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Freshwater Lens Observation: Case Study of Laura Island, Majuro Atoll, Republic of the Marshall Islands

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Abstract**—**Atolls are low-lying small islands with highly permeable ground that does not allow rivers and lakes to develop. As the water resources on these atolls basically rely on precipitation, groundwater becomes a very important water resource during droughts. Freshwater lenses develop as groundwater on relatively large atoll islands and play a key role in the stable water supply. Atoll islands in the Pacific Ocean sometimes suffer from drought due to El Nino. The global warming effects are noticeable, particularly on atoll islands. The Republic of the Marshall Islands in Oceania is burdened with the problems common to atoll islands. About half of its population lives in the capital, Majuro, and securing water resources for these people is a crucial issue. There is a freshwater lens on the largest, Laura Island, which serves as a water source for the downtown area. A serious drought that occurred in 1998 resulted in excessive water intake from the freshwater lens on Laura Island causing up-coning. Up-coning mixes saltwater into groundwater pumped from water-intake wells. Because up-coning makes the freshwater lens unusable, there was a need to investigate the freshwater lens on Laura Island. In this study, we observed the electrical conductivities of the groundwater at different depths in existing monitoring wells to determine the total storage volume of the freshwater lens on Laura Island from 2010 to 2013. Our results indicated that most of the groundwater that seeped into the freshwater lens had flowed out into the sea.

Keywords**—**Atoll islands, drought, El-Nino, freshwater lens, groundwater observation.

I. Introduction

THE Republic of the Marshall Islands (RMI) is an islet country consisting of 29 atolls and five islands, of which 11 atolls and one island are uninhabited. Majuro Atoll is 40 km from east to west and 9.7 km from north to south. Majuro Atoll is composed of the major southern areas of Laura, Arrak, Woja, Ajeltake, Rairok, Delap-Uliga-Djarrit (DUD), and Ejit, and many northern areas [1]. The northern, small islands are separated from each other and from the southern area by sea. The total population of the RMI is 53,158; and 27,797 of these people live in the capital [2]. The freshwater lens on Laura Island is a water source for Woja, Ajeltake, and the downtown DUD area; water is delivered from Laura Island to the downtown region, covering a distance of about 50 km, through a pipeline. Water demand will increase along with the population growth in Majuro Atoll. The increasing burden on the freshwater lens on Laura Island will therefore necessitate the effective use of precipitation. In times of drought, water pumping rates exceed groundwater recharge rates; therefore, it is important to maintain and preserve the water quality of the precious freshwater lens. Considering the occurrence of up-coning (a phenomenon in which, as a result of excessive water pumping from a freshwater lens, a cone of saltwater from the lower part of the aquifer intrudes into the freshwater lens and subsequently salinizes the well water) in the freshwater lens, the question of how much freshwater can be made constantly available without expanding the saltwater cone is a water resource management issue. From this perspective, the freshwater lens on Laura Island was subjected to investigation to find ways for sustainable use of this lens.

In 1998, Majuro Atoll suffered a severe drought due to El Nino. Water shortages during this period were so serious that many people obtained suitable water supply by using water purifiers and desalination units [3]. Precipitation during the dry season in 1998 was only 8.2% of the normal value and the lowest was recorded between 1954 and 2000 [4]. Water pumping during this drought period increased the salinity of the groundwater around water-intake facilities in Laura Island and produced up-coning from deep underground. Although up-coning was not detected in the freshwater lens in 1985, it was observed in 1998.

