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CHAPTER 2

CLIMATE, HYDROLOGY AND WATER RESOURCES OF THE COCOS (KEELING) ISLANDS

BY

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CLIMATE AND HYDROLOGY

GENERAL FEATURES

The Cocos (Keeling) Islands are situated in the Humid Tropical zone. For most of the year they are under the influence of South East Trade Winds. Cyclonic conditions are sometimes experienced, particularly between November and March. Rainfall on the island is influenced to some extent by El Niño events.

The main climatic features are:

- annual rainfall varying between about 850 and 3300 mm,
- annual potential evaporation of about 2000 mm,
- relatively uniform temperatures, ranging from about 18°C to 32°C,
- relative humidity varying from about 65% to 84%,
- daily atmospheric pressures ranging from 973 to 1018 hectopascals, and
- mean daily wind speeds varying from 4.7 and 8.1 metres/second with a maximum gust during a cyclone recorded at 48.8 metres/second (176 kilometres/hour).

METEOROLOGICAL DATA

CURRENT NETWORK

A meteorological station (No. 200284, Cocos Island A.M.O.) has been operated continuously on West Island on the eastern side of the airstrip by the Bureau of Meteorology (Australia) since February 1952. It is located at latitude 12°11'S, longitude 96°50'E and at an altitude of 3 metres. At the station, the following meteorological parameters, important to water resources assessment, are measured and recorded:

- air temperature (wet and dry bulb, and dew point),
- atmospheric pressure,
- cloud cover,
- wind speed and direction,
- rainfall, and
- pan evaporation.

Temperature, atmospheric pressure, cloud cover and wind are measured every 3 hours. Daily averages can be derived from eight readings. Daily total wind run is also

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recorded. Rainfall and pan evaporation are measured daily at 9 a.m. Rainfall is also recorded on a pluviograph (continous recorder). In addition to the above surface level measurements, upper air data is collected via regular balloon releases from the station.

Daily rainfall is measured and recorded at two other sites on the South Keeling atoll. The first site is located on a peninsular about 100 metres north of the jetty on Home Island. Data has been recorded at this site by the Cocos (Keeling) Islands Council (formerly Home Island Council) since 28 May 1986. This site is now described as station number 200733 by the Bureau of Meteorology. The second site is located on the eastern side of the administration building at the Quarantine Station on West Island. Data has been recorded at the second site by Quarantine Station personnel since 1 January 1989. Some of the data at both of these sites has not been recorded each day but rather recorded as a total for two or three days. Therefore, these records cannot be used for accurate daily rainfall analyses but they are suitable for monthly rainfall analyses. No meteorological data is recorded on the North Keeling atoll.

PREVIOUS DATA COLLECTION SITES

In 1904 a rainfall station was opened on Direction Island and operated by staff at the cable station. A climatological station was opened "probably soon after, although no files survive to prove this" (Bureau of Meteorology 1978). Other notes in the file entry indicate that this station operated to 1952 when the current station opened on West Island.

There is some anecdotal evidence that the Clunies-Ross family recorded rainfall on Home Island. However, no records were sighted and it is not known whether any of these records were incorporated into the Bureau's records. As the rainfall records extend back to December 1901, it is probable that rainfall was recorded on Home Island from then until the rainfall station on Direction Island was opened in 1904.

Rainfall records under the heading 'Cocos Island Composite' are available from the Bureau of Meteorology for all but 17 months from December 1901 to the present. Months with missing data are November and December 1914, all months of 1915, January 1916, April 1946 and February 1952. An early entry in a Bureau of Meteorology file states that "the records for 1915 were incomplete on account of the instruments being destroyed in November 1914 by German warship 'Emden'. Records were recommenced in November 1915". The missing data in 1946 and 1952 appears to be due to staff and location changes. Overall, the length of record and the small number of missing months (and hence days) of record, have ensured a very good data set for the Cocos (Keeling) Islands.

SELECTED METEOROLOGICAL DATA FROM WEST ISLAND

Graphical and tabular summaries of important meteorological parameters recorded at the West Island meteorological station are presented in this and the next two sections. Summaries of temperature, relative humidity (a derived parameter), atmospheric pressure, cloud cover, wind speed and wind direction are presented in this section. More extensive summaries of rainfall and evaporation are provided below. The data used for these summaries, unless otherwise indicated, are for the period February 1952 to December 1991.

TEMPERATURE

Mean, maximum and minimum daily temperatures are shown in Figure 1 and in Table 1 for each month of the year. The maxima and minima are extreme values derived from all of the 3 hourly data. The mean values were estimated by averaging mean daily maxima and minima.

The mean daily temperature is highest in March (27.5°C) and lowest in July and August (25.8°C). The extreme maximum temperature is 32.4°C recorded in February 1979 and the extreme minimum temperature is 18.3°C recorded in August 1979.

RELATIVE HUMIDITY

Mean, maximum and minimum daily relative humidities are shown in Figure 2 and in Table 2, for each month of the year. These values are derived from 9 a.m. and 3 p.m. readings of wet and dry bulb temperature and atmospheric pressure using standard meteorological methods.

The mean daily relative humidity is highest from April to July (77%) and lowest from September to December (72%). The mean daily maximum relative humidity is 84% recorded in the months of June and July 1960, April and August 1973, and April 1974. The mean daily minimum relative humidity is 65% recorded in November 1956. Extreme maxima and minima were not computed.

ATMOSPHERIC PRESSURE

Mean, maximum and minimum daily atmospheric pressures are shown in Figure 3 and in Table 3, for each month of the year for the period February 1952 to July 1987. The shorter period was used as extreme maxima and minima had not been computed for the full data set. The maxima and minima are extreme values for each month and, as with the mean values, they are derived from the full 3 hourly data set.

The mean daily atmospheric pressure is highest in September (1012.2 hectopascals) and lowest in February (1008.4 hectopascals). The extreme maximum atmospheric pressure is 1018.5 hectopascals recorded during the months of October 1952 and July 1984 and the extreme minimum atmospheric pressure is 970 hectopascals recorded during cyclone 'Doreen' on 21 January 1968.

It is noted that the atmospheric pressures referred to in this section are at the level of the station. The atmospheric pressure at mean sea level is obtained from these readings by adding an amount of less than one hectopascal. Due to this small difference and the low altitude of the islands, the atmospheric pressure at the station can be used as an indicator of atmospheric pressure throughout the islands.

CLOUD COVER

Cloud cover (or cloudiness) is measured in oktas or the number of eigths of the sky filled with cloud. Mean, maximum and minimum daily values for each month of the year are shown in Figure 4 and Table 4. Data are derived from all observations for the period 1952 to 1987.

The mean daily cloud cover varies between 5.0 and 5.3 oktas, from April to July and 4 oktas for the other 8 months. The mean daily maximum cloud cover is 6.8 oktas recorded in November 1973 and the mean daily minimum cloud cover is 3 oktas recorded in December 1987. Extreme maxima and minima were not computed.

WIND SPEED

Mean, maximum and minimum wind speed are shown in Figure 5 and in Table 5, for each month of the year. The mean values are taken from the 3 hourly data set from February 1952 to July 1987. The maxima and minima are extreme instantaneous values for each month for the full period of record (February 1952 to December 1991).

The mean daily wind speed is highest in January (8.1 metres/second) and lowest in February (4.6 metres/second). The mean daily maximum wind speed is highest in August (14.2 metres/second) and the mean daily minimum wind speed is lowest in March (just above zero). The extreme maximum wind speed was recorded at 48.8 metres/second during cyclone 'Doreen' on 21 January 1968. This wind speed is equivalent to 95 knots or about 175 kilometres/hour. The extreme minimum wind speed is zero (calm) which has been recorded on many occasions during all months of the year.

WIND DIRECTION

Figure 6 shows the wind direction resolved as a percentage of time for each month (January to June in left hand graph and July to December in right hand graph). Eight points of the compass are used. The graphs are for average wind directions from 9 a.m. and 3 p.m. readings for the period February 1952 to December 1990. The legends show the percentage of time that calm periods were recorded for each month .

The predominant wind direction is east to south east for all months, showing the influence of the South East Trade Winds on the islands. South easterly winds varied from 37% of the time in February to 60% of the time in November and December. Easterly winds varied from 17% in January to 44% in September. By comparison winds from the north, north east, south west, west and north west occurred for less than 6% of the time in all months and were often 2% or less. Southerly winds were experienced from a low of 2% of the time in September and October up to 17% of the time in January.

OCCURRENCE OF CYCLONES

A cyclone database maintained by the Bureau of Meteorology shows that a number of cyclones have affected the Cocos (Keeling) Islands. Table 6 presents data about cyclones since 1959 which have passed within approximately 100 kilometres of the island. One of the most damaging cyclone appears to have been 'Doreen' which passed directly over the South Keeling atoll. An interesting account of this cyclone is provided in Ryan (undated).

RAINFALL DATA AND ANALYSES

INTRODUCTION

As rainfall is one of the most important determinants of the water resources of the islands, a more detailed analysis of rainfall is presented. This section describes characteristics of the annual, monthly and daily rainfall. In addition to analyses of the temporal distribution of rainfall, comments about the spatial distribution of rainfall on the South Keeling atoll are made.

It is noted that from a water resource viewpoint, rainfall at time scales of days and months are of most significance. For recharge analysis, as part of groundwater studies on atolls such as South Keeling, daily rainfall data has been found to have sufficient time resolution. Monthly rainfall data can be used instead of daily rainfall data with a small loss in accuracy. For rainwater catchment studies, long sequences of daily rainfall data are ideal.

SPATIAL VARIATION OF RAINFALL

At the scale of the Indian Ocean, the variation of rainfall has been reported in Stoddart (1971) and Unesco (1977). Stoddart (1971) reviewed earlier reports and produced updated isohyetal maps for annual, seasonal and monthly rainfall based on coral island stations, primarily those with records longer than 10 years. The mean annual rainfall distribution is shown in slightly modified form in Figure 7.

The isohyetal map of mean annual rainfall shown in Unesco (1977), not shown here, is quite different particularly in the centre of the ocean. In the region of the Cocos (Keeling) Islands, however, the two maps are similar with isohyets approximately horizontal. The reason for the differences is not clear. On the South Keeling atoll, the spatial variation rainfall has been analysed by Falkland (1992a).

ANNUAL RAINFALL

The mean annual rainfall recorded at the West Island meteorological station is 1954 mm for the 40 year period of record from 1953 to 1992. Using the available annual record from 1902 to 1992, the mean annual rainfall is 1982 mm. In the longer data set, the annual rainfalls in 1914, 1915, 1916, 1946 and 1952 are missing giving a total number of 86 years. For the period 1902-1952, during which time the rainfall was recorded primarily on Direction Island, the mean annual rainfall is 2006 mm. Figures 8 and 9 show, respectively, histograms of annual rainfall for the periods 1902 to 1952 and 1953 to 1992.

Using the meteorological station records, the highest annual rainfall on record is 3291 mm which occurred in 1942 (Direction Island) while the lowest is 856 mm in 1991 (West Island). By comparison, the annual rainfall in 1991 on Home Island and at the Quarantine Station were, respectively, 837 and 820 mm.

The difference in the mean annual rainfalls for the two periods 1902-1952 and 1953-1992 is 2.6% of the latter period mean annual rainfall. This is considered a minor difference, given that site differences can easily account for long term rainfall depth differences of 10% or more. This result shows that the total depth of rainfall in the first half of the century (1902-1951), recorded primarily on Direction Island, is similar to that recorded in the second half of the century (1953-1991) on West Island.

The standard deviations of the annual rainfalls for the periods 1902-1992 and 1953-1992 are, respectively, 519 and 594 mm, showing a higher variability in the second half of the century. The coefficient of variation (Cv) of annual rainfall (obtained by dividing the standard deviation by the mean) for the two periods are, respectively, 0.26 and 0.3, again indicating the higher variability of recorded rainfall in the second part of this century on the island. These Cv's of annual rainfall are moderate when compared with other islands, especially low lying coral atolls. Christmas Island (Australia), a raised limestone island, about 900 kilometres north east of the Cocos (Keeling) Islands, has a similar Cv of 0.29. The atolls of Tarawa and Kiritimati (Christmas Island), Republic of Kiribati in the Pacific Ocean have higher Cv's (0.42 and 0.64, respectively). By comparison, Kwajalein atoll in the Marshall Islands Pacific Ocean has a much lower Cv of 0.14 (Falkland et al. 1991). The variation in annual rainfall between the three raingauge sites can be seen in Table 7.

From the data in Table 7, the rainfall for 1987 on Home Island is suspect as it is very low (only 65% of that at the meteorological station) and is inconsistent with the relative rainfall pattern between Home and West Island for the following years. Disregarding the suspect 1987 data for Home Island, there is slightly less rain occurring on Home Island than on West Island. The total rainfall recorded on Home Island from 1988 to 1992 is 5.3% less than at the meteorological station. The data also shows that the rainfall recorded on Home Island and at the Quarantine Station is, respectively, 3.4% less and 5.3% greater than at the meteorological station during the four year period 1989 to 1992.

Overall, the variation of rainfall between the three sites is not greatly significant when it is considered that the recording accuracy of rainfall at any one site is generally not better than about 10%. Although the period of concurrent rainfall records is short and therefore not suitable for making long term predictions, it is reasonable to conclude that the annual rainfall on the South Keeling atoll can be adequately described by the rainfall record at the West Island meteorological station.

MONTHLY RAINFALL

Mean, maximum and minimum monthly rainfalls recorded at the West meteorological station are shown in Figure 10 and in Table 8, for the March 1952 to December 1991. The mean monthly rainfall is highest in April (234 mm) and lowest in October (70 mm). The maximum monthly rainfall is 649 mm recorded in June 1988 and the minimum monthly rainfall is 2.8 mm recorded in September 1986.

A comparison of the monthly rainfalls recorded at the meteorological station and on Home Island for the period 1987 to 1991 is shown in Figure 11. A comparison of the meteorological station and the Quarantine Station monthly rainfalls for the period 1989 to 1991 is shown in Figure 12. A comparison of the cumulative monthly rainfall recorded at the three sites for the period of concurrent records (1989-1991) is shown in Figure 13.

Figures 11 and 13 indicate that the rainfall recorded at the Home Island site is less than that at the meteorological station. The lower rainfall recorded on Home Island may be due to a rain shielding effect of nearby tall vegetation at the raingauge site. Similarly, Figures 12 and 13 show that the rainfall recorded at the Quarantine Station site is slightly greater than that recorded at the meteorological station.

Double mass curves using cumulative monthly rainfall were plotted to check if any changes in the relative rainfall at the Home Island and the Quarantine Station sites had occurred during the periods of concurrent record. Figure 14 is the double mass curve using the rainfall data from the meteorological station and Home Island for the period 1987-1991. The plotted line shows some variation in slope, particularly from the early (1987) data to later data. Figure 15 is the double mass curve using the rainfall at West Island meteorological station and at the Quarantine Station for Home Island for the period 1989-1991. The corresponding Home Island data is also plotted in Figure 15. Very little variation in slope is shown for the Quarantine Station curve, indicating that there has been no major changes in this site or the method of recording since data collection commenced. However, the Home Island data indicates a greater variation. The variations in the Home Island record could be due to a number of reasons including progressive 'shading' of the raingauge from nearby trees, and errors or changes in the method of reading and recording rainfall data.

Regression analyses of monthly rainfalls at Home Island and the Quarantine Station with the meteorological station are summarised in Figures 16 and 17. The analysis using 60 monthly rainfall pairs for Home Island and the meteorological station gave a correlation coefficient (r) of 0.92 which indicates a reasonably good correlation. The value of r for 36 pairs of data from the Quarantine Station and the meteorological station was 0.97 which indicates a very good correlation. The regression equations are shown in Figures 16 and 17, respectively. These could be used to estimate monthly rainfalls at the two sites from the meteorological station monthly rainfall. They should be updated with additional data if they are considered for future use. The Home Island equation should be treated with caution as some of the Home Island data is suspected of being in error.

DAILY RAINFALL

While daily rainfall records are available from the Bureau of Meteorology for the full period of record (1904-1992) from the stations on Direction Island and West Island, only the data from the latter station were obtained for analysis. Daily rainfall has been recorded at the West Island meteorological station from 15 February 1953 to the present.

Daily rainfall has also been recorded on Home island (28 May 1986 to present) and at the Quarantine Station (1 January 1989 to present), as described previously. Daily data from all 3 stations was reviewed to the end of 1992.

The maximum recorded daily rainfall at the West Island meteorological station is 287 mm on 28 August 1956. There have been 54 days when the rain exceeded 100 mm and 6 days when it exceeded 200 mm. The maximum daily rainfall on Home Island, 242 mm, was recorded on 11 November 1989. On the same day the rainfalls recorded at the meteorological station and the Quarantine Station were, respectively, 203 mm and and 220 mm. The maximum daily rainfall at the Quarantine Station was 248 mm, recorded on 4 July 1992. On the same day the rainfalls recorded at the meteorological station was 252 mm. No daily rainfall was recorded at Home island on 4 July 1992 but the three day total to 6 July was only 141 mm.

