Tidal Effects on Groundwater in a Very Small Tropical Island: A Study on the Groundwater Resources of Pag-asa Island, Kalayaan Island Group

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ABSTRACT

The Pag-asa Island, with its very small land area and low relief, has a very limited fresh water supply occurring as a thin freshwater lens. Climate, topography, vegetation, lithology, human abstractions, and tides affect the volume of the freshwater lens. Topographic and hydrogeologic surveys, coupled with a 72-hour groundwater-monitoring program were done to assess the effects of tides on the freshwater lens.

Groundwater parameters measured in wells during the monitoring program include variations in water table depths, specific electrical conductivity (SEC), and temperature. Changes in these parameters were then correlated with the observed variations of the tides.

The groundwater levels oscillate with the tides at varying amplitudes. The hydraulic properties of the lithologies making up the island's aquifer influence the amplitude of the oscillations. Groundwater level oscillations are least in the reef materials and greatest in the sandy materials where it is nearly simultaneous with the tidal variations. High electrical conductivity values are marked in wells built near the coasts and in sandy materials.

The average annual precipitation is approximately 2,020 mm. Based on empirical studies, the estimated sustainable yield for small tropical islands is 6% of the lowest annual rainfall or about 20,300 m^3/yr for Pag-asa Island.

Keywords: Kalayaan Island Group, Pag-asa Island, hydrogeology, small island, groundwater, tidal effects

INTRODUCTION

Pag-asa Island, internationally known as Thitu Island, is the largest island in the Kalayaan Island Group (KIG), which is part of the disputed Spratly Islands Group in the South China Sea. Located about 500 km northwest of Puerto Princesa City, Palawan (Fig. 1), the island has an area of 31.5 hectares.

The Spratly Islands, together with North Palawan, the Calamian Islands, and western Mindoro, are believed to be part of a micro-continental block that was rifted from mainland China (Holloway 1982, Hinz and Schlüter

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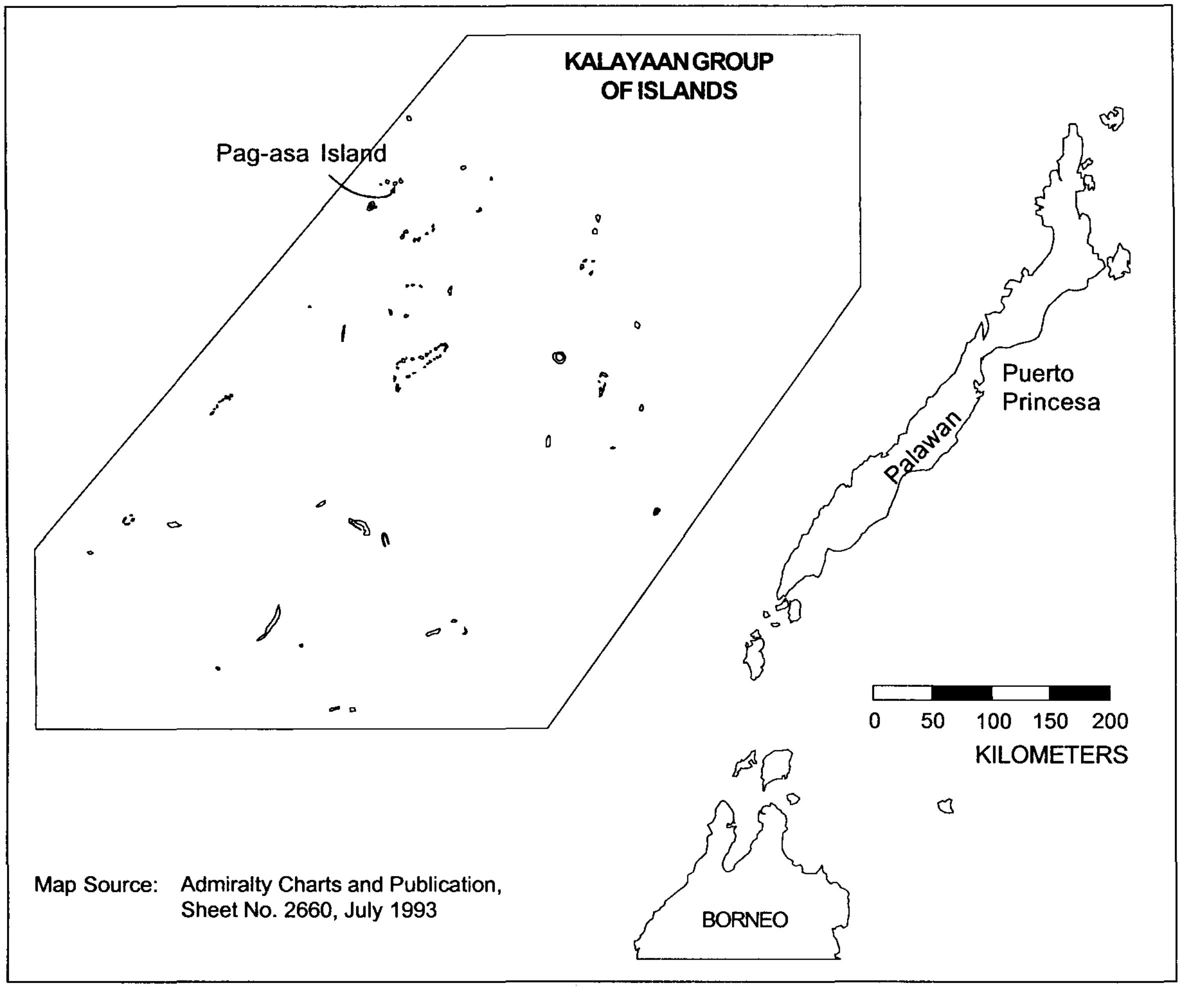

Fig. 1. Location map of Pag-asa Island

1985). The region beneath the Spratly Islands was modified by a complex system of tilted horsts and half-grabens that developed mainly when rifting occurred during the pre-Late Oligocene (Hinz and Schlüter 1985). By about mid-Oligocene, these continental blocks were finally separated from the proto-China margin, and seafloor spreading started along an east-west trending spreading center forming the South China Sea (Taylor and Hayes 1982). The Spratly Islands are the exposed parts of recent reefs that developed on the crests of these tilted horsts. Pag-asa Island is the subaerial part of an atoll (Fig. 5).

