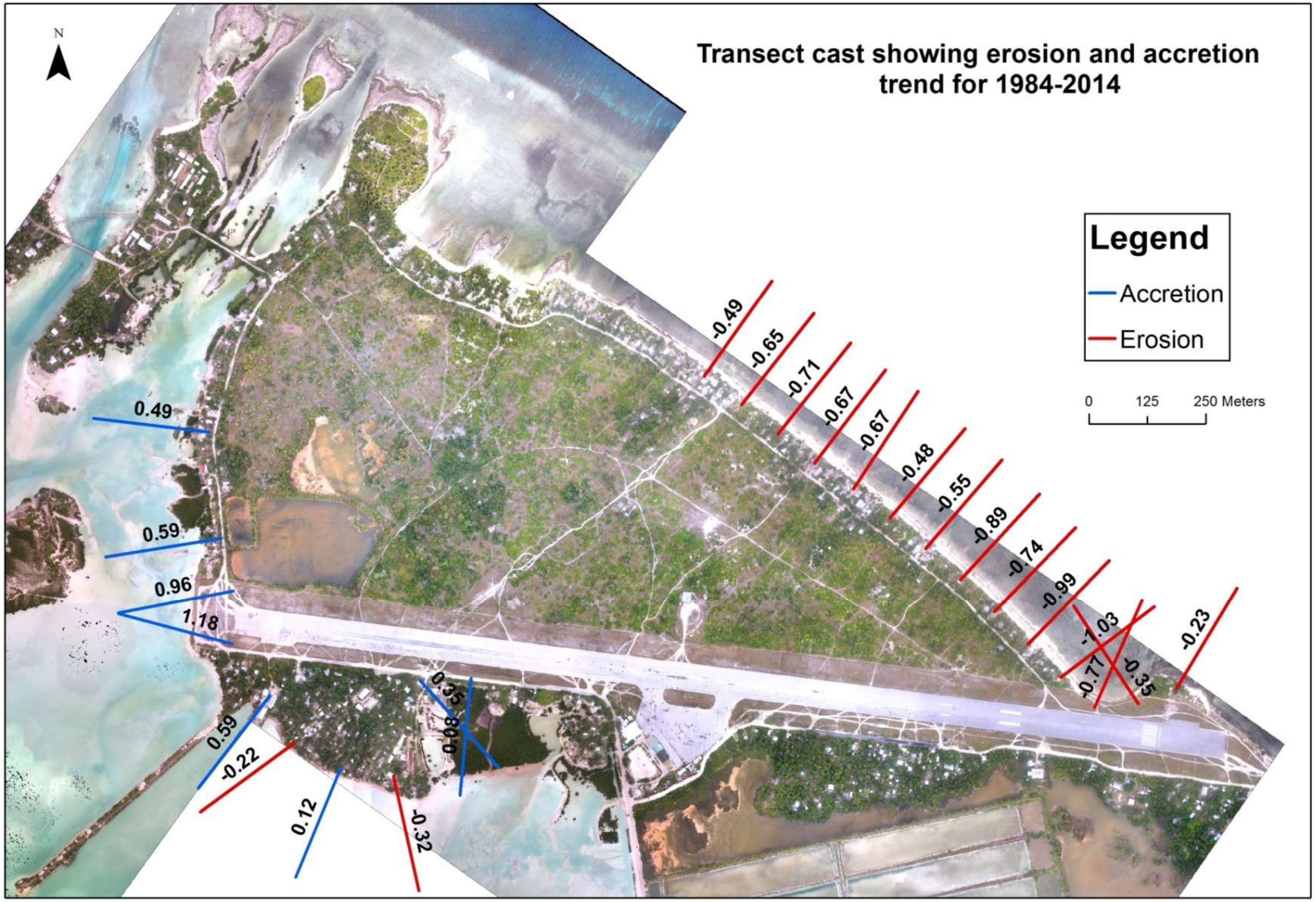


Figure 3: *Transect cast showing accretion and erosion rates (m/year) at Bonriki from 1984 to 2014.*

3.3. Coastal investigations

3.3.1. Oceanographic data

Oceanographic data were acquired from the lagoon and reef environment surrounding Bonriki over 14 months, with a major exercise in December 2013. Some trends observed in the data are listed below.