On a daily basis, the rainfall records show considerable variation between the three rainfall recording sites, as some of the above results show. This is confirmed by general observations that individual storms can affect small areas of the atoll while leaving other areas quite dry. Hence, in the short term the rainfall pattern on Home island or elsewhere on West Island cannot necessarily be deduced from the West Island meteorological station records. Daily variability can also be seen from a number of high rainfall days in 1990 and 1992 when all three rain gauges were operational. The list below shows, in order, the date and the rainfalls at the meteorological station, Home Island and the Quarantine Station:

12 January 1990:	162, 164 and 171 mm,
14 April 1990:	117, 83 and 116 mm,
17 July 1990:	158, 210 and 115 mm,
6 September 1990:	30, 23 and 116 mm,
28 February 1992:	26, 112 and 87 mm,
14 April 1992:	6, 102 and 8 mm, and
4 May 1992:	11, 122 and 29 mm.

The longest period without any rainfall at the meteorological station is a period of 28 days in November 1985. The longest period when the total rainfall was less than 10 mm occurred between November 1985 and January 1986 when only 6.2 mm fell in 69 days. Long dry periods are of particular interest in the study of the island's water resources, as described below.

PLUVIOGRAPH RECORDS

A pluviograph (continuous rainfall recorder) is operated at the West Island meteorological station. These records enable rainfall patterns to be analysed (at time resolution in minutes). Such data are useful to analyse storm events and to construct rainfall intensity-frequency-duration (IFD) curves, for possible use in the design of stormwater facilities (e.g. roof gutters and downpipes). The Bureau of Meteorology has processed IFD information from pluviograph records between 1971 and 1991. This information is not presented here.

EVAPORATION DATA AND ANALYSES

INTRODUCTION

Estimation of actual or catchment evaporation is essential for any water resources study. Evaporation from a catchment includes evaporation from soil, water and other open surfaces such as paved areas and from the leaves of grasses, plants and trees. Evaporation from the stomates of leaves is called transpiration and the combined effects of this process and other evaporation is often described as evapotranspiration. The two processes are basically variations of the one process, namely, the conversion of water from a liquid to a gaseous state and some authors use the term evaporation instead of evapotranspiration. The term evaporation will normally be used instead of evapotranspiration for present purposes.

The estimation of actual evapotranspiration (ET_a) is generally done as a two stage process. Firstly, ET_p is estimated using a method based on meteorological data, such as the Penman (or Combination) formula (Penman 1948, 1956), or from pan evaporation data multiplied by appropriate pan coefficient(s). The Penman equation has generally been found to be a good ET_p estimation method in the humid tropics (Fleming 1987). Estimations using both the pan and Penman methods were made for the study of groundwater resources on the South Keeling atoll (Falkland 1988). Secondly, ET_a is determined using a water balance procedure taking into account the soil and vegetation conditions present on the island.

The estimation of ET_p, using both pan evaporation records and the Penman approach, is described below while the estimation of ET_a is described in a later section on water balance.

PAN EVAPORATION DATA

Daily pan evaporation has been recorded at the West Island meteorological station using a U.S. Class A pan from December 1981 to the present. Mean, maximum and minimum monthly pan evaporation totals are shown in Figure 18 and Table 9, for the period January 1982 to December 1991.

The mean monthly pan evaporation is highest in December (241 mm) and lowest in June (171 mm). The maximum monthly pan evaporation is 273 mm recorded in both December 1983 and December 1985. The minimum monthly pan evaporation is 146 mm recorded in May 1987.

EVAPORATION ESTIMATION (Penman equation)

The following meteorological parameters were available for use in the Penman equation:

- dry bulb temperature,
- wet bulb temperature,
- dew point temperature,
- cloud cover, and
- wind speed.

Using mean monthly values of the parameters above, estimates of monthly ET_p were made using the Penman equation (Penman 1948, 1956) for the period January 1982 to March 1986. This period was the longest period of available concurrent data at the time of investigations (Falkland 1988).

Water balance simulations (Falkland 1988) showed that similar results in terms of groundwater recharge were obtained from monthly data sets using either actual or mean values of ET_p. This shows the relatively constant nature of potential evaporation for a given month from year to year in a humid tropical environment such as the Cocos (Keeling) Islands. In the humid tropics, the net radiation energy term dominates the aerodynamic term in the Penman equation and it has been found that the simplified Priestly-Taylor method can also be used (Chang 1989). In the Priestley-Taylor method ET_p is equated to 1.26 times the energy term from the Penman equation (Priestley and Taylor 1972).

EVAPORATION ESTIMATION (pan method)

Pan evaporation requires multiplication by an appropriate pan coefficient to obtain estimates of ET_p. An initial estimate of the pan coefficient of between 0.7 and 0.75 was obtained by a procedure developed by Doorenbos and Pruitt (1977) using meteorological and specific site parameters.

The pan coefficient was later adjusted to 0.8 after sensitivity analyses were conducted with trial data using water balance simulations. The water balance results in terms of recharge to groundwater using five years of rainfall data (1982 to 1986) were found to be very similar for Penman estimates of ET_a and for pan data using a pan coefficient of 0.8 (Falkland 1988). Results were also similar for simulations using actual and mean monthly pan data.

Figure 19 shows the comparison of mean monthly ET_p estimates using both the Penman and pan methods for the five year period 1982 to 1986. The pan estimates are mean values for each month. The Penman estimates are based on mean monthly values of the relevant meteorological parameters. The mean annual ET_a based on the pan method was 1983 mm compared with the annual ET_a of 2048 mm based on the Penman method. This difference of about 3% is insignificant for practical purposes.

As the results from the two methods are very similar, the pan method using mean monthly data was adopted as ET_p estimates could be more easily computed with this method. Later studies (Falkland 1991, 1992a) used mean monthly pan evaporation data for the period 1982 to 1987. Recently, additional pan data to December 1991 was obtained and the mean monthly estimates of ET_a for the periods 1982-1987 and 1982-1991 were compared. The results are very similar. The mean annual values are in fact only 1 mm different (1986 and 1987 mm for the shorter and longer periods, respectively).

TRANSPIRATION MEASUREMENTS

At the commencement of detailed water resources investigations in 1987, it was realised that coconut trees (*Cocos nucifera*), prolific on most atolls including the Cocos (Keeling) Islands, are a major source of transpiration and, hence, loss from freshwater lenses. Direct measurements of coconut tree transpiration were, therefore, undertaken during the study. Due to time limitations, lysimeter or ventilated chamber methods could not be used. Instead, measurements were undertaken using a heat pulse velocity meter. The meter and its associated electronic data logger measures and records the velocity of an injected heat pulse in the sapwood of a tree by timing movement over a known distance. The technique had been used successfully on other types of trees but never, to the author's knowledge, on coconut trees. The results obtained from the one-week study suggested that transpiration rates per tree varied from about 70 to 130 litres/day (Bartle 1987). The range of values was considered to be the result of diurnal climatic variations.

The values obtained must be considered preliminary owing to a number of simplifying assumptions and the short period of observations. Further study over a longer time period is warranted as part of general scientific research. Based on this limited data, the total transpiration rate due to coconut trees is about 400-750 mm per year per tree in areas with 100% tree cover, where typical tree spacings of about 8 metres prevail. This has implications for water resources management and it may be prudent to selectively clear coconut trees from some freshwater lens areas to maximise the supply of water.

INFLUENCE OF EL NIÑO ON THE CLIMATE

Considerable research has been undertaken into the influence of the El Niño phenomenon (also called the El Niño Southern Oscillation or ENSO) on climatic patterns, particularly in the Pacific Ocean. Effects of strong El Niño events in the Pacific Ocean include significant sea surface temperature changes, ocean current and wind direction reversals, extreme variations in rainfall patterns, higher tides, storm activity in some locations and severe droughts in others.

The influence of the El Niño phenomenon is felt more widely than just the Pacific Ocean. Some research has been conducted into the connections between El Niño events and the weather patterns occurring in the north-eastern Indian Ocean area around Indonesia. Quinn et al. (1978) studied the connections between El Niño events and droughts in Indonesia. Their general conclusion was that droughts in Indonesia, indicated by low rainfall periods on Java, occurred in years when El Niño events were evident. A significant connection between low rainfall years and El Niño events was found for Christmas Island in the Indian Ocean (Falkland 1986).

The influence of El Niño events on the rainfall of the Cocos (Keeling) Islands is outlined in Falkland (1988, 1992a). A graph showing the relationship between the Southern Oscillation Index (an index of the strength of ENSO activity) on an annual basis and annual rainfall (expressed as a percentage of mean annual rainfall) is shown in Figure 20 for the period 1953 to 1991. Negative values of SOI are associated with El Niño activity with the more negative values indicating increased strength. Positive values indicate that El Niño activity is absent.

Figure 20 shows that there is a reasonable correlation between SOI and annual rainfall, with negative annual SOI values corresponding in general with less than average rainfall and vice versa. This trend is not always present, an example being the highly negative SOI during the 1982/83 El Niño when the rainfall was near average. Using linear regression analysis between annual SOI and rainfall data, a correlation coefficient of only 0.58 was obtained, indicating that the correlation is not strong. In certain periods (for example, 1953 to 1960, 1967 to 1981) the correlation is much better as can be seen in Figure 20 (r=0.89 and 0.82, respectively). It can be concluded that there is a reasonable correlation between El Niño activity in the Pacific Ocean and rainfall in the Cocos (Keeling) Islands.

WATER RESOURCES

TYPES

The water resources of the Cocos (Keeling) Islands consist essentially of groundwater and rainwater. Where conditions are favourable, fresh groundwater occurs on coral islands in the form of shallow freshwater lenses. Such lenses are found in some of the larger islands within the Cocos (Keeling) Islands. The groundwater from these lenses has been and is currently used as the major source of freshwater for potable and other uses on Home and West Islands.

Due to the generally porous nature of the soils and underlying geology, there is no significant surface runoff. Runoff only occurs in localised areas where the ground is compacted or paved and only for very short periods after heavy rain. Rainwater collected directly from roofs of buildings is a valuable supplementary source of water.

GROUNDWATER OCCURRENCE

FRESHWATER LENS CHARACTERISTICS

Freshwater lenses occur beneath the surface of some islands. The upper surface of a freshwater lens is the water table and the lower surface is a boundary between freshwater and saline water. The lower boundary is not a sharp interface but rather is in the form of a transition zone. Within the transition zone the water salinity increases from that of freshwater to that of seawater over a number of meters.

A typical cross section through a small coral island showing the main features of a freshwater lens is presented in Figure 21. It must be noted that there is considerable vertical exaggeration in the diagram. In practice, the vertical scale is much smaller compared with the horizontal scale. The transition zone tends to be as thick as or thicker than the freshwater zone on many small coral islands. As shown in the diagram, there is often an asymmetric shape to the lens with the deepest portion displaced towards the lagoon side of the island.

The salinity of the upper surface of a freshwater lens can be obtained by measurements at exposed water surfaces such as wells and pumping galleries. The lower surface can be determined accurately by establishing a recognisable salinity limit for freshwater and drilling through the lens and testing the water at different depths for salinity. It can also be estimated approximately by surface geophysical (electrical resistivity and electromagnetic) techniques.

The salinity limit adopted for freshwater for the Cocos (Keeling) Islands is 600 mg/l chloride ion concentration. This limit is approximately equivalent to an electrical conductivity (specific conductance) reading of 2600 μmhos/cm at the standard temperature of 25°C (Falkland 1988, 1992a).

According to classical 'Ghyben-Herzberg' theory (Badon Ghyben 1889, Herzberg 1901), for every unit height of fresh water occurring above mean sea level there will be about 40 equal units of underlying fresh water below mean sea level. This theory assumes that the two fluids, freshwater and seawater, are immiscible (i.e. that they do not mix). In practice, the two fluids do mix due to mechanical and molecular diffusion and a transition zone forms with salinity gradually increasing from that of freshwater to that of seawater. In practical situations, the 1:40 ratio can be used as a guide to determine the mid-point of the transition zone from the water table elevation above mean sea level. It does not provide a means of determining the base of the freshwater zone and other methods described above are required.

INFLUENCING FACTORS ON FRESHWATER LENSES

The size and salinity distribution of freshwater lenses, particularly the thickness of freshwater and transition zones, are dependent on many factors but the most important are:

- rainfall amount and distribution,
- amount and nature of surface vegetation and the nature and distribution of soils (these factors influence the evapotranspiration),

- size of the island, particularly the width from sea to lagoon,
- permeability and porosity of the coral sediments, and the presence of solution cavities,
- tidal range, and
- methods of extraction and quantity of water extracted by pumping.

For small coral sand islands, an approximate relationship has been derived (Oberdorfer and Buddemeier 1988) between freshwater lens thickness, annual rainfall and island width as follows:

$$H/P = 6.94 \log a - 14.38$$

where

H = lens thickness (depth from water table to sharp interface or mid-point of transition zone in metres),
P = annual rainfall (metres), and
a = island width (metres).

This equation indicates that no permanent freshwater lens can occur regardless of rainfall where the island width is less than about 120 metres. Using the mean annual rainfall (1938 mm measured at the West Island meteorological station) for the Cocos (Keeling) Islands, the minimum island width for a small freshwater lens (say 5 metres thick) to occur is about 280 metres (say 300 metres). Thus, as an approximate guide, it is unlikely that a permanent freshwater lens suitable for groundwater extraction could be found on the South Keeling atoll where the width of the island is less than about 300 metres. It is noted, however, that other factors which are not accounted for in the above relationship, particularly the permeability of the coral sediments and the density of vegetation, have an effect on the occurrence of freshwater lenses. Further comments based on observed data on West Island are given later. The geological influences are considered in more detail below.

GEOLOGICAL INFLUENCES ON FRESHWATER LENSES

The geology of the South Keeling atoll consists of coral sediments, several hundreds of metres thick, overlying a volcanic seamount. From a hydrogeological viewpoint, the geology of most interest is that of the upper part of the atoll where freshwater lenses are found to occur. From a number of recent water investigations on the South Keeling atoll (Falkland 1988, 1991, 1992a, 1992b), freshwater lenses do not exceed 20 metres in thickness. Within this 20 metre zone, two major geological layers are found: a younger (Holocene), upper layer consisting of unconsolidated coral sediments and an older (Pleistocene), deeper layer of coral limestone. While no extensive investigations of surface geology have been undertaken on North Keeling atoll, it is expected that similar geological conditions would prevail there.

Similar to findings on other atolls in the Pacific Ocean, an unconformity was found from drill cores between the relatively low permeability Holocene sediments and underlying higher permeability Pleistocene limestone at depths of less than 20 metres (Falkland 1988). Using the early results and data from additional boreholes on West Island, Home Island, South Island and Horsburgh Island, the unconformity was found at depths varying between about 8 and 17 metres below ground surface (Woodroffe et al. 1991). These depths correspond, respectively, to depths between 7 and 16 metres below mean sea level.

The presence of this unconformity is due to a period of emergence of the island with solution and erosion forming a karst surface. Uranium-series dating of the older limestone indicates that it was formed during the last inter-glacial period about 120,000 years ago (Woodroffe et al. 1991). The upper sediments have been laid down in the Holocene since about 10,000 years ago. Three phases of deposition have been identified in the Holocene (Woodroffe et al. 1990a, this volume). From the start of the Holocene to at least 5000 years ago, sediments accumulated rapidly as sea level rose. A conglomerate platform radio-carbon dated at 3000 to 4000 years ago was then formed during a period of relatively stable sea level. Since then unconsolidated sands and larger sediments have been deposited to form the present reef islands. Dating of *in-situ* corals has shown that the sea level was about 0.5 to 1.5 metres higher about 3000 years ago than today (Woodroffe et al. 1990a, 1990b).

The unconformity described above is very significant to the formation of freshwater lenses. The limestone sediments below this unconformity have relatively high permeabilities and mixing of freshwater and seawater is readily facilitated. In the relatively less permeable upper sediments, mixing is less likely to occur. The unconformity, therefore, is one of the main controlling features to the depth of freshwater lenses.

WATER BALANCE AND RECHARGE ESTIMATION

RECHARGE

The freshwater lenses in the Cocos (Keeling) Islands are recharged naturally from rainfall. Not all rainfall incident on the islands, percolates to groundwater, as much of it is evaporated or transpired. Essentially, natural recharge is the net input from rainfall to groundwater after all evaporative losses have been deducted and soil moisture requirements have been met.

It is important that accurate estimates of recharge be obtained as it is one of the main determinants of the sustainable yield of freshwater lenses. Recharge can be estimated by a number of techniques. One of the most common and useful techniques is a water balance (or water budget) approach where water inputs to, and water outputs from, the surface of the island are quantified. This approach was used in water resources investigations of Home and West Islands (Falkland 1988, 1992a) and South Island (Falkland 1991).

WATER BALANCE EQUATION

Recharge can be described by a water balance equation using a specified reference zone and a specified time interval. The reference zone for a freshwater lens on a coral atoll is that zone extending from above the surface of the island down to the water table. In this zone, the flow of water is essentially vertical. The water balance equation for the upper zone on a coral island, such as those in the Cocos (Keeling) Islands, can be described as:

$$R = P - ET_a + dV$$

where

R = recharge,
P = rainfall,

ET_a = actual evaporation from all surfaces, and
dV = change in storage within the soil moisture zone (it can be a positive or negative change)

As noted earlier, there is no term for surface runoff as this does not occur due to the very high infiltration capacity of the coral soils.

The actual evaporation term (ET_a) includes evaporation from interception storage (for example, the leaves of trees, bushes and grass), from vegetation tapping water from the soil moisture zone and from trees with roots that penetrate to the water table and thus transpire water directly from the freshwater lens.

Computations with this equation were conducted using a daily time interval, as recommended by Chapman (1985). It has been shown that computations using a monthly time step leads to an under-estimation of recharge for the Cocos (Keeling) Islands (Falkland 1988) and on other atolls (for example, Kwajalein: Hunt and Peterson 1980). Daily rainfall data and mean daily evaporation estimates were, therefore, used.

