Case Study A

VULNERABILITY OF FRESHWATER LENS ON TARAWA – THE ROLE OF HYDROLOGICAL MONITORING IN DETERMINING SUSTAINABLE YIELD

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EXECUTIVE SUMMARY

The climate is getting warmer and warmer due to the "GREEN HOUSE GAS EFFECT" and Kiribati groundwater resources are threatened by extreme weather events. With Kiribati population projection of around 165,000 to 351,000 inhabitants in 2100, the strain on the groundwater resources will be even more severe and will further increase vulnerability. A World Bank Study carried out in August 2000 indicated that the cost impacts on groundwater due to climate change (change in rainfall, inundation, change in temperature) are between US$1.4-2.7 million per year.

Groundwater apart from rainwater catchments is the main source of freshwater. As for South Tarawa – the capital of Kiribati - groundwater is extracted from two islands, Bonriki and Buota.

A number of investigations and monitoring has been carried out on the groundwater since 1960's and produced different results. The investigation and/or monitoring ranges from simple salinity measurement to water level measurement, borehole salinity measurements to computer analysis. New investigations and/or monitoring methods keep appearing as years go by.

Based on experiences, it seems that borehole salinity measurements are probably the best of all as they actually measure the groundwater salinity at a number of depths. This also qualifies it for monitoring the impact of climate change on groundwater. Theoretical analysis like computer simulations can only be effective if they are calibrated with actual measurements. In this paper, we will be talking about the evolution of groundwater investigations and monitoring and their usefulness in monitoring the impact of climate change on groundwater.

1) INTRODUCTION

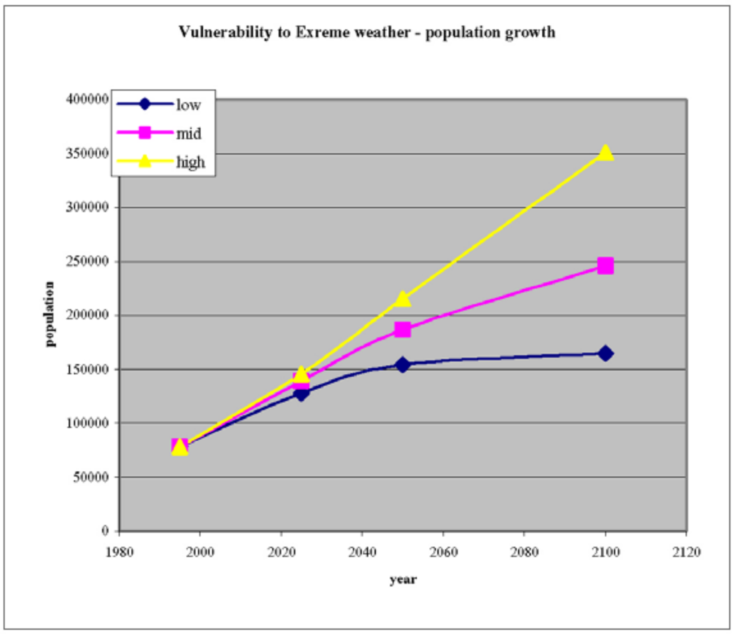
Physiography

Kiribati consists of three main island groups (Gilbert, Phoenix and Line) scattered over three million square kilometers of sea in the Central Pacific, between 4° N and 3° S, and 172° E to 157° W. The total land area is 810.8 km^2 which is divided into 32 low-lying coral islands plus Banaba – Gilbert (17), Phoenix (8) and the Line (8).

Tarawa atoll – the island capital and is in the Gilbert Group, consists of more than 20 named islets, six of which in the south are linked by causeways. Most of the islands, with the exception of Banaba, are no more than 5 meters above mean sea level.

Climate Changes

Over the past 100 years, the earth has been warmed by 0.6 degrees Centigrade, and the 1990s have been the warmest decade with the year 1998 being the warmest year. These increases in temperature could not be accounted for by known natural phenomena, but with the enhanced greenhouse effect they can be explained. Temperature increase scenarios are between 4 Deg C and 5.8 Deg C by the year 2100 (Zillman, 2001). The global sea level has risen by a range of between 1 to 2 mm/yr also over the past 100 years, and it is very likely that this increase is partly due to anthropogenic greenhouse gas emissions. IPCC projection of accelerated sea-level rise, however, has not been observed globally. The explanation might be an underestimation of terrestrial storage of water in the IPCC earliest assessment reports. Current scenarios for sea level rise, depending on emission profile projections that are based on the 'business as usual' scenario; indicate a range between 9cm and 88cm over the next 100 years (Zillman, 2001).



