

Sea Level Rise Impact on Underground Freshwater Lens – A Case Study

Areke Alexander Tiareti¹ and Dr Babar Mahmood²

¹ Water and Sanitation Engineer, Ministry of Infrastructure and Sustainable Energy, Betio Tarawa,

² Senior Lecturer at Unitec Institute of Technology, Auckland, New Zealand.

Abstract

Sea-water intrusion is a growing environmental concern for communities that live along the coastal line and rely on local aquifers/fresh water reserves to meet their water supply & demand. The rising sea level is likely to enhance saltwater intrusion and potentially contaminate (in terms of chlorides/salts levels) many underground freshwater reserves. This study was conducted for South Tarawa atoll, which is located in Kiribati (*pronounced as Kiribas as "ti" sounds as 's'*), just north of the equator in a region of the Pacific. In this area, rainfall is highly variable largely due to the influence of El Niño and La Niña episodes. In Kiribati, groundwater is one of the main sources of water supply for domestic use. Apart from over pumping (due to local increasing water demand) climate change is putting a pressure on the available freshwater lens (es) (i.e. fresh water bodies below ground surface that is lying above the seawater-freshwater (**SW-FW**) interface or transitional zone) in South Tarawa. Therefore, the *focus* of this study was to collect and collate the site specific data such as rainfall, temperature, sea level and groundwater thickness (i.e. underground freshwater lens thickness) in an attempt to understand the impacts of predicted climate change on the local groundwater resources of South Tarawa, Kiribati. A brief discussion on the effect of sea level rise (**SLR**) on salt water intrusion is also covered here (based on three conceptual models as reported in the literature). The results of this study showed that Tarawa's contribution to global greenhouse gases - **GHGs** (CO₂, CH₄, N₂O) emission is very small (< 0.1 MtCO₂e). However, the total GHG emissions (measured in terms of CO₂ equivalent) has increased 100% (i.e. from 0.04 to 0.08 MtCO₂e) since 1990. It was estimated that the future total GHG emissions for Tarawa may continue to rise to 0.11 MtCO₂e by 2030. The monthly mean temperature of Tarawa is around 28 °C and hasn't changed much since 1970. But, it was estimated that the future temperature of Tarawa may increase upto 1°C by 2030. Total rainfall pattern is very extreme (i.e. varying between 150 and 4356 mm per year). It was estimated that total annual rainfall has increased at a rate of 44 mm per year since 1970, and it may increase by 11% by 2030. Tarawa sea level had also risen by 300 mm (i.e. from 1460 mm to 1760 mm) since 1993 and the sea level is expected to increase to 1830 mm by 2030. The study highlighted the fact that there is a direct link between the SLR and the thickness of the freshwater lens, as the thickness of the freshwater lenses is measured from the

groundwater table to the mid-point of transitional zone (i.e. an interface between SW-FW). If all these climatic and non-climatic factors continue to rise, then groundwater resources in Tarawa may not be sufficient and reliable (due to seawater intrusion) to be used by the people of Tarawa, and also there is a possibility that this Island may disappear in future.

Keywords

Sea Level Rise, Groundwater, Freshwater Lenses, Environmental Concerns.

PRESENTER PROFILE

The presenter is an Environmental Engineer by profession, and currently working as a Senior Lecturer in the Civil Engineering Department of Unitec. The presenter has 29 years of experience working with water industry (including working on international & local projects related to THREE waters). The presenter has 38 publications (including this) and supervised 35 industry projects. The presenter has performed the duties of a "Reviewer" for international Journals and Conferences, and also worked as a Programme Leader/Director for Environmental Engineering programmes at Unitec.

1 BACKGROUND

The Republic of Kiribati, formerly known as the Gilbert Islands is a low-lying country made up of 33 chain of islands formed of coral called atolls, straddling the equator in the central Pacific Ocean with an average elevation of less than 3 metres above sea level. Roughly half of the population of approximately 110,000 (MFED, 2016) reside on the small atoll of South Tarawa (area 30 km²) with population densities approaching 10,000 heads per km² in the most crowded parts of the atoll (Metai, 2002). South Tarawa is a strip of land that stretches from Betio to Buota Village on Tarawa. It is the capital and hub of the Republic of Kiribati. The climate in South Tarawa and all other islands in Kiribati is hot and humid with very small variation in maximum and minimum temperatures.

Apart from rainwater, the predominant water resource in South Tarawa is groundwater - which occurs in the form of underground freshwater lenses, which are formed under the surface of the coral. The term "**freshwater lens**" can be misleading - it simply implies a fresh groundwater aquifer with distinct boundaries. It mainly comes from rain that soaks into the ground, where it moves down (due to gravity and passing through soil particles, sand, gravel or rock) and becomes a part of the groundwater. It is well known that freshwater and sea-water do not mix very readily due to different densities. Freshwater often floats over sea-water (refer to Figure 1). The boundary between freshwater and underlying seawater is a transition zone (Metai, 2002).

