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Impacts of climate change on small island hydrogeology - a literature review

Groundwater Science Programme

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BRITISH GEOLOGICAL SURVEY

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) with the aim of reviewing the potential impacts of climate change on small island hydrogeology in the context of developing future groundwater modelling capability to assess these impacts. It has been carried out under the Groundwater Modelling Team with the support of Andrew Hughes.

Contents

Summary

This report comprises a review of literature relating to the impacts of climate change on small islands. Given the diversity of material presented on climate change studies this review has intentionally focussed on small island hydrogeology, the impacts of climate change specifically on small islands and finally a review of impacts associated with extreme events.

The small islands and climate change literature is abundant. It assesses and predicts change and associated impacts. Perhaps the greatest uncertainty relates to manifestation of climate change impacts and their attribution to natural or anthropogenic causes. Many researchers also highlight the interdependencies between environmental, social and economic determinants.

An assessment of impacts of climate change across the various types of small islands is highlighted by the Inter-governmental Panel on Climate Change (IPCC) as an area requiring consideration that is lacking within the literature and would benefit from further research.

1 Introduction

1.1 BACKGROUND

With the association of increased greenhouse gas emissions and climate change well-documented and accepted by the scientific community (Jackson et al., 2006), attention is increasingly turning to the assessment of impacts arising from climate change scenarios. The Intergovernmental Panel on Climate Change (IPCC) within their 2008 report on Climate Change and Water (Bates et al., 2008) are clear about observed changes in climate. A global increase in surface temperature between 1906 and 2005 of 0.74°C is reported along with changes in precipitation patterns and changes in weather intensities and extremes. Moreover the shifts in climate are translated to a global mean sea-level rise of 1.8 ± 0.5 mm/yr between 1961 and 2003 (Bindoff et al., 2007). There is an acceptance however that attribution of the observed climate change is difficult with many anthropogenic influences and decadal variability associated with 'teleconnections' such as the El Nino Southern Oscillation (ENSO) (Bates et al., 2008). The frequency and distribution of tropical cyclones, typhoons and hurricanes in small islands regions for example is strongly linked to ENSO and displays decadal variability. Attribution of changes in climate and underlying trends are difficult to detect in shorter, less reliable data sets, however, a substantial upward trend in potential destructiveness of tropical storms is proposed (Bates et al., 2008).

The manifestations of climate change will arguably be wide in range and spatially variable. Many authors highlight the inter-dependence of the impacts across social, economic and environmental communities (White et al., 2007a, Lal et al., 2002, Mimura et al., 2007). Ranjan et al., (2009) for example, recognise that impacts of sea-level rise will be exacerbated when coupled with reduced aquifer recharge and increased coastal urbanisation and water usage. The occurrence and impact of extreme storm and precipitation events has generally received greater interest from researchers with investigation into the effects of droughts receiving less attention. Coupled with droughts the IPCC highlight the need to consider increased abstraction rates and greater risk of saline intrusion while dry weather persists (Bates et al., 2008).

Small islands, typically defined to be less than 5000 km^2, have a unique and delicately balanced hydrological system that has been subject to extensive research (Falkland and Custodio, 1991). The geometry of groundwater resources on small islands typically assumes an unconfined, less dense, fresh-water lens which rests on underlying saline water (Herbert and Lloyd, 2000). The interface between the fresh-water lens and saline water is described as the transition zone and is approximated using the Ghyben-Hertzberg principle, though recent investigations prefer the use of advection-dispersion models (Herbert and Lloyd, 2000).

Small islands by nature are prone to the effects of climate change, sea-level rise and extreme events. The islands are low-lying, their climates are characterised by large seasonal variations in precipitation and many islands have limited surface water resources (Mimura et al., 2007). Considering specifically small islands and the integrated management of coastal aquifers the impacts of climate change may extend to one or all of the following:

- Increase in sea-level and loss of fresh-water aquifer storage.
- Increase in severity or intensity of storm events with tidal extremes causing saline inundation.
- Increase in frequency or duration of drought periods.
- Reduction in aquifer recharge.
- Increased demand for groundwater resources.

- Reduction in surface water drainage to coastal systems.
- Increased erosion of coastal systems.

In their 2008 report, the IPCC comment that nearly all climate change scenarios indicated that water resources on small islands are likely to be seriously compromised (*very high confidence*). This forecast is reflected in the small island states concern about freshwater availability in terms of both quantity and quality and their expression for integrated watershed planning (Bates et al., 2008).

1.2 AIMS AND OBJECTIVES

With an extensive array of climate change issues represented within the literature this report aims to focus only on three principle areas of relevance to small island states. The report has been structured to reflect the three main aims of the literature review with sections on small island hydrogeology, the relevance of climate change for small island states and the effect of extreme events. The literature review is summarised in the final section along with ways in which small island investigations maybe carried forward. Whilst the availability of material relating to climate change is diverse, efforts have been made to restrict sources to those which are in the first instance pertinent to small islands and secondly subject to peer-review and accessible to a general audience. In such case journals have been researched in preference to internal reports from independent organisations.