DESCRIPTION OF THE RECHARGE MODEL

A recharge model was developed, and a computer programme (WATBAL) written, to simulate the water balance in the upper zone and derive a monthly time series of recharge. The model is shown in Figure 22 and a brief description follows.

The recharge model allows for interception storage by vegetation. A maximum value for the interception storage (ISMAX) can be defined and it is assumed that this store must be filled before water is made available to the soil moisture storage. Typical values of ISMAX are 1 mm for predominantly grassed catchments and 3 mm for catchments consisting predominantly of trees (particularly coconut trees). The airfield area on West Island is predominantly grassed while South Island and some of the northern parts of West Island consist predominantly of trees. Much of Home Island is intermediate between these two limits. Evaporation is assumed to occur from the interception storage at the potential rate.

The recharge model incorporates a soil moisture zone from which the roots of shallow rooted vegetation (grasses, bushes) and the shallow roots of trees can obtain water. Water requirements of plants tapping water from this zone are assumed to be met before any excess drains to the water table. Maximum (field capacity) and minimum (wilting point) limits are set for the soil moisture in this zone. Above the field capacity, water is assumed to drain to the water table. Below the wilting point, no further evaporation is assumed to occur.

The thickness of the soil moisture zone (SMZ) for the Cocos (Keeling) Islands was estimated as 500 mm based on observations of the soil profile and from studies on other atolls. Field capacity (FC) was assumed to be 0.15 based on observations of local soil type and typical values for this type of soil. Wilting point (WP) was assumed to be 0.05 based on typical values (for example, Linsley and Franzini 1973) for sand-type soils and from studies elsewhere. The operating range of soil moisture is thus assumed to be from 25 mm to 75 mm.

In the model, the amount of evaporation from the SMZ is assumed to be related to the available soil moisture content. At WP, zero losses due to evaporation are assumed to occur from this zone. Maximum or potential evaporation is assumed to occur when the soil moisture zone is at FC. A linear evaporative loss relationship is assumed to apply between the two soil moisture limits. Thus, at a soil moisture content midway between FC and WP, for instance, the evaporation rate is half that of the potential rate.

Water entering the water table is 'gross recharge' to the freshwater lens. A further loss, however, is experienced due to transpiration of trees whose roots penetrate to the water table. 'Net recharge' is that water remaining after this additional loss is subtracted from 'gross recharge'. Observations in dug pits and trenches on Home and West Islands reveal that a considerable number of roots penetrate to the capillary fringe just above the water table which typically occurs at depths of one to two metres below ground level. It is estimated that about 50% of the roots from mature coconut trees penetrate to the water table. Because the movement of the water table is relatively small, even during drought periods, these roots allow transpiration to occur even when the soil moisture store has been depleted. This is the reason that coconut trees are able to survive prolonged drought periods on coral atolls when other shallow rooted vegetation has reached wilting point and possibly died.

Vegetation is assigned a 'crop factor' (Doorenbos and Pruitt 1977) according to its type. Each plant (or crop) type has its evaporative potential compared with that of a 'reference crop'. The reference crop evaporation is equal to the potential evaporation, as derived from an appropriate method. The crop factor is a coefficient which is used to derive an adjusted potential evaporation of other crops from the potential evaporation (or the reference crop evaporation).

The crop factor for most grasses and other shallow rooted vegetation is assumed to be 1.0. The crop factor for coconut trees was taken as 0.8 based on values for similar types of trees listed in Doorenbos and Pruitt (1977). Thus, the potential evaporation rate for coconut trees is taken to be 80% of that for grasses or other shallow rooted vegetation.

The proportions of freshwater lens areas covered by deep rooted vegetation were estimated from coloured aerial photographs taken in April 1987 and from ground inspection. From recent investigations (Falkland 1991, 1992a), the proportions were estimated to be 0.15 for Home Island, 0 for the West Island Airfield and 0.8 for the northern part of West Island and South Island.

RESULTS AND DISCUSSION

Water balance analyses were conducted for freshwater lenses on West, Home and South Islands in a number of studies (Falkland 1988, 1991, 1992a). Series of monthly recharge estimates were obtained in each case, enabling drought sequences to be further analysed for estimation of sustainable yields.

Graphical comparisons of annual recharge and annual rainfall (obtained by summation of monthly values) for the period 1953 to 1991 are provided in Figures 23 and 24 for, respectively, the West Island Airfield Lens and the West Island Northern Lens.

A significant variation in recharge from year to year can be seen from Figures 23 and 24. In some years, recharge is actually negative (i.e. there is a net loss of water from the freshwater lens). Figure 24 shows that 'negative recharge' occurred in the Northern Lens in 1953, 1962, 1977 and 1991 with the most negative value occurring in 1991 (corresponding to the lowest annual rainfall). In general, years of high annual rainfall result in years of high annual recharge and vice versa. However, there is no simple relationship between the two parameters. This is because annual recharge is a function of the pattern of daily rainfall and not simply a function of the annual rainfall total.

For the 39 year period of record (1953-1991), the following mean annual recharge estimates were obtained:

- West Island Airfield Lens:	950 mm/year (49% of rainfall),
- Home Island Lens:	855 mm/year (44% of rainfall),
- West Island Northern Lens:	564 mm/year (29% of rainfall).

The results for South Island are the same as for the Northern Lens as similar parameters were used in the recharge analysis.

Figure 25 compares the annual recharge estimates from three lenses (West Island Airfield and Northern Lenses and the Home Island Lens). There are significant recharge differences between the three lenses, the main cause being differences in the density of the deep rooted vegetation, predominantly coconut trees, above the freshwater lens areas. Figure 26 shows the relationship between mean annual recharge (as a percentage of rainfall) and the percentage tree cover. This graph and the tabulated results above show that recharge can nearly be doubled by reducing the tree cover from 80% (as for the Northern Lens) to zero (as for the Airfield Lens). Due to the significant effect that coconut tree density has on groundwater recharge, one management option for increasing freshwater supplies is to selectively clear vegetation in areas where freshwater lenses occur (see also section on transpiration measurements).

Cumulative annual recharge graphs for the West Island and Home Island lenses are shown in Figure 27. These graphs enable sequences of dry and wet years to be easily seen. For instance the lowest 5 year recharge period occurred from early 1976 to the end of 1981. Another low recharge period of 5 years occurred from early 1961 to the end of 1965.

GROUNDWATER INVESTIGATIONS

In the previous section, a number of freshwater lenses were named (e.g. West Island Airfield Lens, West Island Northern Lens and Home Island Lens). Groundwater investigations over a number of years were conducted to locate and quantify the depth and areal extent of these lenses. This section briefly describes these investigations and details of the freshwater lenses.

PRELIMINARY INVESTIGATIONS

The groundwater resources were first studied by Jacobson (1976a, 1976b). His investigation was limited to Home Island and involved observations of water table elevations and salinities of shallow water obtained from wells. Using this limited information he estimated the thickness of the freshwater lens at 10 to 15 metres and the sustainable yield to be 200 kilolitres per day. He recommended that more detailed investigations were warranted to confirm the preliminary results obtained. Later investigations showed that the actual thickness of the lens was not greater than 6 metres and that the estimated sustainable yield was approximately half of his estimate.

DETAILED INVESTIGATIONS

Detailed investigations of the groundwater resources were undertaken from 1988 to 1992 (Falkland 1988, 1991, 1992a, 1992b). The aims of the groundwater investigations were to determine the location, lateral extent and depth of freshwater lenses and to determine hydrogeological properties necessary for an analysis of long-term sustainable yields from the lenses.

A combined drilling and geophysical programme was used. This combined approach allowed for an accurate determination of the thickness of lenses at selected locations using the drilling programme and for reasonable estimates at intermediate sites using the electrical resistivity method. The drilling programme was relatively slow and costly but yielded accurate data whereas the resistivity programme was relatively quick and inexpensive but had a lower level of accuracy. The latter method, however, provided good estimates of lens thickness after correlation with salinity profiles obtained at borehole sites.

A limited amount of seismic work was conducted at boreholes to gain a better understanding of the subsurface geological properties. Observations of topographic features, measurement of salinity levels at exposed water surfaces (wells, ponds, pumping galleries) and recording of water table movements relative to tidal movements were conducted to provide additional data.

Details of all the investigations are beyond the scope of this report. Some details about the drilling programme are provided, however, as they were the most useful in terms of initial and continuing data about the freshwater lenses.

A total of 29 boreholes were drilled from 1988 to 1992 on West Island (16 holes), Home Island (12 holes) and South Island (1 hole) and equipped with salinity permanent monitoring systems. Details of these holes including year of drilling, reduced level (RL) relative to mean sea level (MSL), depth to water table and depth to the unconformity between Holocene and Pleistocene sediments are shown in Table 10. The location of the boreholes are shown in Figure 28. Drilling logs with further details are contained in Murphy (1988), Falkland (1991), Murphy and Falkland (1992a) and Falkland (1992b).

The permanent salinity monitoring system used in each borehole is shown diagrammatically in Figure 29. Water samples are pumped to the surface from each of the separate tubes by a portable electric pump and tested for electrical conductivity. Using the monitoring data, salinity profiles can be constructed for each borehole at intervals of typically one to three months. By obtaining a set of such salinity profiles, the salinity distribution over time can be viewed for each borehole. This data has yielded valuable information about the response of the freshwater lenses to variations in recharge. Figures 30 and 31 show the variation in the depth to the base of the freshwater zone in a number of West Island (Airfield Lens) and Home Island boreholes together with monthly recharge for the period 1988 to 1991. The antecedent recharge in 1987 is also shown.

The permeability of the coral sediments was measured *in-situ* using falling head tests in some of the boreholes during drilling. The average permeability in the Holocene sediments was about 6 metres per day while the average permeability in the upper part of the Pleistocene sediments was about 30 metres per day. On occasions during drilling below the unconformity, karst zones such as solution channels were intersected where circulation (of water and drilling mud) was lost. In some of these zones, the permeability was estimated to reach 1000 metres per day. The specific yield (or effective porosity) was estimated to be 0.3.

FRESHWATER LENS DETAILS

Using the results of the drilling, geophysical and other investigations, freshwater lenses were located on West, Home and South islands.

On West Island, two permanent freshwater lenses have been identified underlying, respectively, the airfield and the northern part of the island. These have been named, respectively, the Airfield Lens and the Northern Lens. A permanent freshwater lens has been identified on Home Island underlying the inhabited area. In addition, one large and two smaller lenses have been identified on South Island (Falkland 1991). The locations of these lenses are shown in Figure 28.

Approximate areas, maximum freshwater thicknesses, volumes and turnover times of these lenses are shown in Table 11. The areas and volumes vary with time according to antecedent recharge conditions. The areas shown in Table 3 are the maximum values and the volumes are the range of values estimated during the period of record. The turnover times are a measure of the average residence time of water within the freshwater zone and are calculated by dividing the average thickness of the freshwater zone by the mean annual recharge. A cross section through one of the lenses including details of a number of boreholes is shown in Figure 32.

Some of the other islands in the Cocos (Keeling) Islands also have small freshwater lenses. Based on limited on-site tests (Jacobson 1976a, Falkland 1988), a freshwater lens is known to exist on Horsburgh Island but its sustainable yield cannot be assessed without further investigation. Preliminary investigations on North Keeling (Falkland 1988, 1992b) indicate the presence of a very thin freshwater lens at least on part of the island. It is not known whether the lenses on Horsburgh Island and North Keeling are permanent.

A major influence on the thickness of the thicker lenses, particularly the Airfield Lens, is the geological unconformity between upper and lower sediments. As stated earlier, this unconformity is a very significant influence on the formation of freshwater lenses as the sediments below this unconformity have relatively high permeabilities and mixing of freshwater and seawater is readily facilitated. The depths to the unconformity are shown in Table 10. In all but one borehole in the Airfield Lens, the freshwater limit (2600 µmhos/cm) occurs at all times within a zone about 2 to 3 metres below this unconformity. In general, it is evident that the unconformity is providing a limit to the formation of a deeper freshwater lens. When recharge is low, as occurred in 1991, the lens contracted to a position close to or above the unconformity. In dry periods, therefore, the lens becomes limited by recharge at this location while in wetter periods the lens is limited by the geology. It can be concluded that the underlying geology has a strong influence on the freshwater lens at the Airfield. Some of the boreholes in the Northern Lens exhibit similar behaviour while others within that lens and all of the Home Island boreholes show that the freshwater lens is contained wholly within the Holocene sediments.

An interesting observation was made in the most recent investigations (Falkland 1992b). At borehole WI 22 near the southern end of the Northern Lens a reasonably thick freshwater zone of 7 metres was found during drilling in August 1992. The thickness of the lens to the mid-point of the transition zone (25,000 µmhos/cm) was about 11 metres. This result was better than expected as the width of the island at this location is only about 270 metres. Based on the approximate relationship outlined earlier, the minimum width required to support a freshwater lens of this thickness is over 750 metres. This shows that the approximate relationship should be treated with some caution as other factors not accounted for may have a significant bearing on lens thickness. At this borehole the unconformity occurs at almost precisely the same depth as the limit of the freshwater zone, indicating that it is a major influencing factor. Based on thickness and salinity of the freshwater zone at borehole WI 22, it is considered that the lens at this location will not disappear during drought periods. Future monitoring data will be used to establish the validity of this assumption.

FRESHWATER LENS DYNAMICS AND MODELS

Flow through freshwater lenses is complex and is influenced by hydrologic (variable recharge), geologic (variable permeabilities with depth and with distance from one side of island to the other), oceanic (tidal movements) and anthropogenic (water extraction) factors.

Early conceptual models and solution techniques for freshwater lens flow assumed a sharp interface between freshwater and seawater. Observations have shown that this is not the case on atolls and wide transition zones are the norm. Sharp interface models can at best only provide an estimate of the depth to the mid-point of the transition zone, yielding no information about transition zone width. Such models also assumed horizontal flow within the lens with freshwater outflow occurring around the perimeter of the island and did not account for tidal movements.

A more realistic conceptual freshwater lens flow model has evolved (Buddemeier and Holladay 1977, Wheatcraft and Buddemeier 1981, Oberdorfer et al. 1990, Peterson 1991, Underwood et al. 1992) based on detailed observations on atolls. The conceptual model accounts for vertical and horizontal tidal propagation through a dual aquifer system consisting of the upper (Holocene) and lower (Pleistocene) sediments. This conceptual model is supported by observations on a number of atolls in the Pacific (Buddemeier and Holladay 1977, Hunt and Peterson 1980, Wheatcraft and Buddemeier 1981, Anthony et al. 1989) and in the Cocos (Keeling) Islands (Falkland 1988) which have shown that tidal lags and efficiencies at water level monitoring locations within atolls are largely independent of horizontal distance from the shore. Tidal lag and efficiency (or the time difference between, and amplitude ratio of, water table movement to tidal movement) are in fact greatly influenced by the depth of the holes used for water level monitoring. Vertical propagation of tidal signals tends to be dominant in the middle of the island whereas both horizontal and vertical propagation are significant near the edges.

Using the above conceptual model, the numerical solution of freshwater lens flow problems can more realistically be made with models which can account for a two layered hydrogeologic system, flow of variable density water and the mixing of fresh water and seawater. One such computer model, SUTRA, developed by the United States Geological Survey (Voss 1984) has been applied to the study of freshwater lenses and coastal aquifers on a variety of islands. Case studies of atolls and small carbonate islands include Enewetak atoll, Marshall Islands (Oberdorfer and Buddemeier 1988, Oberdorfer et al. 1990), Majuro atoll, Marshall Islands (Griggs and Peterson 1989) and Nauru, a raised atoll, (Ghassemi et al. 1990).

SUSTAINABLE YIELDS

The sustainable (or safe) yield of an aquifer is the rate at which water can be extracted without causing adverse effects. For non-coastal mainland aquifers, the sustainable yield can be approximately equated to the long-term recharge. For freshwater lenses on small islands and some coastal mainland aquifers, such an approximation is not valid as only a small portion of the recharge is available as sustainable yield. Most of the recharge is required to counteract the effects of dispersion between the freshwater layer and underlying saline water.

To avoid adverse effects from extraction (i.e. to avoid an increase in the salinity of extracted water), the overall extraction rate from the lens should not exceed the sustainable yield. An additional requirement is that pumping be distributed over the surface of the lens to avoid local upconing of saline water.

Methods for estimating sustainable yield range from simple empirical approaches to complex numerical models (e.g. SUTRA). Due to time limitations, an empirical approach suggested by Mink (1976) was adopted for the Cocos (Keeling) Islands. Mink suggested that an extraction equal to 25% of the 'flux' or flow through the lens was a good first approximation to the sustainable yield. This is equivalent to 20% of the mean annual recharge based on the simple water balance equation for the freshwater lens outlined below.

The water balance equation within the lens can be expressed simply as:

$$R = Q + X + dV$$

where

- R is the recharge into the lens after all evapotranspiration losses have been taken into account, including transpiration directly from the lens by deep-rooted vegetation,
- Q is the lens 'flux' (outflow at the edge of the lens and mixing with the transition zone at the base of the lens),
- X is the total amount of water pumped from the lens,
- dV is the change to the freshwater volume.

In the long term, dV tends to be negligible and can be removed from the equation. Hence, the equation can be written as:

$$R = Q + X$$

This indicates that the maximum extraction (or sustainable yield) is 20% of mean annual recharge based on the condition that extraction should be less than 25% of flow through the lens. Given that mean recharge in the Cocos (Keeling) Islands is in the order of 25 to 50% of mean rainfall, the allowable extraction (or sustainable yield) is about 5 to 10% of mean rainfall.