The depth of the saltwater–freshwater interface of a freshwater lens is usually determined from the chloride concentration, which is a measure of salinity or electrical conductivity (EC) [5]. The chloride concentration at the interface is usually 500 mg/L [4], and the EC is 200 mS/m [6]. Groundwater observation is simpler and faster by using EC than by using chloride concentration. In the existing monitoring wells, the vertical distribution of EC cannot be observed if the well is of the all-strainer type. To examine the saltwater–freshwater interface of the freshwater lens on Laura Island, groundwater observation was performed by [7] and [8]. In their groundwater observations, performed in 1985, ECs and chloride concentrations were measured in nine wells driven to different depths—three wells at each of the three groundwater monitoring sites (D, E, and F). Relative salinity was calculated from the chloride concentration in saltwater (19,000 mg/L) and in freshwater (10 mg/L). On a graph with the vertical axis and the horizontal axis representing depth and relative salinity, respectively, the saltwater–freshwater interface of the freshwater lens was found to have a depth corresponding to a relative salinity of 2.6%. According to WHO standards, the depth of the interface corresponds to a chloride concentration of 500 mg/L. The depth of the interface in each monitoring well depicts a smooth curve that is used to draw a cross-sectional diagram of the freshwater lens. Monitoring-well sites D, E, and F no longer exist today. They were located near the monitoring

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wells, which were used in the 1998 groundwater observations [4]. The screen interval of the monitoring wells used in 1985 was about 0.75 m; that of the wells installed in 1998 was about 0.6 m [7]. These groundwater-monitoring wells vary in structure, as well as in location and depth, according to installation year.

Up-coning causes pumped-up groundwater to be salinized, and thus, to become unusable. To preserve the Laura Lens, we investigated the groundwater in the monitoring wells. Both water-pumping methods to reduce up-coning and pumpage standards to prevent up-coning need to be developed [9]. With the aim of understanding the current status of up-coning in the freshwater lens on Laura Island, we observed the depth of the saltwater–freshwater interface and calculated the total storage volume of the lens.

II. Method

To assess the current cross-sectional shape of the up-coning that occurred in the central part of the freshwater lens on Laura Island in 1998, as well as the planar saltwater-freshwater interface, total storage volume, and water level of the lens, the groundwater needs to be observed. Here, we describe methods for observing the saltwater-freshwater interface by using ECs measured in monitoring wells. For easy and rapid EC determination, we used EC sensors for automatic observations, and EC measurement cells and EC meters for manual observations. Time-series variations in the depth of the freshwater lens in the monitoring wells were recorded to estimate the total storage volume of the freshwater lens.