2 Small Island Hydrogeology

Many papers have been published which describe the hydrogeology of small islands. Prior to the 1990's most of these papers described investigations into the numerical modelling of small island hydrogeology and definition of equations to describe the geometry of groundwater lenses and water resource availability (Chidley and Lloyd, 1977, Cant and Weech, 1986 and Mather, 1975). The numerical assessments within these papers are largely based on the Ghyben-Herzberg and Dupuit approximations, though Jacobson and Hill (1980) note that the groundwater lens in the Niue Island, South Pacific does not comply with the Ghyben-Herzberg approximation. Definition of the saline interface on small islands is also discussed by Rushton (1979) and Stewart (1982), with Rushton (1979) highlighting the difficulty of using observation boreholes to define the interface due to hydrostatic interference and Stewart (1982) evaluating the use of electromagnetic techniques. This later work by Stewart is arguably now out-dated due to recent advancement in geophysical surveying. A list of small island papers prior to 1990 is provided in Appendix I.

Much of the theory described and proposed by early authors is presented in '*Hydrology and water resources of small islands: a practical guide*' published by UNESCO (Falkland and Custodio, 1991). The text itself is extremely comprehensive and includes sections on the characterisation of small islands from climatic scenarios through to geological settings in addition to sections on groundwater hydrology with emphasis on freshwater-saltwater relationships and water resource assessment and management. The book also provides small island case studies for example of the Canary Islands, Hawaiian Islands, Montserrat and the Scottish Islands. More recent literature about the numerical conceptualisation of small islands is lacking though Herbert and Lloyd (2000) and Singh and Gupta (1999) both discuss advances in modelling of freshwater – saltwater relationships.

Herbert and Lloyd's (2000) paper, '*Approaches to modelling saline intrusion for assessment of small island water resources'* outlines the current modelling approaches to quantitatively assess salinity across the transition zone. The models are often too simplistic being based on the Ghyben-Herzberg approximation or advection-dispersion equation. The Ghyben-Herzberg approximation applies only to a steady-state flow condition and maps a sharp interface between fresh and saline water rather than a transition zone. Advection-dispersion models are being adapted to predict saline intrusion (Ghassemi et. al., 1990) with parameters often determined from tracer tests, though Herbert and Lloyd (2000) note that the advection-dispersion equation does not consider the density variation of saline waters. Additionally the paper describes some of the difficulties in determining the hydraulic properties of the small island aquifers e.g. specific yield. In addition to Ghassemi et. al., (1990), Singh and Gupta (1999) in *'Groundwater in a coral island'* use advection-dispersion equations in a SUTRA package to determine the water resource availability from a groundwater lens in Kavaratti, Arabian Sea.

A paper by Robins and Lawrence (2000) considers hydrogeological problems on small islands with particular reference to the island type. Crucial to the assessment of water resources on small islands, Robins and Lawrence (2000) specify the availability and distribution of data, dynamics of the freshwater lens and evaluation of groundwater recharge and discharge being particularly problematic. These constraints are further compounded by the high ratio of coastline to surface area, extreme topography and calculation of baseflow to rivers in small islands. Six island types are defined based on work by Falkland and Custodio, (1991) and a water balance scenario is completed for those island types based on aquifer recharge, storage, yield and groundwater quality. Within their discussion Robins and Lawrence (2000) explain the limitations of applying the Gyben-Hertzberg equation.

Recent attention on climate change scenarios and increased pressures on available water resources has led to a shift in published literature on small islands with recent papers focussing more on climatic settings and associated sea-level rise, saline intrusion (e.g. Diamantopoulou and Voudouris, 2008 and Momii et al., 2005) and sustainability issues (e.g. White *et al*., 2007a). A recent paper by Schneider and Kruse (2005) uses variable density models to look at controls on lens geometry on barrier islands in Florida, USA, including recharge variations, geology, aquifer properties, tidal effects and coastal erosion rates. The results showed that there was minimal seasonal variability in the lens morphology, however, they did conclude that lens thickness does correlate with elevation and vegetation and hence recharge. The lens thickness is also dependant on island development with a thinner lens where development is greatest. Island erosion was found to have a significant impact on the groundwater lens with indications that the current groundwater lens is not in equilibrium with current boundary conditions and the lens is likely to thin further. Schneider and Kruse (2005) conclude however that decadal-scale variability associated with climate cycles and climate change would significantly affect the availability of freshwater rather than inter-annual variability.

White et al., (2007a) provide a general account of the '*Climatic and human influences on groundwater in low atolls*' including water supply issues as well as examining the relationship between groundwater, rainfall and ENSO in Tarawa, Kiribati. The paper concludes that changes in groundwater levels due to pumping from infiltration galleries are less than changes induced by natural processes such as diurnal tidal variations. An ENSO event can produce a sea-level rise of 0.25m. Whilst climate change is not discussed within the paper the issue of prolonged drought is considered. White et al., (2007a) show that large freshwater lenses (widths approaching 1 km) are more robust to prolonged drought (30 months) with only moderate increases in groundwater salinity. A second paper by White et al., (2007b) discusses preliminary estimates of climate change and comments that changes in rainfall is the most important factor effecting groundwater in atoll islands, going on to say that small sea level rises with current mean rainfall may slightly increase the quantity of groundwater in some atolls.

3 Climate Change

Climate change literature is both large in number and highly variable in nature with published research juxtaposed with informal untested hypotheses. This review only considers climate change literature from reputable sources and those subject to peer review. A summary of peer-reviewed literature is provided below.

3.1 INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

The IPCC is a scientific intergovernmental body set up by the World Meteorological Organization (WMO) and by the United Nations Environment Programme (UNEP) with the aim of providing an objective source of climate change information. IPCC reports are neutral and offer a high scientific and technical standard. The IPCC do not conduct their own research rather their reports are an assimilation of recent climate change publications and research. The IPCC reports themselves are a review of climate change literature. Many reports have been compiled by the IPCC which discuss the physical science of climate change, impacts adaptation and vulnerability and mitigation of climate change.