In relatively stable lenses, a proportion greater than 20% of the available recharge can be extracted without adverse effects on the lens. In a study of the 'Central Lens' on

Bermuda, for instance, it has been suggested that about 75% of recharge could be extracted (Rowe 1984). This, however, is not considered appropriate for thin lenses, such as the Home Island Lens, at least until further monitoring results provide a more accurate insight into lens dynamics. In fact, because the Home Island Lens is a very thin and fragile lens, there is a strong case for lowering the sustainable yield estimate to slightly less than 20% of recharge. A value of 17% of recharge based on current pumping there (115 kilolitres/day) was adopted as the sustainable yield at least until more extensive salinity monitoring records are obtained and analysed.

Under present vegetation conditions, the sustainable yields of the major lenses are estimated to be (Falkland 1991, 1992a, 1992b):

- West Island Airfield Lens: 520 kilolitres/day,
- West Island Northern Lens: 300 kilolitres/day,
- Home Island Lens: 115 kilolitres/day,
- South Island lenses: 220 kilolitres/day,

If vegetation was substantially cleared from above some of these lens areas, the sustainable yield could be increased. In particular, it is estimated that the yields from the Northern Lens and from the lenses on South Island could be increased, respectively, to 400 and 330 kilolitres/day.

It is noted that the sustainable yields for the Cocos (Keeling) Islands are based on an empirical approach. This approach, based on observations of the effects of pumping and on the results of extensive modelling on other atolls, has been shown to be at least a good approximation. It is noted that a similar 20% of mean annual recharge was used to estimate sustainable yield for the island of Laura on Majuro atoll in the Marshall Islands (Hamlin and Anthony 1987). The effects of pumping at different rates were investigated by Griggs and Peterson (1989) using the SUTRA model. They concluded that the lens was capable of extracting at least 20% and up to 30% of mean annual recharge. At extraction rates of 40% of mean annual recharge, the upconing of seawater below the gallery systems was found to be excessive.

For the freshwater lenses in the Cocos (Keeling) Islands, it is intended that salinity monitoring at the network of monitoring boreholes will continue. Long term records obtained from these boreholes will enable the effects of recharge and extraction on the lenses to be evaluated. Adjustments to the present sustainable yield estimates may then be warranted.

GROUNDWATER DEVELOPMENT

On small coral islands, such as the Cocos (Keeling) Islands, small hand dug wells have been used for extraction of small quantities of water (e.g. at the household level). For larger centralised water supply systems, more extensive systems are required. There are three main alternative systems for larger scale pumping of water from freshwater lenses, as follows:

- borehole systems,
- wells, and
- infiltration galleries.

Boreholes and wells, while possibly suitable in large freshwater lenses, are not considered suitable in the Cocos (Keeling) Islands because they extract from a localised area and can lead to excessive drawdowns. To avoid excessive drawdowns, many boreholes or wells would need to be drilled or dug. The cost of drilling or excavating, pumps and pipework would not be economical for the quantity of water extracted.

Infiltration galleries (or 'skimming wells') are considered to be the best solution as they skim water from the surface of the lens thus minimising drawdown. These types of systems have recently been installed on Home Island and in the West Island Northern Lens. In many cases they have replaced earlier dug well systems with short radial pipes extending from their bases.

Infiltration galleries consist of a horizontal, permeable conduit system laid at or close to mean sea level, enabling water to be easily drawn towards a central pump pit. Figure 33 shows the type of infiltration gallery used on Home Island (Falkland 1988). Salinity data collected before and after the galleries were installed have shown a general reduction in the salinity of the pumped water.

Current water usage from each of the major lenses as a proportion of the estimated sustainable yields are as follows:

- West Island Airfield Lens: 27%
- West Island Northern Lens: 50% (present vegetation), 30% (cleared vegetation),
- Home Island Lens: 100%, and
- South Island lenses: 0%

It can be seen there is ample capacity for expansion of current water usage at the Airfield Lens and no spare capacity on Home Island. The Northern Lens has sufficient spare capacity for some additional use, particularly if some clearing of the existing thick vegetation occurred. South Island remains at present an untapped resource.

OTHER WATER RESOURCES

Roof catchments and relatively small tanks (mainly 4.5 kilolitre capacity) provide supplementary rainwater to Home Island residents. Rainwater is also collected from a limited number of buildings on West Island.

Desalination of seawater or brackish groundwater is a possibility but would be expensive. A detailed analysis of water resources (Falkland 1988) showed that groundwater is the cheapest resource to develop. Using Home Island for a pilot study, it was found that the unit costs (capital plus operating costs) of a desalination plant using the reverse osmosis principle would be about 7 times more expensive than the development of groundwater. Even if groundwater was piped from South Island to Home Island, an option which in the long term may be preferable if the Home Island lens becomes polluted, desalination would be more expensive by a factor of 3. By comparison, rainwater catchment as the sole source of water is the most expensive, being about 10 times more expensive than groundwater development on Home Island.

The most appropriate option from an economic, quality and security viewpoint was the development of groundwater as the primary source of water with rainwater being used as a supplementary source. This option has been implemented.

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Table 5. Wind speed (metres/sec).

Month	Daily Mean (1952-1987)	Extreme Max. (1952-1991)	Extreme Min. (1952-1991)
January	5.3	48.8	0
February	4.6	34.0	0
March	5.3	28.3	0
April	6.1	29.3	0
May	6.9	27.8	0
June	7.0	30.9	0
July	7.8	24.7	0
August	8.0	36.0	0
September	8.1	24.2	0
October	7.5	24.2	0
November	7.2	40.1	0
December	6.0	27.3	0

Table 6. Cyclones passing over or close to the Cocos (Keeling) Islands, since 1960.

Name and number	Date of passing closest to island	Approx distance away (km)	Min. central pressure when passing closest to island/ min. pressure on island(hecto-pascals)	Max. wind speed on island (km/hour)	Total rainfall (mm)
Unnamed (668)	13/2/61	60	991/992	122	71
Hazel (542)	9/3/64	80	988/991	102	121
Carol (548)	27/12/65	100	997/1002	95	48
Nancy (555)	14/3/66	100	997/1000	91	26
Doreen (566)	21/1/68	20	970/970	176	219
Dianne	6/1/70	80	996/1005	98	124
Paula (591)	27/3/73	20	999/1006	83	25
Annie (682)	25/11/73	40	995/1002	145	71
Deidre (684)	21/12/73	30	995/994	85	72
Denise (455)	23/5/75	30	995/1002	100	28
Daphne (711)	15/1/82	60	995/998	81	66
Annette (696)	5/2/84	30	994/999	81	142
Daryl (699)	11/3/84	80	984/1001	92	253
Ophelia (742)	12/1/86	30	986/1002	93	252
Alison (752)	8/4/86	30	988/1002	106	112
Frederic (784)	30/1/88	40	988/995	111	90
Herbie (783)	19/5/88	50	990/995	87	57
John (767)	25/1/89	10	997/1000	61	106
Leon (769)	17/2/89	90	990/1006	63	27
Pedro (786)	10/11/89	100	982/1001	137	299
Graham (802)	5/12/91	100	925/1004	98	49
Harriet (803)	27/2/92	10	975/982	163	80
Ken	21/12/92	55	990/1001	111	162

Notes:

- data are from the Bureau of Meteorology's cyclone database and other information
- listed are cyclones which passed within 100 km of the islands and had a minimum central pressure less than 1000 hectopascals
- rainfall totals are to the nearest 1 mm over a 2 day period.

Table 7. Annual rainfall (mm) at three raingauge sites on the South Keeling atoll.

Year	West Island (Met Station)	Home Island	West Island (Quarantine)	% variation from West Island
1987	1871	1222	-	
1988	2220	1976	-	
1989	1963	1863	2210	
1990	2271	2145	2410	
1991	856	837	820	
1992	2579	2568	2637	
Total (1987-92)	11760	10611	-	-10.8
Total (1988-92)	9889	9389	-	-5.2
Total (1989-92)	7669	7413	8077	-3.4/+5.3

Table 8. Monthly rainfall (mm): 1952-1991 data.

Month	Monthly Mean	Mean Monthly Max.	Mean Monthly Min.
January	199	561	7
February	161	409	7
March	232	630	39
April	234	551	21
May	194	646	17
June	201	649	7
July	217	643	25
August	201	468	18
September	217	277	3
October	70	512	4
November	94	574	3
December	114	447	5

Table 9. Pan evaporation (mm): 1982-1991 data.

Month	Monthly Mean	Mean Monthly Max.	Mean Monthly Min.
January	220	254	195
February	198	220	170
March	205	226	195
April	189	207	165
May	189	211	146
June	171	186	150
July	186	198	174
August	208	226	171
September	219	249	201
October	229	251	217
November	231	246	222
December	241	273	217

Table 10. Monitoring borehole details.

Lens and Borehole	Year of drilling	RL relative to MSL (m)	Depth of water table (m)	Depth of unconformity (m)
Airfield Lens, West Island				
WI 1	1987	2.16	1.8	12.6
WI 2	1987	2.84	2.6	11.7
WI 6	1987	2.33	1.7	11.8
WI 7	1987	3.11	2.5	12.9
WI 8	1988	1.33	0.9	10.3
WI 9	1988	3.57	3.3	13.4
WI 11	1990	2.93	1.9	12.9
Northern Lens, West Island				
WI 3	1987	1.74	1.5	12.0
WI 4	1987	1.65	1.2	14.9
WI 5	1987	1.85	1.9	14.8
WI 10	1988	1.70	1.2	13.2
WI 12	1990	1.43	1.4	10.5
WI 13	1990	1.18	1.3	15.2
WI 14	1990	1.37	1.5	14.7
WI 15	1990	1.71	1.4	14.6
WI 16	1990	n.a.	1.4	12.3
WI 17	1992	2.56	2.2	12.7
WI 18	1992	2.09	1.6	10.5
WI 19	1992	2.19	1.8	15.4
WI 20	1992	1.81	1.6	12.2
WI 21	1992	1.77	1.4	12.2
WI 22	1992	2.21	2.1	9.3
Home Island				
HI 1	1987	2.05	1.6	>15.5
HI 2	1987	1.26	1.0	10.6
HI 3	1987	1.89	1.6	11.9
HI 4	1987	1.70	1.1	9.6
HI 5	1987	1.65	1.1	>12.2
HI 6	1987	1.59	1.2	17.2
HI 7	1987	1.52	1.0	>15.6
HI 8	1987	1.27	1.0	>12.2
HI 9	1990	1.27	1.1	>15.8
HI 10	1990	1.26	1.0	>16.0
HI 11	1990	1.08	1.5	>16.1
HI 12	1990	1.14	1.7	>15.9
South Island				
SI 1	1990	n.a.	1.4	13.8

n.a. = not available

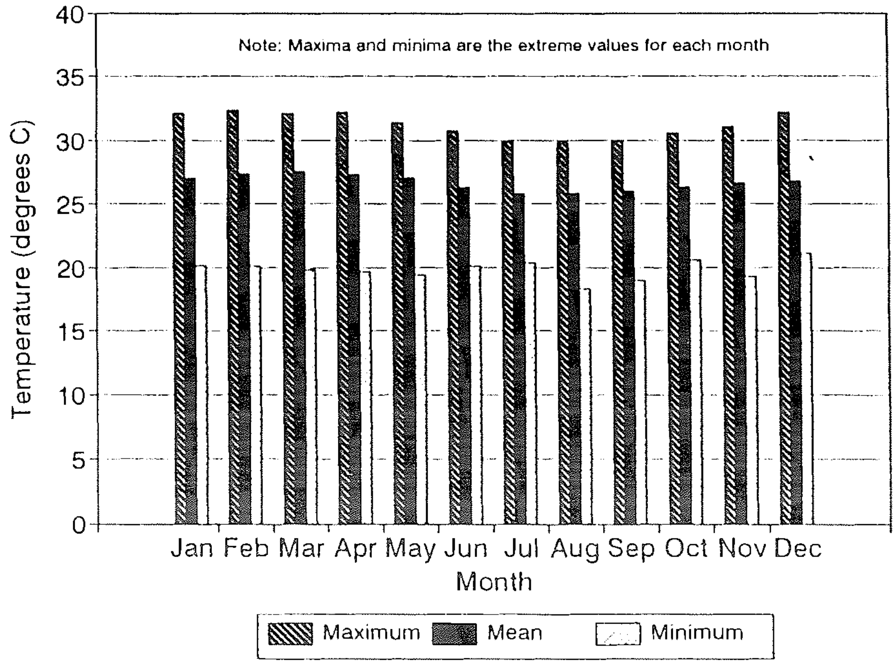

Figure 1. Mean, maximum and minimum daily temperature.

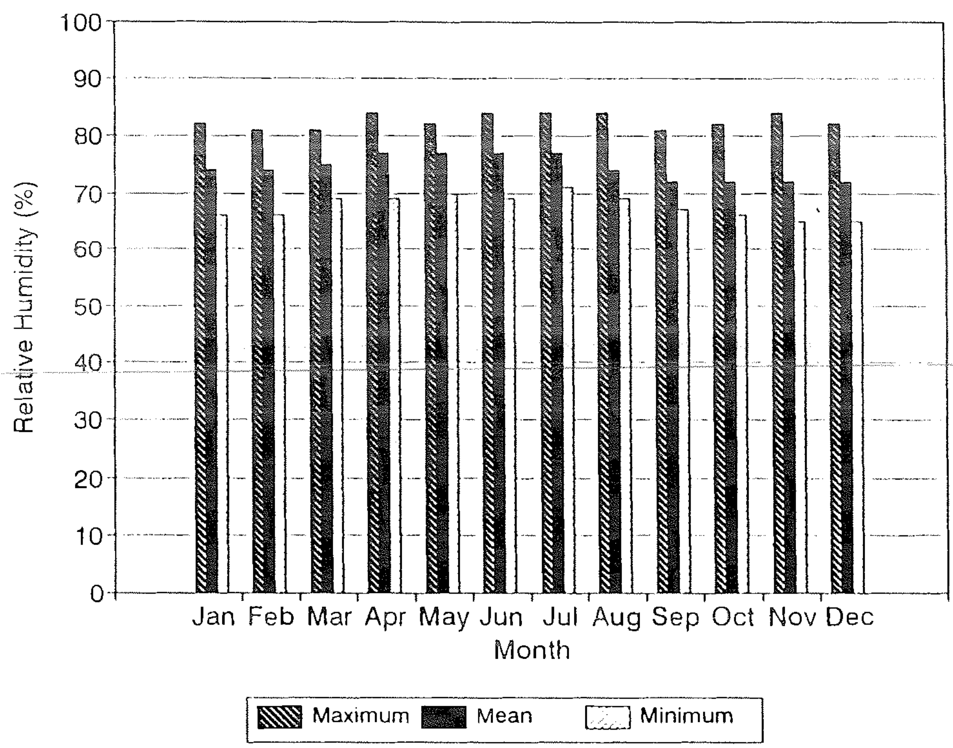

Figure 2. Mean, maximum and minimum relative humidity.

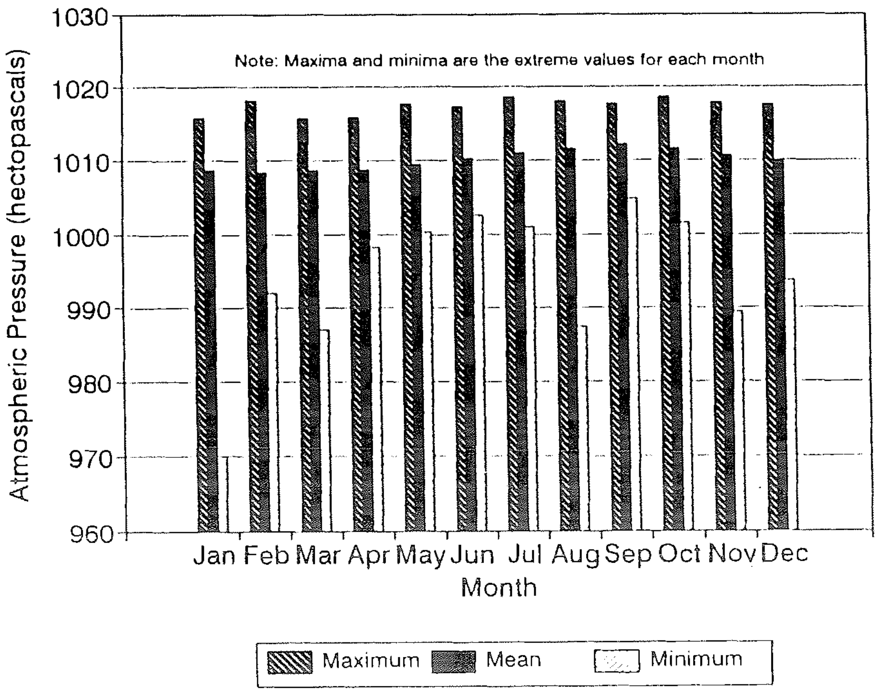

Figure 3. Mean, maximum and minimum atmospheric pressure.