The KIG is composed of very small islands, defined as having areas of <100 km^2. These islands have very limited freshwater resources that are traditionally extracted from groundwater occurring as a freshwater lens (Fig. 2). The freshwater lens held in the geologic materials "floats" on top of the denser seawater at some depth below the surface. Recharge to the freshwater lens occurs primarily through precipitation and is affected by (a) climate, (b) topography, (c) vegetation, (d) tides, (e) lithologies, and (f) human abstractions. These factors are the major stresses that affect the amount of freshwater present.

This study focuses on the effects of these factors on the physical and chemical characteristics of the freshwater resources of Pag-asa Island. Data obtained from this study are important for the formulation of

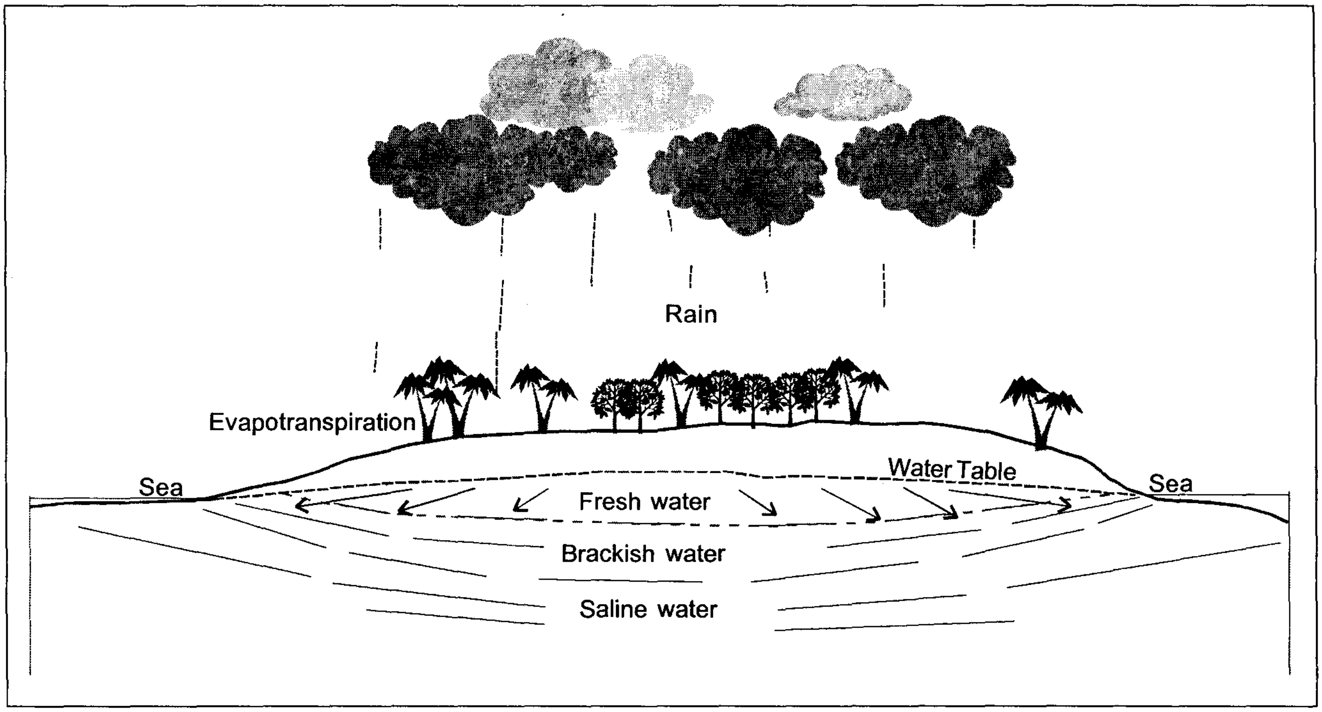

Fig. 2. Cross-section of a very small tropical island and the freshwater lens. For small islands, there is a substantial mixing or transitional zone between the fresh water and the sea-water. The vertical scale is exaggerated.

appropriate groundwater management schemes in very small islands.

MATERIALS AND METHODS

Topographic and hydrogeologic surveys

Topographic and hydrogeologic surveys were conducted from 28 April to 5 May 1999 to establish the island's morphology and groundwater condition. Similar to the findings of Thompson and Baedke (1997), pebble trains along the swash zone of the beach were used to approximate the mean sea level. The elevation of 16 wells and the ground level of the southern half of the island were surveyed. The northern half of the island was not surveyed because of the difficulty of traversing the mangrove area. Land-use mapping was also conducted to identify possible sources of groundwater contamination.

Tidal readings were taken from the tidal monitoring station located beside the benchmark on the southwestern section of the island. The 72-hourly tidal readings measured from 2-5 May 1999 were compared with predicted tides of Villanoy and Mancebo (1998) for the island in determining the mean sea level.

Sixteen of the 17 wells in the island were monitored for 72 hours from 2 to 5 May 1999. Groundwater parameters measured from the wells include groundwater levels, specific electrical conductance (SEC), and temperature. Groundwater depths were measured with water level dippers. *Electrical conductance*, the ability of water to conduct electric current, depends on ionic concentrations, mobility, and valence, and the temperature of the solution. SEC is the actual measurement corrected to 25°C, and is expressed in microsiemens per centimeter (µS/cm). SEC and temperature were measured using the *Yellowspring Instrument*™ YSI 85.

Abandoned wells were purged of stocked water prior to the commencement of the monitoring exercise. To detect stratification, SEC was measured at the top and bottom of the water column in each well. During the period of highest and lowest groundwater levels, water samples were obtained from selected wells for chloride content analysis. The samples, stored in polyethylene bottles and kept in cold storage (at about 4°C), were later titrated with silver nitrate to determine the total chloride content.

Variations in the measured groundwater parameters were correlated with the monitored tidal fluctuation.

Approximation of aquifer hydraulic parameters

Hydraulic conductivity is the ability of aquifer materials to conduct a certain type of fluid. Hydraulic conductivities of the underlying rocks were estimated by conducting the rising head slug test on two wells. This test is performed by suddenly removing a volume or slug of water from the well; after which, recovering water level is measured as a function of time. The theoretical equations developed by Hvorslev (1951) were used in evaluating the slug test data.

Transmissivity is the effectiveness of an aquifer to transmit water and is the product of hydraulic conductivity and the effective saturated thickness of the aquifer. The aquifer thickness was estimated by measuring the average thickness of the freshwater lens.