Computer simulations (Alam and Falkland, 1997) indicated that changes in rainfall would have a significant impact on the freshwater lens thickness. A 25% reduction in long term daily rainfall would reduce the average thickness of freshwater lens by 64%. Any rise in MSL would also raise the groundwater table in almost the same proportion assuming the island widths are not affected by inundation.

A study carried out by the World Bank (2000) in Kiribati indicated that some Scenarios are more certain than others.

Impact	2025	2050	2100	Level of Uncertainty
Seal level rise (cm)	11-21	23-43	50-103	High
Air temperature increase (Centigrade)	0.5-0.6	0.9-1.3	1.6-3.4	Low
Change in rainfall (%)	-4.8-3.2	-10.7-7.1	26.9-17.7	High
Cyclones				
Frequency	Conflicting results			Very high
Intensity (%)	0-20			Moderate
Region of formation	No change			High
Region of occurrence	No change or increase to north and south			High
ENSO	A more El Nino			Moderate
Note: Sea level from global projection, Temp and rainfall from CSIRO9M2, ENSO and cyclone (Jones and other 1999)				

Considering the above, it is very well understood that Kiribati as well as other South Pacific countries are already considered as being at high-risk to sea-level rise and increasing impacts from extreme weather events.

PRESENT LOCATION OF FRESHWATER LENS

Hydrogeology

Tarawa atoll consists of coral sediments and limestone of unknown thickness, overlying a volcanic seamount. From a hydrogeological viewpoint, the geology of most interest is the upper part of the atoll where freshwater lenses are formed. The freshwater lenses in the islands of Tarawa atoll are up to 30 m deep (Falkland, 1992). Two major geological layers are found within this 30 m zone, a younger layer (Holocene age) consisting largely of unconsolidated coral sediments overlying an older layer (Pleistocene age) of coral limestone.

An unconformity between the above-mentioned two layers has been found at depths generally between about 10 and 15 meters below mean sea level (Jacobson & Taylor, 1981). This unconformity is very significant to the formation of freshwater lenses. The Pleistocene limestone below the unconformity has relatively high permeability's which enhances the mixing of freshwater and seawater. Mixing is less likely to occur in the relatively less permeable upper Holocene sediments. The unconformity, therefore, is one of the main controlling features to the depth of freshwater lenses.

D is dispersion at the base of the groundwater,
Q is groundwater extraction (normally by pumping), and
ΔS is change in freshwater zone storage.

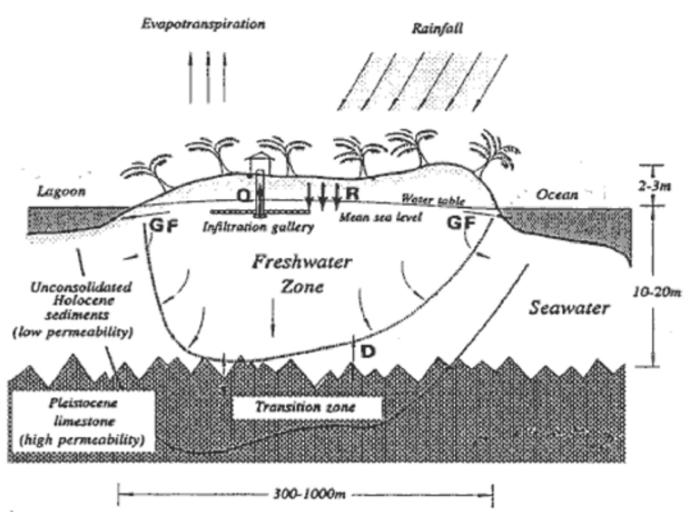


Figure 1: Typical cross section through a coral island with a freshwater lens

Water Reserves

Bonriki and Buota have been declared as water reserves (Figure 3: Map of Bonriki and Buota (Water Reserves)). Other declared water reserves were on Betio and between Teaoraereke and Antebuka (generally known as the Teaoraereke water reserve). However, due to over-pumping and pollution from human settlement, these water reserves are no longer in use. A further water reserve was located to the east of Bikenibeu near the new hospital but this was relinquished prior to construction of the new hospital.