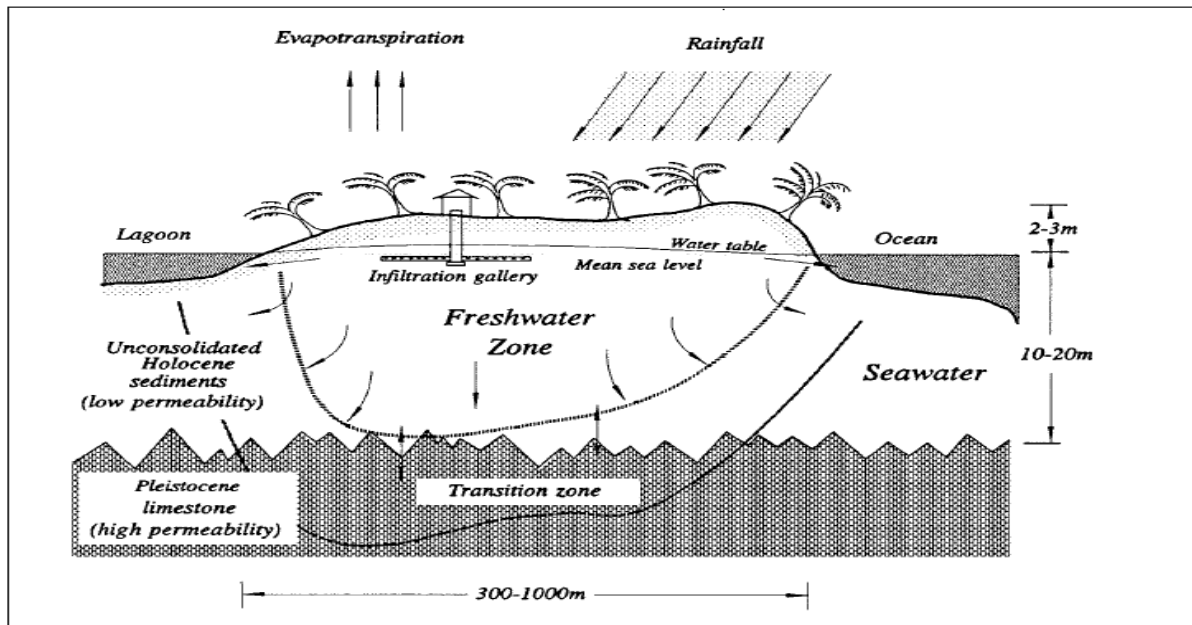


Figure 1: A cross sectional view of a small coral island showing main features of a freshwater lens and location of an infiltration gallery used for groundwater extraction in Kiribati (**Sourced:** Metai, 2002).

The occurrence and distribution of freshwater lens(es) on South Tarawa is dependent on a number of factors such as rainfall amount and its distribution; amount and nature of surface vegetation; the nature and distribution of soils (mainly formed from calcareous sand consisting mostly of shells of marine algae); size of the island - particularly the width from sea to lagoon; permeability and porosity of the aquifer formations; tidal range; and methods of extraction and quantity of water extracted by pumping, etc. (Jacobson & Taylor, 1981; Metutera, 2002). It is suggested that domestic water need is about 65 – 68 L/d per capita (with a small allowance for climate change after 2020) in today's modern time of Tarawa (White, 2010).

As mentioned earlier, that freshwater lenses (groundwater) are the main source of water supply for the people on the island. Rainwater is also another source of water supply on the island, which is harvested and stored in a water tank. People use groundwater for drinking, washing, and cooking. However, groundwater resources on South Tarawa are now becoming more unreliable due to the impacts of predicted global climate change (personal local knowledge of the first author). As per latest IPCC (2014) report, the climate is changing, sea level is rising, atmosphere and oceans are warming (though warming of the climate is unequal over the globe), snow is melting, etc. Thus, these climatic changes are going to affect everyone (i.e. people, animals, plants) on this planet. Climate change is also likely to have an impact on Pacific Islands (including Kiribati) groundwater quality and quantity (i.e. thickness of freshwater lens) due to variations in rainfall, evapotranspiration, SLR in response to greenhouse gases (GHG) (i.e. Carbon dioxide - CO₂, Methane - CH₄, Nitrous Oxide - N₂O) emissions and extreme events

of rainfall/storms, cyclones, etc. (Australian Bureau of Meteorology and CSIRO, 2011; IPCC, 2014). Therefore, the main aim of this study was *to assess the impacts of predicted climate change on the local freshwater lenses (groundwater resources) of South Tarawa, Kiribati*. The specific objectives of this study were to (i) conceptualise how the SLR may cause seawater intrusion and lift the groundwater table in coastal areas such as Kiribati; (ii) assess impacts of changes in climatic factors (i.e. GHG emissions, temperature, rainfall, sea level) on thickness of underground freshwater lens of South Tarawa; and (iii) assess how the local rainfall, temperature, and sea level might change by 2030.

2 METHODOLOGY

2.1 CONCEPTUAL MODEL TO VISUALISE THE IMPACT OF SLR ON GROUNDWATER

From reader's point of view, a brief explanation of how an increase in sea level could affect the groundwater levels in coastal areas is given below. Chang et al. (2011) provided a comparison of three conceptual models to visualise the impacts of SLR on salt-water wedge profile (i) initial salt-water wedge profile before SLR, (ii) salt-water wedge profile after SLR, which is a traditional concept that ignores the groundwater lifting process, and (iii) a new concept of salt-water wedge movement with groundwater level lifting process (refer to Figure 2).

It is well understood that under natural flow conditions, the denser sea-water has the ability to move beneath the freshwater/groundwater bodies. The spatial extent of the sea-water wedge (*also called sea-water toe*) movement would depend on local aquifer characteristics such as hydro-geological properties, recharge rate, regional aquifer discharge or pumping rates, and the sea-water levels in the region (Chang et al., 2011; Cheng et al., 2008; Werner & Simmons, 2009).

Figure 2b shows a commonly assumed conceptual model Werner & Simmons (2009); Cheng et al. (2008); Custodio & Bruggeman (1987) that illustrates how the rising sea level would impact the groundwater table and its quality by forcing the wedge to move inland. However, this traditional conceptual model ignores the fact that when the sea-water rises at the sea-side boundary then the sea-water would pressurise the groundwater level and therefore the groundwater table is likely to be lifted throughout the aquifer.

Whereas, Figure 2c illustrates a revised model, and this model does account for the up-lift of the groundwater table over the entire system due to the SLR. Chang et al. (2011) reported that *"It is expected that after a long period (i.e., at or near steady state) this lifting effect would approximately raise the entire fresh water body (measured from the bottom of the aquifer) by an extent similar to the sea-level rise (i.e. a similar order of magnitude). One could intuitively expect this lifting mechanism to counteract and reduce the impacts due to the sea-level rise.*

However, it is unclear to what extent this lifting process could reduce the overall impacts due to sea-level rise”.

