WATER RESOURCES ASSESSMENT

Laura, Majuro, Marshall Islands

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1 INTRODUCTION

The water supply on Majuro is from two sources: the airport runway catchment area in the south and the Laura groundwater lens in the western side of Majuro (Figure 1). The groundwater potential in the latter has to be safeguarded from two different risks: saltwater intrusion and aquifer pollution.

The development of a protection plan including the installation of a groundwater monitoring network, executing water and sanitation surveys and construction of appropriate water and sanitation facilities was suggested by SOPAC in 1999. The protection of the freshwater lens at Laura has been repeatedly indicated as a priority action by the Republic of the Marshall Islands Environmental Protection Agency (RMIEPA) and the Majuro Water and Sewage Company (MWSC).

In response to the El-Niño-related drought in 1998, a team from the Water Resources Division of the United States Geological Survey (USGS)[1] installed a monitoring network of 36 wells at 11 locations and carried out complementary monitoring of the 6 abstraction wells. The Water Resources Division is providing assistance to MWSC to advise on maximum abstraction rates and safe yield.

During a SOPAC mission to Majuro from 16-20 October 2000, a small geophysical survey was carried out as well as a visit to the existing monitoring network.

Steve Balos from MWSC assisted in the fieldwork for the Laura electrical resistivity survey and was provided with hands-on training on the application of this geophysical detection method.

[1] Todd Presley (USGS) was contacted in Honolulu by telephone. Further development of a proposal on the Laura groundwater lens should include close collaboration with the Water Resources Division of USGS in Hawaii.

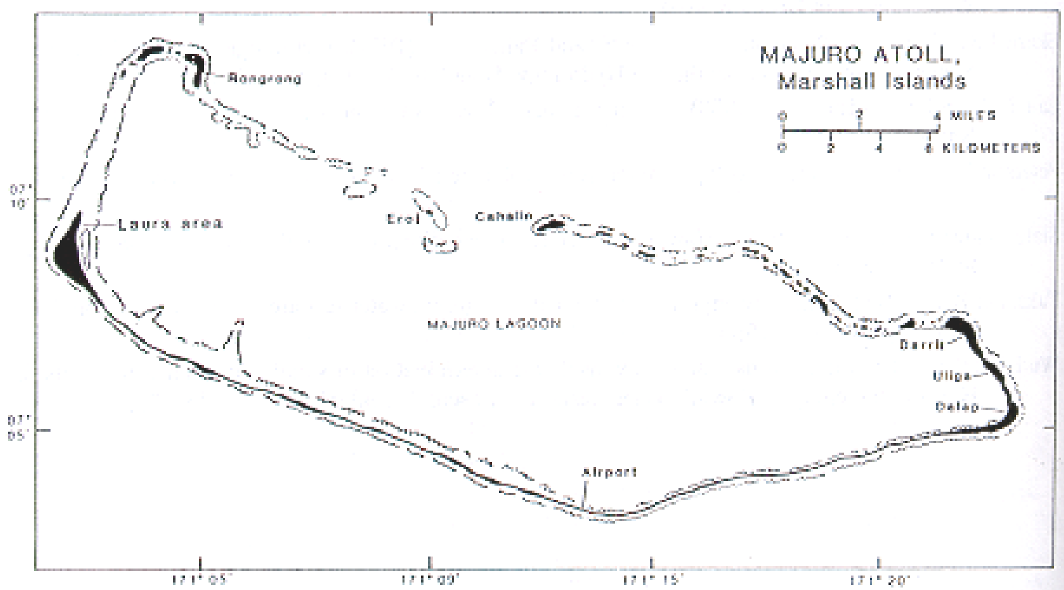

Figure 1 Majuro atoll.

Figure 1. Majuro atoll (adopted from: Falkland, 1991).

1.1 Climate

Majuro has a tropical oceanic climate influenced by northeasterly tradewinds that prevail from December to April. Periods of weaker winds and calms occur in the autumn (fall). The annual rainfall averages about 3560 mm (NOAA, 1984), but droughts are not uncommon. June through November are normally the wettest months. Mean monthly temperatures vary within a range of one degree (27^o to 28^o C) between the coolest and warmest month. Average daily temperatures are between 25^o and 30^o C. Relative humidity is uniformly high throughout the year at about 80 %.