- As expected, ocean waves are aligned in an onshore direction, with observed wave heights averaging 0.5 m and occasionally reaching 1.2–1.4 m. The wave period averaged 10 s, with periods of 16 s also observed.
- Currents on the reef slope are bidirectional, trending from NNW to SSE and generally averaging 0.2 m/s.
- Wave heights in the lagoon are generally 0.1 m, with a period averaging 0.05 s.
- Deployments in the lagoon observed currents running in a WNW to ESE direction, with speeds generally at 0.1 m/s. However, currents toward the ESE dominate, with speeds occasionally reaching 0.2 m/s.

In early March 2014, an extratropical storm that developed in the north Pacific generated a large swell that propagated across the ocean. The swell impacted Tarawa on 3–4 March. At the time of the impact, the directional wave gauge was deployed on the reef slope in front of Bonriki and recorded a maximum significant wave height of 2.5 m. This information, combined with a ground-truthing survey of the inundation extent, was used to validate the numerical inundation model.

3.3.2. Oceanographic processes and inundation in Bonriki

Analysis of the data collected from the oceanographic study, and of historical tidal records and extreme wave analysis using the Australian Government's Pacific–Australia Climate Change Science and Adaptation Planning Program wave hindcast model confirmed several oceanographic features around Bonriki.

- Short swell energy dominates the offshore wave spectrum, whereas low-frequency, infragravity or even far-infragravity energy dominates in the reef flat spectrum.
- The wave heights on the reef flat are tide dependent for both short swell and infragravity bands – that is, higher tidal levels result in larger wave heights.
- Easterly trade wind conditions have dominated 96% of the time over the 34 years for which records have been kept, resulting in an easterly wave climate.
- Analysis of the modelled wave heights shows that ocean surface waves reaching Tarawa are relatively small. Over the past 34 years, Tarawa predominantly experienced waves with a significant wave height under 2 m; waves over 3 m occurred only 0.12% of the time.
- Tides are typically higher in Tarawa during February and August. Mean sea levels tend to be higher in October, and storm surges may occur throughout the year. This suggests that Tarawa is more vulnerable to coastal flooding due to tide, sea level and storm surges during February, August and October.

3.3.3. Inundation modelling

After modelling the 72 inundation scenarios, the inundation impacts were grouped into five separate categories. Each category is defined by the inundation extent and the potential impact on the groundwater lens, as summarised in Table 4.

Table 4: *Grouping of inundation scenario impacts (minor, moderate, severe and extreme).*

Inundation impact group	Summary
Minor A	Minor inundation, with no impact on groundwater. Inundation extent is contained near the shoreline, from 10 to 30 m inland.
Minor B	Minor inundation, with no impact on groundwater. Inundation only affects coastal area but extends further than minor A; in places, sea water reaches as far as the coastal road.
Moderate	Moderate inundation, with minor impact on groundwater. This group of scenarios represents significant inundation; in places, sea water reaches further inland. Sea water reaches some groundwater infrastructure (galleries and pumps), with a potential impact on the groundwater resource.
Severe	Severe inundation, with moderate impact on groundwater. From the ocean side, the inundation reaches the central part of the islet, affecting numerous groundwater abstraction galleries. Ocean scenarios lead to a significant overtopping of the road on the western side. Lagoon scenarios show saltwater intrusion into the saltwater marsh.
Extreme	Extreme inundation, with significant impact on groundwater. Inundation extends from the oceanic shore to the lagoon, and also reaches the runway. At least half of the groundwater abstraction galleries are within the inundated area.