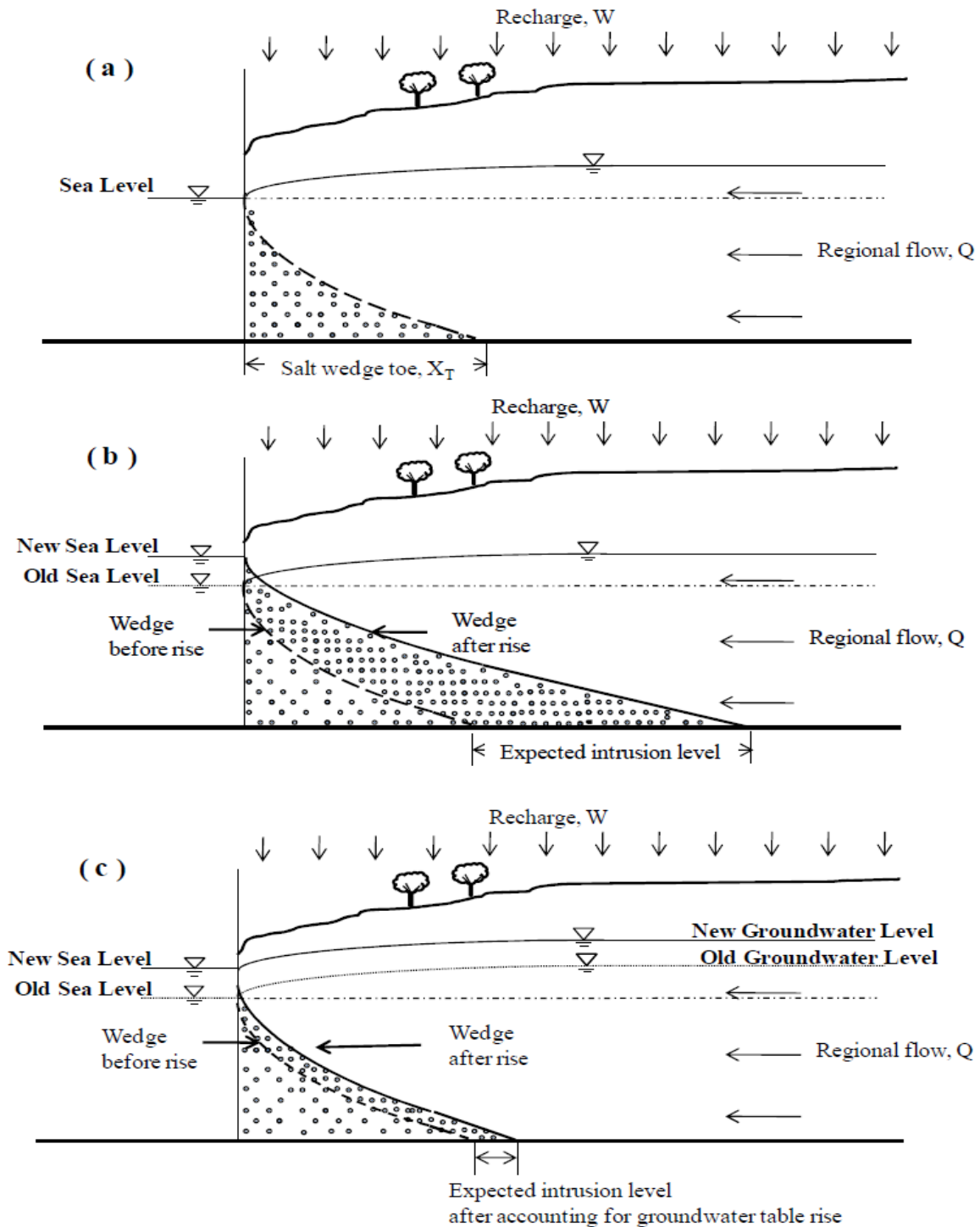


Figure 2: Comparison of three conceptual models (i) initial salt water wedge before SLR, (ii) traditional concept i.e. sea-water wedge movement and no lifting of groundwater level, (iii) new concept of groundwater lifting in response to sea-water intrusion due to SLR (**Sourced:** Chang et al., 2011).

2.2 SITE SPECIFIC INFORMATION

Rainfall and Temperature Data – Annual average rainfall and temperature data for the study area was sourced from the Kiribati Meteorological Service in Betio and was used to determine the change in rainfall pattern and the recharge of groundwater freshwater lens over the past years since 1970. This data was then used to predict how rainfall and temperature might change by 2030.

GHG Emission Data - The GHG emission (in terms of CO₂ equivalent) data was also sourced from the Kiribati Meteorological Services for the past years (i.e. 1990 to 2012). As we know that the GHG emissions in terms of CO₂ equivalency means that the amount of CO₂, for a given mixture of GHG, that would have the same global warming potential for a specified time period (normally 20 or 50 or 100 years). In simple terms, it shows the quantity of emissions rather than concentration (ppm – parts per million) of GHG in the atmosphere.

Due to unavailable GHG emission data for South Tarawa, annual-total data for the whole Kiribati was used as almost 90% of CO₂ emission in Kiribati come from the main island, South Tarawa. The collected GHG emission data were then used for future estimation (by 2030) by calculating an increase per year starting from 1990 through to 2012.

Annual Mean Sea Level (MSL) Data – Annual MSL (using monthly mean data) was also sourced from the Kiribati Meteorological Service for the 1993-2010. An analysis of how the changes in sea level may influence the thickness of the underground freshwater lens during the study period.

Underground Freshwater Lens Thickness - An annual (i.e. monthly average) groundwater thickness data was sourced from the PUB (Public Utilities Board) in Bikenibeu for years from 1993 to 2010. This data was collected to see if there is a link between rise in MSL and changes in groundwater freshwater lens thickness. It should be noted here that the groundwater / freshwater lens thickness in Tarawa are often measured using hydrologic models. The thickness of groundwater/freshwater lens is taken to be the distance from the groundwater table surface to the midpoint of the transition zone (refer to Figure 1).

3. RESULTS AND DISCUSSION

3.1 TYPICAL WEATHER PATTERN OF SOUTH TARAWA

The average monthly temperature is around 28.4°C across Tarawa and the rest of Kiribati. Its climate is closely related to the temperature of the oceans surrounding the small islands and atolls. From season to season, the temperature changes by no more than 1°C. Kiribati has two seasons –the dry season (**te Au Maiaki**), and the wet season or (**te Au Meang**). The periods of the seasons vary

from location to location and are strongly influenced by the seasonal movement of the South Pacific Convergence Zone (**SPCZ**) and the Inter-Tropical Convergence Zone (**ITCZ**). The two zones are extended across the South Pacific Ocean from the Solomon Islands to the east of the Cook Island, and across the Pacific just north of the equator (Australian Bureau of Metrology & CSIRO, 2011).

South Tarawa's climate varies considerably from year to year and the main reason for this variability was due to the EL Nino-Southern Oscillation (**ENSO**), a natural climate pattern that occur across the tropical Pacific Ocean and affects weather around the world. There are two extreme phases of the ENSO (known as El Niño and La Niña), there is also a neutral phase. Many Kiribati islands including Tarawa lie within the equatorial waters that warm significantly during an El Niño event and cool during a La Niña event. As a result, rainfall is much higher than normal during an El Niño and much lower during a La Niña. Maximum air temperatures tend to be higher than normal during El Niño years, driven by the warmer oceans surrounding the islands, while in the dry season minimum air temperatures in El Niño years are below normal (Australian Bureau of Metrology & CSIRO, 2011).