There are plans under the Sanitation and Public Health Environment (SAPHE) project to include Abatao and Tabiteuea as water reserves.

Significance of groundwater supply

There are three main sources of freshwater for the South Tarawa residents:

- The public water supply from PUB which extracts water from Bonriki and Buota,
- Private wells, and
- Rainwater catchments

Public water supply from the Bonriki and Buota lenses

The current total pumping capacities of the Bonriki and Buota freshwater lenses are approximately 1,000 m^3/day and 300m^3/day, respectively with an average electrical conductivity (EC) of about 600-700 ? S/cm but it varies between about 400 ? S/cm after heavy rains to over 1000 ? S/cm during dry periods. There are 18 water supply galleries operating at Bonriki lens and a further 6 galleries at Buota. Each gallery, except one older gallery at Bonriki consists of 300 m long slotted PVC pipe systems laid below the water table and connected to a pump well and has a capacity of approximately 55 cubic m^3/day. To minimize the impact of pumping on the lens, the gallery pumps are run continuously. The public water supply has been unable to meet the demand due mainly to high losses (50% leakage: SOPAC, 1998a***) in the distribution pipelines.

Private wells

Most South Tarawa residents use private wells to supplement their water needs (bathing, washing etc) however it is also been observed that some use it for cooking and drinking. In prolonged droughts, many private wells have salinities above the freshwater limit. The quality of the water from wells especially in urban areas – Betio, Bairiki and Bikenibeu – is deteriorating and high faecal coliform counts are obtained (Ministry of Health, 1998***). The sources of pollution are septic tanks, pit toilets; leachate from solid waste as well as organic and inorganic pollutants from congested and developed areas.

Rainwater catchments

Rainfall utilization as a source of water, for drinking as well as for other purposes, has been in practice in Kiribati for many years (Metutera, 1994; 2002***). Even though in theory rainwater catchments are more efficient in storing rainfall than groundwater, because of frequent month long droughts and their initial construction cost, they are regarded as supplementary, rather than a main source of water.

Editorial comments yet to be addressed by Author:

*** put details of SOPAC (1998a) into reference list..maybe it should be SOPAC (1998)?… unless there is also a SOPAC (1998b) publication cited in the paper

*** put details of Ministry of Health, 1998 into reference list

*** need to put details of Metutera, 1994 into refrence list (also could reference his case study for this consultation meeting

2) HISTORY OF GROUNDWATER DEVELOPMENT

Stage 1 – 1960's (various 1960's reports to Government)

Nature of groundwater use

In the 1960's groundwater was extracted from wells at Bikenibeu, Bairiki and Betio.

Investigations and recommended pumping rate

A number of groundwater investigations were carried out in the 1960's, the 1970's and the 1980's. In 1961, Kirk, Grundy and Partners undertook the study to improve water supplies for Betio, Bairiki and Bikenibeu. After field observations of water table fluctuations, water sampling and a preliminary study of the water balance for both groundwater resources and rainwater catchments, they recommended the design of 200 feet (approx. 60m) gallery and the pumping rate to be set at 1,000 gallons per hour (approx. *110 m^3/day*) for limited periods (Kirk, Grundy and Partners, 1961).

In 1967, Wilton and Bell, Dobbie and Partners recommended further development of the groundwater resources on Betio, Bairiki and Bikenibeu and the declaration of water reserves at Betio, between Teaoraereke and Antebuka for Bairiki and at Temaiku for Bikenibeu (Wilton and Bell, Dobbie and Partners, 1967).