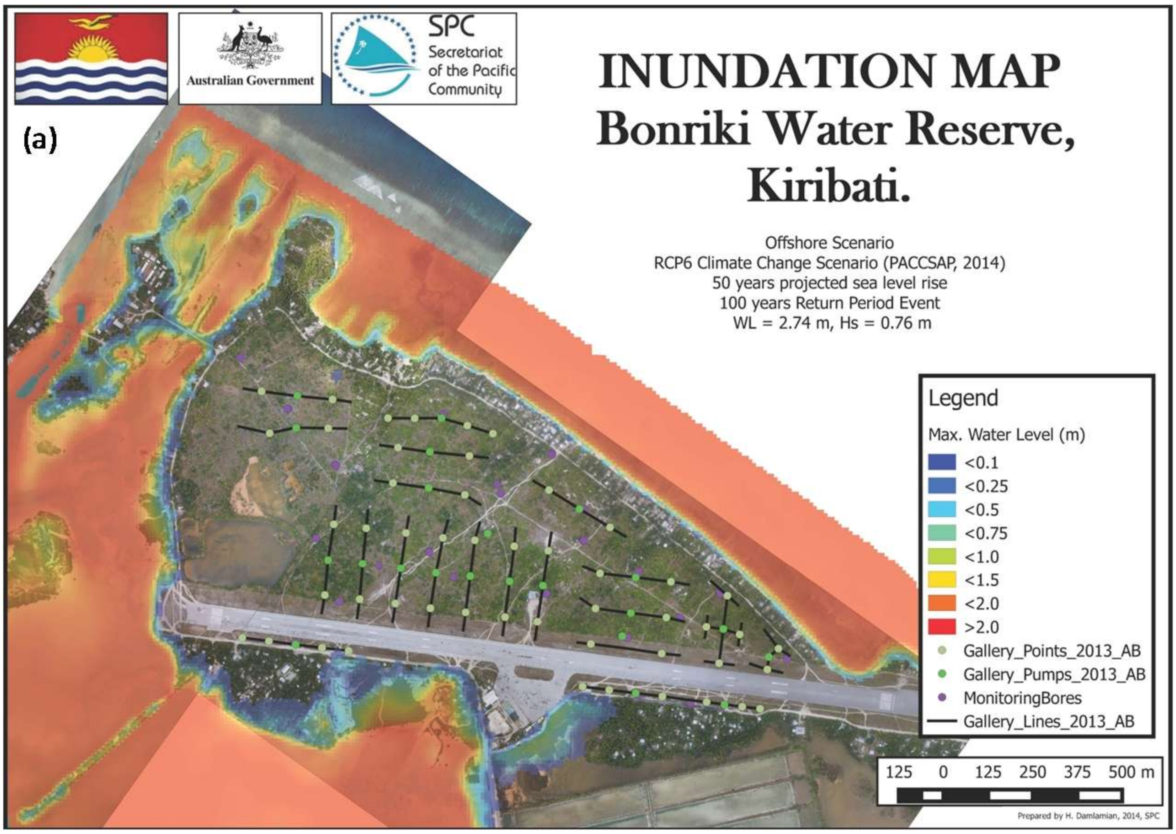
The scale of the impact in terms of the extent of inundation into the Bonriki Water Reserve was also evaluated from the 72 modelled scenarios. Key points from this analysis are as follows.