3.2 ANNUAL AVERAGE TEMPERATURE

The annual average temperature (using monthly average values) for Tarawa during the past 40 years (1970-2010) has not been consistent, there were some years when the temperature dropped down and there were also years when temperature was stable. The highest mean temperature was 29.2°C in 2005 and the lowest was 27.4°C in 1971 (Figure 3). The data showed that annual average temperature was 28.4°C over the past 40 years (i.e. from 1970 to 2012). It is estimated that the annual average temperature for South Tarawa is likely to reach 29 °C by 2030 (Figure 3).

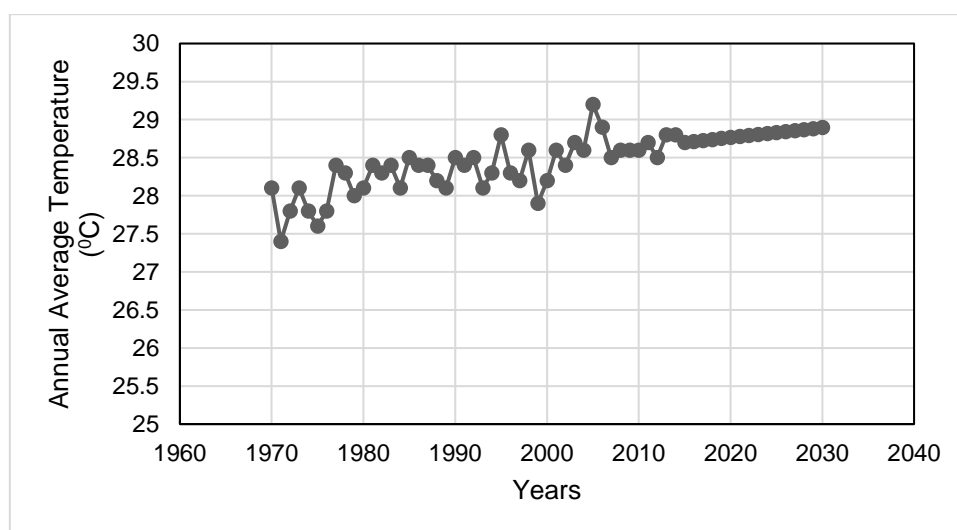


Figure 3: Annual average temperature for Tarawa from 1970 to 2012 with projected figures until 2030.

It is clear from Figure 3 that there were some years when the annual mean temperature drops but this was insignificant and will not cause a big change in the average temperature for Tarawa. Overall, there has been an increase in temperature of about 1 °C over the last 40 years (since 1970).

Further, throughout the period of observation, it appears that any temperature trends which may have occurred at Tarawa since 1970 have been masked by physical changes at and about the temperature measuring site. There is little to suggest that there has been any continuous upward trend in temperature since 1970, and when observed temperature data smoothed over ten years was approximately 0.5 °C higher than usual (Figure 3).

3.3 TOTAL ANNUAL RAINFALL

Total annual rainfall data showed that how variable rainfall pattern was for Tarawa during 1970 and 2015 (Figure 4). While its annual average precipitation is reasonably high of about 2000 mm, which is a lot higher than average rainfall in Auckland city of New Zealand. However, 2000 mm is about an average annual rainfall at sea level for a lot of islands in the Pacific Oceans region but it varies from year to year. The lowest total annual rainfall recoded was down to 150 mm in 1989. Highest rainfall is normally associated with the ITCZ moving furthest south and closer to Tarawa, and low rainfall is associated with when ITCZ moved away from Tarawa.

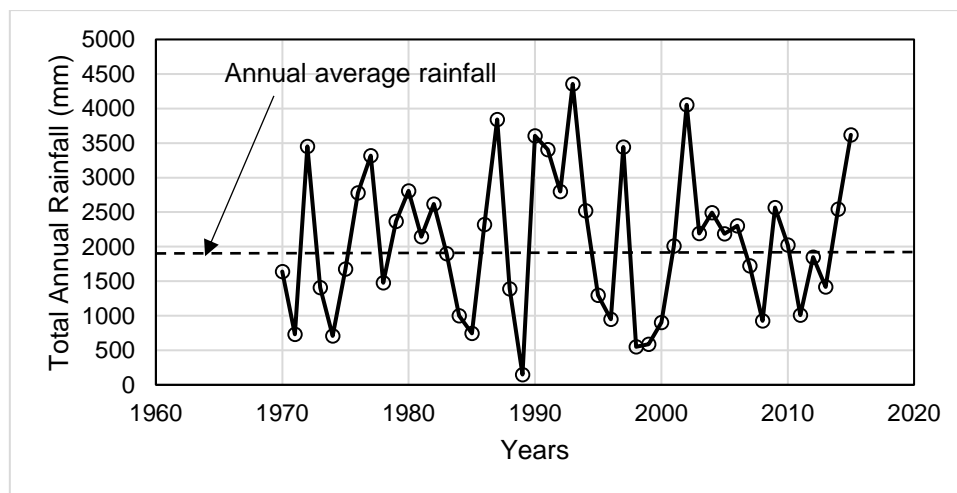


Figure 4: Total annual rainfall and worst drought years for Tarawa from 1970 to 2015.

The results showed that there were times when Tarawa received lower and higher rainfall than annual average rainfall (i.e. 2000 mm - refer to Figure 4). It is also clear from Figure 4 that year 1989 and years from 1998 to 2000 were the driest years on record, when an average annual rainfall on Tarawa actually gone below the average total annual rainfall of 2000 mm. It was estimated that (on average) the total annual rainfall increased at a rate of 44 mm per year, and perhaps the

total annual rainfall may increase up to 4281 mm by 2030 (if it continued to increase at this estimated rate).

Preliminary literature reviewed (related to the impacts of global warming on the groundwater resources on South Tarawa) states that climate change will make current development challenges worse throughout Kiribati. Coastal erosion, depletion of marine resources, overcrowding, lack of water resources, and poor water quality are the main current issues that are being faced by the South Tarawa Community. Therefore, necessary actions must be taken as soon as possible. The long term outlook for the whole of Kiribati looks uncertain as more recent scientific evidence suggests a faster SLR compared to the past (Kiribati Climate Change, 2012). Literature states that climate variability may continue to cause an increase in surface air and sea temperatures, increasing precipitation throughout the year, also more days of extreme rainfall and extreme heat & rising sea level (Kiribati Climate Change, 2012; 2013).