1.2 Geology

Three geological units can be defined from the results of an earlier drilling programme executed at the center and lagoon side of the Laura area in 1987 and are varying from the shallowest to deepest: the upper sediment (uncemented grainstone), lower sediment (unlithified grainstone and wackestone) and lower limestone units (consolidated limestone) (Anthony and Peterson, 1987).

The distribution of fresh groundwater in the Laura aquifer system is influenced by the large contrast in permeability between the lower limestone unit and the overlying unconsolidated sediments, the latter being thought to be much less permeable (Anthony *et al*, 1989).

1.3 Vegetation and Agriculture

The vegetation in the Laura area includes coconut trees, palms and vegetation and babai (swamp taro) pits, all of which are potential sources of organic matter input to the lens.

High-nitrate levels were found in shallow groundwater in the Laura area, probably as a result of human-waste disposal and agricultural activities (pig pens and vegetable gardens). Two farms are present in the Laura area (vegetable and fruit) and are known to apply fertilisers and a variety of pesticides that may affect the groundwater quality.

1.4 Population

The rapid increase in population in Majuro (67 % since 1980) as a result of reduced infant death rates, increased fertility rates and immigration from outer islands has surpassed the capacity of existing water supplies, solid and sewage waste disposal facilities. Over 50 % of the registered deaths in 1991 were due to diseases commonly associated with lifestyle and poor living conditions (Barber, 1994).

In a census in 1988, Majuro had a total population of 19 664 of which 1450 were residing in the Laura area (Anthony et.al., 1989). Estimates in a report on the rural and urban water supply and sanitation review in 1994 mention 25 000 residents in Majuro (Barber, 1994) and 30 000 in 1998 (Galbraith, Bendure and Friary, 2000) whereas the latest report mentions a Majuro population of 33 045 (Goodwin, Zheng and Mistry, 2000).

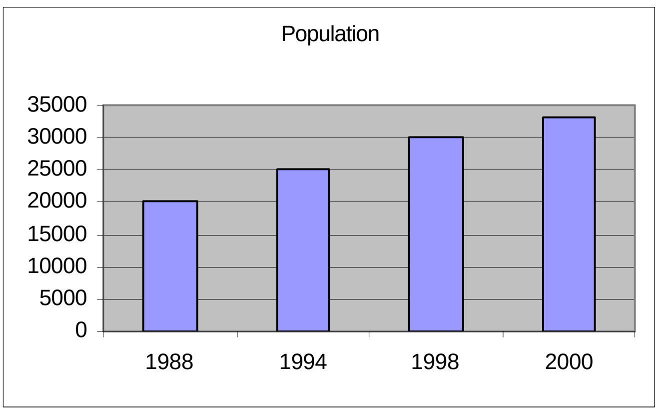

Figure 2. Population on Majuro.

The trend shown in Figure 2 shows an average rise in population of about 5 % per annum, projecting a population of 36 500 in Majuro by the year 2003.

1.5 Water Demand

The Majuro Water and Sewage Company (MWSC) is a private company under contract to the Government to provide piped water to the entire atoll; and sewerage services in the urban areas. Since there is no surface water on Majuro, all water is processed rainwater collected from the international airport runway (Figure 3) supplemented by water abstraction via wells and infiltration galleries in the Laura area.

Figure 3. Runway rain water catchment.

Unrestricted utilization levels for Majuro have been estimated to be about 45 gallons per person per day which equals 170 L/p/d (Barber, 1994). In effect 70 % of the population in Majuro has access to treated municipal drinking water and 25 % untreated well water in the Laura area.

Past projects planned for Majuro have targeted 40 gallon/day (gpd) with an estimated current population in 1994 of 25 000 resulting in a daily consumption of 1 million gallon. Hence, the storage provided by the existing reservoirs (23 Mega gallon) is less than a months supply in times of drought without the additional water supply from the Laura area.