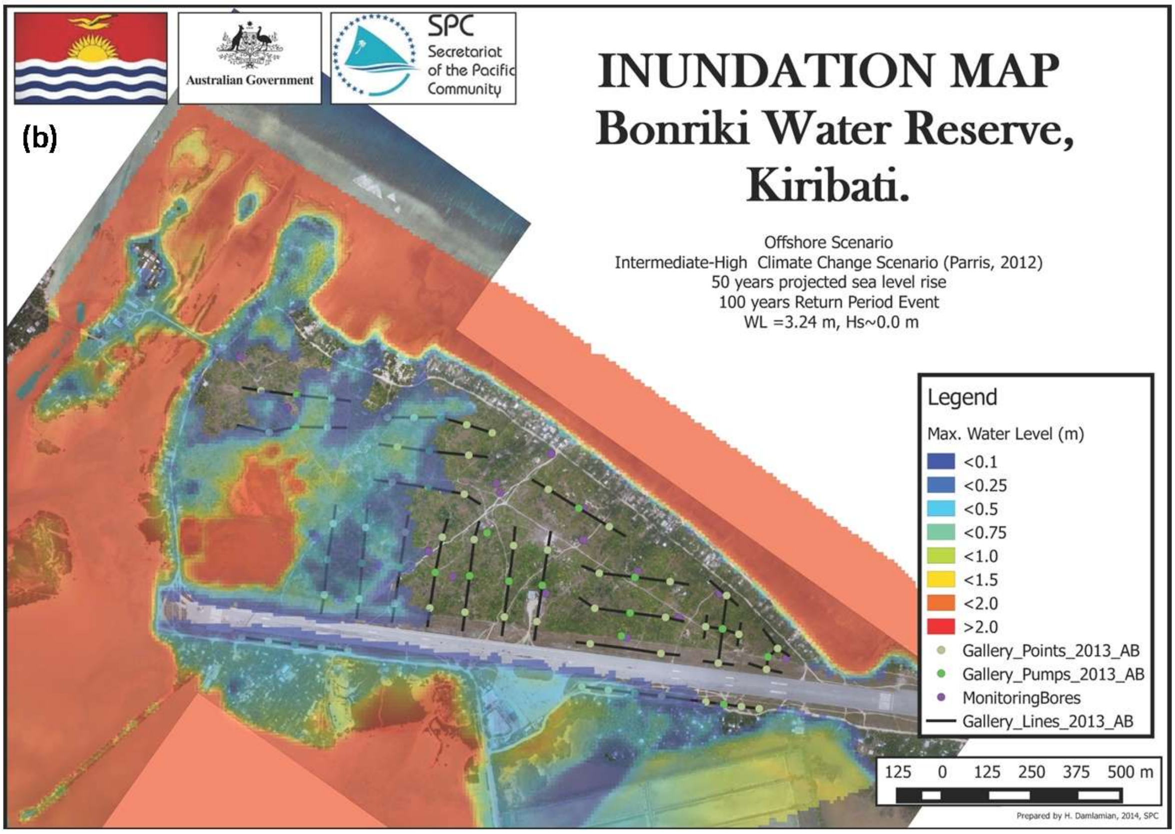
- Of the 18 scenarios modelled with ***current sea levels***, all but one was categorised as having a ***minor*** impact. This highlights that, under existing sea levels and climate conditions, the risk of impact on the Bonriki Water Reserve from inundation is low.
- The inundation event that occurred on ***3 March, 2014*** was a ***100-year return interval event*** – that is, the probability of its occurring in 2014 was 1%. The impact of this event is categorised as minor B, because seawater overtopping reached only the outer edges of the island, and no groundwater monitoring or abstraction assets were inundated.
- SLR significantly exacerbates the risk of inundation. The two most likely emissions scenarios (RCP6.0 and RCP8.5) increase the inundation impact to moderate and severe, respectively. Only scenarios using the intermediate–high scenario (from Parris et al. 2012) lead to extreme inundation, with potentially significant impact on the freshwater lens.

In addition to the impact analysis, the study also categorised the vulnerability of particular areas along the Bonriki coastline to inundation. Outcomes of the vulnerability analysis are listed below.

- The Bonriki International Airport runway is not significantly flooded in any of the 72 scenarios modelled, indicating that the current design and level of the runway are resilient to these possible inundation events.
- The western coastline, on the ocean side, is categorised as highly vulnerable and is a primary inundation pathway, in part because of its low beach berm. However, the shoreline change analysis shows this section of coastline to have a strong accretion trend (2.5 m/year). The fast and consistent changes occurring in this area could lead to a significant reduction in the inundation risk over time, if the area is well managed.
- The ocean side of Bonriki, although categorised as having a low vulnerability to inundation, has experienced high erosion rates since 1984. Since this area is subject to relatively large waves, there is an increased potential for it to experience inundation in the future, if coastal management plans are not put in place to increase the health and resilience of the area.
- The saltwater marsh (ponds) on the western side of Bonriki is currently protected from inundation by the height (above sea level) of the narrow road separating the coastline and the ponds. Any lowering of the road level could cause contamination of the freshwater lens from saltwater intrusion if sea water overtops into the ponds. This area should be carefully monitored and the road level maintained.

The inundation maps used for the groundwater modelling, presented Figure 4, provide examples of the output from the inundation modelling.





Hs = wave height; WL = water level

Figure 4: *Spatial distribution maps of (a) moderate and (b) extreme inundation scenarios over the Bonriki lens used for groundwater modelling (source: Damlamian et al. 2015b).*

3.4. Groundwater investigations

3.4.1. Groundwater field investigations

Some key findings from analysis of the data collected in this part of the project improve our understanding of the groundwater system in Bonriki.