Storativity in unconfined aquifers is equivalent to its specific yield. *Specific yield* (S_y) is the ratio of the volume of water (V_w) that will drain by gravity from a rock or soil that was initially saturated to the volume of the rock or soil (V_b), as given by the equation:

$$S_y = V_w/V_b$$

Aquifer storativity values are important in calculating the amount of water stored in an aquifer. These values were estimated based on the grain sizes observed in the field.

Filtering of tidal effects from measured groundwater levels and sp. electrical conductivity

Time series of groundwater levels were interpolated to integral hourly values. The tidal component of the groundwater levels were removed based on a modified filtering procedure by Erskine (1991). The least-squares method was then used to approximate the receding groundwater curve. Tidal efficiency (TE) and time lag (TL) were considered for the removal of tidal effects.

TE is the ratio of the amplitude of groundwater level fluctuation and tidal fluctuation. To obtain a more objective estimate and remove the errors arising from reading individual peaks, the ratio of the standard deviation of groundwater and tidal fluctuations was used to compute TE.

TL is the time difference between the tidal and groundwater level crest or trough. To determine TL, oscillations in the groundwater level were first amplified by dividing the time series of groundwater levels with the TE value. The tidal curve was shifted by 10-minute time increments to match the amplified groundwater levels. TL is obtained by subtracting the tidal curve from the amplified groundwater levels. The minimum standard deviation obtained from the previous differences is chosen as the TL value (Equation 1).

$$Tide\,(t + t_{lag}) - \frac{Well\,(t)}{T.\,E.} = \min$$

where Tide (t) = tide level at time t
Well (t) = well water level at time t
t_{lag} = time lag
T.E. = tidal efficiency

After calculating the TE and TL values, groundwater level readings were adjusted to compensate for tidal effects using Equation 2:

$$Well_{filtered}\,(t) \quad = \quad Well\,(t) - (T.E. * Tide\,(t - t_{lag}))$$

where $Well_{filtered}$ (t) = filtered well water level at time t
Well (t) = well water level at time t (raw data)
T.E. (t) = tidal efficiency
Tide (t) = tide level at time t
t_{lag} = time lag

SEC readings were measured at the top and bottom of the water column in each well to detect stratification. The cyclical SEC readings were filtered using the least-squares method, leaving the general linear trends.

RESULTS

Precipitation

Precipitation is the only source of fresh groundwater recharge in the island. Based on a nine-year monthly rainfall hydrograph, the average annual precipitation at Pag-asa Island is 2,020 mm (Fig. 3). The dry season is typically from January to May and the wet season, from June to December. Extended rainfall events are beneficial in recharging the groundwater. Extended dry spells, some extending to six months, put great pressure on the available water resources of the island.

Prior to the groundwater monitoring exercise, a low-pressure area developed over the study area. Approximately 270.5 mm of rain fell on the island in a period of seven days (Fig. 4). Variations in the signs

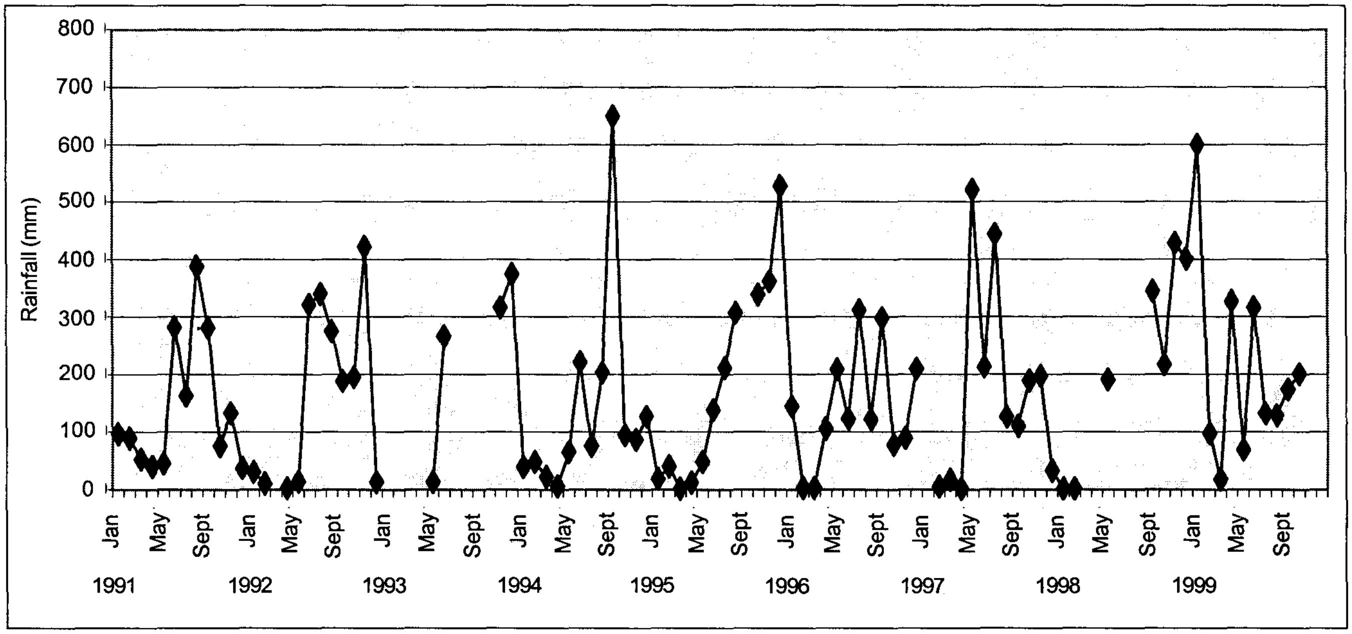

Fig. 3. Rainfall distribution in Pag-asa Island from 1991 to 1999 recorded in the island's PAGASA station