IPCC CLIMATE CHANGE AND WATER (BATES ET AL., 2008)

The most recent report by the IPCC is a special publication summarising information about climate change and water from other IPCC literature. The paper deals only with freshwater, though sea-level rise is covered in respect of its impacts on freshwater availability in coastal zones.

The impact of climate change on hydrological processes is discussed in depth along with water resource implications under various climate change scenarios. Both observed and projected changes in climate components including precipitation, sea-level, evapotranspiration, soil moisture and run-off and river discharges are outlined, the results of which are summarised in Appendix 2. The observations in climate trends are greatly affected by availability and reliability of data and measuring techniques, with great regional disparity. The lack of groundwater data coupled with a slow reaction of groundwater systems means climate related changes in groundwater recharge have not been observed. Decreasing trends are seen in aquifers but are often attributed to increased abstraction rates.

Section 5.8 of the report specifically analyses regional aspects of climate change and water resources for small islands. In line with previous sections of the report both observed and projected changes in climate are discussed. Many of these conclusions have been tabulated in Appendix 2 of this review. In general terms temperature observations over land and sea display consistent warming across all small-island regions (1901–2004), though trends are non-linear and historical data are lacking. In particular the South Pacific has experienced, during 1961 – 2003, an increase in the number of hot days and warm nights, particularly after the onset of ENSO. A similar warming trend has also been seen in the Caribbean, with an additional prediction of reduced summer rainfall. Increased winter rainfall is unlikely to fully compensate summer reductions due to increased run-off from high intensity events and low storage potential.

Climate models for the Tarawa Atoll, Kiribati in the Pacific currently predict a rainfall reduction of 10% (by 2050) coupled with a 20% reduction in the size of the freshwater lens. A trend like this observed in the Bahamas where freshwater lenses are the only groundwater source would be of great concern.

Considerable progress has recently been made in regional sea-level projections but problems associated with down-scaling makes them difficult to transpose to small island settings, where greater resolution and local data are required. Sea-level rise is seen as a critical issue in

Kiribati, Tuvalu, Marshall Islands and the Maldives, though across all small island locations the IPCC report notes that the impacts of sea-level rise are not only related to water resource availability but also to the stability of coastal ecosystems and tourism.

Section 8 of the report considers the uncertainties in current climate change research and projections, illustrating gaps in existing knowledge and proposals for further work.

The main areas of uncertainty being:

- Socio-economic development scenarios.
- The range of climate model projections for the various scenarios.
- Down-scaling the climate effects to local or regional models.
- Modelling the feedbacks of adaptation and mitigation efforts.

These uncertainties are compounded by the fact that observational networks are often inadequate e.g. precipitation measurements over the oceans by satellites are still being developed and techniques to measure streamflow, soil moisture and evapotranspiration are not robust. Groundwater investigations have been lacking compared with surface water studies and are neither well monitored in many regions nor are the mechanisms controlling groundwater depletion and recharge are well-modelled.

The report calls for a greater confidence in attributing observed climate changes to natural or anthropogenic causes particularly for extreme events and at smaller scales and suggests that the development of indicators of climate change impacts on freshwater and systems to monitor them are required. In particular the report comments that climate change impacts on water quality are poorly constrained especially in assessing the impact of extreme events.

With particular reference to small island climate change impacts (section 5), the report identifies several gaps in current research including:

- The role of coastal ecosystems such as mangroves, coral reefs and beaches in protecting against sea-level rise and storm events.
- Establishing the response of upland and inland ecosystems to changes in temperature and rainfall events.
- Identifying which of the many ‘island types’ are the most vulnerable, given their diverse character and location.

IPCC 4TH ASSESSMENTS REPORTS: CLIMATE CHANGE 2007

In 2007 the IPCC published assessment reports covering the physical science of climate change, impacts adaptation and vulnerability and mitigation of climate change. Several chapters within these reports are pertinent to the review of climate change impacts on small islands.

Climate change 2007: The physical science basis, chapter 3 (Trenberth et al., 2007) includes a section describing changes in extreme events with particular consideration of variability in or extremes in temperature, precipitation and tropical storms. The report concludes an increase in the number of warm nights and reduction of cold nights and an increase in the number of heavy precipitation events with some associated increase in flooding. A lack of data, however, limit the analysis of extreme precipitation events in the tropics and subtropics. In general an increase in the intensity and duration (but not in the frequency) of tropical storms has been identified, though large interannual variability limits the evaluation of these trends. Chapter 5 of the report looks specifically at oceanic climate change and sea level, including changes in temperature, salinity and ocean circulations. In summary the report concludes an increase in global ocean temperature of 0.10°C from surface to 700m depth (1961–2003) with some cooling since 2003.

Salinity increases are identified in shallower parts of the tropical and subtropical oceans whilst freshening is occurring in subpolar latitudes. In particular freshening is marked in the Pacific whilst the Atlantic and Indian Oceans show increasing salinities. Sea-level rises echo those reported in the IPCC Climate Change and Water report (Bates et al., 2008).