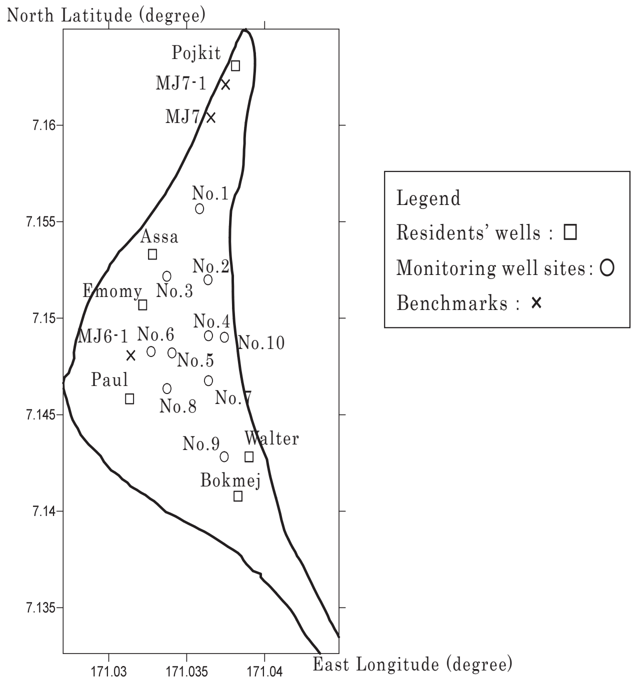
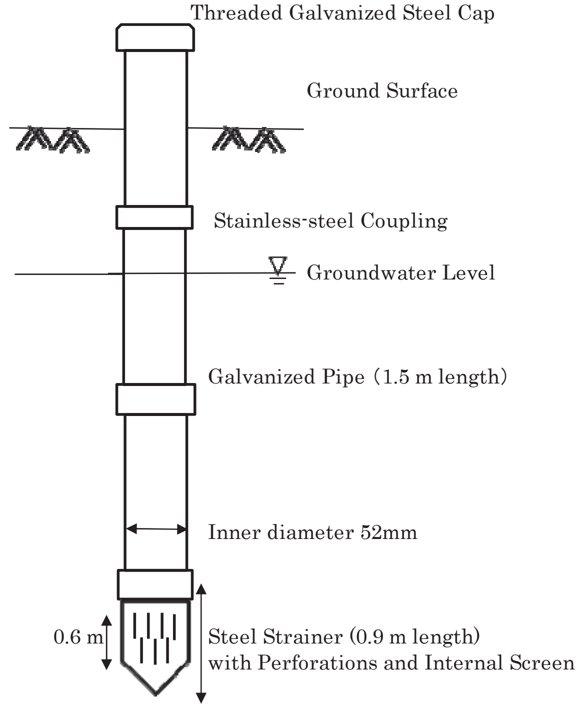
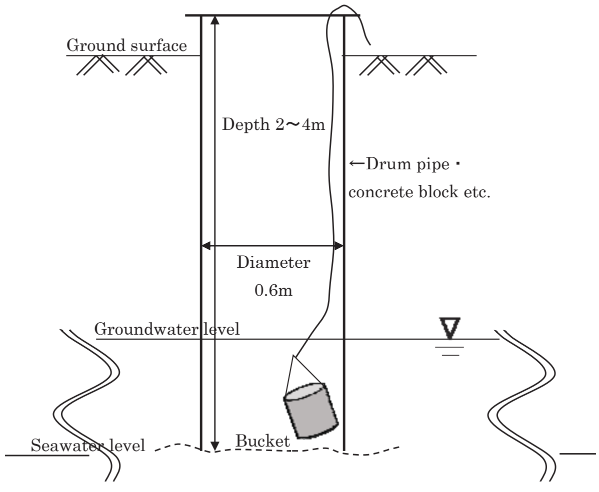


Fig. 1 Location map of monitoring-well sites, shallow wells, and benchmarks



(a) Monitoring well



(b) Residents' shallow well

Fig. 2 Structures of wells

To study inter-annual variations in the saltwater–freshwater interface, we used 10 monitoring-well sites that had been constructed by the United States Geological Survey (USGS) in 1998 for the lens observations. Two to four monitoring wells with openings at different altitudes were installed at each site. For these monitoring wells, we not only used the previous observational results [4] but also the collected groundwater observational data manually. In addition, an EC sensor was placed at the altitude of the well opening for continuous automatic observation. We also selected residents' wells to observe the water table and the planar saltwater–freshwater interface. These monitoring and residents' wells were located in such a way so as to enable us to draw a contour map of the depths of the interface and the water levels. Fig. 1 shows a location map of the monitoring-well sites, shallow wells, and benchmarks used. In 1998, the groundwater observation item was chloride concentration, but in this study it was EC. We observed hydraulic head manually and hydraulic pressure automatically in the monitoring wells, and the water table manually in the residents' shallow wells.

Altitudes of the monitoring wells were determined by leveling based on the benchmarks. The land-surface altitude was the altitude of the ground at the center of each monitoring-well site. These benchmarks were constructed by the National Institute for Environmental Studies in 2006. Fig. 2 shows a diagram of the structures of a monitoring well installed by the USGS and a resident's shallow well on Laura Island. An EC sensor was placed at the altitude of the opening of the monitoring wells, and the EC and hydraulic pressure were automatically monitored at 0 minute of every hour at 1-hour intervals. In addition, manual observations (about once a month) were made of the hydraulic head from the pipe head to groundwater level by using a water-level gauge sensor and of ECs by using the EC meter of an EC cell. In the case of residents' shallow wells, similar manual observations were done about once a month. The water table from the pipe head to groundwater level was examined by using a water-level gauge sensor and the ECs near the well bottom, by using the EC meter of an EC cell.