- The rate at which the freshwater lens thins during low or no recharge was slower than the rate at which the lens was able to recover (or thicken) during a significant recharge event.
- The average rate of change in the freshwater lens thickness decreases with depth; however, the greatest variability (thickening or thinning) of the lens is observed in the transition zone – the zone between fresh water (<2,500 µS/cm) and saline water (nominally 2,500–10,000 µS/cm). This highlights the importance of monitoring in the transition zone because this zone is most likely to show the effects of climate and abstraction.
- Groundwater levels in the Bonriki Water Reserve are highly variable because of the effects of tides on water levels in the lagoon and ocean. Tides have a significant impact on groundwater water levels, causing variations of more than 0.5 m in some bores, and averaging 0.2 m for the bores assessed.
- Tidal lag[11] and tidal efficiency[12] were investigated at different points across the groundwater system. It was expected that the tidal lag would increase with distance from the tidally influenced ocean or lagoon. However, this was not observed for all sites in Bonriki, indicating that the geology in some areas allows the tidal pulse to be registered more quickly than expected.
- The watertable sits above mean sea level (AMSL) up to a maximum elevation of 1.5 m AMSL. It is interpreted that there are two distinct mounds in the groundwater level surface: one in the southeast and another in the centre of the island.
- The maximum freshwater lens thickness was estimated, based on geophysics and the available groundwater monitoring. During the monitoring period, the thickest part of the freshwater lens was 15 m. This occurred in the centre of the island.
- A review of salinity fluctuations and rainfall indicates spatial variations in recharge responses. That is, recharge increases along the edges of the runway as a result of increased run-off. There is also some indication that recharge is slower in some areas of the water reserve, such as in the eastern portion.
- From 2003 to 2013, the average rainfall was approximately 7% lower than the long-term average, coinciding with a thinning of the fresh groundwater lens in Bonriki. The cumulative long-term impact of groundwater abstraction is also believed to contribute to this thinning trend of the water resource.

The information collected as part of the groundwater investigations has been used to develop the numerical groundwater model.

[11] The time difference between high tide in the ocean and high tide at some location in the aquifer
[12] The ratio of well water-level fluctuation to that of the ocean

3.4.2. Groundwater modelling

Six modelled scenarios were analysed, and the scale of the impact on the freshwater lens of each scenario was evaluated in terms of the salinity and recovery of the freshwater lens. The following key conclusions have resulted from this analysis.

- ***The current abstraction rate is causing an increasing trend in salinity.*** This trend is observed in the historical salinity records, and in predicted modelling scenarios under the modelled climate conditions for pumping regimes of 1,700 m3/day and 2,000 m3/day. For modelled extended dry conditions, a particularly sharp increase in salinity is observed. Improvements in model calibration and abstraction values will improve confidence in the ability of the model to predict the absolute changes in salinity under different climate scenarios.
- ***Abstraction and rainfall recharge are more critical*** in influencing the lens and affecting salinisation than is inundation. The freshwater lens is extremely vulnerable to prolonged drought, and recovery from the effects of abstraction takes longer than recovery from the effects of inundation.
- ***The moderate inundation scenario shows negligible effec***t on the salinity of the galleries.
- ***The extreme inundation scenario shows a significant effect*** on the salinity of individual galleries and the trunk main for both dry and wet conditions. However, the galleries that were not inundated do not appear to be affected. This may indicate that galleries that have not been inundated could continue to be used for water supply during an inundation event. On the other hand, those galleries that are inundated are significantly affected.
- ***Recovery from an extreme inundation event takes 2–5 years, depending on rainfall.*** Under dry conditions, salinity in the trunk main recovers significantly after inundation in about five years. Under wet conditions, salinity in the trunk main starts to recover after about 1–2 years. The simulations also show that saline groundwater that enters the system during the inundation event can become entrapped in parts of the lens that are only slowly flushed, and that small but observable salinity increases persist in the pumped water for years.
- ***The impact on groundwater salinity from SLR[13] is negligible*** – assuming that the island area remains the same – except during an inundation event.

3.5. Economic analysis

Some findings from the economic analyses are listed below.

- Extraction of groundwater from the Bonriki Water Reserve is the cheapest source of water for South Tarawa. The more groundwater there is, the less money needs to be spent on supplementing water with rainwater or desalination. Logically, then, protecting groundwater reserves from pressures such as over-abstraction or salinisation is a priority.
- A period of low rainfall is extremely costly because it reduces the amount of groundwater available for abstraction at salinities of <1,500 µS/cm. In comparison, seawater inundation

[13] SLR under the intermediate–high scenario (from Parris et al. 2012) in 2064 was used to consider the impact of SLR.

arising from storm surges has a relatively minor impact on salinity and therefore a relatively minor impact on water supplies. The effect of seawater inundation (although still relatively small) is only observed in the groundwater models during high rainfall periods. This is because, during low rainfall periods, the effect of reduced recharge on the groundwater and the resulting salinity completely obscures any effect of inundation.