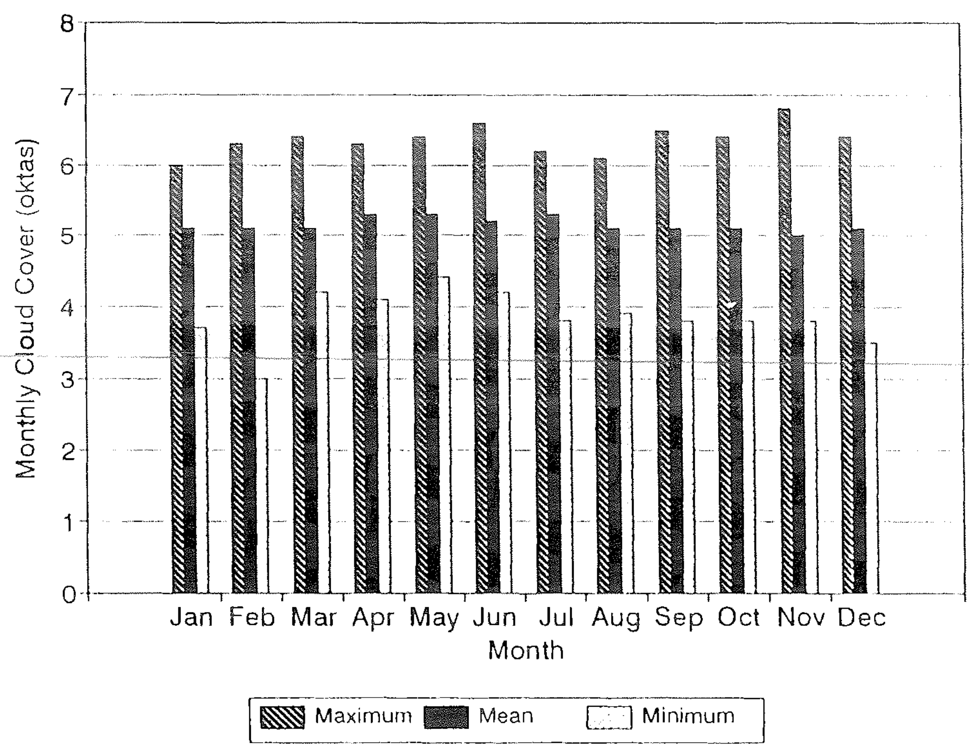

Figure 4. Mean, maximum and minimum cloud cover.

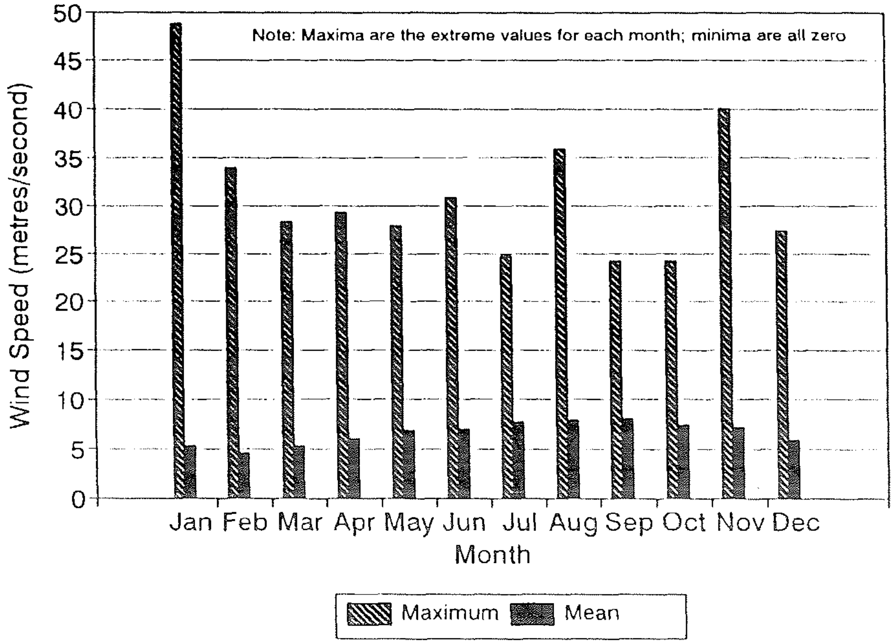

Figure 5. Mean, maximum and minimum wind speed.

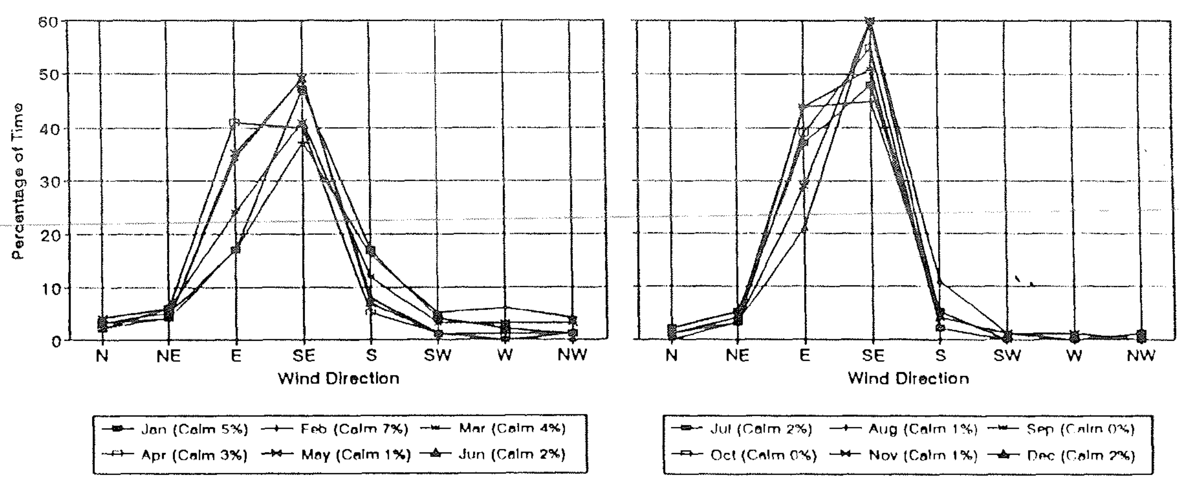

Figure 6. Wind direction.

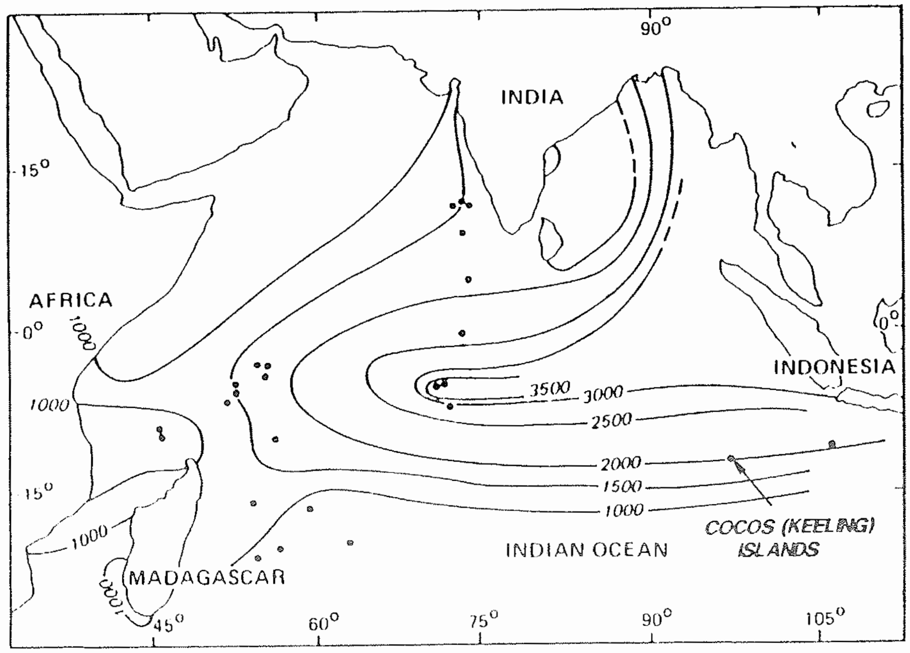

Figure 7. Isohyetal map of mean annual rainfall for the Indian Ocean (modified from Stoddart 1971).

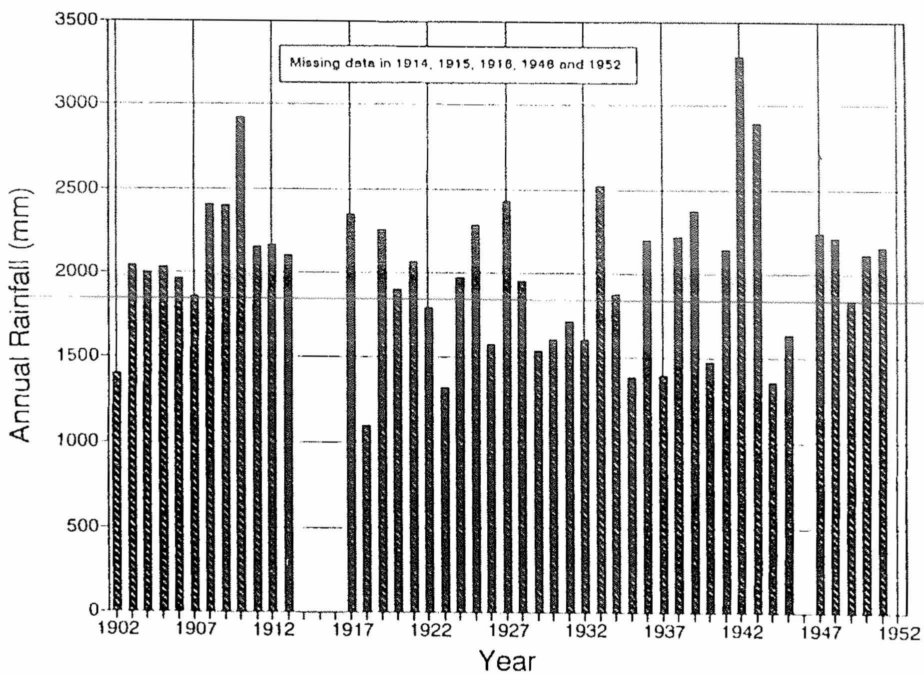

Figure 8. Annual rainfall, 1953-1991 (composite record with some missing data).

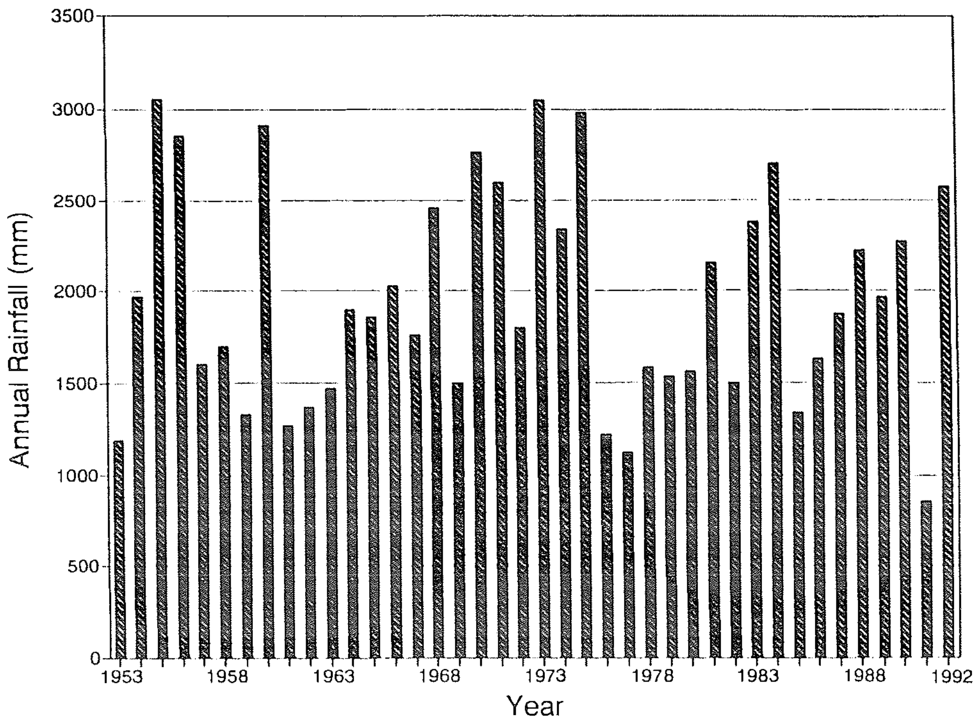

Figure 9. Annual rainfall, 1953-1991 (West Island meteorological station record).

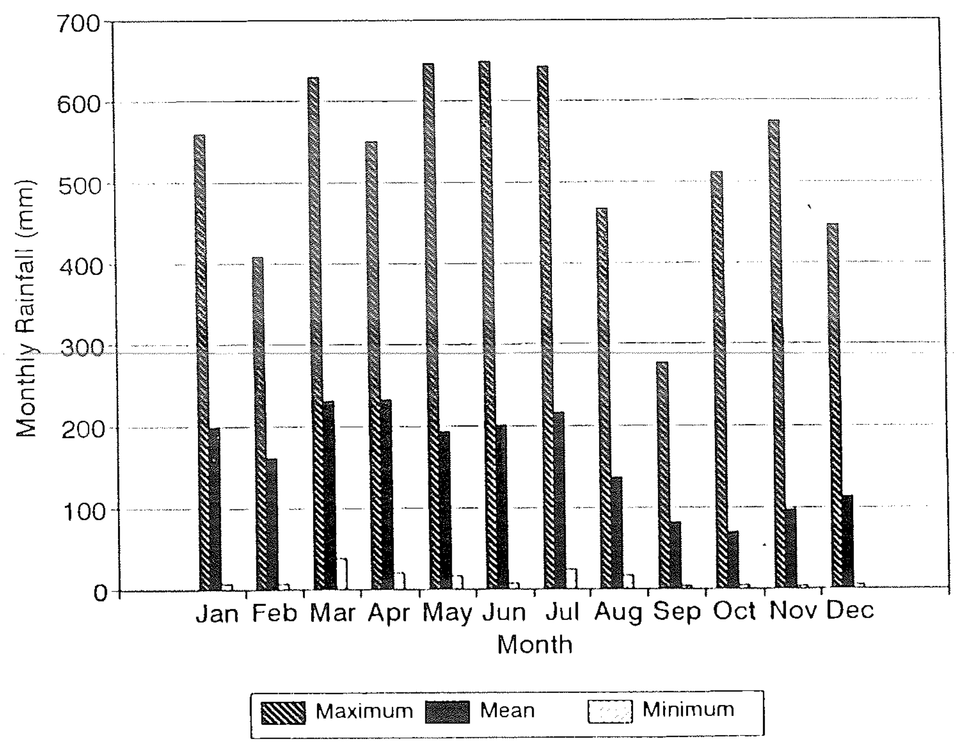

Figure 10. Mean, maximum and minimum monthly rainfall.

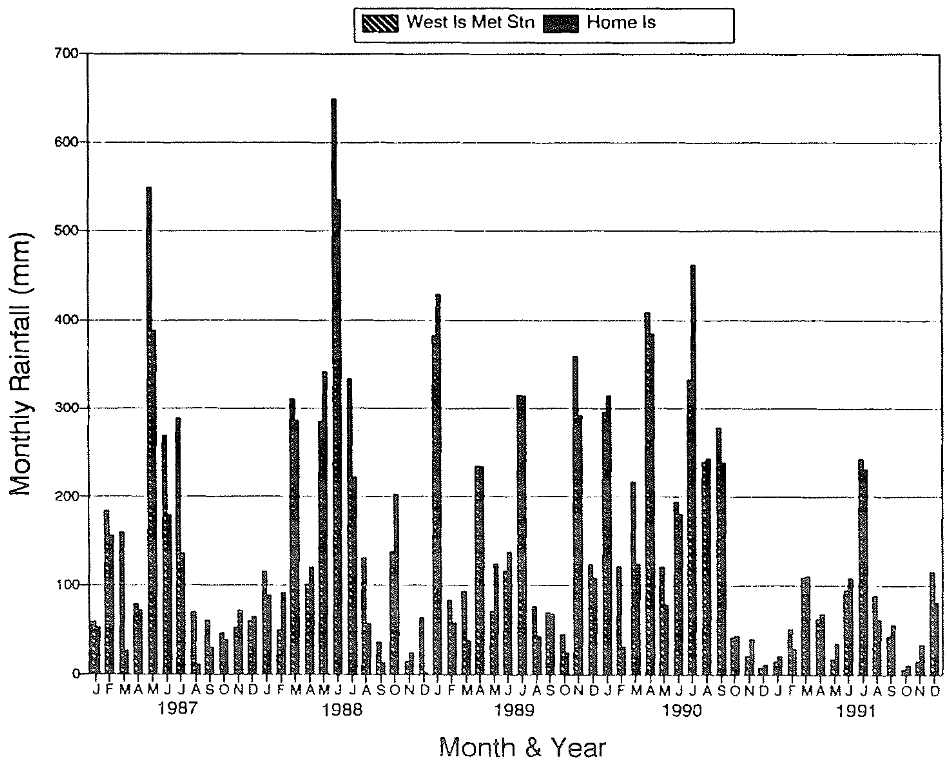

Figure 11. Monthly rainfall at thee meteorological station and Home Island, 1987-1991.