3.4 RAINFALL INFLUENCE ON UNDERGROUND FRESHWATER LENS THICKNESS

It is clear from Figure 5 that the change in thickness of the freshwater during wet and dry periods does correspond to the rainfall events for Bonriki and Buota groundwater reserves in Tarawa starting in 1980 and moving through to 2015.

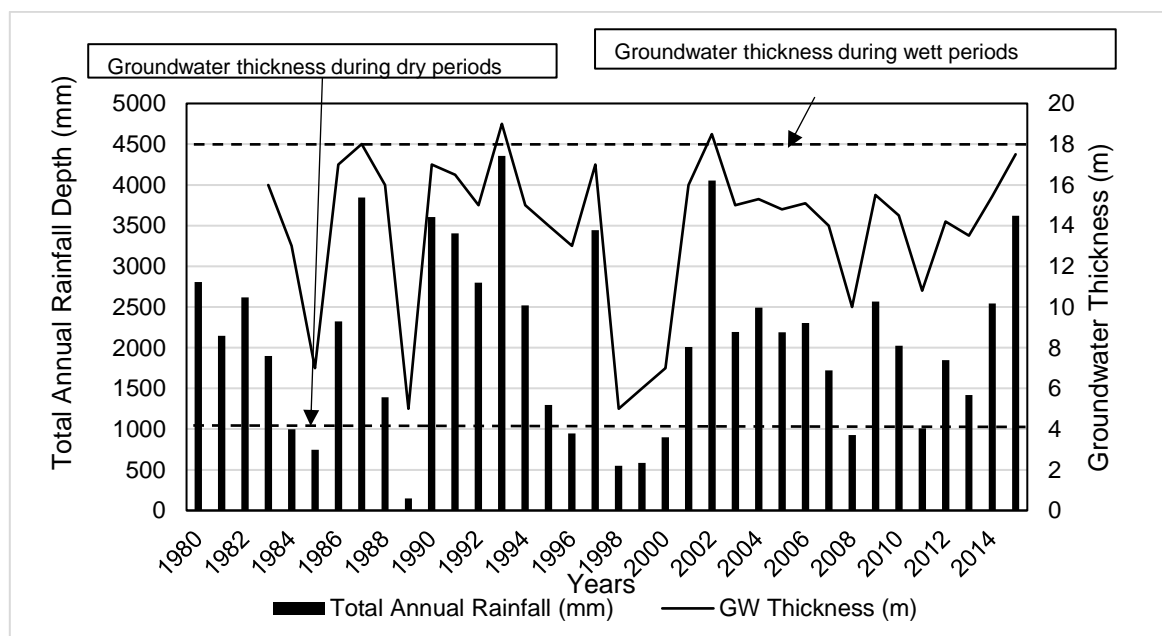


Figure 5: Groundwater thickness corresponding to annual rainfall amounts for South Tarawa.

The groundwater thickness varies between 4 and 5 m during dry periods i.e. when the annual rainfall was below 1000 mm, on average. The groundwater thickness was around 18 m during wet seasons i.e. when the annual total was more than

the annual average of 2000 mm (Figure 6). This shows that the depth of freshwater lens depends on the amount of rainfall in the region. A correlation of 72.42% was found between the groundwater thickness and annual average rainfall depth (Figure 6).

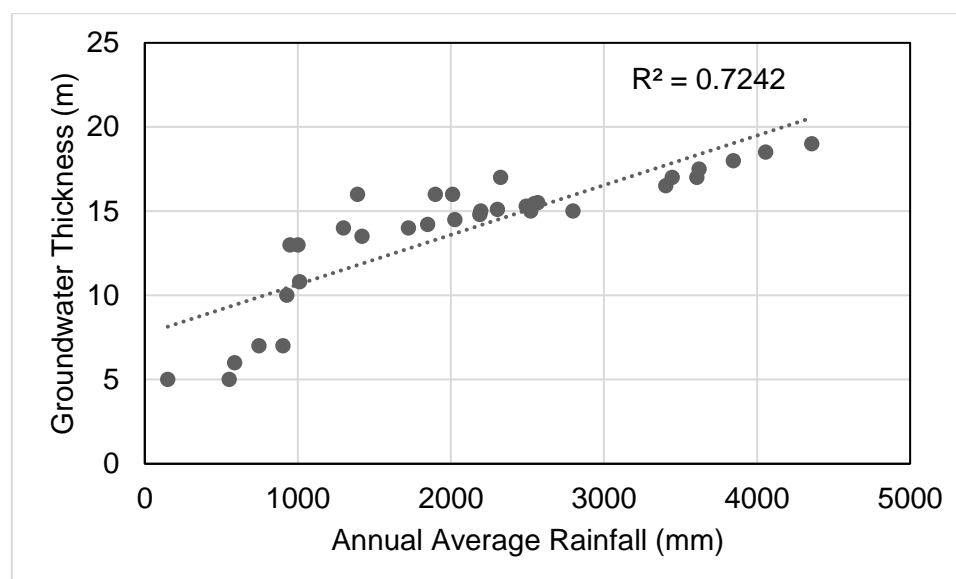


Figure 6: A graph showing the relationship between groundwater thickness and annual rainfall amounts for South Tarawa.

3.5 TOTAL ANNUAL GHG EMISSIONS (IN TERMS OF CO₂ EQUIVALENCY)

The total GHG emissions in Kiribati were even less than 0.1 MtCO₂e during 1990-2012. However, it is clear from Figure 7 that the total GHG emissions in Kiribati had increased from 0.04 MtCO₂ in 1990 to 0.08 MtCO₂ in 2012. Even though total GHG emission in Kiribati is very low (as compared to other countries such as total GHG emissions values of 10975.5 MtCO₂e, 6235.7 MtCO₂e, and 3013.7 MTCO₂e for China, USA & India, respectively – CATI Climate Data Explorer, 2015).

As reported by (IPCC, 2014), the global climate change is likely to impact on the groundwater resource of coastal areas including South Tarawa (*as a result of SLR associated with ice melting and thermal expansion of sea-water*). And, this is a direct result of actions of others around the world (big industrialised countries), while people on Tarawa and other low lying nations stand in the frontlines of these impacts. There is a possibility that Kiribati GHG emission will continue to increase in many more years to come and this can threaten the lives of people in Tarawa as groundwater resources in the island will no longer be safe for use. It is estimated that the GHG emissions in Tarawa may go up to 0.11 MtCO₂e (i.e. 37.5% increase) by 2030 (Figure 7).