In 1984 a surface geophysical survey in the Laura area by the USGS indicated the thickness and extent of the freshwater lens (Anthony *et al.*,1989). With an average rainfall of 130 inches (3300 mm/yr) sustainable yield was estimated to be 400 000 gpd (1500 m^3/day) in average years.

1.6 Water Supply

The runway rainwater is conveyed through a gravity collection system to a pump station and stored in three 5-million and two 3-million gallon[2] capacity open storage ponds. Water is treated using rapid sand filtration, chlorination and then stored in a 2-million gallon covered reservoir and distributed to the households in the urban area known as DUD (Delap, Uliga and Darritt). The total storage capacity is 23 million gallons (87 000 m^3).

Since 1992 water is being pumped from 6 abstraction wells and infiltration galleries using low pressure pumps which were originally rated at 70 000 gpd (circa 50 gallon/minute) each. A seventh well (well no. 4) has not been used since 1994 because of lease problems with the landowner. During the 6-month drought in 1992 the Laura lens was the only source of water for all of Majuro's residents (Barber, 1994).

Consultants discovered in 1995, that 5 wells were operational (one pump failed and was non-operational) at a rate of only 20 gallon/minute each. The situation was corrected by repositioning the pumps and installation of float switches after which each well delivered 50-60 gallon/minute each for a total of about 400 000 gpd (Parsons Engineering Science, 1995).

A distribution main transports water from Laura to the airport reservoirs for treatment and supplies water to homes and businesses along the way via a pipe to a meter on the property. An ADB loan to improve Majuro's water supply provided a small water treatment plant in Laura.

The Pacific Management Services Company developed a Laura Lens Monitoring Program (PMSC, 1992) for the monitoring network that existed in 1992 following the recommendations by USGS. The borehole sites have since been lost and a new network was installed in May 1998 by USGS.

Data collected in the 36 monitoring wells and the 6 abstraction wells were analysed by USGS in 1998. Production wells will be shut down when chloride levels are 240 mg/l and above. During the time of the SOPAC mission (October 2000) well no. 6 was out of production as a result of excessive chloride levels found since 1999. Monitoring of the network has not been carried out since 1998 but sampling and analysis of the 5 remaining abstraction wells is continued by MWSC on a monthly basis.

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[2] U.S. units are used throughout the report and US gallons are meant when gallons are mentioned. Note: 1 US gallon equals 3.79 Litres.

The assumption of 50 % evapotranspiration loss by USGS in 1984 was reviewed in 1992 by ADB indicating that an actual loss of 25 % would be more appropriate due to the extensive coconut tree cover. However, other studies show that coconut trees can reduce the amount of rain reaching the aquifer. They consume high amounts of water and with a full tree cover the recharge can reduce to about 30 % of the rainfall (Falkland, 1992).

Concern was expressed by Parsons Engineering Science (contracted by ADB) on the Government practice of the leasing land in the Laura well field area and it was recommended to acquire the land occupied by the facilities and to develop legislation to control the use of the land containing the aquifer. In addition they recommended that the Government develop a building code with a section devoted to water supply (plumbing) and roof catchments (Parsons Engineering Science, 1995).

Data to evaluate the lens performance and capacity is not available due to a lack of monitoring at observation wells. In the position statement on the Rural and Urban Water and Sanitation Review, it was indicated that the potential existed to increase the daily supply from the Laura lens but suggested that a detailed study would be necessary to redefine sustainable yield (Barber, 1994).

Recommendations for technical assistance mentioned in the Water and Sanitation Sector Strategy and Action Plan, mention the setting up of a long term continuing monitoring programme and investigation into the effects of land use on the quality of the groundwater (Doig, 1996).

1.7 Wastewater

In Laura the USEPA provided a grant to install a wastewater system. The project, designed to protect the groundwater lens, consisted of a septic tank and leach field for every family in the immediate area from which water was withdrawn.

Clusters of houses were connected to the same gravity-flow transmission lines to remote leach fields along the ocean and lagoon sides of the island. Unfortunately due to design flaws many of these systems were not functioning properly and raw sewage backs up into the toilets and overflows. In addition these systems have a limited life expectancy of 5 years. There are no septic system cleaning companies or facilities, such as sewage pump-out trucks to maintain these systems.