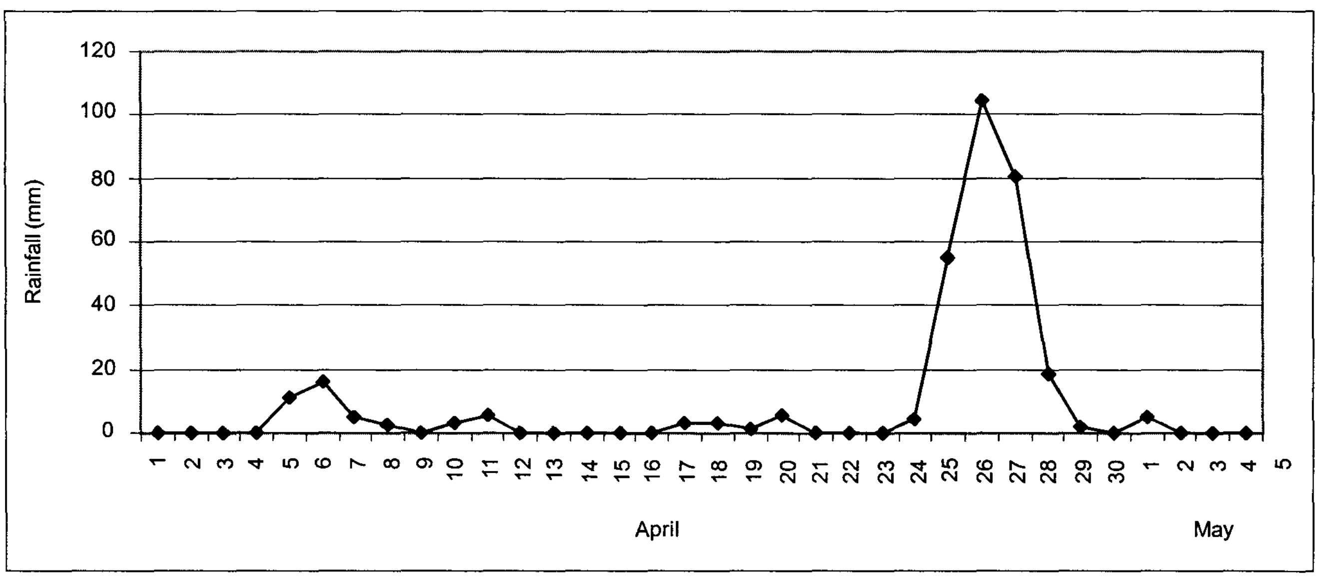

Fig. 4. Rainfall hydrograph in Pag-asa Island prior to the 72-hour monitoring program from 2-5 May 1999

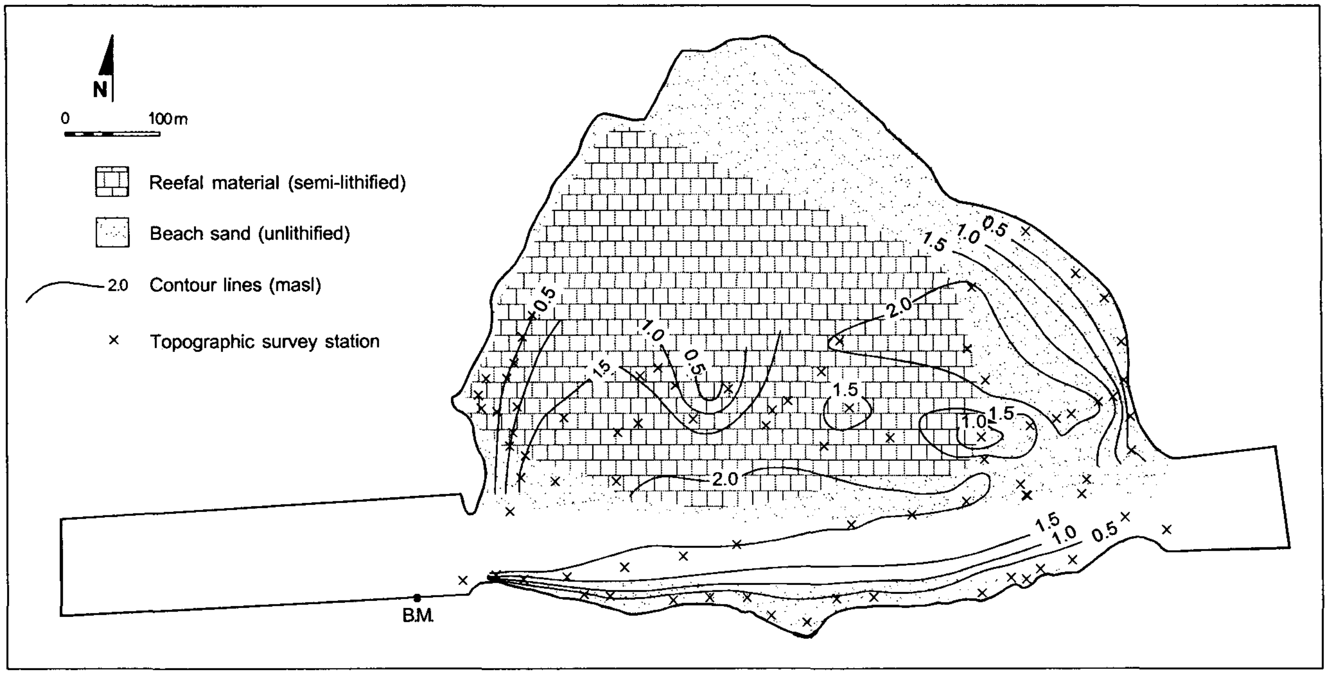

Fig. 5. Topographic and lithologic map of Pag-asa Island. The Island is the subaerial part of an atoll.

Table1. SEC trends and the relative change in SEC values in wells

Well no.	Measurements taken immediately below water table		Measurements taken at well bottom	
	SEC	Rel. SEC Change	SEC	Rel. SEC Change
1	-0.33 x+ 1083	-24	-0.31 x+ 1094	-22
2	-0.10 x+ 741	-7	-0.09 x+ 740	-7
3	-0.04 x+ 538	-3	0.00 x+ 536	0
4	-0.39 x+ 605	-27	-0.38 x+ 605	-27
5	0.07 x+ 476	5	0.06 x+ 477	5
6	-0.15 x+ 696	-11	-0.10 x+ 696	-7
7	-0.28 x+ 745	-20	-0.29 x+ 748	-20
8	0.01 x+ 1002	1	0.09 x+ 1004	6
9	-0.49 x+ 465	35	0.56 x+ 465	40
10	-0.12 x+ 516	-8	-0.18 x+ 521	-13
11	0.13 x+ 1233	9	-1.91 x+ 1432	-136
12	0.13 x+ 664	9	0.17 x+ 664	12
13	-0.13 x+ 693	-9	-0.11 x+ 695	-8
14	0.64 x+ 449	46	0.76 x+ 447	54
15	-4.18 x+ 2318	-299	17.9 x+ 2290	1280

and rates of SEC slopes during the three-day monitoring period indicate strong influence from the antecedent rainfall event (Table 1). A positive SEC-time series slope trend indicates increased salinity of the groundwater, and vice versa.