Mather in 1973 conducted a number of field tests including measurements of water level and water chemistry at wells, an electrical resistivity survey and a limited drilling programme. His conclusions were (Mather, 1973):

- Betio safe yield was about 90 m^3/day,
- The Bairiki safe yield was much less than Betio,
- Based on salinity observation, Teaoraereke water reserve was to be used as a source of brackish water.
- The Bikenibeu area was not suitable for sustainable potable water source,
- Bonriki lens had a thickness excess of 12 meters thick,
- There was a presence of an extensive lens on Buota,
- A thin lens was present on Abatao and on Tabiteuea.
- Recharge was not more than 10 inches per year (about 250 mm per year or about 12% of mean annual rainfall).

In 1977, Wagner summarized some of the previous studies and concluded that (Wagner, 1977):

- Teaoraereke, Bonriki and Buota had safe yields of about 295 m^3/day (period of normal rainfall) and about 180 m^3/day (drought periods). The actual pumping rate at the time of Wagner's study was about 210 m^3/day (40 m^3/day from Teaoraereke, 85 m 3 /day from Bonriki and 85 m^3/day from Buota).

Richards and Dumbleton (1978) investigated water resources for Tarawa including a re evaluation of groundwater potential using a sharp-interface type model and concluded that:

- Bonriki lens could not sustain itself even under very small pump rates in a 1 in 50 year (2%) drought with duration greater than one year. Accordingly, these authors concluded that the potential for further groundwater development was limited and that alternative water sources should be considered. (This conclusion has been found to be in error by the sustainability of the Bonriki lens in the 1998-2000 drought)

DHC in 1982 also carried out an investigation on the groundwater resources of Tarawa following geophysical investigations (Jacobson and Taylor, 1981) and a drilling programme (Murphy, 1981) and concluded that the safe yield were as follows adopting that the sustainable yield was about 10% of mean annual rainfall;

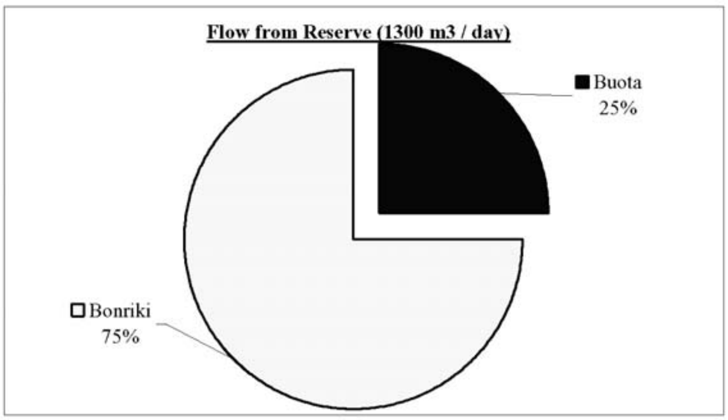
- Bonriki: - 750m ^{3}/day
- Buota: - 250 m^3/day
- Teaoraereke: - 150 m^3/day
- Abatao: - 200 m^3/day

- Tabiteuea: - 150 m^3/day
- Total: - 1500 m ^{3}/day

Stage 2 – 1990's (Review of Tarawa Freshwater Lenses by Tony Falkland)

Nature of groundwater use

According to the 1990 census the population of South Tarawa was about 24,000 and fresh water supply for the residents was derived from three sources (the public water supply system that extracted groundwater from freshwater lenses at Bonriki and Buota, private wells that were generally located close to some residences, and rainwater catchments at some houses). The total pump rate during April 1992 from the galleries at the Bonriki and Buota lenses was approximately 1,300 m^3/day of which about 75% (about 975 m^3/day) was pumped from Bonriki while the rest was from Buota.



Due to overuse of the public water supply system and probably high leakage from it, water supply to consumers was restricted. On working days, the hours of supply were 0600-0900, 1100-1400 and 1600-2100 giving a total of 10 hours per day. On weekends, the hours of supply are from 0600 to 2100 giving a total of 15 hours per day. The reason for restrictions was essentially that the supply from the combined galleries at Bonriki and Buota are unable to keep up with the demand.

Investigations – Monitoring methods

There were three monitoring methods (borehole salinity monitoring data, galley pumping and groundwater salinity measured at the galleries) employed to monitor the water supply and groundwater resources at the water reserves.