Power, water and tv-cable are now available in Laura, leading to increased development in that area with many new homes and businesses being constructed requiring additional sanitation facilities. At present without a centralized sewerage system and ocean outfall, septic systems or pit latrines are used. Since soil conditions are not favourable for septic tanks due to the shallow water table and high permeabilities a real potential for pollution of the aquifer exists (Barber, 1994).

1.8 Sanitation Services and Extension Services

Republic of the Marshall Islands Environmental Protection Agency (RMIEPA) has developed Toilet Facilities and Sewage Disposal Guidelines for the Marshall Islands. The regulation has taken effect in 1994 but enforcement of these rules by RMIEPA has continuously been problematic.

The College of Micronesia has provided through its Cooperative Extension Program a Water Quality Extension Agent based in Majuro. At the time of the mission a new Agent just took up his duties (Mr Almat Kaleman).

The main objective of this program is raising awareness among communities on hygiene and sanitation, providing information on best practices, assisting in facilitation of regulations and organising workshops and seminars in the urban and rural setting.

SOPAC provided an overview to the Marshall Islands on the application of small-scale wastewater treatment plants in 1999 and an appraisal of feasible options to alleviate drought impacts in the Majuro area in 1998.

2 HYDROGEOLOGY

2.1 Water Balance and Recharge

Each groundwater reservoir has a certain recharge and, on average, an equal discharge. Recharge and discharge are flows of groundwater and can be expressed in volume per time for a specific area (e.g. mm/year) (Figure 4).

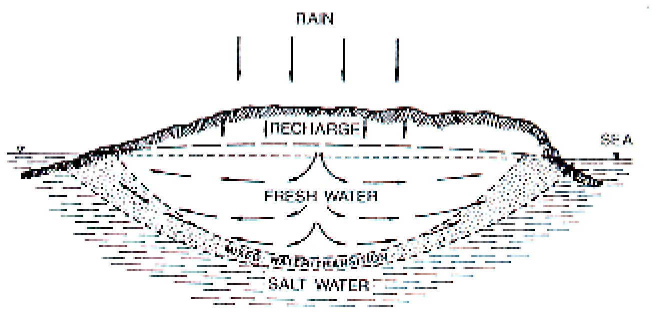

Figure 4. Freshwater-saltwater relationship under oceanic island (from: Falkland, 1992).

A Water Balance can be used to estimate the groundwater recharge using the following formula:

$$R = P - R_o - ET_{act} + \delta S$$

where
R = recharge (mm/day)
P = precipitation (mm/day)
R_o = runoff (mm/day)
ET_{act} = actual evapotranspiration (mm/day)
δS = storage change (soil moisture) (mm/day)

Annual actual evapotranspiration has been estimated at 50 % of the rainfall by Anthony and Peterson (1987) or about 1800 mm/year. With a total catchment area of 0.9 km^2 and no significant runoff the average annual recharge amounts to 1800 mm/year or 1 162 500 gpd (4400 m^3/day). The optimum withdrawal of groundwater resources can only be a part of the recharge. It is advisable to restrict the withdrawal to a certain percentage of the recharge. If a value for the safe yield is taken of 30 % as is commonly applied (Meinardi, 1991) the safe yield amounts to 348 750 gallon/day (1320 m^3/day).

Accurate rainfall data is required to estimate the changes in the recharge and determine the potential effect of groundwater abstraction on the freshwater lens. Additional data should be collected including pan evaporation, temperature (max, min) etc.

2.2 Geo-electrical Soundings

Fresh groundwater underneath small islands normally takes the form of a lens, “floating” upon more dense saline water with a transition zone in between. The transition zone between fresh and brackish groundwater is relatively thin. Because saline water is more conductive than freshwater, geo-electrical soundings can be used to detect the interface between freshwater and brackish water.

A resistivity measurement is carried out using four electrodes on a line (Figure 5). A known current is injected using two current electrodes (A and B) and the resulting voltage difference between two measuring electrodes (M and N) is measured. The quotient of current and voltage differences multiplied by a factor for the electrode separations gives the “apparent resistivity”.