Climate change 2007: Impacts, Adaptation and Vulnerability, includes a full chapter (Chapter 16) on Small Islands (Mimura et al., 2007). The report discusses the sensitivity and vulnerability of small islands in addition to observed and projected impacts, uncertainties and research proposals. This chapter is a fuller and more detailed account of the small island section within the subsequent 2008 IPCC 'Climate Change and Water' report, with nearly 200 references (published post-2000) cited. Whilst the observed and projected changes in climate are largely identical to the 2008 IPCC report there are notable additions e.g. In line with the 2008 report an increase in cyclone intensity is expected with wind intensities increasing by 5 – 10 % by 2050 and peak precipitation rates likely to increase by 25% as a result. Also if the 10% reduction in precipitation and subsequent 20% reduction in the thickness of the freshwater lens at Kiribati (earlier reported) is investigated alongside the accompanying loss of land due to sea-level rise the reduction in thickness of the freshwater lens would actually be 29%. This earlier report has another distinct advantage in that it describes in more detail the range of climate change impacts that would be felt differently across the various island types. For example, severe island erosion due to increased sea-levels is expected in the Pacific but contrary evidence shows that uninhabited islands in the Maldives are more resilient and may persist. In contrast erosion of Arctic islands will be exacerbated by warming of permafrost, ice sheets and higher wave energy. That said there is agreement across literature that atoll islands are most vulnerable.

3.2 PUBLISHED PAPERS

The IPCC 4th Assessment Report (2007), Chapter 16 (Small Islands) cites nearly 200 references (published post-2000) which consider the impact of climate change on Small Islands. Most of these papers fall into the following general categories, (i) impacts of climate change on ecological environments, (ii) socio-economic implications including effects on tourism, health and coastal communities, (iii) mitigation of and adaptation to climate change and (iv) environmental impacts including sea-level rise, changes in oceanic behaviour and ENSO events. Few papers deal directly with the implications of climate change on the availability of fresh groundwater resources in small islands.

A general paper by Lal et al. (2002) uses an ensemble of coupled atmosphere-ocean global climate models (A-O GCMs) e.g. HadCM2 (UK) to project climatological scenarios across the small island states. Precipitation climatology over oceans and high altitudes is considered less reliable due to lack of observations. The data sets generated from the A-O GCM are lodged with the Data Distribution Centre which contains quality controlled climate change and socio-economic data which are made available for fast-track regional climate impact assessment studies. The models simulate a change in annual mean rainfall across the islands of <10%. In the northern hemisphere summer rainfall is expected to decline everywhere except over the Pacific Islands, coupled with an increase in rainfall intensity. A summary of the precipitation changes is tabulated within the paper. The impact of sea-level rise and coastal erosion is also discussed peripherally with Lal et al., (2002) noting that many small islands rarely exceed 3 to 4 metres above present mean sea-level and most infra-structure is located along coast margins. A 1m sea-level rise, for example, is estimated to cause the submergence of 1190 small islands which form the Republic of Maldives.

Observed sea-level rise at small islands within the Pacific and Indian Oceans along with a critique of the data sources and methodologies applied, is discussed by Church et al. (2006).

Sea-level rises were calculated using a combination of individual tide gauge records, TOPEX/Poseidon satellite altimeter and sea-level reconstructions to provide greater validation. In line with the IPCC reports and other papers, Church et al. (2006) express the difficulty in assessing long-term trends when inter-annual and decadal variability is high and monitoring records are short. The author also highlights the need to correct for external factors such as isostatic adjustment, atmospheric pressure and land subsidence.

In the period 1993–2001 the data show rates of sea-level rise in the western Pacific and eastern Indian Ocean approaching 30 mm/yr and a reduction in sea-level in the eastern Pacific and western Indian Ocean of nearly -10 mm/yr. These results are reported to be influenced by the ENSO. For the period 1950 to 2001, the average sea-level rise in the Pacific calculated from tide-gauges is 2.0 mm/yr after corrections (which is consistent with the global average) with the variance in monthly average sea-level after 1970 being twice that before 1970. The paper contradicts work by Morner et al. (2004) which claimed a fall in sea level in Maldives, by proposing a rise in sea-level at Tuvalu of 2 ± 1 mm/yr (1950–2001). Tide Gauge records for the Indian Ocean at Port Louis and Rodrigues Island show sea-level falling at rates of 3 ± 2 mm/yr (1986 – 2000), with the satellite altimeter also showing a fall in sea level. Reconstructed sea-levels over the period 1950 – 2001 show a sea-level rise of 1.5 mm/yr at Port Louis and 1.3 mm/yr at Rodrigues Island. The main observations are included in Appendix 2, along with other reported climate change scenarios for small islands.

Most recently Ranjan et al., (2009) have explored the effect that climate change may have on the availability of coastal groundwater resources and is unique in that they apply a global model. Whilst the paper does not specifically address small islands the coastal setting is analogous. The model used is kept intentionally simple to avoid the difficulties arising over lack of data and calibration of many variables and consider only rainfall, temperature and hydraulic conductivities. Groundwater recharge is derived from measured precipitation and temperature data and saline intrusion is estimated using the sharp interface concept, the use of which is justified by the authors given the long-term nature of forecasting climate change impacts. A sensitivity analysis conducted by Ranjan et al., (2009) showed that hydraulic conductivity is the most sensitive hydrogeological factor in the calculation of the saline-freshwater interface. The model concluded that Central America, North part of South America, Southern Africa and Australian regions have a higher reduction in groundwater resources in the future. Most of Asia showed a medium reduction and upper latitudes show an increase in available resource. The hydrogeological modelling is also coupled with changes in population growth to incorporate global vulnerabilities. Within their paper Ranjan et al., (2009) reference the work of Melloul and Collin (2006) who use basic hydrogeological conceptualisation to estimate aquifer loss due to sea-level rise and change in groundwater drainage basin characteristics. In order for the calculations to be made Melloul and Collin (2006) had to make assumptions about the aquifer geometry and shape and in addition note the importance of coastal topography in determining impacts.