Boreholes salinity monitoring data

A number of boreholes were drilled at the water reserves including Teaoraereke, Bonriki, Buota, Tabiteuea and Abatao– some boreholes were installed way back in 1980 when during the construction period for the water and sewerage supply systems on South Tarawa. The boreholes consisted of small tubes within the borehole terminating at different depths and hydraulically isolated from each other by bentonite layers interspersed between selected small (pea size) gravel backfill within the hol*e*. (see Figure 4: Borehole monitoring system). The procedures for monitoring the salinity monitoring boreholes are well described in Murphy (1987). At each monitoring 'run' water samples are pumped from the 'monitors' at different depths in each borehole. The samples are tested for salinity using a portable EC metre.

Gallery pumping

Pumping data were collected from meters located at each galley at Bonriki and Buota and a combined flow meter on the bulk main at Bonriki on a daily basis. It was found from the data collected that the combined pumping from all galleries at Bonriki and Buota was about 1,300 m^3 /day. This was found to exceed DHC 1982 estimated for sustainable yield of 1000 m^3 /day.

Groundwater salinity

Salinity data were collected/measured at the water supply galleries to monitor the level of salinity. The adopted limited of freshwater was 2,500 ? S/cm (in electricical conductivity or EC units) and the data collected indicated that the EC of water obtained from Bonriki, Buota and Teaoraereke were below this limit.

Investigations – Analysis methods

The dynamics of the freshwater lens was analyzed using the borehole data.
Some of the findings were:

- As expected the boreholes closer to the edges of the island showed thinner freshwater lens than those at the center or the thickness of the freshwater increased as the distance from the edge of the island increased,
- The thickness of the lens varied from 4m to 21m between dry periods (1984 & 1989) to wet periods (1987),
- Bonriki and Buota lens have maximum thickness of around 20 to 25m,
- Pumping did not have an adverse effect on the lens during the dry period.

Predicted long term safe yield

Based on the above analysis and observations the safe yield for the following water reserves are:

- Bonriki - 1,000 m^3 /day
- Buota - 300 m^3 /day
- Teaoraereke - 100 m^3 /day
- Total 1,400 m^3 /day

Stage 3 – 2000's (Most Recent Report)

Nature of groundwater use

Like in previous years, the main sources of freshwater were from public water supply, private wells and rainwater. According to the 1995 census, the population on South Tarawa was 30,000 and the majority of people were still using groundwater (public water supply and private wells) as their main sources of supply.

The total quantities of water pumped from Bonriki and Buota freshwater lenses were about 1,000 and 300 m^3/day, respectively. However this amount of water still failed to meet the demand probably due to the high leakage.

Investigations – Monitoring methods

The three monitoring methods (boreholes salinity monitoring data, galley pumping and groundwater salinity measured at the galleries) employed in the early 1990's are still employed to monitor the groundwater. Vandalism has recently reduced the number of usable boreholes. There is a need to expand the scope of measurements to include evaporation, and groundwater levels. Additional monitoring boreholes were drilled as part of the SAPHE project to replace some of the original boreholes that had suffered from vandalism and to extend the network to other parts of Bonriki.

Investigations – Analysis methods

The analysis has greatly improved especially with the availability of computers. Alam and Falkland (1997) analyzed the impact of climate change on the Bonriki freshwater lens using the SUTRA groundwater modelling program. In addition, an analysis has been made of the effect of droughts on rainwater (White et al, 1999).

Description of sustainable yield

Based on the analysis and observation of data, the following observations were made:

- The current pumping rates at Bonriki and Buota match to previously estimated (revised) sustainable yields (Falkland, 1992).

- Higher pumping rates could be sustained but that this requires confirmation by further groundwater investigation and modeling (Falkland, 1992, Alam & Falkland, 1997, White et al, 1999).
- The current extraction rate, about 10% of mean annual rainfall (Falkland, 1992), appears conservative.
- Ignoring dispersion, outflow and direct evaporation losses, and in the absence of any rain, the current pumping regime would take approximately 10 years to deplete the lens (White et al, 1999).