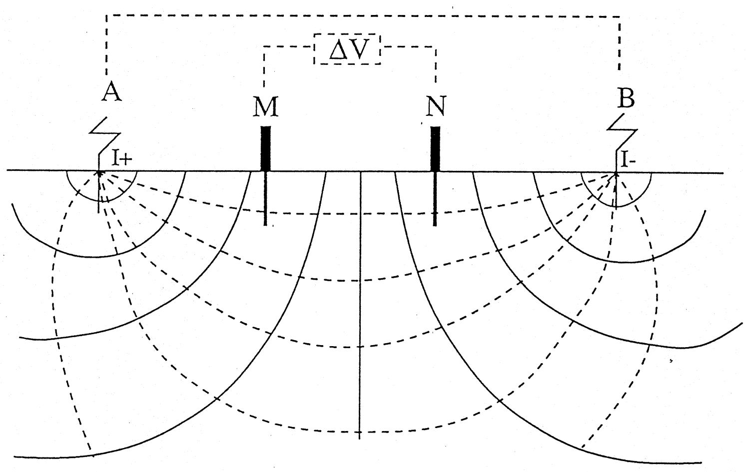

Figure 5. Geo-electrical sounding with current flow (dotted lines) and equipotentials (solid lines) between two electrodes (A-B) in a homogeneous ground.

A number of measurements are made with increasing electrode spacing, resulting in measurements of resistivities of ever-deeper layers. The result of the soundings is plotted versus the current electrode spacing, resulting in a “sounding curve”. The curve is interpreted by curve matching with standard curves and leads to the interpretation of a number of distinctive earth layers of various thicknesses with various resistivities (van Putten, F., 1989).

The electrical resistivity is a function of the composition of the deposits, the degree of water saturation and the salinity of the water. Typical resistivity values for rock/water mixtures are provided in Table 1.

Table 1. Typical resistivity values.

Coral sand saturated with sea water	2-10 ohm m
Hard coral saturated with sea water	5-15 ohm m
Sand or rock saturated with fresh water	50-300 ohm m
Dry sand or rock with very little water	500-3000 ohm m

(From: Dale, D., 1986).

Nine geo-electrical soundings were executed to determine the depth and thickness of a possible freshwater lens which is expected to have its water table at or around mean sea level. The soundings were taken in a North-South direction oriented parallel to the coastline where a more uniform lithology can be expected. Figure 7 shows the location of the soundings.

The geophysical detection method used was the Offset Wenner configuration with the ABEM Terrameter SAS 300B instrument (Figure 6).

Figure 6. Geophysical detection method.