The influence of topography and island morphology in assessing vulnerability to sea level rise in atoll communities is presented by Woodroffe (2008). A detailed account of sea-level change and associated changes in depositional setting is provided by the author for the Cocos (Keeling) Islands, Maldives Archipelago, Chagos Archipelago, Kiribati and Tuvalu, noting island morphology, tidal range and susceptibility to storm events. The stability of reef development during Quaternary sea-level transgression and recession is placed in the context of modern sea-level change. Whilst most land in atoll islands lies below 2 m above sea-level (asl), there is significant variation geographically. A third of land in the Kiribati-Tuvalu chain is above 2 m asl, whilst only 4% of the Maldives is. The oceanward ridge which frequently rises higher than surrounding land is also considered important in the vulnerability of the islands, in most cases adding an extra metre to island elevations.

Atoll islands are typically micro-tidal with a tidal range between 1–2 m, though Woodroffe (2008) highlights that low-lying internal atoll lagoon sections already suffer from inundation under high tide scenarios, a situation exacerbated during storm surges. Shoreline erosion, especially during storm events, is perceived to be a great risk to small island states, evidence of which is found in prominent scarps and undercut vegetation (Woodroffe, 2008). Woodroffe (2008) argues however that oceanward beaches are actually net sediment sinks with evidence of progradation as shown in radiocarbon chronologies and photographic imaging. In his discussion Woodroffe (2008) urges better understanding of the geomorphological response to sea-level rise, in addition to a clearer understanding of spatial variations in water levels during extreme events (given tidal influences), water table behaviour and ponding of water in atoll islands interiors.

The Tyndall Centre, based at the University of East Anglia is dedicated to climate change research. A review of their projects indicates that much of their work on climate change and sea-level rise focuses on UK coastal systems. However they have investigated the impact of sea-level rise on coastal biodiversity and economic activity in the Caribbean islands. Whilst the work concentrates on ecological and economical impacts rather than groundwater issues they did find that 32% of beaches may be lost for a 0.5 m rise in sea-level.

4 Extreme Events

The main concern for impacts in Small Island States is not necessarily mean climate changes but with the extremes that are superimposed on those means (Lal et al., 2002). There are several publications which address the seriousness of extreme weather events, though research has tended towards extreme precipitation events and away from droughts. The issue of prolonged drought in low atolls is, however, considered by White et al. (2007a) highlighting that droughts can last as long as 43 months and occur with a frequency of 6-7 years. Rainfall is reduced from 980 mm/yr to 200 mm/yr with a predicted reduction in thickness of the freshwater lens to 50% of its long-term mean. White et al. (2007a) also show that large freshwater lenses (widths approaching 1 km) are more robust to prolonged drought (30 months) with only moderate increases in groundwater salinity.

The climate change impacts on water quality are poorly constrained in assessing the impact of extreme events (Bates et al., 2008), though there are recent publications which consider the groundwater quality impacts arsing from the Sumatra Tsunami which may be considered as a proxy for storm surge over-topping.

The IPCC held a workshop on extreme weather and climate events in 2002, the results of which have been published and include sections on precipitation and tropical cyclones (IPCC, 2002). The discussion identifies the advances, weaknesses and knowledge gaps in the modelling of primary parameters such as precipitation intensity, storm surging and internal variability to characterise the extreme events. The report does not consider the secondary impacts of extreme events on groundwater for example but does recognise the need for integrated assessments, e.g. looking at impacts of combined events such as tidal processes coupled with sea level rise. A review of extreme storm events and tsunami literature is provided below.

4.1 STORM EVENTS

Storm surging, overwash and flooding is recognised as a key consideration in salinisation of coastal aquifers yet few investigations are reported in peer-reviewed literature (Anderson and Lauer, 2008). The influence of overwash and storm events on coastal mixing zones in barrier islands (Hatteras island, North Carolina) is considered by Anderson and Lauer (2008). In 1993 the coastal aquifer, comprising medium to coarse-grained sands, was inundated with saline water during Hurricane Emily which gave rise to 3 m high storm waves. The multiple wash-over events caused elevated TDS (total dissolved solids) levels that persisted for more than 3 years. Using the SUTRA modelling package, Anderson and Lauer (2008) propose that overwash occurring during storm events is the principle control on barrier-island mixing zone morphology, though recognise that local heterogeneity and recharge variations cause small scale changes in morphology. The authors also appreciate the influence of island type; noting that previous literature considers aquifer parameters and tidal forcing to be the greatest influence on mixing zones, Anderson and Lauer (2008) conclude that this is so for atoll islands where the atoll limestone geology has a far greater permeability but not so for lower permeability barrier islands, where the tidal signal does not penetrate far inland.