3) DISCUSSION

It is clear that monitoring and analysis methods have evolved as years went by. In the 1960's, monitoring and analysis were limited to just surface groundwater level and salinity measurements. In the 1970's electrical resistivity surveys and a limited drilling programme were added. In the 1980's, more detailed geophysical investigations and an extensive drilling programme, and monitoring of the boreholes were carried out. In the 1990's and the 2000's, groundwater level and salinity measurements using data loggers and climate monitoring at Bonriki were introduced for a few years.

As new monitoring methods are introduced, more and more is known about the groundwater.

Richards and Dumbleton who investigated the water resources for Tarawa including a re-evaluation of groundwater potential using a sharp-interface type model in 1978 indicated that Bonriki lens could not sustain itself even under very small pump rates in a 1 in 50 year (2%) drought with duration greater than one year. This was later proved to be incorrect.

In 1982, investigations of the groundwater resources (AGDHC, 1982) concluded that the safe yield estimates of about 10% of mean annual rainfall were: Bonriki (750 m^3/day), Buota (250 m^3/day), Teaoraereke (150 m^3/day), Abatao (200 m^3/day), and Tabiteuea (150 m^3/day). However recent observations indicated that Bonriki could sustain higher pumping rate.

4) CONCLUSION

There is no doubt that the climate is getting warmer and warmer due to the "GREEN HOUSE GAS EFFECT" and Kiribati as well as many other Pacific countries are vulnerable and must learn to face/adapt to this reality, especially extreme weather events.

Some people may argue that this is a problem far in the future and so we do not need to worry about it. However frequent extreme weather events are now being felt in Kiribati. With population projections indicating that Kiribati will have between 165,000 to 351,000 inhabitants in 2,100, the strain on the water resources will be severe and will further increase vulnerability.

Predictions indicate that changes in rainfall (-10%), sea level rise (+0.4m), and island widths reduced by inundation in 2050 could reduce the groundwater (-38%) costing between US$1.4-2.7 million per year. (World Bank Study, 2000).

In order to reduce the impact of climate change, it is best that Kiribati must adopt adaptation measures. In order for adaptation measures to be effective they must run in parallel with monitoring.

Based on the previous discussion, we can see that theoretical analysis has to be calibrated or confirmed with actual measurements. In the case of groundwater resources, this means the monitoring of recharge, using climatic data, pumping and groundwater conditions, using the network of special salinity monitoring boreholes.

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APPENDIX

Figure 2. Aerial photo of Bonriki.

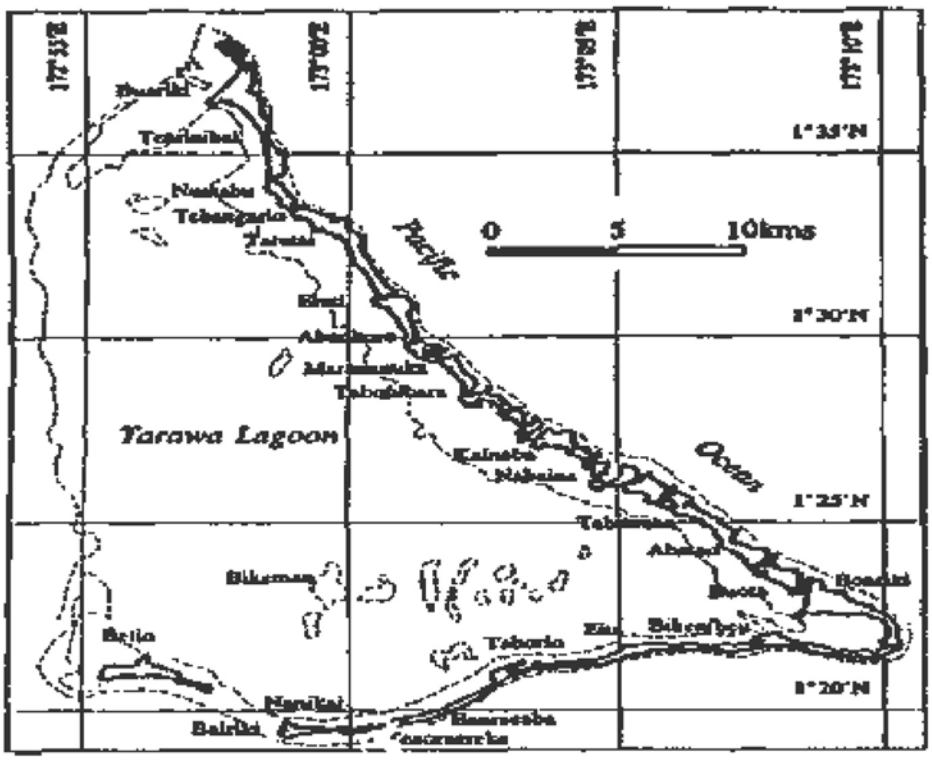

Figure 3. Map of Bonriki and Buota (Water Reserve).