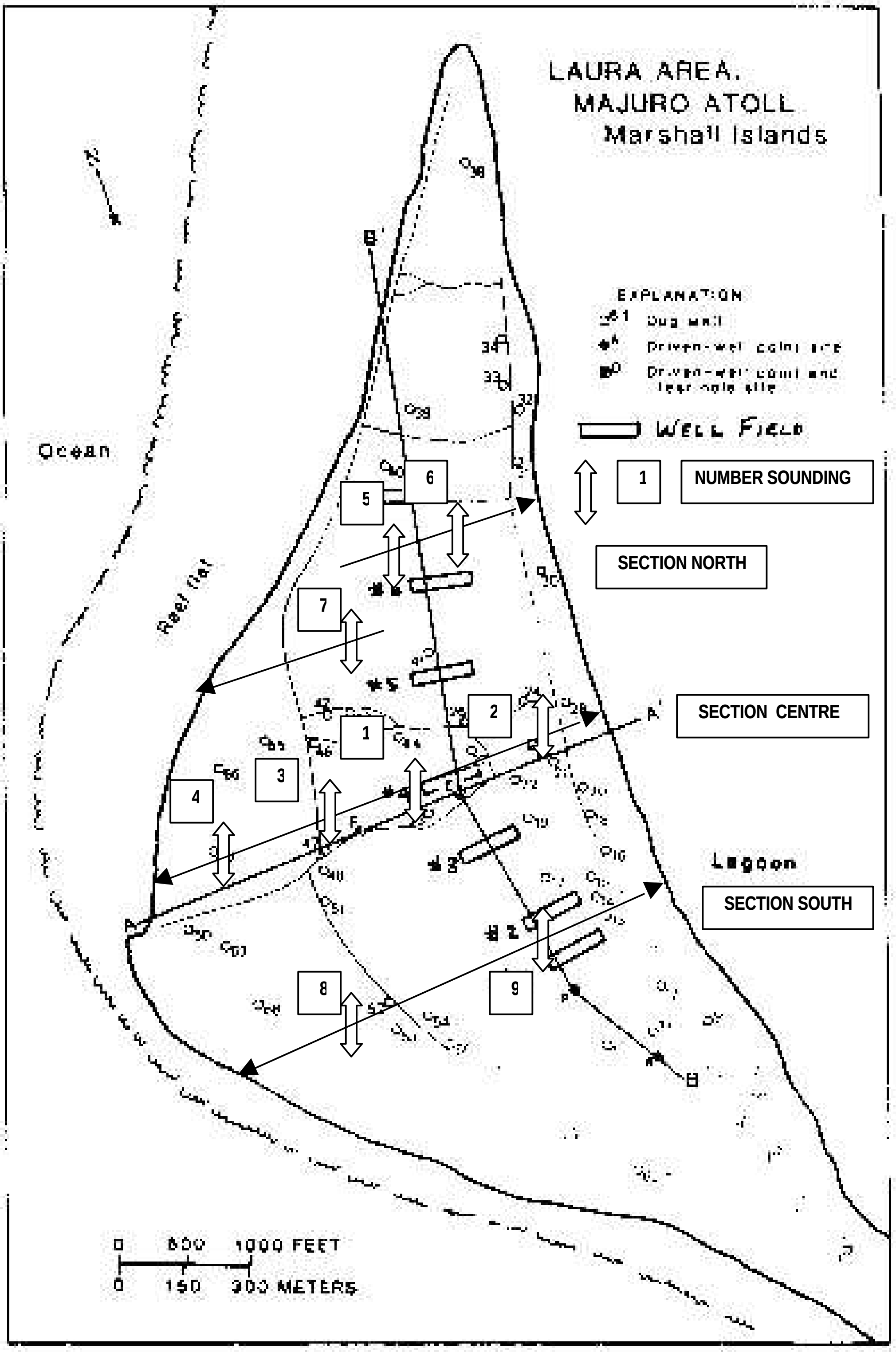

Figure 7. Geo-electrical soundings Laura.

Routine interpretation of the resistivity curves is only possible with a horizontal and uniform stratification. Interpretation of the soundings was done by iterative modeling with the software package RINVERT for Windows version 2.0. As far as possible a five-layer model was applied with the characteristics shown in Table 2. Table 3 shows the models interpreted from the data for the nine soundings.

Table 2. Five-layer model for Laura soundings.

		thickness range (m)	resistivity range (ohm m)
1	Topsoil	0.05 – 0.2	100 – 200
2	Dry zone	0.5 – 1.5	200 – 1000
3	Fresh water zone	1.0 – 10	50 – 300
4	Brackish water zone	5 – 15	15 – 50
5	Saline water zone	∞	< 15

Table 3. Geophysical models Laura.

No. of Sounding	1		2		3	
	thickness (m)	resistivity (ohm m)	thickness (m)	resistivity (ohm m)	thickness (m)	resistivity (ohm m)
Layer 1	0.12	140	0.1	86	0.9	146
Layer 2	1.1	490	0.9	61	2.6	286
Layer 3	2.6	66				
Layer 4	11.5	30	10.1	25	2.6	27
Layer 5	∞	< 1	∞	<1	∞	<1

No. of Sounding	4		5		6	
	thickness (m)	resistivity (ohm m)	thickness (m)	resistivity (ohm m)	thickness (m)	resistivity (ohm m)
Layer 1	0.3	77	0.1	52	0.5	98
Layer 2			0.4	820	0.8	187
Layer 3	2.6	5	5.2	105	0	66
Layer 4	11.1	2	17	35	10.3	23
Layer 5	∞	< 1	∞	7	∞	<1