Topography and land use

Pag-asa Island has an area of 31.5 hectares and a perimeter of 2.22 km. It has a flat terrain raised to only about 2 m above msl, and with local depressions at its center (Fig. 5). Beach sand and reef materials underlie the island. Most of the beach and sand deposits are mobile, but have been stabilized in some areas by the presence of vegetation. Beach and reef materials are primarily composed of calcium carbonate and may undergo various diagenetic changes immediately after deposition.

Extensive beach erosion occurs along the western side of the island, exposing the underlying reef deposits (Fig. 5). Erosion takes place along the edges of the runway where tilted concrete bunkers were observed.

Possible and potential groundwater contamination may come from the nine latrines in the island (Fig. 6). Four latrines are located on the central portion of the island, two on the eastern side, and three on the western side. Other possible sources of contamination include a dumping ground and fuel storage area located on the central portion of the island.

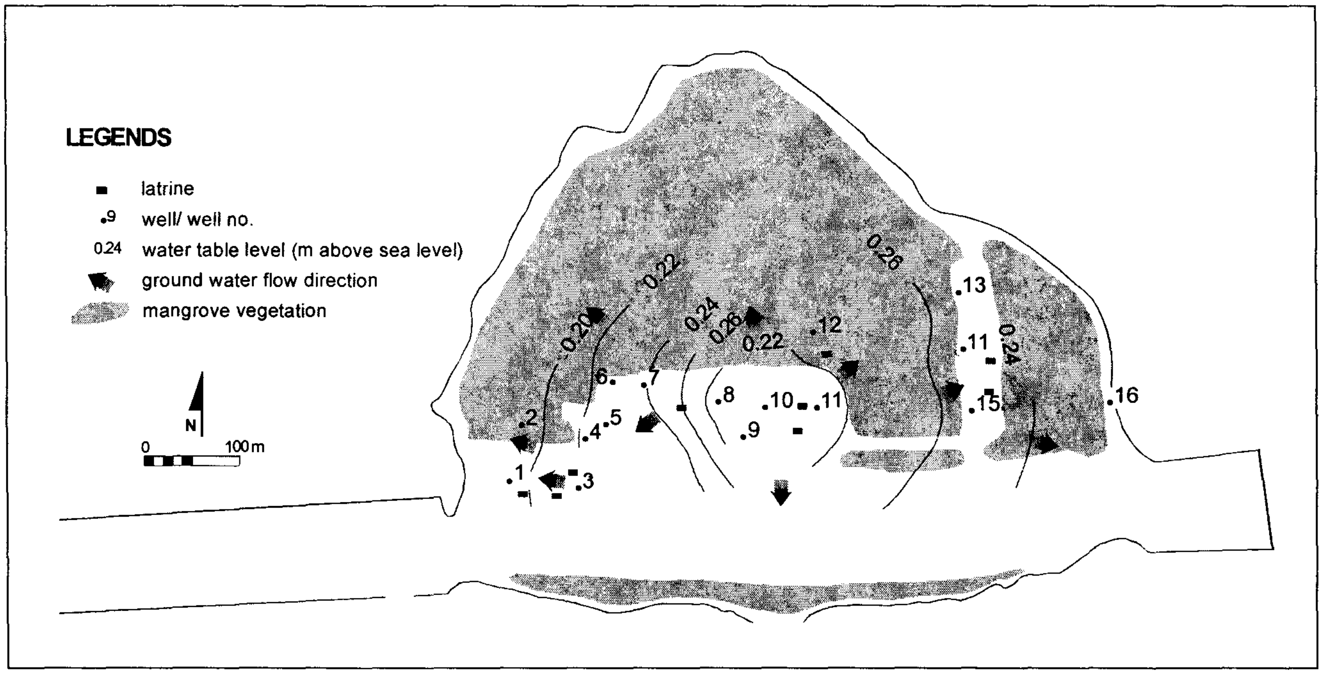

Fig. 6. Water table and vegetation map of Pag-asa Island in early May, 1999. The groundwater flowlines and location of wells and latrines are also shown.

Vegetative cover strongly influences evapotranspiration and is important in small islands. Mangroves are the dominant vegetation, occupying nearly half the area of the island (Fig. 6). Some of the original mangrove areas have been replaced with coconut, *talisay,* and papaya to provide additional sustenance for the inhabitants; others have been removed for constructing houses and other infrastructures. Beach areas are covered with grasses and shrubs.

Well inventory

A total of 17 wells have been dug and drilled since 1976 and are distributed in an east-west direction. The inventory of wells and their uses are cartographically illustrated in Fig. 7.

Tidal fluctuations

During the groundwater monitoring period, high tides occurred at around 12:00 noon and low tides, between 7:00 and 9:00 PM. The tidal amplitude was approximately 1 m, fluctuating from +0.50 m to -0.50 m relative to msl.

Aquifer hydraulic parameters

Hydraulic conductivity values of 8.6×10^{-5} m/sec and 3.9×10^{-4} m/sec were obtained for Wells 2 and 4, respectively. Such values indicate permeabilities equivalent to those of coarse sand for Well 2 and coarse sand to gravel for Well 4.

Transmissivity is not well defined because of the unconfined nature of the aquifer. With an aquifer thickness of 0.52 meters and using the average hydraulic conductivity obtained from the slug tests, transmissivity is approximately 10 m^2/day. The low transmissivity is due to the limited water resources in the island. The lithified reef materials have high transmissivity and low storativity while the sandy materials have high transmissivity and low storativity.

For coarse grained materials in an unconfined aquifer, storativity is estimated to be 0.2.

Using these storativity and transmissivity values, the following estimates of freshwater volume in the island are derived.