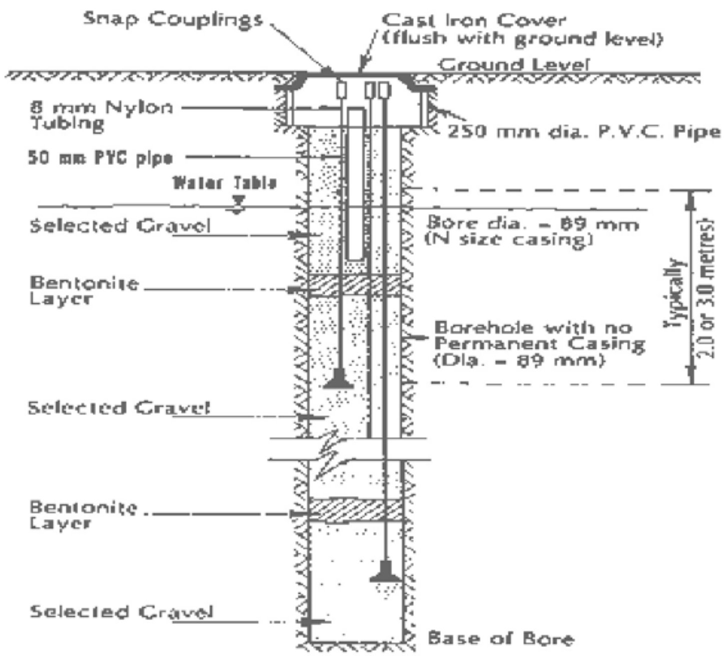

Figure 4. Borehole monitoring system.

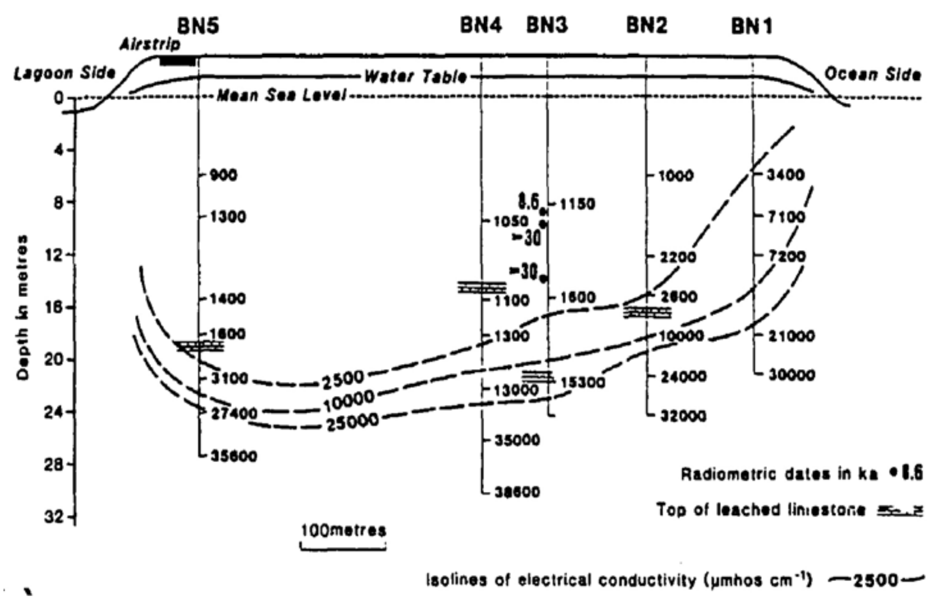

Figure 5. Depth of freshwater limits at selected cross-sectional area.