No. of Sounding	7		8		9	
	thickness (m)	resistivity (ohm m)	thickness (m)	resistivity (ohm m)	thickness (m)	resistivity (ohm m)
Layer 1	0.3	140	0.4	774	1.7	593
Layer 2	0.6	486	0.7	497		
Layer 3	1.9	66	1.1	49	7.3	31
Layer 4	7.5	28	3.8	8	13.6	4.8
Layer 5	∞	10	∞	10	∞	<1

The elevation of each survey site was not accurately measured nor was the depth to the water table at each site due to time constraints. Data from 1998 was used to estimate the top of the freshwater zone (layer 3). In future geophysical surveys these essential data should be determined and taken into account in the modeling.

2.3 Freshwater Lens

The average thickness of the freshwater lens is crudely estimated from the geophysical interpretations and are provided in Table 4.

Figure 8 shows three cross sections through the island indicating the depth to the saline water zone in the centre of Laura lens area (I), the northern side (II) and the south side (III).

Table 4. Laura freshwater lens.

Site	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Cross section	I (centre)				II (north)			III (south)	
Depth to freshwater zone (m)	1.2	1.0	0.9	0.3	0.5	1.3	0.9	1.1	1.7
Depth to brackish zone (m)	3.8	1.9	3.5	2.9	5.7	1.3	2.8	2.2	9.0
Depth to saline zone (m)	15.3	11.1	6.1	14.0	22.7	11.6	11.3	6.0	22.6
Lens thickness (m)	14.1	10.1	5.2	13.7	22.2	10.3	10.4	4.9	20.9

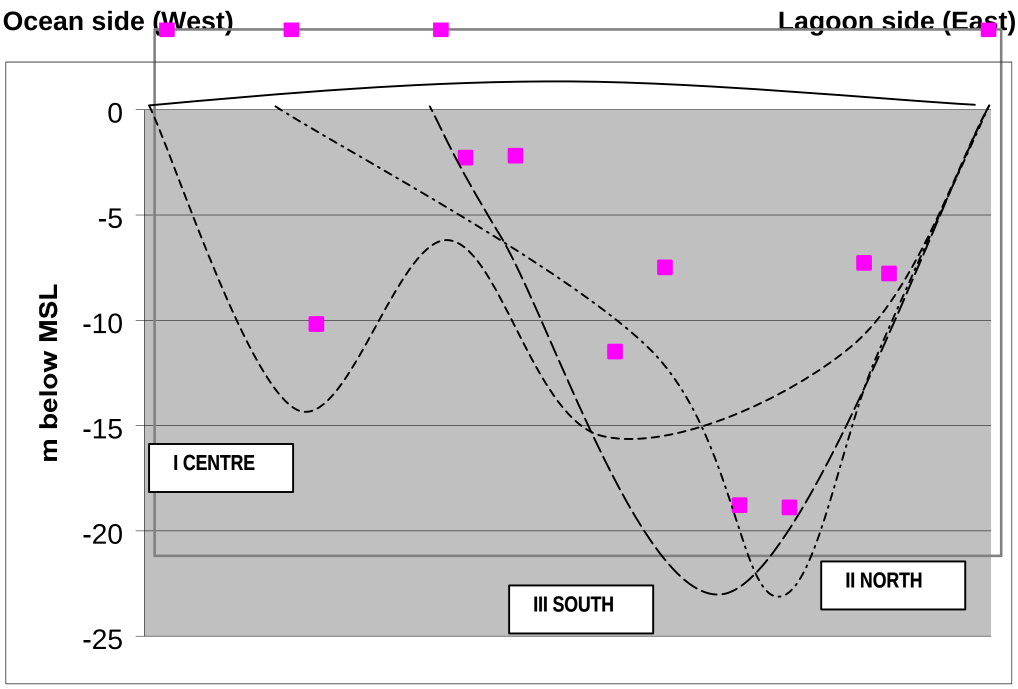

Figure 8. Depth to saline water boundary (m below MSL).