A second paper by Vandenbohede and Lebbe (2006) considers a unique inverse density distribution setting arising from infiltration of saline water during high tide and may mimic the dynamics of a storm wave. Using modelling package MOCDENS3D to simulate groundwater flow and solute transport Vandenbohede and Lebbe (2006) investigate the effect of changing the tidal range, shore width and presence of a semi-pervious layer on the existence of the inverse density distribution. The authors conclude that a large tidal range, wide shore morphology and permeable aquifer drive the inverse distribution, by where saline groundwater overlies the freshwater lens. Rather than being a discrete event arising only from high tide or storm surges, the system is believed to be persistent and in dynamic equilibrium. There is agreement with the Anderson and Lauer (2008) paper that the freshwater-saline water interface is controlled not by tidal oscillations but actually by the long-term presence of tidal water on a shallow shoreline.

4.2 TSUNAMI

There are a handful of papers published since the Sumatra earthquake and resulting tsunami in 2004 which assess the impact of the event on coastal aquifers and groundwater supplies. All of the papers investigated consider the impact of inundation of seawater on freshwater supplies and provide an analogy for the impacts of extreme storm waves. Peripheral papers which examine other impacts of the tsunami such as erosion (Kench et. al., 2008) and habitat degradation are present in the literature but not discussed within this report.

Leclerc et al., (2008) investigated the impacts of the tsunami on shallow groundwater in the Ampara district of Eastern Sri Lanka, where approximately 80% of the rural domestic supplies are provided by dug wells and tube wells between 3 and 7 m deep. Inundation of seawater is believed to have come from three main sources, direct over-topping by the tsunami wave, slow diffuse infiltration where seawater collected in lagoons and thirdly due to propagation of the pressure wave underground modifying the freshwater-saltwater equilibrium. Leclerc et al., (2008) found that there was a strong spatial heterogeneity in field conductivity measurements, attributed to local factors. Interestingly the author does not explore local factors such as geological variations and borehole depth. Conductivity measurements were found to be lower behind the ‘impact area’ suggesting that inundation by the storm wave was the primary source of salinity. Desalination of the wells with time was measured as part of the investigation being of the order of -0.132 - -0.246% per day, though again there was high heterogeneity in the results, depending on initial conductivities and borehole pumping regime. Not surprisingly the author found that pumping the boreholes increased salinity and monsoon rain reduced salinities.

Work by Matteson et al., (2009) also considers the recovery of ground conditions after inundation by salt water. 14 months after the Sumatra tsunami salinity levels in the soil were found to be low while water wells remained contaminated. Of 150 soil samples only 8 were above the 4 mS/cm threshold all of which were in mangrove forest or rice fields. The low salinity is ascribed to the fast leaching potential of sandy coastal soils. In contrast all wells sampled, apart from one, within 200m of the coast in the sandy soils were found to be contaminated recording salinity levels in excess of the 2 mS/cm acceptable limit. Work by Matteson et al., (2009) echos that of Leclerc describing the benefit of monsoonal rain but highlighting the local factors which add variability to the results.

A further paper by Illangueskare et al., (2006) considered the effects of the tsunami on the groundwater lens in Sri Lanka using real data and a sand tank model. In line with other work the paper proposes that there are three sources of salinity; (i) direct inundation into the well by the storm wave, (ii) infiltration through the vadose zone and (iii) recharge of seawater through coastal lagoons, with a combination of forced convection and free convection. The groundwater lenses varied from 1–10 m thick with the water table 2–6 m bgl. Illangueskare et al., (2006) propose that the travel time of saline water through the groundwater lens is of the order of 10 days, though residual seawater remains in the well which requires purging. Flushing of the vadose zone to pre-tsunami levels was predicted to occur within a ‘few’ rainy seasons.

Following the tsunami in Sumatra aid organisations tasked with drilling boreholes for water supply found that they were encountering salt water. As a result projects were set up to help the Indonesian government to re-establish essential water supplies for which hydrogeological and geophysical surveys were carried out. The results of one of the projects from Sigli, Northern Sumatra are reported by Steuer et al., (2008) (work has also been undertaken by Siemon et al., 2007 but is not fully investigated here). Steuer et al (2008) used airbourne and ground-based electromagnetic profiling to map saltwater intrusion within the shallow coastal aquifer in addition to the deep aquifer system. The shallow coastal aquifer is sandy in lithology with a water table of 0.5 – 3 m bgl and conductivities in the region of 1 mS/cm prior to the tsunami. In Feb 2005, two months after the tsunami conductivities were in excess of 4 mS/cm. In November 2005 wells were still highly saline (Steuer et al 2008, ref therein). The paper finds that surface salinisation extends less than 3 km inland to a depth of about 15 m bgl. Freshwater strips along the river being recharged from surrounding foothills are less affected at depth and the freshwater-saltwater interface is pushed back offshore at depths of 60 m bgl. Saline intrusion does not appear to be strengthened by the tsunami as a result. Fish ponds located immediately behind the coast allow permanent influx of saline water through tides.

Singh et al. (2008) also investigated the impact of the tsunami on groundwater salinity, this time in Neill Island, South Andaman. In contrast to the work of Steuer et al. (2008) which showed wells to be highly saline a year on from the tsunami, Singh et al (2008) found that rainfall and associated recharge was successful in reducing salinity from 0.6–5.6 mS/cm in Jan 2005 to 0.2–0.6 mS/cm within a year; though one notes that rainfall was 15% in excess of the long-term average. The geological setting within the two study areas is also different with the base of the sandy coral and limestone aquifer on Neill Island lying above mean sea-level in most places and ordinarily unaffected by saline intrusion. The source of salinity was inferred to be due to inundation by the tsunami wave in addition to ingress along cracks in the limestone aquifer generated by the earthquake. Where underlain by mudstone the shallow aquifer was not affected.