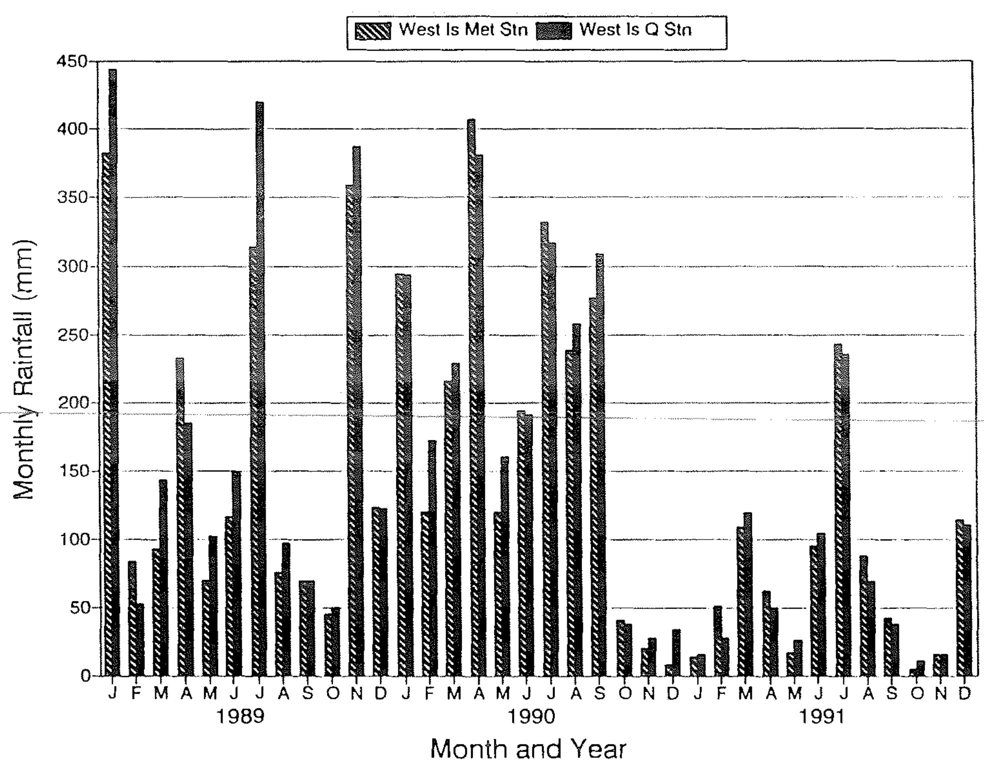

Figure 12. Monthly rainfall at the meteorological and Quarantine stations, 1989-1991.

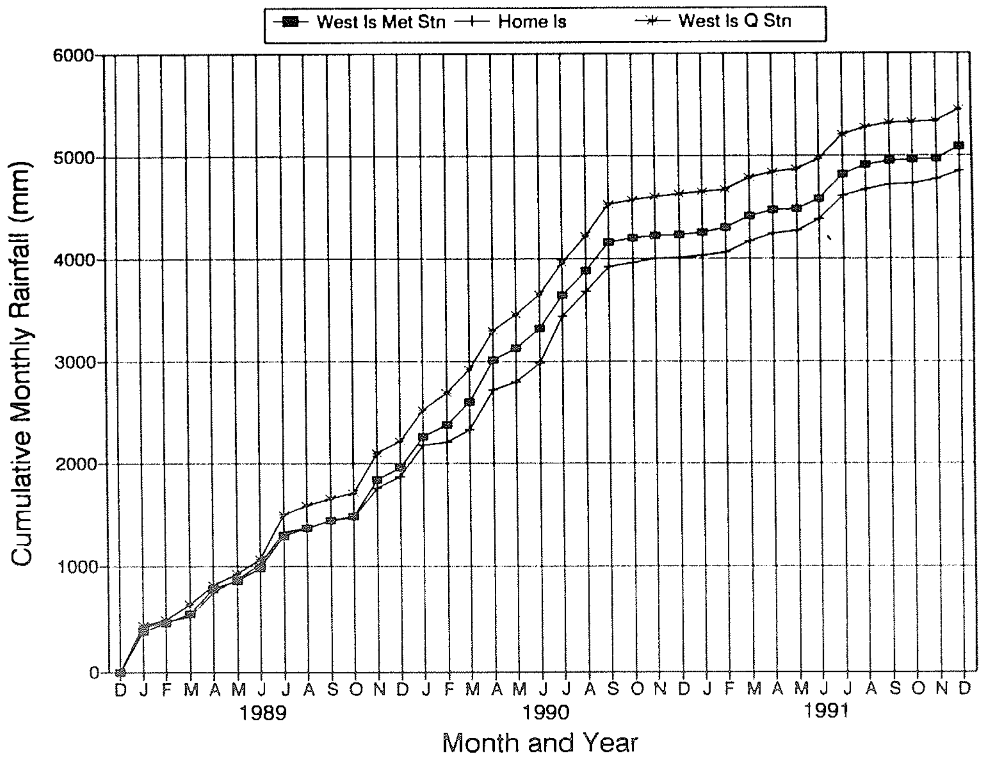

Figure 13. Cumulative monthly rainfall at the meteorological station, Home Island and the Quarantine Station, 1987-1991.

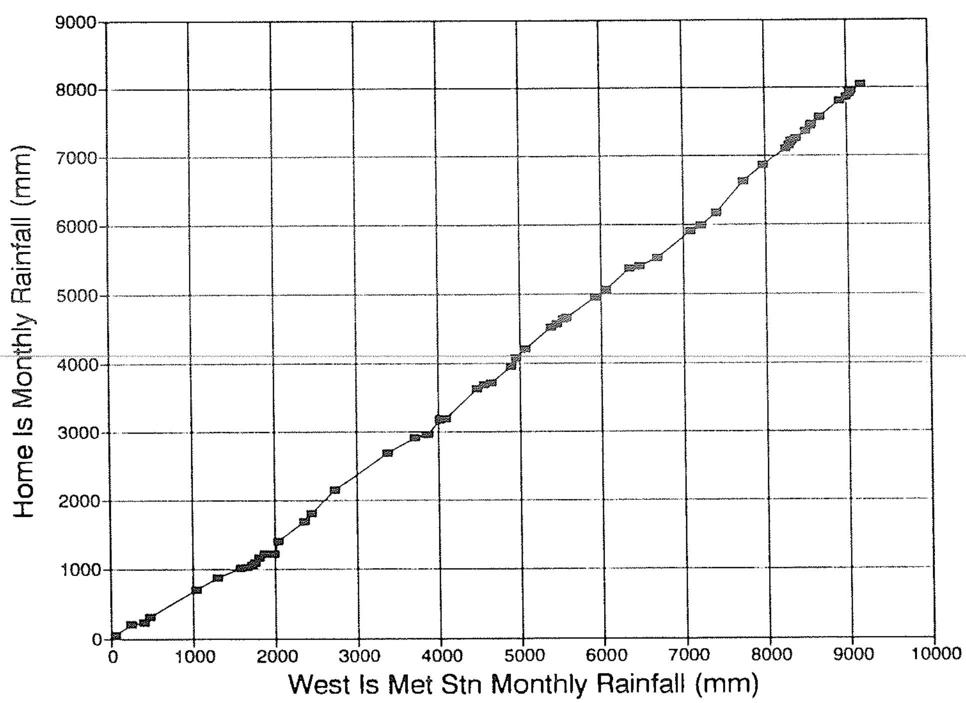

Figure 14. Double mass curve of monthly rainfall for the meteorological station and Home Island, 1987-1991.

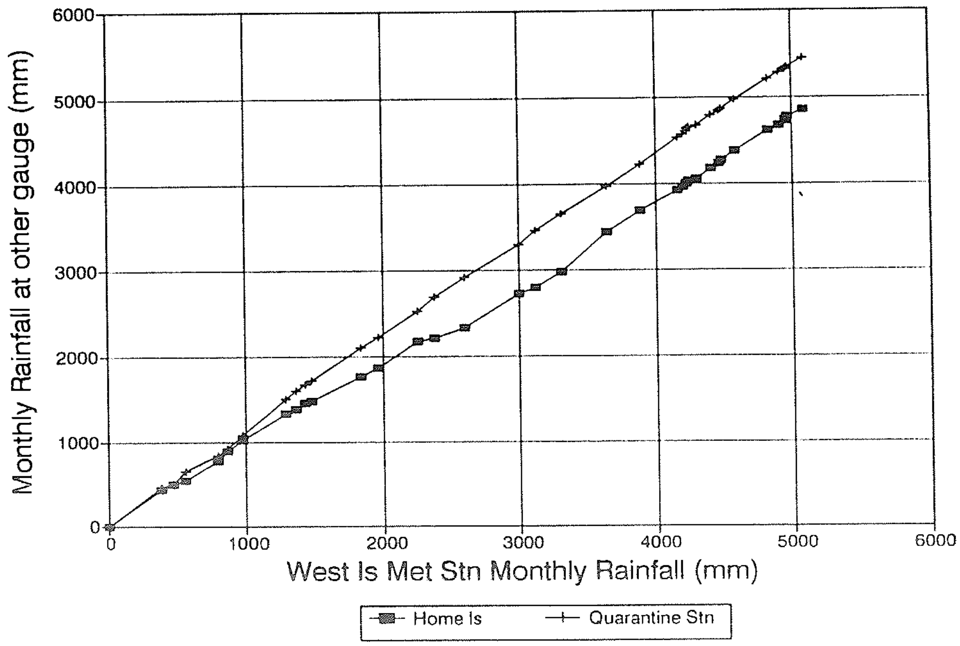

Figure 15. Double mass curve of monthly rainfall for the meteorological station and Home Island and the Quarantine Station, 1989-1991.

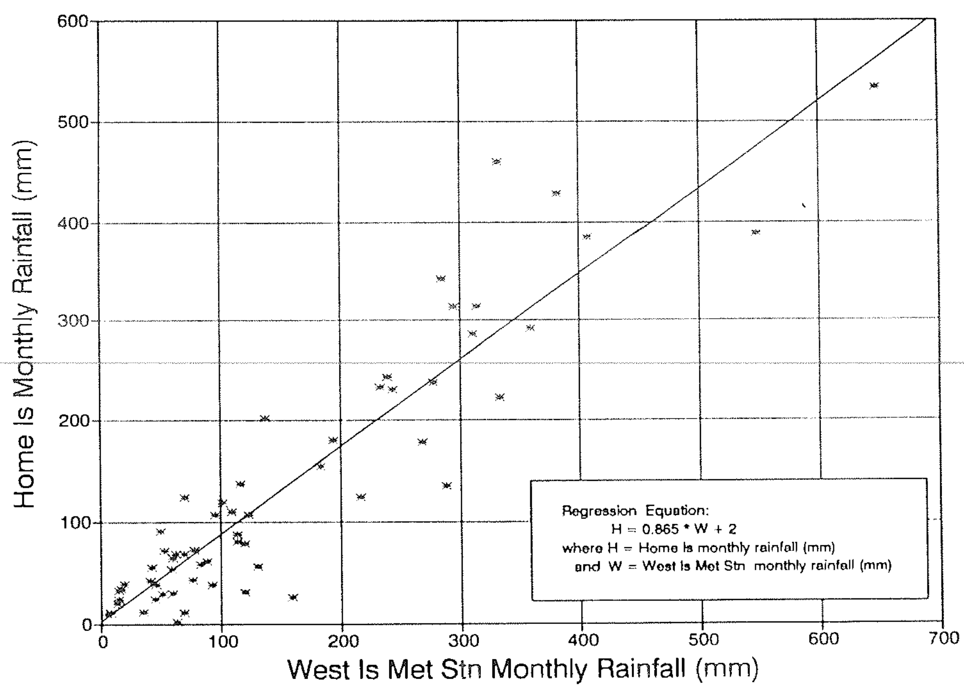

Figure 16. Regression analysis of monthly rainfall at the meteorological station and Home Island, 1987-1991.

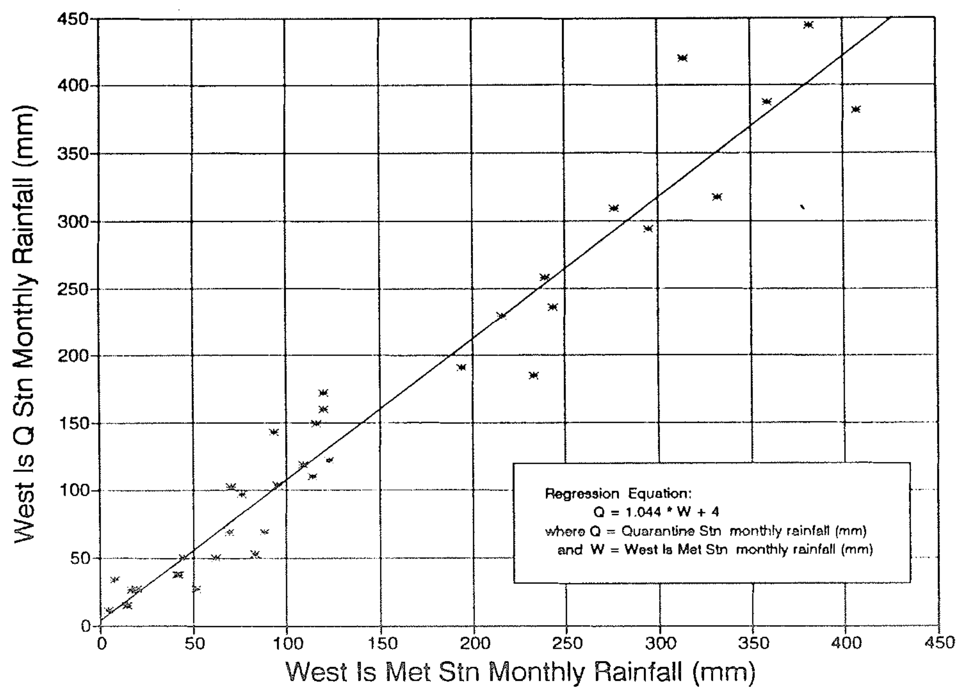

Figure 17. Regression analysis of monthly rainfall at the meteorological station and the Quarantine Station, 1987-1991.

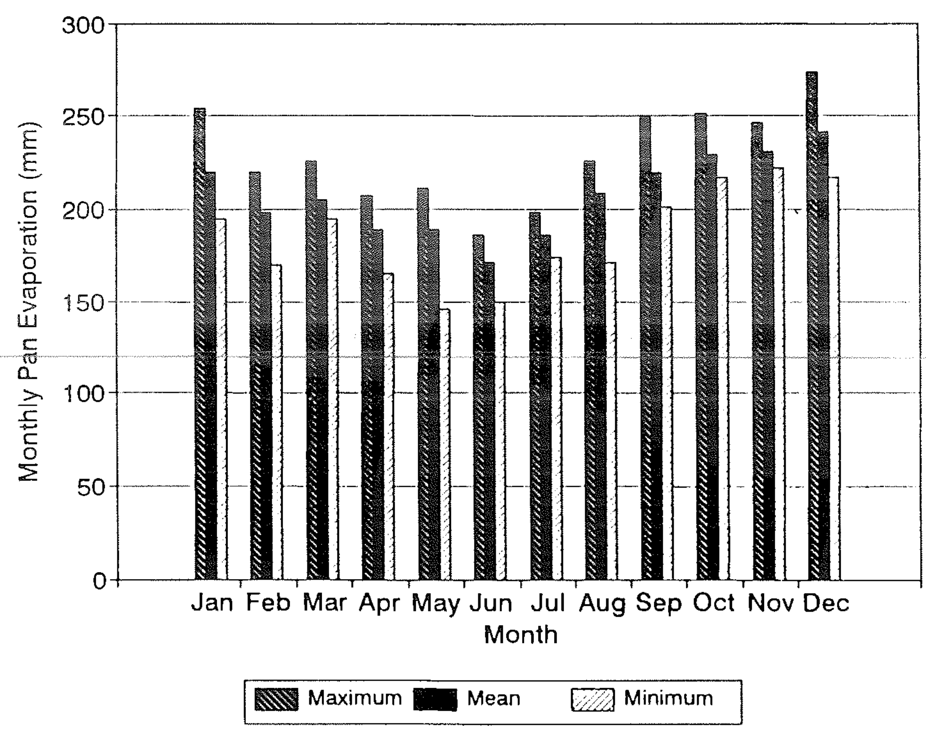

Figure 18. Mean, maximum and minimum pan evaporation.

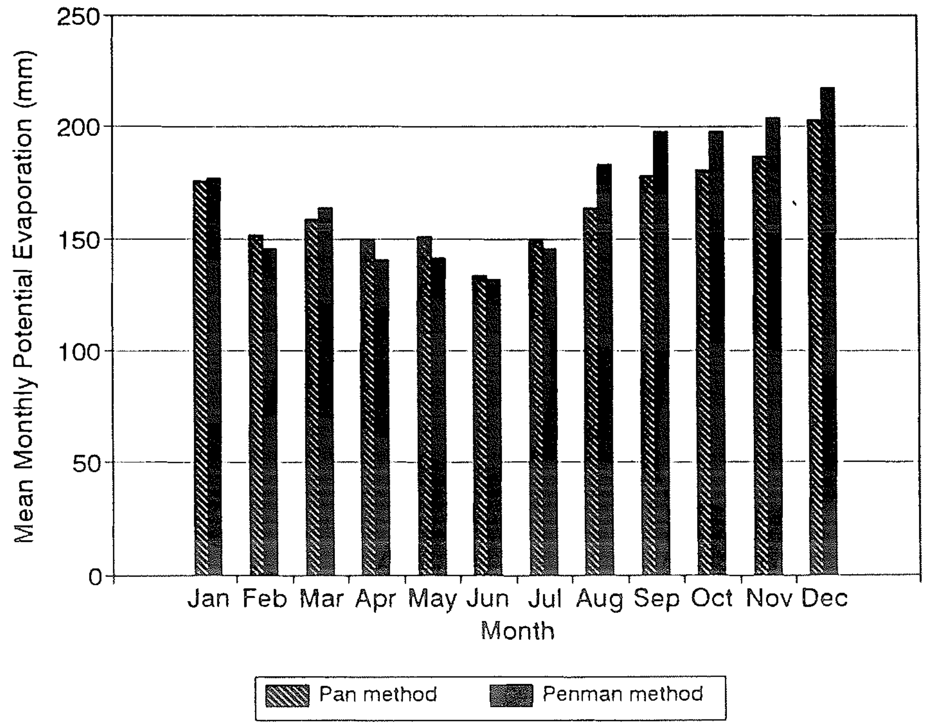

Figure 19. Mean monthly potential evaporation estimates using pan and Penman methods.