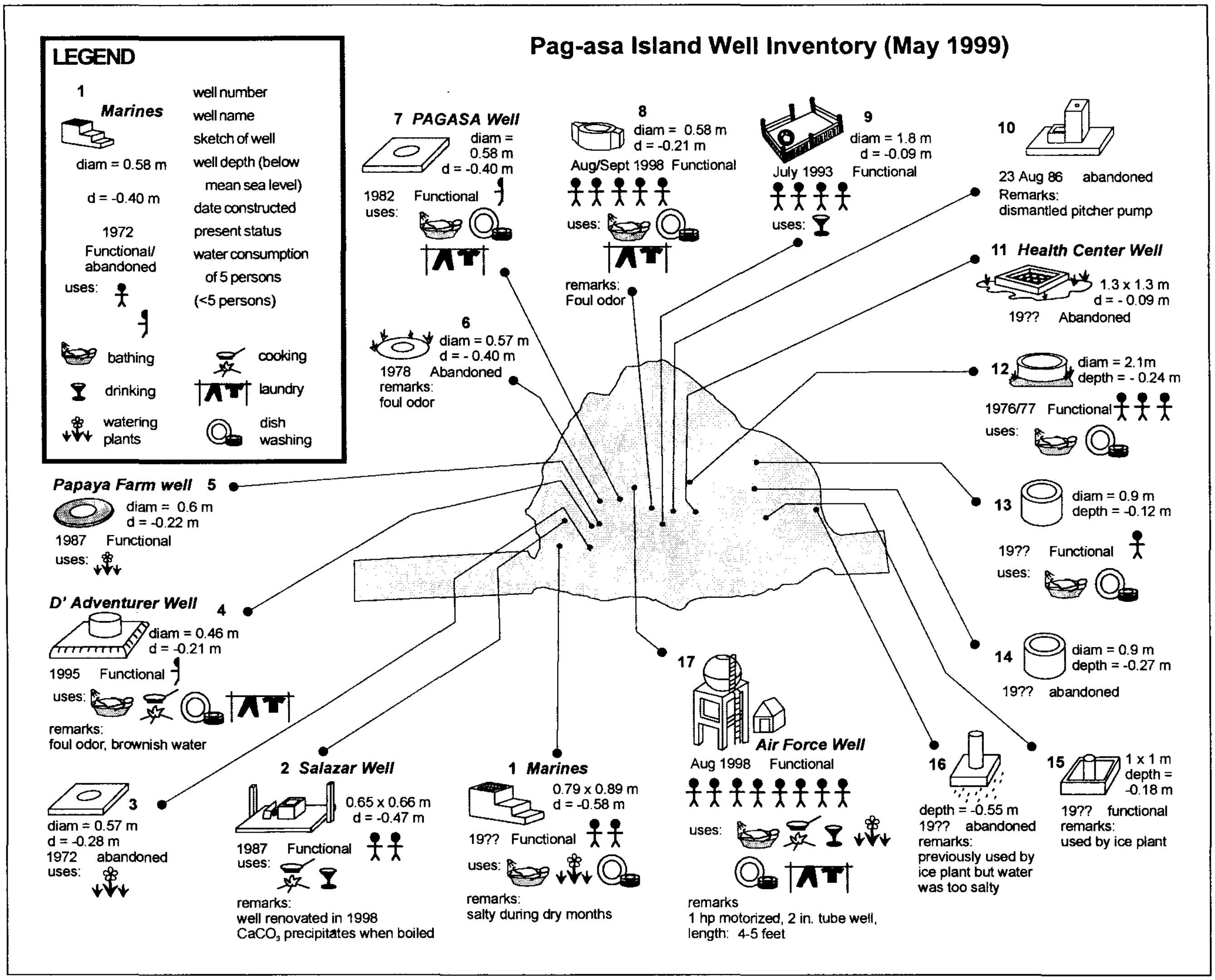

Fig. 7. Inventory of wells in Pag-asa Island (1999)

a) Volume of freshwater (as of 5 May 1999)

On 5 May 1999, the average height of the water table was 0.206 m above msl. The safe freshwater depth was estimated to be 0.3 m below msl. Imposing a 50-meter buffer zone from the coastline and excluding the protruding runway area, the effective freshwater area in the island is 21.3 hectares. The buffer zone is based on the observation that wells constructed within 50 m from the coastline tap brackish water.

Using the storativity value of 0.2, an effective area of 21.3 hectares and a water thickness of 0.52 meters, the maximum volume of freshwater in the island at that time was approximately (21,300 m^2 x 0.52 m x 0.2 =) 22,150 m^3. For practical limitations, not all of this water can be extracted from the aquifer. In the absence of rainfall, this volume also decreases in time as groundwater continuously discharges into the sea.

b) Volume of freshwater lost (during the period 2-5 May 1999)

During the monitoring period, the average lowering of the water table was 5.8 cm. Using this drained depth in an area of 31.5 hectares and a storativity of 0.2, the total amount of freshwater lost in three days was estimated at 4,070 m^3. These losses corresponded to the bulk seaward discharge of freshwater, evapotranspiration, and human abstractions. From 24