5 Summary and Way Forward

A review of literature pertaining to small islands and climate change has shown there to be great variety in both assessment and prediction of the change and their associated impacts. Perhaps the greatest uncertainty relates to manifestation of climate change impacts and their attribution to natural or anthropogenic causes. Whilst there is general agreement that temperatures and sea-levels are rising, there is uncertainty about whether there will be an associated change in precipitation and storm activity etc and how the climate change effects are translated geographically. The uncertainty in climate forecasting is further compounded by the inter-annual and decadal variability in trends associated with ENSO events and the requirement to down-scale global models for a local or regional scenario.

Many researchers highlight the interdependencies between environmental, social and economic determinants. In the context of sea-level rise one must consider also the change in island morphology, increasing destructiveness of storms, reduced annual recharge, in addition to increased demand for groundwater resources, displaced populations, reduced tourism and ecological resilience. The result is a system of great complexity and recent investigations tend towards one area of research only. None the less the IPCC considers the need to expand research to include:

- The role of coastal ecosystems in protecting against sea-level rise and storm events.
- The response of upland and inland ecosystems to changes in temperature and rainfall events.
- Identifying which island types are the most vulnerable.

With reference to the latter area of uncertainty addressed by the IPCC, it is surprising given their diverse character that a global assessment of climate change impacts across the various island types has not been completed and offers an opportunity for further research. There are several papers which point to the importance of small islands variability. Robins and Lawrence (2000) define six island types and characterise their water balance but do not consider separately how each may respond to climate change. Mimura (2007) and Anderson and Lauer (2008) discuss within their work how vulnerability to island erosion and storm events may differ across island types but do not place their findings in the context of groundwater resource availability. Melloul and Collin (2006) do consider loss of groundwater storage due to sea-level rise in coastal settings but make assumptions about the aquifer geometry and shape rather than explore defined island types.

Given the spatial heterogeneity in climate change impacts, the geographical spread and geomorphological diversity in island types it is recommended that a modelling exercise to evaluate the effect of sea-level rise and changes in precipitation events be completed for characteristic small island types. Across the island types the work should aim to characterise the variation in the following which may result from climate change:

- Aquifer storage.
- Recharge patterns (temporal and spatial).
- Shifts in drainage patterns and groundwater lens development.
- Susceptibility to tidal surging and storm events.

Whilst one can accept the complexity involved in small island systems, a model to investigate the implications of climate change would ideally incorporate geomorphological stability and allow for both climatic and human forcing of the overall water balance. Given the uncertainty in current climate forecasts it would be beneficial for any groundwater model to be easily adapted to respond to refinements in forecasts or be capable of running a range of scenarios. Geographical variability in climate projections should also be allowed for.

Appendix 1 Small Island Papers Pre-1990

Ayers and Vacher (1983) A numerical model describing unsteady flow in a fresh water lens
Ghyben-Herzberg and the Dupuit approximations are used to develop a 2-D numerical model which simulates water table configuration in unsteady flow conditions. Model results show good agreement with field observations. Applied to Somerset Island Bermuda where island geometry is varied and recharge is varied.

Cant and Weech (1986) A review of the factors affecting the development of Ghyben-Hertzberg lenses in the Bahamas.
The groundwater lenses on the islands of the Bahamas are characterised and contrasted thus illustrating the control that island size, shape, climate and geology has on the geometry of the lens.

Chidley and Lloyd (1977) A mathematical model study of fresh-water lenses
Development of the Ghyben-Herzberg relationship to determine lens thickness. Demonstrates that the steady-state analysis is a sound basis for estimating the long-term yield if droughts are not prolonged.

Goodwin (1984) Water resources development in small islands, perspectives and needs.
The water resource development of the Caribbean Islands, in light of unfavourable hydrogeological conditions is discussed along with water supply systems designed to meet requirements of residents and tourists. Management and conservation of water by water supply agencies is all described.

Jacobson and Hill (1980) Hydrogeology of a raised coral atoll – Niue Island, South Pacific Ocean
An assessment of the hydrogeology and water resource availability of Niue Island is made, including sustainable pumping rates. The groundwater lens does not comply with the traditional Ghyben-Herzberg approximation due to the irregular shape of the island and variations in permeability of the limestone.

Mather (1975) Development of the groundwater resources of small limestone islands
An estimate of sustainable yields from groundwater lenses is made on the assumption that abstracting groundwater from the lens is equivalent to reducing vertical recharge. Storage which must remain in the lens during a drought period is taken into account along with the increase in transition zone due to pumping. Developing groundwater resources on small islands depends on the depth to the water table, thickness of the lens and aquifer properties.

Rushton (1979) Differing positions of saline interfaces in aquifers and observation boreholes
Field investigations showed that the saline interface in monitoring boreholes did not match the saline interface within the aquifer. This is so because the interface in the borehole is controlled by hydrostatic laws where as the interface in the aquifer is governed by the laws of groundwater flow.

Stewart (1982) Evaluation of electromagnetic methods for rapid mapping of salt-water interfaces in coastal aquifers
Discusses the positives and negatives of using EM methods to define the salt-water interface in coastal settings, showing that results agree with direct geochemical field techniques.