It is well known that most of the global emissions that contribute to climate change come from burning fossil fuels for transportation, electricity, heating and industry in economically fast-growing and industrialised countries. Kiribati GHGs are insignificant when compared to emissions of other countries since not much industrialisation on the Island. The main sources of GHG emission in Kiribati come from Energy, Agriculture and Forestry (UNFCCC, 2013).

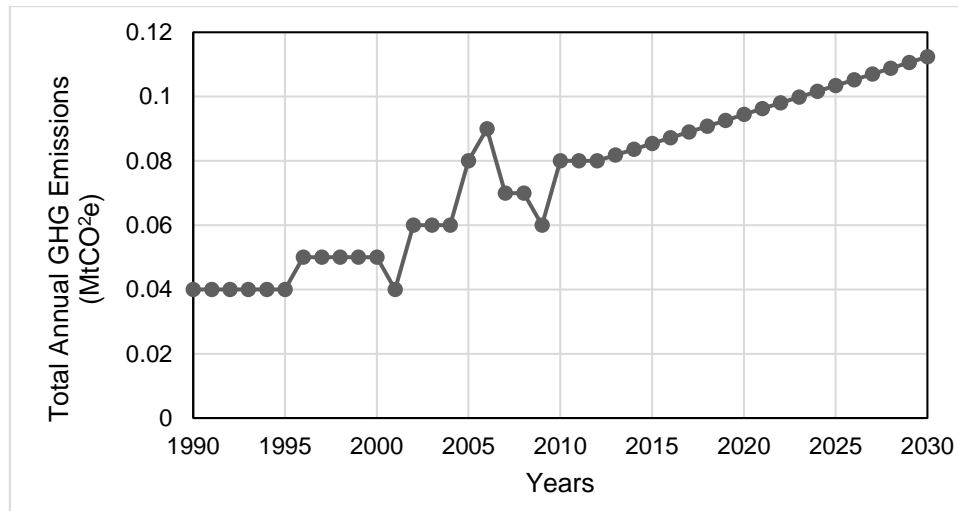


Figure 7: The total annual GHG emissions in terms of CO₂ equivalency (MtCO₂e) from 1990 to 2030) for Kiribati.

3.6 ANNUAL MSL

It is well knowing that globally air temperature is increasing and this is going to have an effect on melting of glaciers, shorter winters, and rising heat of the oceans and therefore a rise in sea level (also supported by IPCC, 2014;2007) is imminent.

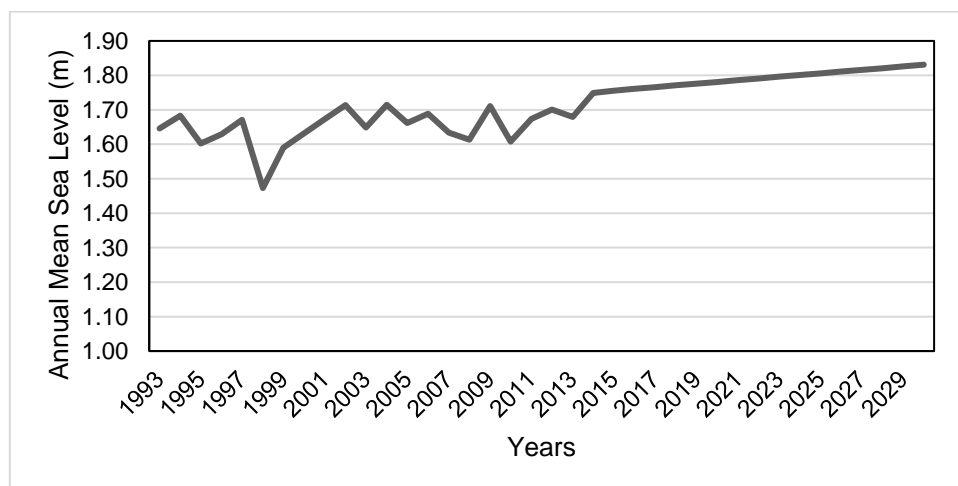


Figure 8: Annual mean sea level for Tarawa region since 1993.

Figure 8 shows an annual sea level at Tarawa during 1993-2015, and projected MSL by 2030. The results showed that the MSL varied between 1.47 (1470 mm) and 1.76 m (1760 mm) during 1993 – 2015. It is estimated that the MSL has increased at a rate of 5 mm per year, and therefore it is expected that the MSL may increase up to 1.83 m by 2030 – which is an alarming rate. It should be noted here that most of the lands on Tarawa are only a few feet above sea level (2 – 3 m), and therefore if this trend continues then the land loss will be significant in the next 20 – 50 years – which means this island may disappear in the future.

Assessments on the impacts of climate change in Kiribati article states that Kiribati is highly vulnerable to the impacts of climate change due to limited land area, over-crowding, low elevation of the islands and the lack of safe and secure supplies of potable water. As highlighted earlier, the particular threats that are posed by climate change for Kiribati include SLR, increasing air and sea-surface temperatures, ocean acidification, altered rainfall patterns and the unpredictability of events such as droughts, storm surges and extreme high winds (Kiribati Climate Change, 2012).

3.7 SLR INFLUENCE ON GROUNDWATER THICKNESS

The annual MSL has varied between 1.47 m and 1.76 m during 1993-2015 (Figure 9).

This study results showed that the thickness of freshwater lens increased with an increase of sea level (Figure 9) and vice versa (i.e. a direct relationship between MSL and groundwater thickness). Remember, in this study the thickness of the freshwater lens was the distance between the groundwater table level and the mid-point of the transitional zone (refer to Figure 1).

It was clear from the results (Figure 9) that as the sea level rises the thickness of the transitional zone increases, which eventually lifted the freshwater lens sitting on top of it. This was also supported by Chang et al. (2011) with new conceptual model (Figure 2c) that the groundwater table lifting process in response to salt-water intrusion associated with SLR at the sea end boundary. As the SLRs (at the ocean side) the transition zone (i.e. SW-FW) is being pushed inwards (lateral horizontal movement), and this causes the groundwater table to be lifted (also supported by Cheng et al., 2011). Thus, the thickness of the underground freshwater lens (sitting on top of transitional zone) may decrease or increase (depending on the local recharge and pumping rates) with sea level variations (assuming that the net flux of the system does not change).