- The amount of water that can be abstracted at salinities <1,500 µS/cm from the Bonriki Water Reserve after a seawater inundation event and during low rainfall periods is reduced. Perhaps surprisingly, reducing abstraction and increasing the supply of water from supplementary sources in such cases can actually save money. This is because it allows the groundwater reserve to recover more quickly, reducing the number of days when salinity is above the 1,500 µS/cm threshold and the consequent volume of expensive supplementary water required.
- Supplementing water supplies with rainwater harvesting on a small scale is usually relatively inexpensive compared with supplementation on a large scale. Nevertheless, small-scale harvesting cannot fully supplement the PUB supply, and cannot produce the volume or security of water on the same scale as the Bonriki Water Reserve, large-scale rainwater harvesting or desalination. Large-scale harvesting is designed to fully supplement PUB supply but its costs are extremely high, requiring extensive areas for catchment and storage if rainwater is to remain available during severe droughts.

3.5.1. Costs of production

For the economic analysis, two target daily water supply volumes were considered: 1,700 kL/day (the current abstraction rate and approximately the currently defined sustainable yield) and 1,960 kL (the high historical abstraction rate). In both cases, water supplementation will need to occur on a *large scale*. The range in cost per unit of water produced by desalination and large-scale rainwater harvesting reflects the range of timescales (10, 20, 50 years) used in the economic analysis (Table 5). For both water supply targets, desalination is the most cost-efficient option to supplement groundwater. The larger the scale of supplementation, the cheaper supplementation with desalination can be expected to become, per unit of production.

Table 5: *Estimated supplementary water production costs over 50 years (zero discount rate).*

Water volume (kL)	Desalination (AUD/unit)	Large-scale rainwater harvesting (AUD/unit)
1,700	5.1–5.5	9.4–21.6
1,960	5.0–5.3	10.0–25.4

AUD = Australian dollar

The cost-effectiveness of desalination becomes more pronounced when shorter timeframes are considered (i.e. production over 10 years versus 50 years) because large-scale rainwater harvesting incurs most costs upfront in the first year, while desalination incurs a lower proportion of its costs upfront. For a 10-year period, the per-unit costs of desalination fall to approximately 20% of the costs of large-scale rainwater harvesting. Large-scale rainwater harvesting is never more cost-effective than desalination; however, the unit cost of water is still lower with a longer time period (see Figure 5).

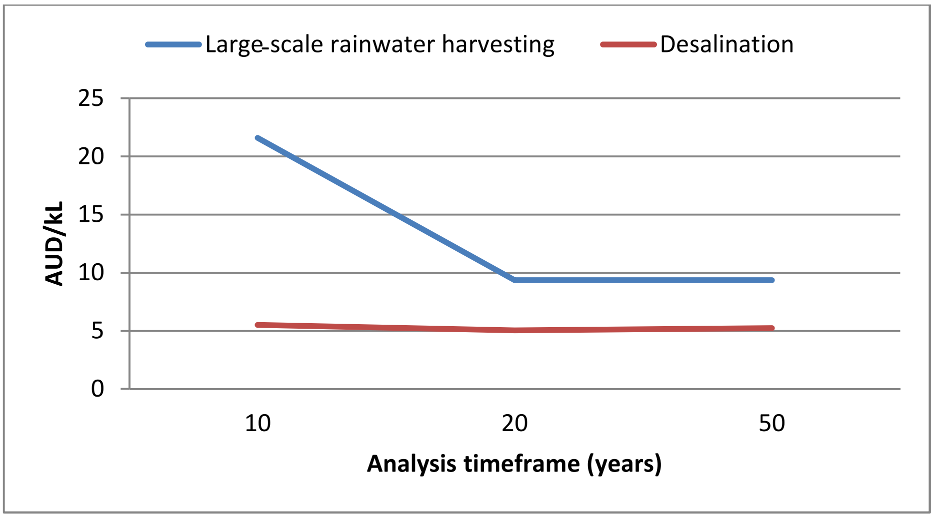


Figure 5: *Cost of large-scale rainwater harvesting compared with desalination, with no discounting.*

3.5.2. Cost of distribution

Once the costs of water distribution are included, unit costs would increase. In fact, desalination (the least costly option analysed) becomes more expensive than small-scale household rainwater harvesting, which is already being used by some families in South Tarawa and does not require distribution of water before consumption.