Vacher, (1978) Hydrology of Small Oceanic Islands – Influence of Atmospheric Pressure on the Water Table

Discussion of sea-level fluctuations being due to diurnal tidal influences as well as barometric effects causing pressure changes which propagate and diminish inland. Pressure related water table fluctuations do not diminish inland as much as tides. A storm front is accompanied by a drop in pressure which causes a rise in the water table which is often wrongly assumed to be due to recharge from the storms rainfall.

Wheatcraft and Buddemeier (1981) Atoll island hydrology

Comparison of field observations and model results in the Marshall Islands indicate that observed results are not consistent with horizontal tidal propagation and that vertical transport between layered aquifers is an important feature of atoll hydrogeology.

Appendix 2 Summary table of climate change for small island states

Observed Trends

Climate change	**Region**	**Monitoring Period**	**Source**
Increase in island air temp of 0.6 – 1.0°C	South Pacific, Southwest of the (SPCZ)	1910 to present	Bates et al (2008) IPCC
Increase in island air temp of 0.3 –0.5°C	South Pacific, Northeast of the (SPCZ)	1970 to present	
Increase in island air temp of 0.24 –0.5°C	Caribbean, Indian Ocean and Mediterranean	1971 to 2004	

Sea-level change	**Region**	**Monitoring Period**	**Source**
Average mean sea-level rise of 0.7 mm/yr	Pacific Basin	25 years	Bates et al (2008) IPCC
Average sea-level rise of 2.0 mm/yr	40°S to 40°N, 30°E to 120°W	1950 - 2001	Church et al (2006)
Sea level rise of 2.0 ± 1.0 mm/yr	Tuvalu	1950 - 2001	Church et al (2006)
Sea level rise of 1.5 mm/yr	Port Louis	1950 - 2001	Church et al (2006)
Sea level rise of 1.3 mm/yr	Rodrigues Island	1950 - 2001	Church et al (2006)

Precipitation	Increase over land between 30°N and 85^{0}N (during 20th century) Decreases in precipitation between 10°S and 30°N (last 30 - 40 yrs) Salinity decreases in the North Atlantic and south of 25°S suggest similar precipitation trends over the sea. Increase in heavy precipitation events observed even in areas with overall reductions in precipitation. Increased tropical cyclone activity in the North Atlantic since 1970s. Reduced snow precipitation and earlier on-set of snowmelt.
Sea-level	Average sea-level rise of 1.7 ± 0.5 mm/yr (20th century) Average sea-level rise of 1.8 ± 0.5 mm/yr (1961 – 2003) Average sea-level rise of 3.1 ± 0.7 mm/yr (1993 – 2003)
Evapotranspiration	Limited literature on observed trends in both actual and potential evaporation.
Soil moisture	Limited literature on observed trends in soil moisture but increasing trends observed in Soviet Union, China, central USA and Ukraine.
Run-off and river discharge	Increase in run-off observed in high latitudes, Decrease in West Africa, southern Europe and southern most South America.

Data derived from Bates et al, (2008)

Predicted Trends

Climate change	**Region**	**Monitoring Period**	**Source**
▪ 1.5 – 2.0 °C increase in air temp ▪ Rainy season reduced by 7-8% ▪ Dry season increased by 6-8% ▪ Increase in heavy rains – up 20%	Caribbean	 By 2050 By 2050 By 2050	Bates et al (2008) IPCC
Percentage precipitation change: -35.6 to +55.1 -52.6 to +38.3 -61.0 to +6.2	Mediterranean	 2010 – 2039 2040 – 2069 2070 - 2099	Bates et al (2008) IPCC
Percentage precipitation change: -14.2 to +13.7 -36.3 to +34.2 -49.3 to +28.9	Caribbean	 2010 – 2039 2040 – 2069 2070 – 2099	
Percentage precipitation change: -5.4 to +6.0 -6.9 to +12.4 -9.8 to +14.7	Indian Ocean	 2010 – 2039 2040 – 2069 2070 – 2099	
Percentage precipitation change: -6.3 to +9.1 -19.2 to +21.3 -2.7 to +25.8	Northern Pacific	 2010 – 2039 2040 – 2069 2070 – 2099	
Percentage precipitation change: -3.9 to +3.4 -8.23 to +6.7 -14.0 to +14.6	Southern Pacific	 2010 – 2039 2040 – 2069 2070 – 2099	

Sea-level change	**Region**	**Monitoring Period**	**Source**
0.88 m rise in sea level	American Samoa	By 2100	Bates et al (2008) IPCC

Precipitation	Differences between climate model precipitation projections are a larger source of uncertainty than internal variability. Increases in precipitation at high latitudes and parts of tropics with more heavy precipitation events and high run-off but more dry days in between. Decreases in precipitation for sub-tropical and lower mid-latitudes Drying in mid-continental areas in the summer. More intense tropical cyclones
Sea-level	Average sea level rise in 21st century expected to exceed the 1961 – 2003 average of 1.8 ± 0.5 mm/yr with thermal expansion being the largest component (70-75%).
Evapotranspiration	Annual average evaporation increases over the oceans in line with surface warming. Potential evaporation is projected to increase.
Soil moisture	Reductions in soil moisture projected for sub-tropics and Mediterranean. Increased soil moisture predicted in East Africa, central Asia and other regions with increased precipitation.
Run-off and river discharge	Increased run-off during high precipitation events. Increases in the high latitudes and wet tropics, decreases in the mid-latitudes. Run-off reductions in southern Europe. Run-off increases in south-east Asia and high latitudes.

Data derived from Bates et al, (2008)

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