Electrical conductivity was measured at abstraction well no. 1 with 696 µS/cm and the neighbouring monitoring well was 548 µS/cm; well no. 2 showed a conductivity of 634 µS/cm and a Taro pond near the location of sounding Lau003 was measured at 590 µS/cm. These conductivity levels indicate acceptable chloride concentrations of 20 to 75 mg/l (comparison with 1998 USGS data).

Table 5. Laura freshwater lens USGS 1998 survey.

Site	a	b	c	d	e	f	g	h	i
Cross section USGS 1998	A	B		C			D		E
Corresponding section 2000		I		II			III		
Depth to saline zone (m)	7.0	10.9	6.7	14.6	6.1	10.1	14.6	12.2	11.3

Comparing the monitoring network survey results (USGS) from piezometers and chloride analysis of 1998 (Table 5) and the geophysical analysis of 2000 (Table 4) we can see that the modeling gives a reasonable indication of the average thickness of the combined freshwater lens and brackish water noting the time lag between the two measurements and the general over-estimation of the depth to the saline water zone.

A determination of the lens storage was based on the volume of the freshwater boundaries adjusted to account for porosity taken as 20 % (Falkland, *et al*, 1991).

A rough calculation can be made for the total volume available. With an average lens thickness of 11.3 m (average taken from Table 4), a porosity of 20 % and an abstraction area of 0.9 km^2 the storage works out to be 2 034 000 m^3.

This very crude estimate for the storage of freshwater at Laura of 2.0 x 10^6 m^3 (7.58 million gallons) compares well with the figures provided by Anthony *et.al.*, (1989) of 1.7 x 10^6 m^3 (6.44 million gallons) in 1984 and Falkland, *et al*, (1991) of 2.1 x 10^6 m^3 in 1985 (7.96 million gallons). The storage represents a volume equal to 454 days (about 1¼ year) at the estimated recharge of 4400 m^3/day.

The geophysical detection method can be used as a tool to indicate freshwater occurrence on atoll islands like Majuro. Once development of the groundwater lens has been established analysis on chloride levels in a monitoring network is essential to evaluate effects of the abstraction.

3 RECOMMENDATIONS AND FOLLOW UP

The monitoring network of 36 wells at 11 locations and 6 monitoring wells in Laura should be maintained and data on the monitoring network, the water quality in abstraction wells and rainfall should be accurately stored and analysed. USGS was providing assistance to MWSC to advise on maximum abstraction rates but missions are carried out on an irregular basis. Close links should be maintained between USGS, MWSC and RMIEPA to ensure follow-up. USGS should leave collected data in hard copy and digital format in the Marshall Islands with the responsible authorities.

Capacity should be improved at both institutes MWSC and RMIEPA to guarantee the sustainable exploitation of the Laura groundwater lens (i.e. safeguarding groundwater quality from pollution and intrusion of saline water).

MWSC should monitor the indicated parameters at abstraction wells and monitoring boreholes with fixed intervals.

Capacity (manpower and computers) is lacking at MWSC to store the data adequately in a database and make the appropriate interpretations. A database can be specifically developed to store data on abstraction rates; water levels; chloride content; conductivity; and nitrate. Only one computer is currently available for this purpose at MWSC.

Sanitation practices can be improved to protect the freshwater lens from domestic pollution. RMIEPA should carry out sanitation surveys in the Laura area to determine potential sources of pollution and organise awareness-raising campaigns for the resident community of Laura. Collaboration with the Community Liaison Extension Agent of the College of the Marshall Islands or other specialised NGO’s could be highly beneficial.

Demonstration projects can help to introduce appropriate wastewater technology. A study should be executed to evaluate the effects of pesticides and fertilizers used on the two farms on the groundwater quality in general.

A groundwater protection plan should be developed including upgrading of the groundwater monitoring network, executing water and sanitation surveys and construction and installation of appropriate water and sanitation facilities with the community in Laura. The development of the protection plan could well serve as demonstration project for the Strategic Action Programme for International Waters of the Global Environmental Facility (GEF).

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