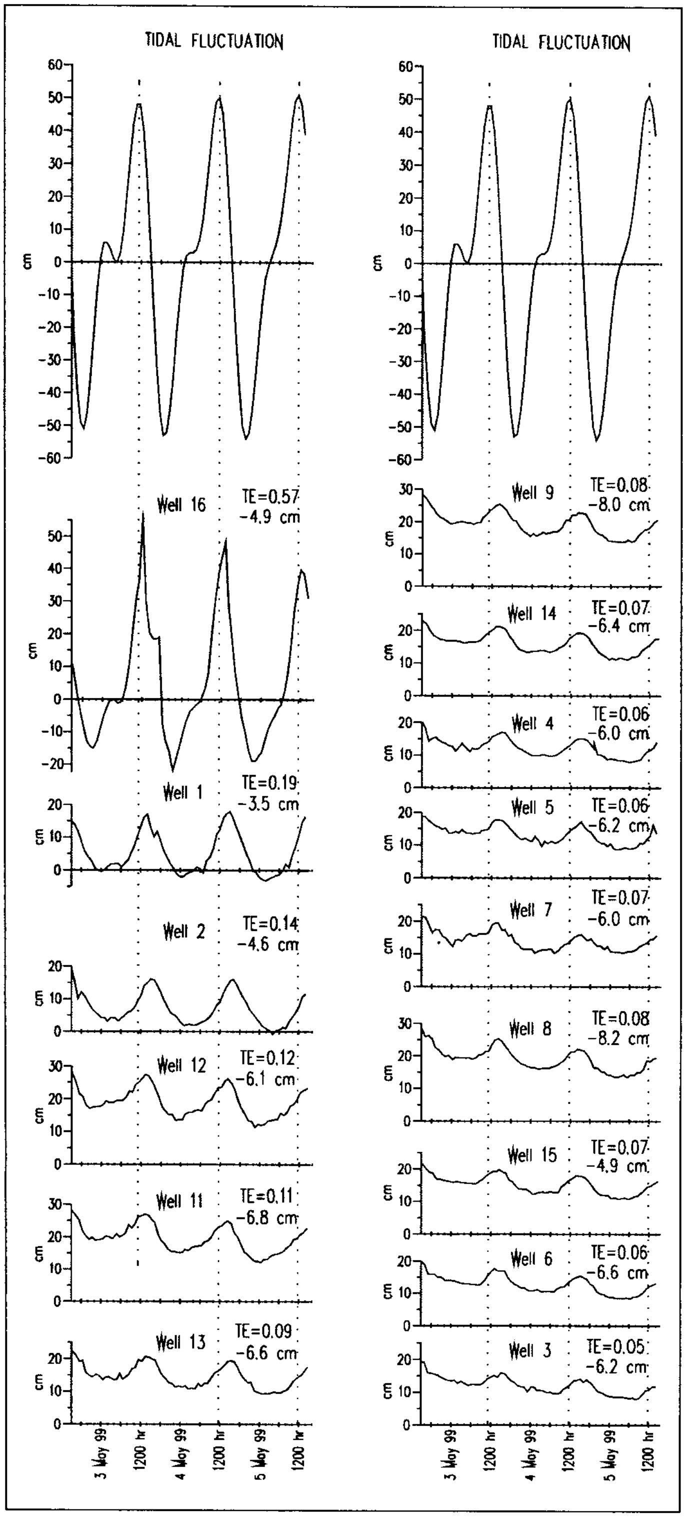

Fig. 8. Tidal groundwater oscillations were observed from 2 to 5 May 1999. Wells are arranged in order of decreasing tidal efficiency (TE). After filtering out the tidal contribution to the groundwater levels, the drop in groundwater level observed during the monitoring period was computed and is indicated below the TE values.

Table 2. Range of SEC values measured from wells during the monitoring period (2-5 May 1999)

Well no.	SEC range (μS/cm)
1	1014-1200
2	726-743
3	530-545
4	571-604
5	472-489
6	679-695
7	700-756
8	976-1041
9	467-523
11	500-526
12	1210-1557
13	657-689
14	677-696
15	461-531
16	1704-6100

April to 1 May 1999, 270.5 mm, or equivalently 94,900 m^3, of rain fell on the island. The volume of freshwater lost is equivalent to 4.3% of the rainfall event and 15.5% of the island's stored groundwater.

In situ measurements of groundwater levels, SEC, and temperature

Groundwater level is highest at the center of the island and decreases radially outward towards the coast (Fig. 8). The water table declined from 26.9 to 20.6 cm above msl in a period of three days, or an average recession rate of 2.8 cm/day. Recession rates were lower towards the coast and higher at the central portion of the island because of relative recharge from the latter towards the former. The average groundwater velocity reduced from 1.5 to 0.8 m/day. TE ratios ranged from 0.05 to 0.57 and TL value, from 0.2 to 3.3 hrs. The rapid decreases in groundwater level and flow, high TL ratios, and low TL values are due to the high permeability of the subsurface material.

The SEC values measured in wells during the monitoring period are shown in Table 2 and Fig. 9. Time series of SEC readings display linearly, receding and increasing trends with cyclical fluctuations. The negative and positive SEC slope trends indicate decreasing and increasing SEC readings, respectively (Table 2). Increasing SEC trends probably result from the cessation of recharge from the previous rainfall event. Wells receiving freshwater recharge from the central part of the island display decreasing SEC trends.

During the three-day monitoring period, the average groundwater temperature was 28.4°C, ranging from 27.9° to 29.3°C. Greater temperature variations exist in the upper part of the water column, as affected by the warmer ambient temperature. Temperature peaks occurred at around 2:00 p.m., the time at which maximum solar heating begins to diminish.

Groundwater chloride content

The maximum chloride concentration for drinking water, as prescribed by the United States Environmental Protection Agency, is 250 mg/l (McGhee 1991). Based on the wells measured for chloride content, Wells 1 and 12 are considered unfit for drinking. Fig. 10 correlates the average conductivity values for

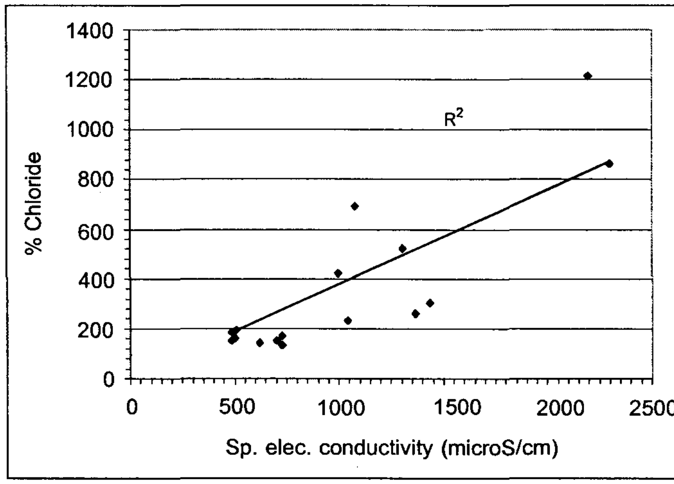

Fig. 10. Correlation of specific electrical conductivity against chloride content in groundwater