Although small-scale harvesting could not be used to fully supplement the Bonriki Water Reserve like the large-scale rainwater harvesting and desalination options analysed, it is still a useful, relatively low-cost option for providing *small* volumes of additional water, and reduces stress on the PUB system during normal weather conditions. As a result, household rainwater harvesting might still be an option to produce additional water independently of the government (PUB) supply system.

4. Application of project findings

4.1. Summary

The BIVA project has improved our understanding of the potential for wave overtopping at the Bonriki Water Reserve, and resulted in the development of advanced numerical models to represent and investigate the impacts of saltwater inundation on the freshwater resource. The project has increased our understanding of how the freshwater lens recovers from a range of inundation, abstraction and climate scenarios.

The groundwater model is a simplification of a complex natural system, and so requires a range of assumptions to be made about the characteristics of the system and the parameters that influence it. Despite the limitations, modelling provides a very useful predictive tool to understand the groundwater system and the impact of changes to certain parameters (rainfall, water level, abstraction). The model incorporates the best information and understanding currently available. The results can reliably be considered to reflect overall trends.

The inundation and groundwater modelling has demonstrated that, although inundation in an extreme event will impact the lens, the probability of this extreme event is low. For example, the inundation event that occurred on 3 March, 2014 was a 100-year return interval event, with a 1% chance of occurring in any future year. However, the severity of inundation is likely to increase during future extreme events, since sea level is expected to rise under climate change. In an inundation event, the impact on the freshwater lens tends to be localised to the areas actually inundated – that is, the coastal fringe. In the areas impacted directly by inundation, the freshwater lens should recover after 2–5 years, depending on rainfall. The analysis has also shown that, although an extreme inundation event will impact the lens, threats from over-abstraction and low rainfall recharge are far more critical to its condition.

The BIVA project has investigated the economic costs and benefits of potential management options in the event that the groundwater resource is too saline for distribution. The economic analysis considered using either desalination or large-scale rainwater harvesting to augment the Bonriki groundwater supply. In all scenarios modelled, desalination was the cheapest option, while groundwater remains the cheapest source of water overall.

4.2. Application of findings to water resource managers of the Bonriki Water Reserve

The threats to the Bonriki Water Reserve are well known by water resource managers in Kiribati. The BIVA project has investigated the threats of inundation, climate variability and abstraction to the freshwater lens.

It is now well understood that, although a threat, inundation impacts are not as significant as drought and abstraction impacts. The economic analysis has also highlighted that, even in an extreme inundation scenario, the costs to supplement Bonriki groundwater when groundwater is too saline for distribution are far below the expected cost of supplementing groundwater during a period of extreme dry weather. Given that policymakers cannot change the climate and that protecting groundwater from extreme inundation events is likely to cost more than the resulting benefits, it is recommended that focus instead turn to more feasible approaches to reduce the cost of supplying PUB water.

For water resource managers and policymakers, this highlights the importance of:

- finalising, enacting and implementing the draft South Tarawa Drought Response Plan. The plan is a key water resource management policy that will outline responsibilities and procedures for monitoring the status of the water resource, drought declaration, and water conservation and water resource management strategies during times of low rainfall;
- continuing to monitor the water resource via the existing borehole infrastructure, and maintaining this dataset by MPWU;
- continuing to monitor abstraction volumes and salinity at individual galleries by PUB;
- maintaining the salinity of the Bonriki Water Reserve at an acceptable level through sustainable abstraction, and developing a more precise understanding of the sustainable yield of the water reserve;
- protecting groundwater reserves from human pressures such as encroachment of settlement; and
- reducing leakage within the water distribution network.

The project has also highlighted the importance of engaging the Bonriki community to improve water resource management. The project developed tools (school education programme and documentary) that can be used to increase awareness within the community of water management issues. Ongoing, long-term community engagement and participation in water resource management are possible through the broader application of these tools and involving community members in management activities such as borehole monitoring. Community participation and improved information flow will develop a stronger sense of ownership and responsibility within the community for management of the water resource.