In addition, there is a possibility that the local groundwater may be contributing to other underground freshwater bodies due to the horizontal lateral movement of groundwater, as a result of SLR and sea-water intrusion. However, this requires further investigation.

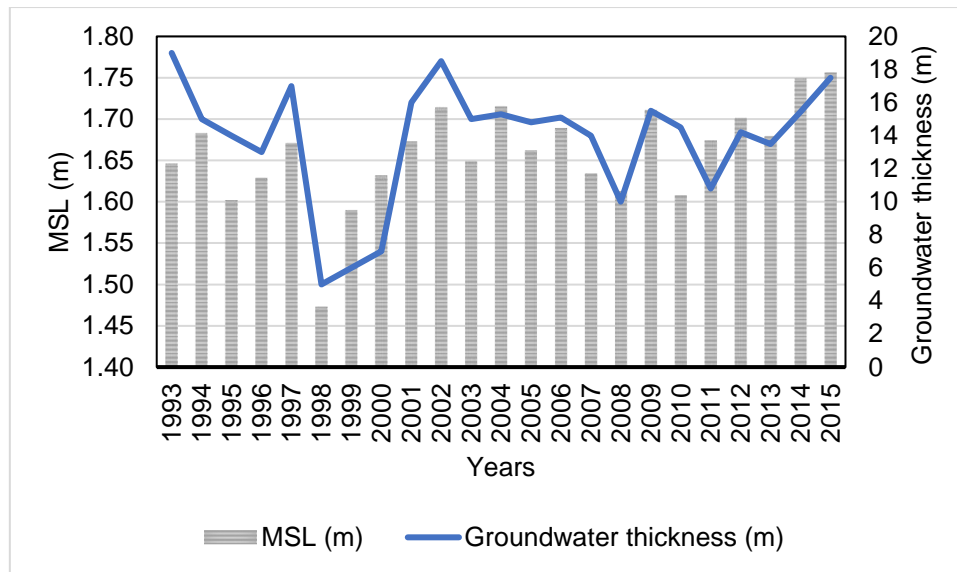


Figure 9: A graph showing how groundwater thickness changes with annual MSL sea level for Tarawa region since 1993.

4.0 SLR, SEAWATER INTRUSION, AND GROUNDWATER – A GENERAL DISCUSSION

According to (IPCC, 2007) report, the global sea level, on average, is expected to rise between 18 and 59 cm this century. On average, the global MSL rose by **19 cm** (ranging between 17 and 21 cm) during 1990-2010 at a mean rate of **1.7 mm per year** (IPCC, 2014). It is expected that global mean sea level rate would be around **3.2 mm per year** for the period 1993-2010 (faster than previous predictions). Thus, environmental governing bodies worldwide are seriously concerned about the impacts of SLR on saltwater intrusion processes, especially in over-utilized, urbanized coastal aquifers that already have low groundwater levels such as Kiribati.

Tarawa Atoll report also stated that a rise in sea level causing coastal erosion to the coast lines of the island can narrow the width of the island. If the width of the islands is being reduced by SLR, then thickness of the freshwater lens (sitting on top of transition zone) is likely to decline by 29% (Kiribati Climate Change, n.d).

Australian Bureau of Metrology and CISRO (2011) reported that an increase in rainfall is likely to increase a recharge in groundwater or by contrast a decline in rainfall is likely to cause a reduction in groundwater recharge as predicted by other models. When the climate is warm, evapotranspiration is increased causing a decline in the groundwater recharge (Australian Bureau of Metrology & CSIRO, 2011). However, most models predicted that Kiribati will experience more rainfall events in the future.

A brief general overview of few studies is provided here to understand SLR and salt water intrusion problems around the world.

Werner and Simmon (2009) completed a study on developing a general understanding of the impacts of SLR on groundwater resource under different boundary conditions using a steady state and sharp interfaced analytical model. This study (i.e. Werner & Simmons, 2009) highlighted the importance of inland boundary conditions to gauge the impact of SLR on sea-water intrusion. Two conceptual framework (i.e. flux controlled in which groundwater discharge to sea is consistent despite changes in sea level; and head controlled systems (in which groundwater abstractions maintain the aquifer's head conditions despite sea level changes) were used to provide a 1st order assessment of sea-water intrusion into the unconfined aquifers due to a rise in sea level. They (Werner & Simmons, 2009) concluded that *"in case of constant flux conditions, the upper limit for sea-water intrusion due to SLR up to 1500 mm is no greater than 50 m for typical values of recharge, hydraulic conductivity, and aquifer depth"*. Whereas, constant head conditions have a major impact on results and the magnitude of sea-water toe migration was in hundreds of meters for the same SLR. Werner & Simmons (2009) suggested that quantification of the position of salt water toes relative to any recharge-dependent-groundwater body should be considered in the assessment of sea-water intrusion in response to SLR.

Cases of salt water intrusion, with varying degrees of severity and complexity, have been documented throughout the Atlantic, India and China coastal areas (Li & Jiao, 2003; USGS, 2000; Lacombe & Carleton, 1992). However, over pumping of coastal aquifers has resulted in reducing groundwater table levels, hence reduced natural flow, and this has led to severe salt water intrusion.

Few studies such as USGS (2000); Li & Jiao (2003); and Michael et al. (2005) reported that freshwater aquifers (along the Atlantic coast) supply drinking water to 30 million residents, and *"normally these coastal aquifers are recharged by rainfall events, and therefore the recharged freshwater flowing towards the ocean would prevent sea-water intrusion into the freshwater lenses"*. This is an important observation to be noted here.

Researchers (Li et al., 2008; Li & Jiao, 2003) have also reported that variations in the sea level and the associated wedge movement can influence the transition zone (i.e. SW-FW interface). Therefore, understanding the dynamics of sea-water intrusion in coastal aquifers and its interconnection to anthropogenic activities (e.g. over pumping and creating more impervious area due to urbanisation) is an important environmental challenge.

Feseker (2007) completed a numerical modelling study to assess the impacts of climate change and changes in land use patterns on the salt distribution in a

coastal aquifer. The study concluded that *"rising sea level could induce rapid progression of salt water intrusion"*. However, the same study (Feseker, 2007) highlighted that *"the time scale of changes resulting from the altered boundary conditions could take decades or even centuries to impact groundwater flows and hence the present day salt distribution might not reflect long term equilibrium conditions"*.