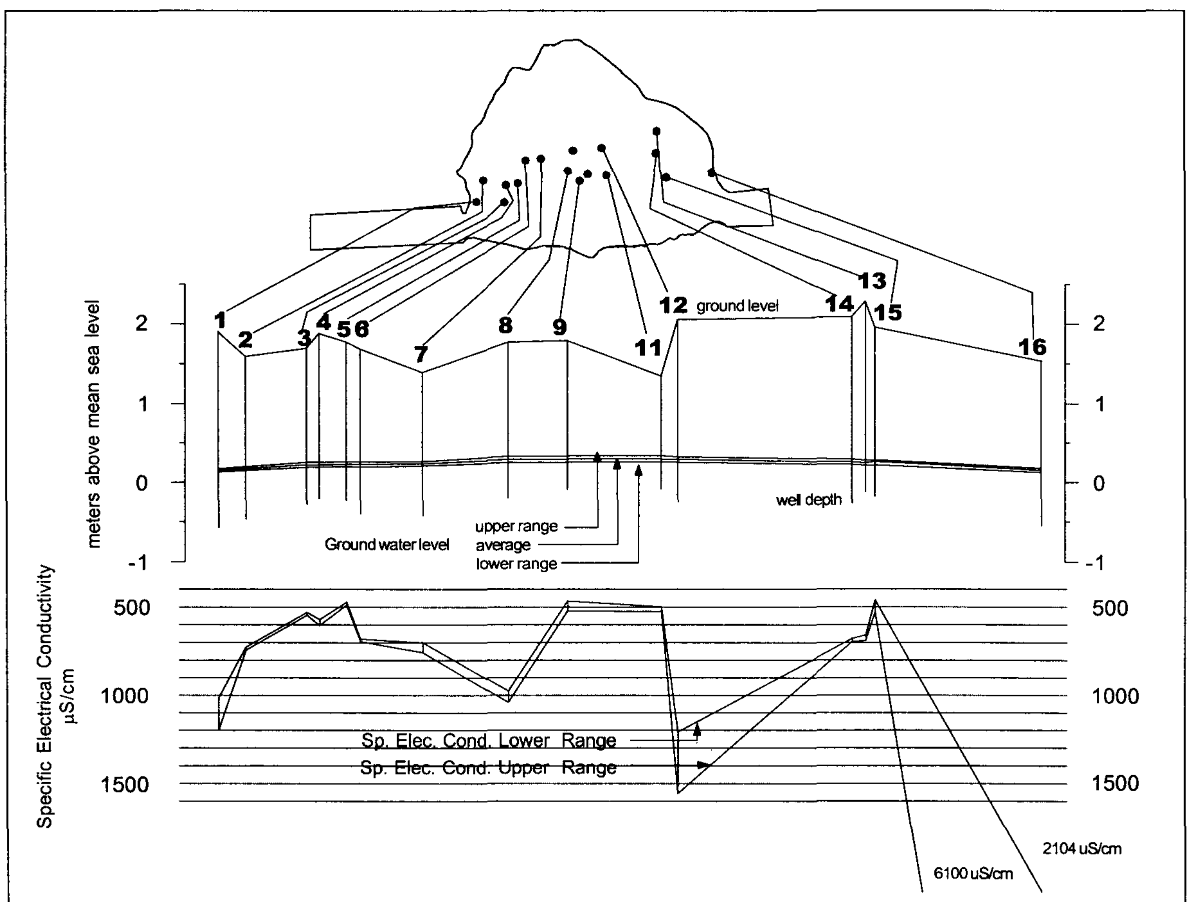

Fig. 9. Average and range of ground water levels and specific electrical conductivity values recorded in Pag-asa Island from May 2 to 5, 1999.

each well with its chloride content. Conductivity values greater than 1,000 mS/cm are not suitable for drinking. This makes the water from Wells 8, 10, and 16 unfit for drinking as well.

DISCUSSION

Physical hydrogeology

Hydraulic gradients are gentler on the eastern section of the island and steeper on the western half. Differences in hydraulic gradients are due variations in the local geology. Sands underlying the eastern section have higher permeabilities relative to the lithified reef materials found at the central and western section. High permeabilities contribute to the gentler hydraulic gradients and low permeabilities, to steeper hydraulic gradients.

The high permeability of the island is reflected by (1) the high TE and short TL values (Fig. 8), and (2) high hydraulic conductivity values, as obtained from slug tests. Tidal groundwater fluctuations exhibit asymmetric oscillations, with the crests being more distinct than the troughs (Fig. 8). Water easily fills the pores during the wetting or high tide phase and is only slowly drained during the drying or low tide phase. Wells built in reef materials exhibit greater asymmetry than those built in sandy materials.

Tidal efficiency and time lag are dependent on well depth, distance to shore, and permeability of the aquifer. Wells 1, 2, and 16 are located nearest to the shore and exhibit high TE and short TL values. Wells 11 and 12 are located in the central part of the island, but also have high TE and short TL values. This indicates the presence of a high permeability zone that is hydraulically connected with the sea and could be due to local diagenetic structures in the reef deposits.

Chemical hydrogeology

Wells 1, 8, 12, and 16 have groundwater with SEC values greater than 1,000 μS/cm (Table 1 and Fig. 9). SEC readings at the top and bottom of the water columns in these wells exhibit stratification. They already tapping the upper portion of the brackish zone (Fig. 2). Groundwater in the remaining wells, except for Wells 10 and 17, have SEC values less than 700 μS/cm and tap groundwater from the freshwater lens at a depth of less than 0.3 m below msl. Well 17 is a motorized well with SEC value of 825 μS/cm and may induce salt water intrusion by over-pumping the freshwater lens.

Freshwater budget of the island

Water budget refers to the accounting of the incoming and outgoing water. The volume of water stored in the freshwater lens is estimated by subtracting evapotranspiration and seaward groundwater discharge from the amount of rainfall in the island. Based on empirical studies, Falkland (1992) reported that only 6 to 12% of the annual rainfall is sustainable for extraction in very small islands. If the sustainable groundwater yield is only 6% of the lowest annual rainfall of 1,590 mm, and the effective area for groundwater recharge is 21.3 hectares, then approximately 20,300 m^3 of sustainable freshwater is available per year.

CONCLUSIONS

1) Pag-asa Island has an area of 31.5 hectares and a perimeter of 2.22 km. It has a flat terrain raised to only about 2 m above msl. Extensive erosion occurs on the western side of the island and along the edges of the runway.

2) Beach sand and reef materials underlie the island. These aquifer materials are highly porous, have hydraulic conductivities of approximately 4×10^{-4} to 9×10^{-5} m/sec and storativity of 0.2. Transmissivity of the island's unconfined aquifer is estimated to be on the order of 10 m^2/day.

3) Wells with groundwater SEC values greater than 1,000 μS/cm contain chloride concentrations greater than 250 mg/l and are considered unfit for drinking.

4) Tidal groundwater fluctuations were observed in all wells. Based on the analysis of TE ratios and TL, a high permeability zone on the eastern portion of the island was inferred.

5) Possible and potential contamination of groundwater may come from unprotected latrines, dumping sites, fuel storage area, and saltwater intrusion by over-pumping the freshwater lens.

6) Estimated sustainable yield for the island is 6% of the lowest annual rainfall or about 20,300 m^3/yr.

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