4.3. Application of findings to operation and management of the PUB water supply system in Bonriki

Some specific operational and management scenarios for the PUB water supply system in Bonriki have been considered as part of the BIVA project analysis, and are listed below.

- ***Management of the infiltration gallery pumps during an inundation event.*** Based on the modelling, inundation impacts appear to be localised. This suggests that pumps not directly inundated could continue to operate. Those that are inundated should be turned off for 2–5 years, depending on rainfall. Switching off the pumps that have been affected in an inundation event may be an effective immediate action for protecting the groundwater system; however, if such a measure is taken, the reduced volume of fresh groundwater supply should be taken into account.
- ***Reduction in abstraction to reduce the likelihood of the freshwater lens salinity exceeding 1,500 µS/cm.*** The economic analysis indicates that, if a high abstraction rate is maintained from the Bonriki reserve (e.g. 2,000 kL/day), the cost to provide an alternative water source when the salinity of the trunk main exceeds 1,500 µS/cm is likely to be greater than if the abstraction rate is reduced to a point where salinity in the trunk main is less than 1,500 µS/cm and a continuous supplementary alternative supply is provided to meet the groundwater deficit (e.g. 1,500 kL/day from Bonriki and 500 kL/day from desalination).
- ***Use of alternative water supplies to supplement the Bonriki groundwater source*** when the freshwater lens is impacted by inundation, abstraction and/or dry climate conditions. Desalination appears to be the cheapest option suitable to back up the Bonriki supply, compared with large-scale rainwater harvesting, while groundwater remains the cheapest source of water overall.

The economic analysis has highlighted the broader issues relating to water supply for South Tarawa – namely, the growing population and the insufficient available supply to meet future water demands. It is important that alternative sources be considered to augment the Bonriki water supply. Although details of this are beyond the scope of the BIVA project, the options considered in the economic analysis were desalination and rainwater harvesting. Rainwater harvesting at a large scale is less economical than desalination. However, household rainwater harvesting can provide a useful supplementary supply, particularly while alternative large-scale supplies and the issues with losses within the PUB reticulated system are being resolved.

4.4. Application of findings to climate change adaptation planning, disaster risk management and coastal zone management

In Kiribati, specific working groups such as the Kiribati National Expert Group on Climate Change and Disaster Risk Management, and the Disaster Management Office within the office of the President require tools and data for planning for future events and threats to the community. The data collected and analysis undertaken as part of the BIVA project provide valuable information for climate change adaptation planning and disaster risk management, as well as integrated coastal zone management.

More specifically, information and tools that can be used for these purposes include the following.

- ***Inundation maps.*** A number of points on the coastline have been identified as prone to submersion and are expected to be frequently inundated. Identifying these weak points along the shoreline is a first step to developing efficient mitigation options against inundation.
- ***Probabilistic hazard assessment.*** The analysis indicated that, although high water levels are most likely to occur in March and October, most of the extreme inundation scenarios had a low probability. During community consultation when this information was presented, it was emphasised that, while the risks may be high, the probability of occurrence is low. Probability of occurrence should be a consideration in any disaster risk planning.
- ***Land use and shoreline mapping.*** Because of the rapid and consistent changes in parts of the Bonriki shoreline, mainly as a result of erosion but also of accretion, inundation pathways and, more generally, inundation hazards can potentially change drastically in the near future. Much effort should be put into building the resilience of the coastline and monitoring any changes; this work can be facilitated by an integrated coastal zone management plan.
- ***Participatory 3D mapping.*** Participatory 3D mapping has been trialled in the BIVA project. This method could be adapted to provide a platform to discuss water and inundation-related issues with the community. It thus presents an opportunity to incorporate local knowledge about geomorphic changes from wave action and inundation events into disaster risk management or adaptation planning.

Except for the community surveys, the BIVA project has not analysed the social impact of inundation events. Although the groundwater modelling indicates that inundation will have minor impacts on the water resource compared with drought and abstraction, from a social perspective, minor inundation will still affect households and community assets located on the coastline. These issues are best addressed through an integrated coastal zone management plan. Furthermore, even minor impacts on the water resource can be considered significant when the outcome is reduced availability of fresh water for the urban population.

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