Leatherman (1984) investigated the effects of rising sea-level on salinization in an aquifer in Texas. Meisler et al. (1985) used a finite-difference computer model to analyse the effect of sea-level changes on the development of the transition zone between fresh groundwater and saltwater in the northern Atlantic Coastal Plain (from New Jersey to North Carolina). Oude Essink GHP (2001) used a three dimensional transient density-driven groundwater flow model to simulate saltwater intrusion in a coastal aquifer in the Netherlands for three types of SLR scenarios i.e. (i) no rise, (ii) a SLR of 500 mm (50 cm) per century, (iii) and a sea level fall of 500 mm per century. They concluded that SLR of half a meter (50 cm) per century is likely to increase the salinity in all low lying regions closer to the sea.

Dausman and Langevin (2005) completed a SEAWAT simulations for a coastal aquifer in Broward County, Florida, and concluded that *"if the SLR becomes greater than 48 cm over the next 100 years then several local well fields would be vulnerable to chloride contamination"*. Melloul and Collin (2006) evaluated the potential of SLR to cause permanent underground freshwater reserve losses in a coastal aquifer in Israel. They assumed a SLR of 50 cm and concluded that 77% of the freshwater loss was due to the lateral movement and about 23% was due to the head changes.

Giambastiani et al. (2007) undertook a study to investigate saltwater intrusion in an unconfined coastal aquifer of Ravenna, Italy. They found that *"the mixing zone between fresh and saline groundwater will be shifted around 800 m farther inland for a 0.475 m per century of sea-level rise"*. Loáiciga et al. (2011) used a numerical model, called FEFLOW, to assess the likely impacts of SLR and groundwater extraction on sea-water intrusion in the Seaside Area aquifer of Monterrey County, California, USA. They reported that *"SLR scenarios were consistent with current estimates made for the California coast, and varied between 0.5 and 1.0 m over the 21st century"*. These authors concluded that *"SLR would have a minor contribution to seawater intrusion in the study area compared to the contribution expected from groundwater extraction"*.

Chang et al. (2011) completed a detailed numerical experiments using the MODFLOW-family computer code SEAWAT to study the transient effects of sea-level rise on saltwater wedge in confined and unconfined aquifers with vertical sea-land interface. The simulation results showed that *"if the ambient recharge remains constant, the sea-level rise will have no impact on the steady-state salt*

wedge in confined aquifers. The transient confined-flow simulations help identify an interesting self-reversal mechanism where the wedge, which initially intrudes into the formation due to SLR, would be naturally driven back to the original position. However, in unconfined-flow systems this self-reversal mechanism would have lesser effect due to changes in the value of the effective transmissivity (or average aquifer thickness). Both confined and unconfined simulation experiments showed that rising seas would lift the entire aquifer and this lifting process would help alleviate the overall long-term impacts of saltwater intrusion”.

Loáiciga et al. (2011) reported that “variations in groundwater extraction (anthropogenic fluxes) was the predominant driver of sea-water intrusion in a model that simulated sea-level rise scenarios for the City of Monterrey, California..... This could impact the overall hydrological budget resulting in less recharge reaching the coastal area and this will hinder the self-reversal process. Therefore, site-specific management models for coastal areas should carefully integrate changes in both natural and anthropogenic fluxes with various sea-level rise scenarios”.

The above brief discussion proves that sea level does have an impact on sea-water intrusions, and this process can lift groundwater table. A better understanding of sea-water intrusions into the formation and its self-reversal (i.e. driven back to original position) mechanism would have an enormous implication on managing the impacts of SLR in coastal groundwater aquifers (both confined and unconfined).

5.0 SUMMARY AND CONCLUSIONS

- The results showed that the air temperature hasn’t changed much since 1970 and has varied between 27.4 °C and 29.2 °C. On average, annual temperature has increased up to 1°C over the last 40 years. The future temperature of Tarawa may be around 29°C by 2030.
- Annual average rainfall patterns in Tarawa varies from year to year due to movement of the ENSO (seasonal rainfall events) causing huge difference in rainfall amounts. The annual average rainfall varied between 150 mm and 4356 mm during the study period, and 2000 mm was the annual average rainfall depth. It was estimated that the average annual rainfall may increase over 4500 mm by 2030.
- The results showed that local GHG emissions have increased by 100% (i.e. from 0.04 to 0.08 MtCO₂e) since 1990. However, Kiribati’s contribution to global GHG emission is insignificant. Further, the total annual GHG emissions (MtCO₂e) for Kiribati from 1990 to 2012 was very low as compared to other countries such as USA, China, India (as reported earlier in section 3.5). It was estimated that the total GHG emissions (MtCO₂e) is likely to rise to 0.11 MtCO₂e by 2030, which is nominal as compared to other big contributors such as USA, China, and India.

- Thus, that is why the global climate change will have more effect (than local climatic conditions) on sea level rise and salt water intrusion in South Tarawa area, which may eventually have an effect on the quality and quantity of the local freshwater lens(es).
- The sea level in Tarawa increased by 280 mm (28 cm) (from 1470 to 1750 mm) during 1993 and 2015. This increase was largely expected and was due to the global climatic effects i.e. melting of land-based ice sheets and glaciers and seawater thermal expansion). The overall trend was 5 mm rise in sea level per year and it was estimated that sea level in Tarawa may rise up to 1.83 m by 2030.
- Further, the study showed that SLR has a direct effect on thickness of underground freshwater lens. Remember, in this study the thickness of the freshwater lens is the distance between the groundwater table level and the mid-point of the transitional zone (refer to Figure 1), and that explains a direct relationship between sea level rise and groundwater thickness for South Tarawa area.
- In summary, both climatic factors (e.g. temperature, rainfall pattern, GHG emission, sea-water intrusion in response to SLR, etc.) and the non-climatic factors such as over-pumping, population growth and physical and chemical pollution to the environment generates threats to underground freshwater lens in Tarawa. If all these climatic and non-climatic factors continue to rise then groundwater resource in Tarawa may not be reliable anymore for the people of Tarawa - thus other options may have to be considered. Scientists predicted that Kiribati could be lost due to rising sea levels in the next 50 years. A recent study (Mouginot et al., 2014) reported that that six massive glaciers in the Amundsen Sea sector "*have passed the point of no return*", clearly showing how melting glaciers greatly impact low-lying islands like Kiribati. If scientist's predictions about the disappearing of nation of Kiribati are correct then there will be no choice for the people of whole Kiribati nation other than relocation to other safer places.

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