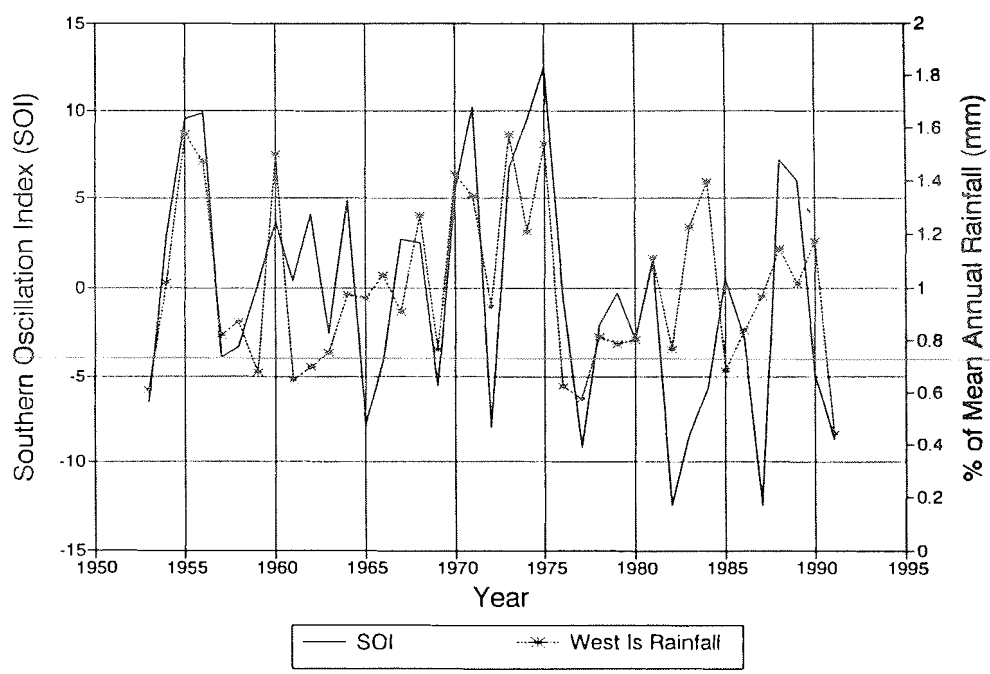

Figure 20. Relation between Southern Oscillation Index and annual rainfall.

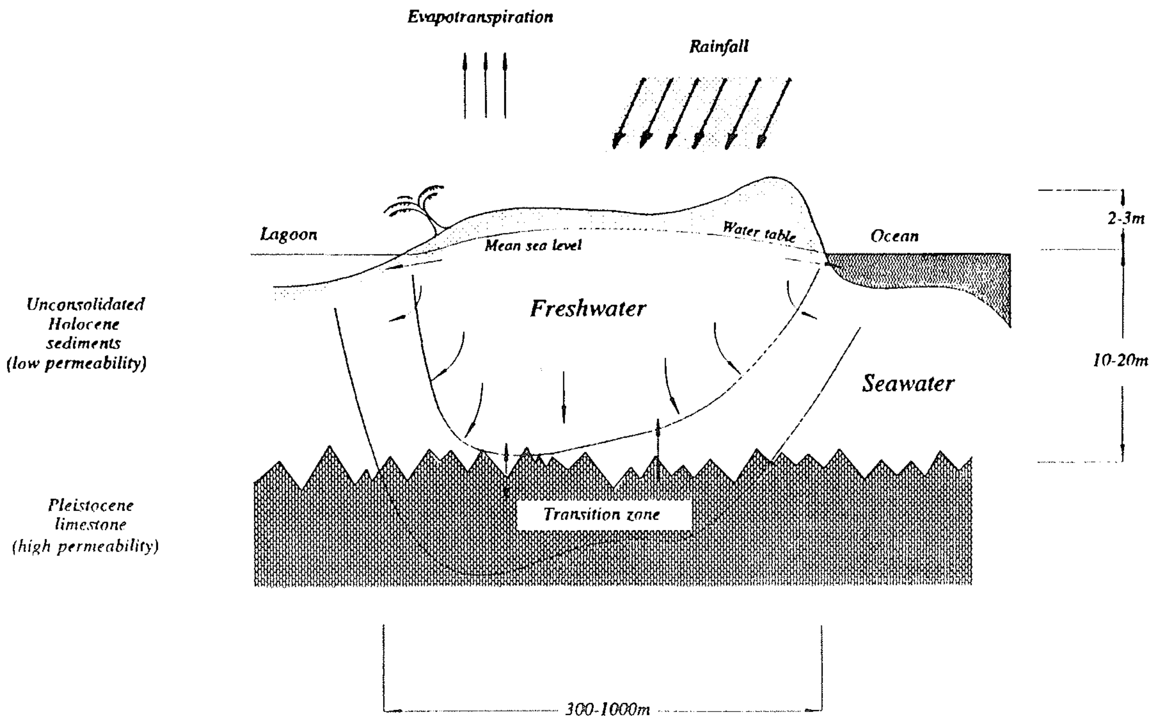

Figure 21. Typical cross-section through a coral island with a freshwater lens.

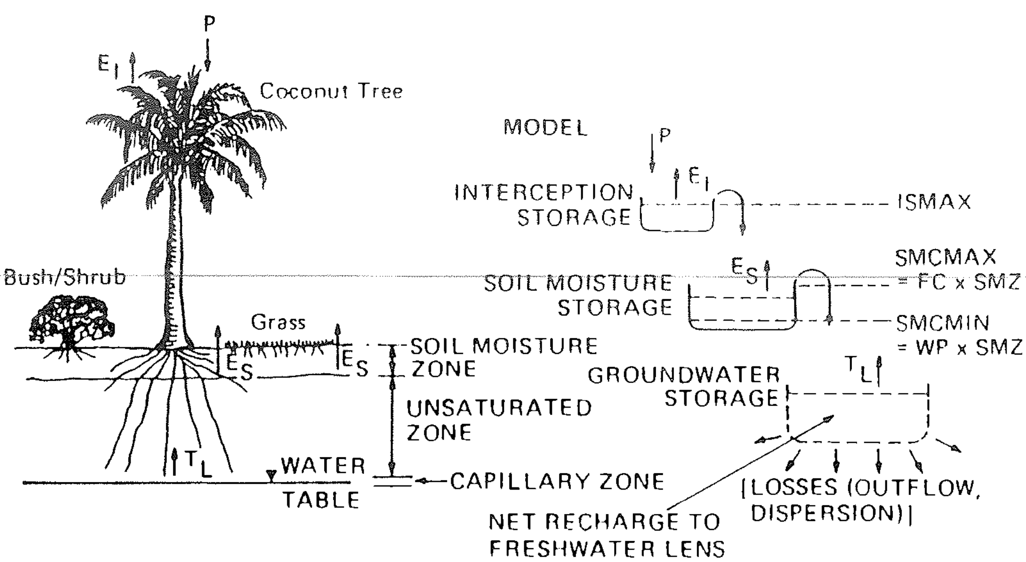

Figure 22. Recharge model.

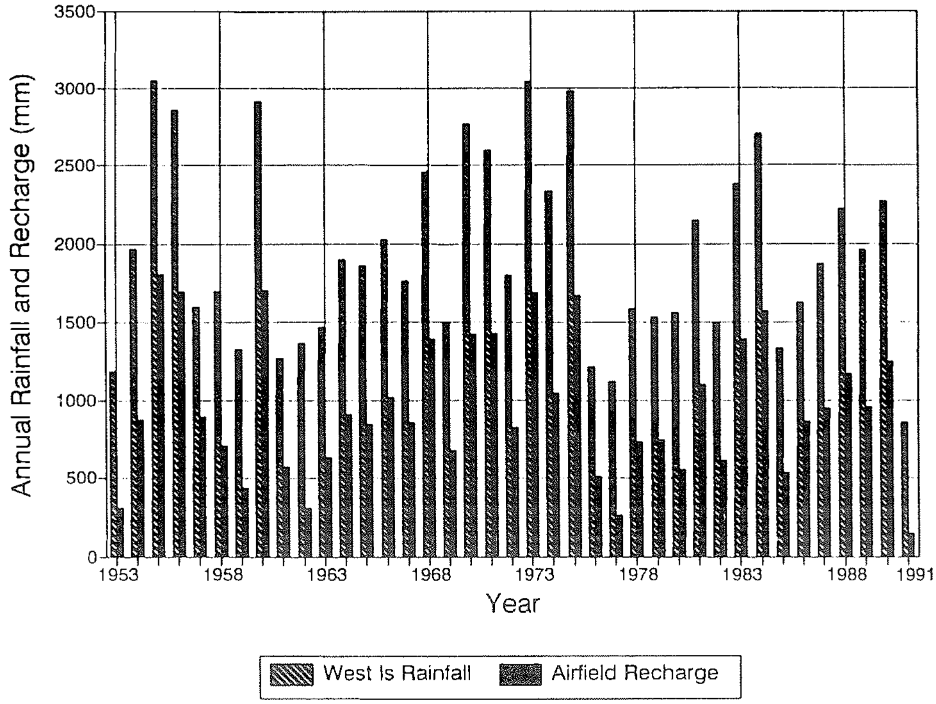

Figure 23. Annual rainfall and recharge, Airfield Lens, 1953-1991.

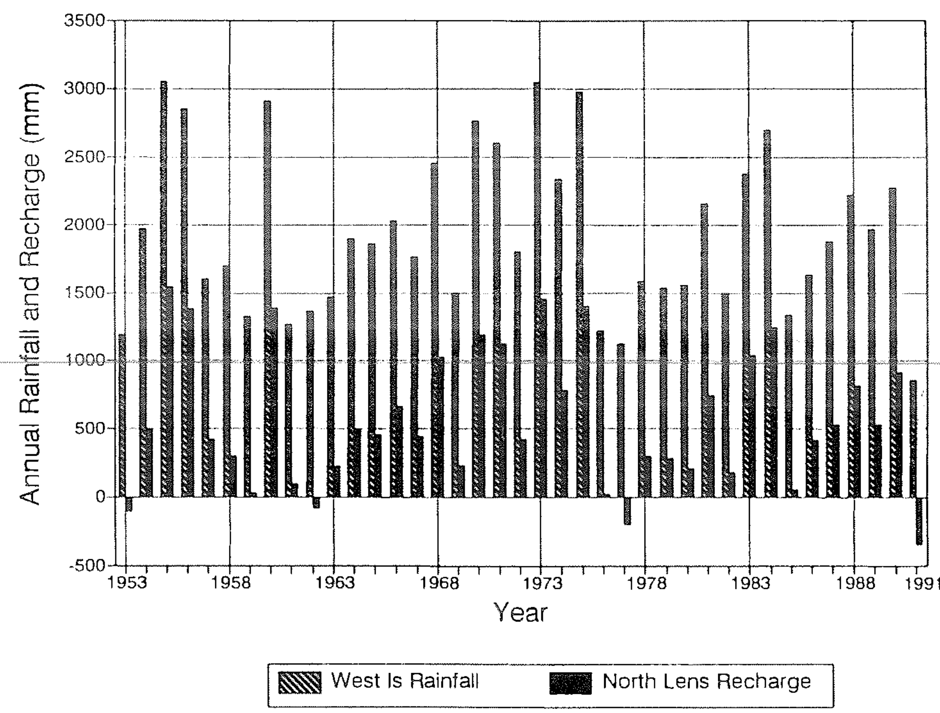

Figure 24. Annual rainfall and recharge, Northern Lens, 1953-1991.

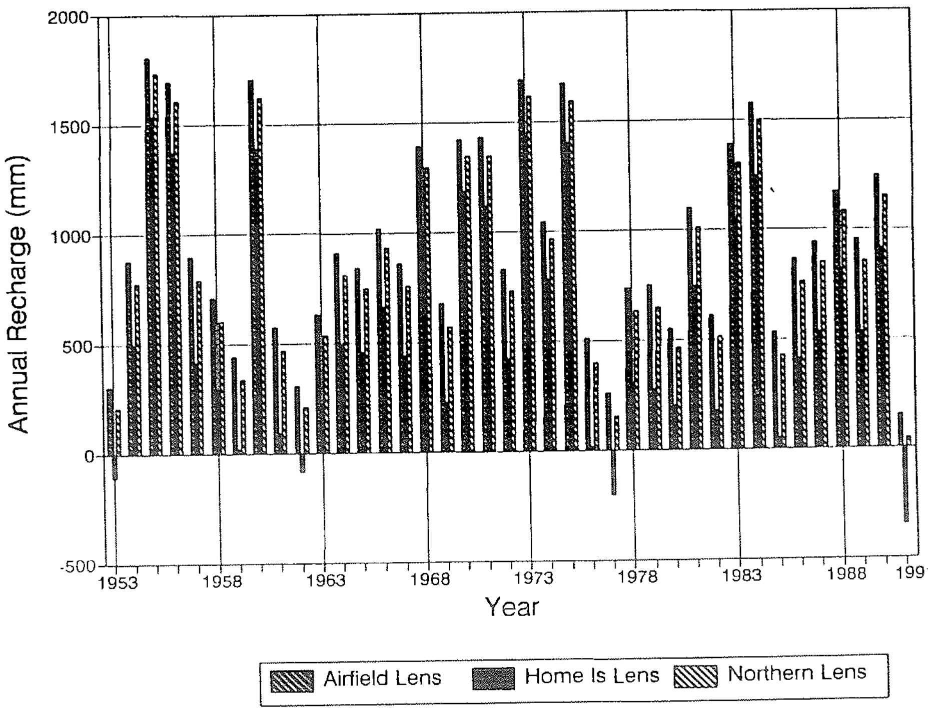

Figure 25. Annual rainfall and recharge, West Island and Home Island Lenses, 1953-1991

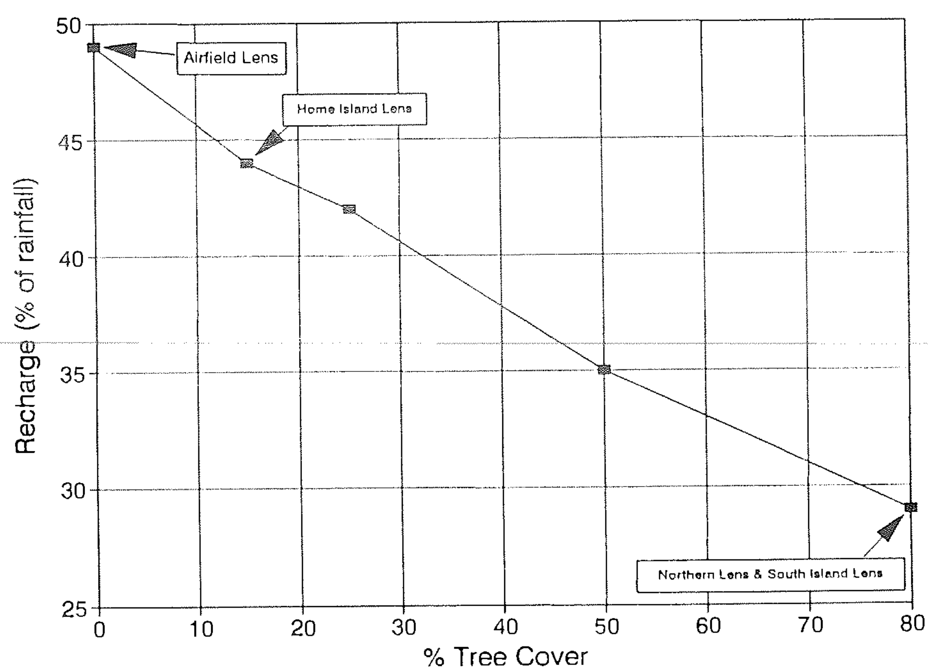

Figure 26. Effects of tree vegetation on mean annual recharge.

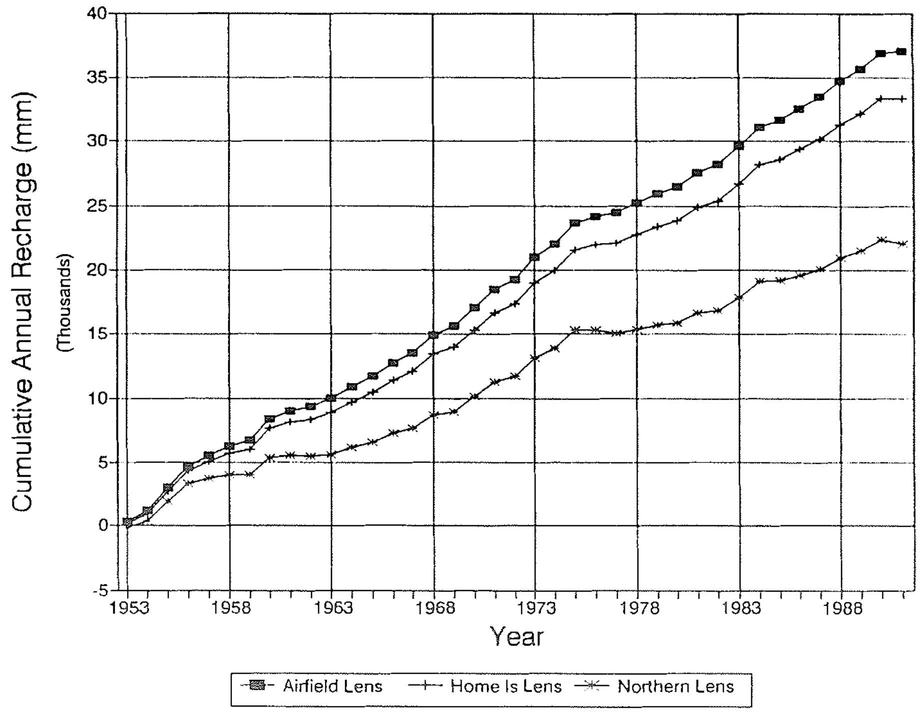

Figure 27. Cummulative annual recharge for West Island and Home Island Lenses, 1953-1991.

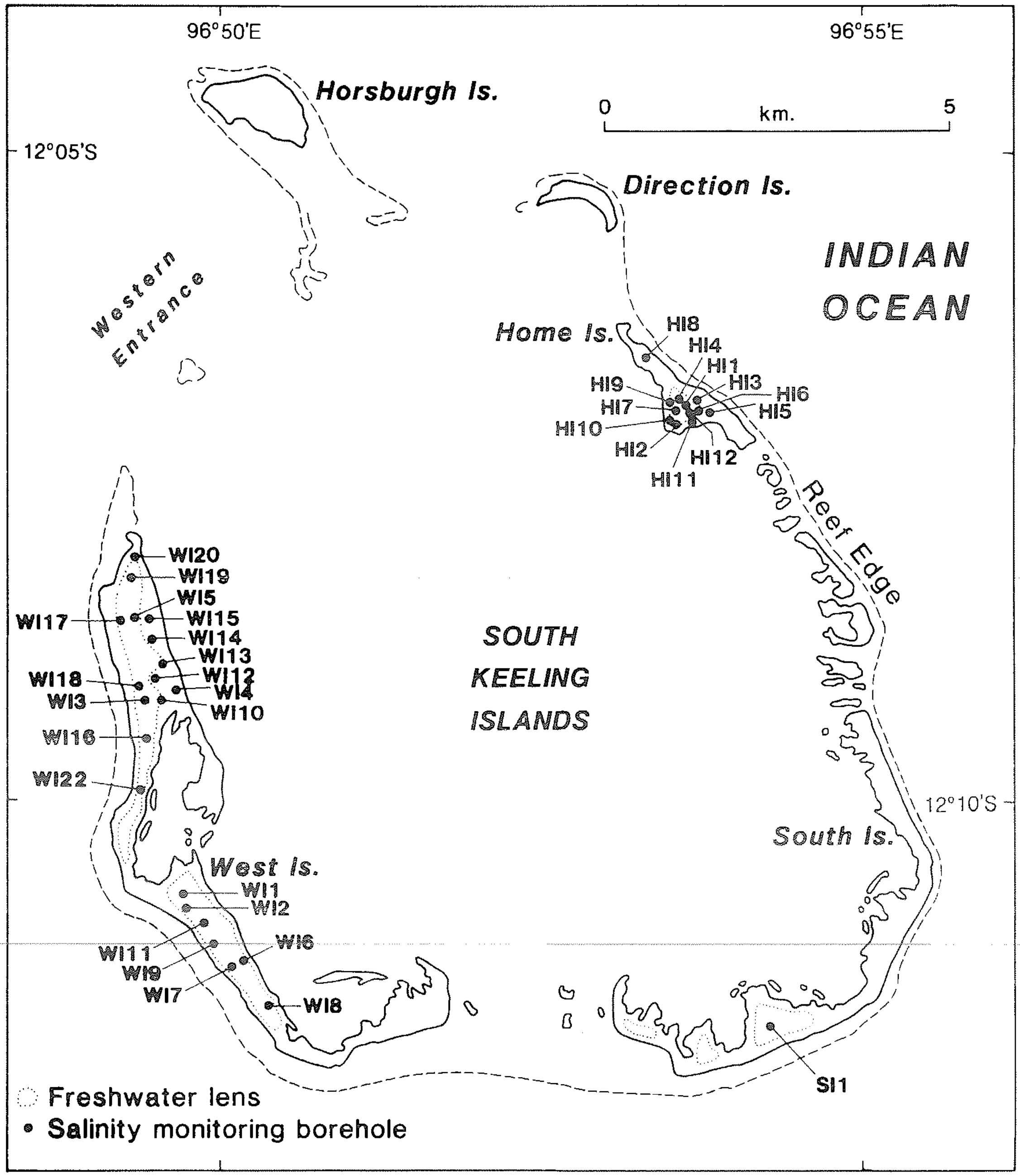

Figure 28. Location of Boreholes and freshwater lenses.

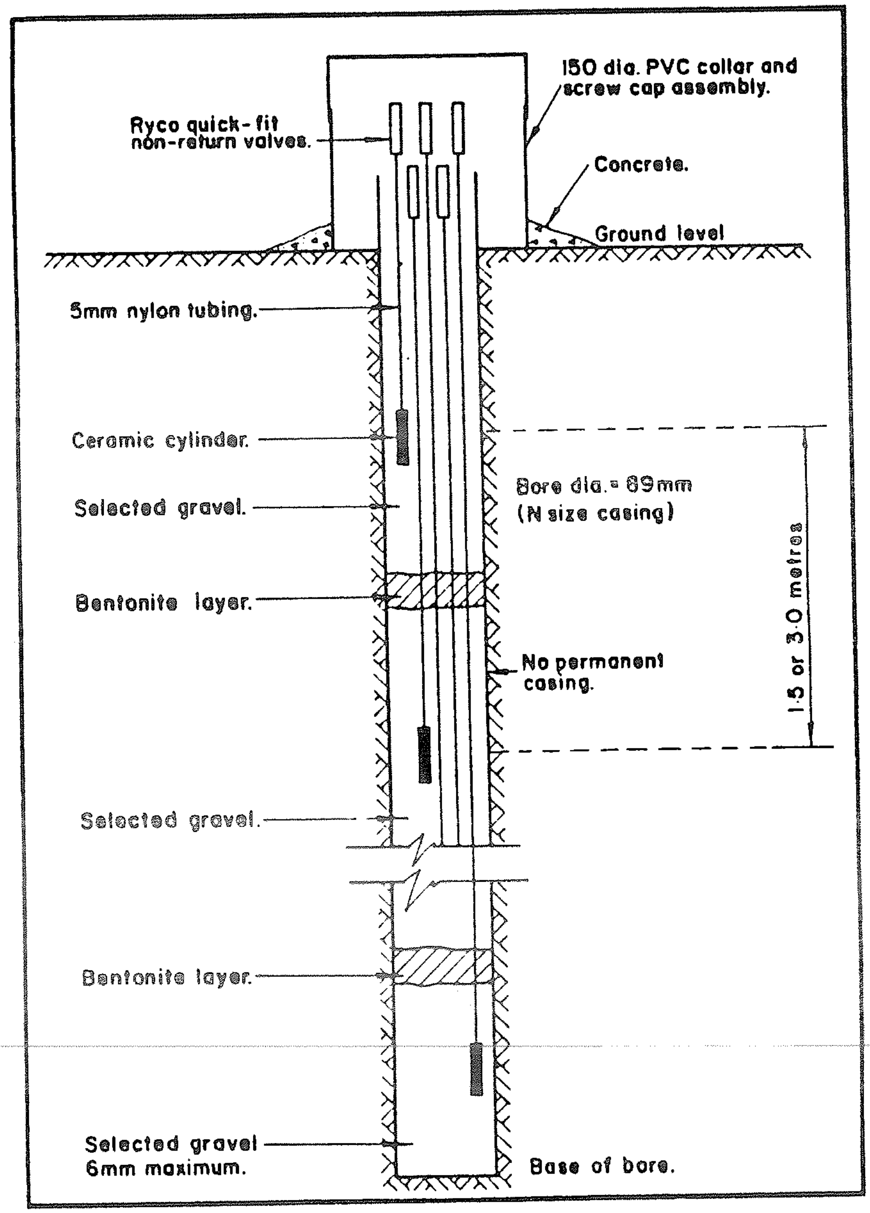

Figure 29. Borehole salinity monitoring system.

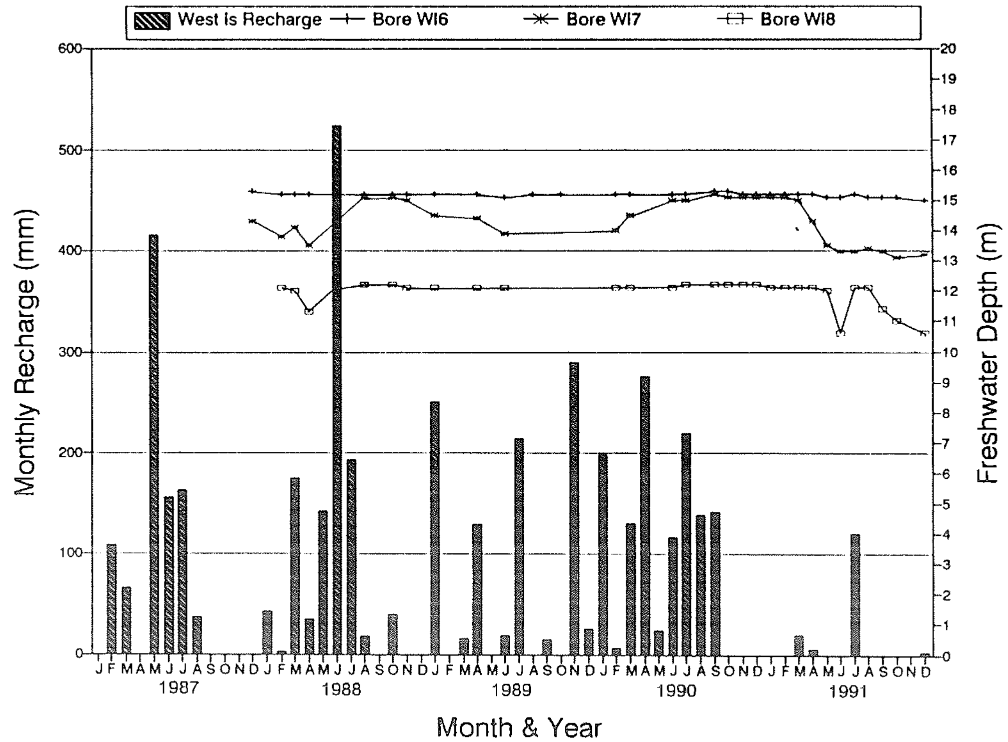

Figure 30. Depth of freshwater zone and recharge for boreholes WI 16, WI 17 and WI 18 on West Island.

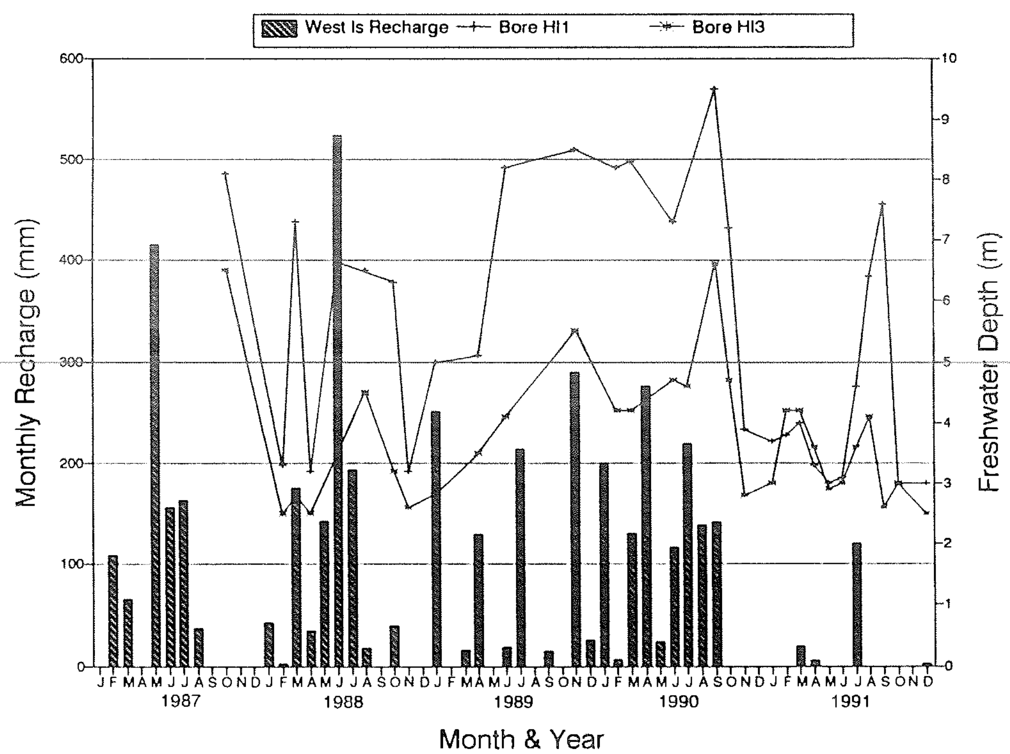

Figure 31. Depth of freshwater zone and recharge for boreholes HI 1 and HI 3 on West Island.

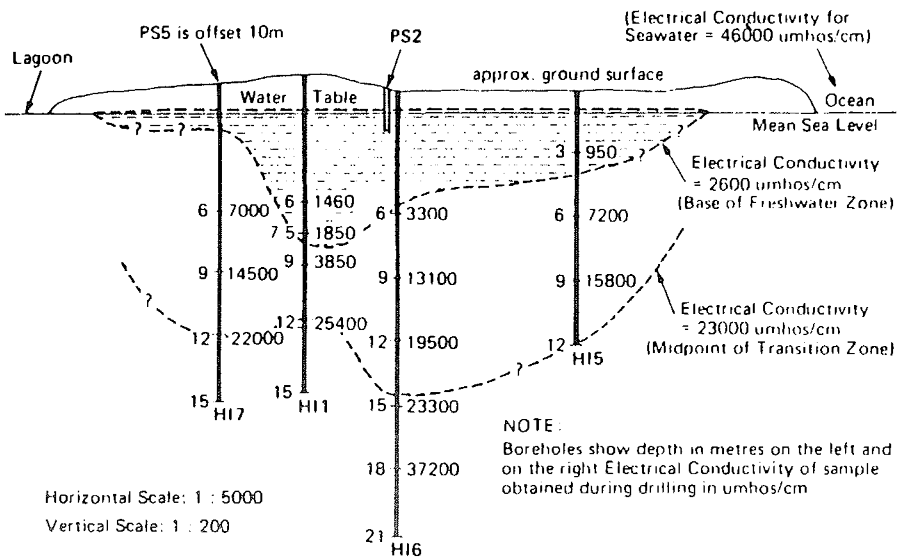

Figure 32. Cross-section through Home Island lens showing shape of lens at time of drilling in Oct/Nov 1987.

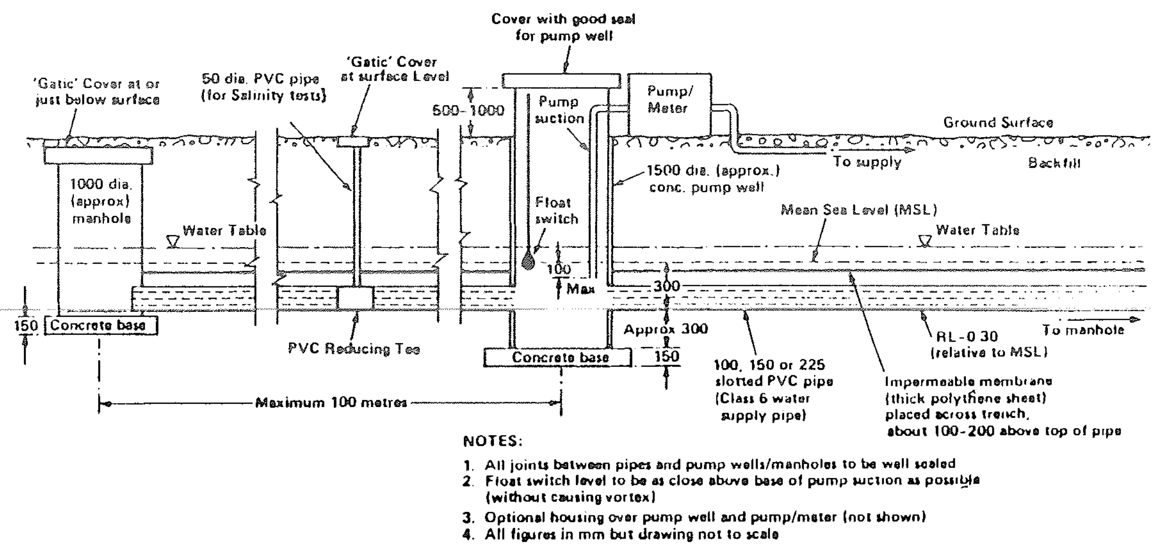

Figure 33. Cross-section through typical Home Island infiltration gallery.