We observed the ECs at two different strainer depths of monitoring wells. The depth at which the EC reached 200 mS/m was calculated by interpolation and was assumed to be the depth of the saltwater–freshwater interface of the freshwater lens. The methods and items we used differed from those in the past; only the three-dimensional locations (coordinates) were the same. When the results of the groundwater observations made in 1998 were assessed or compared with the current ones, it had been necessary to take into account the margin of error between the different observation methods.

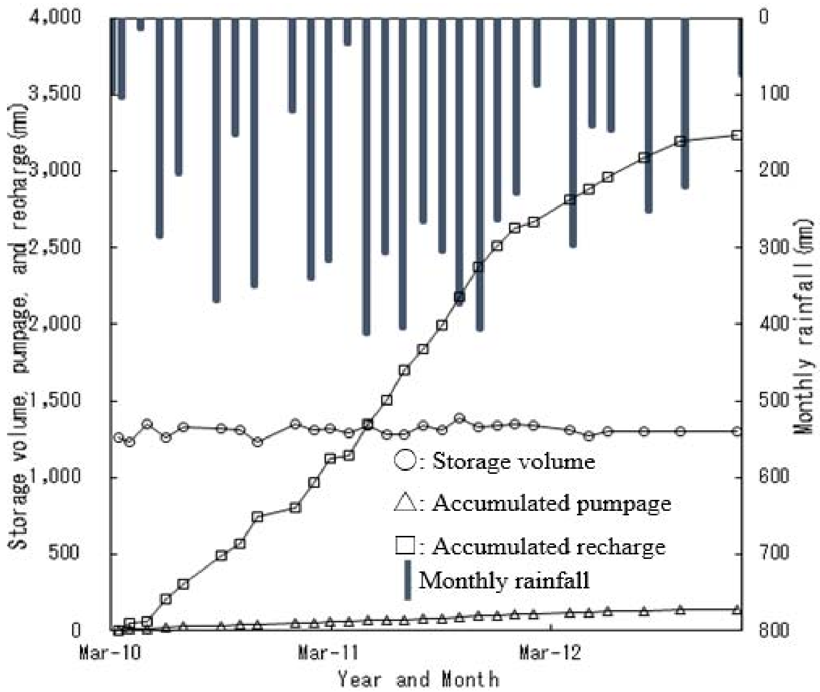


Fig. 3 Variations in the total storage volume of the freshwater lens, cumulative permeation volume, cumulative water pumping volume, and monthly precipitation

III. Results

Residents' shallow wells were used to observe the planar saltwater–freshwater interface, and the existing monitoring wells with openings at different altitudes were used to observe the depth of the saltwater–freshwater interface. The cross-sectional shape of the central part of the freshwater lens investigated in this study revealed that the 1998 up-coning still exists and has changed little in shape.

To determine the planar saltwater–freshwater interface around the ocean side, we selected residents' shallow wells located near the ocean road and observed the ECs on the groundwater surface. Based on our observations of the ECs in these shallow wells on each side of the planar interface (freshwater side and saltwater side) and of their position coordinates, the coordinates at which the EC reached 200 mS/m were calculated by interpolation. In the same way, the coordinates of the planar interface were calculated by using data from the observable shallow wells. To determine the interface on the lagoon side, we conducted test drilling on the lagoon beach at 1 to 1.5 m depth and observed the groundwater EC. We found that the interface of the freshwater lens, which existed on the landward side of the surf, was located at about 23 m from the edge of the surf.

In principle, we manually monitored the groundwater and the EC in the monitoring wells once a month. Based on the relationship between the altitudes of the openings of the monitoring wells and the EC, the depths at which the EC reached 200 mS/m were calculated by interpolation. The depths of the saltwater–freshwater interface at each monitoring-well site were inputted to the software SUFER12, and a contour map of the interface depths was made to estimate the volume of the freshwater lens.

Laura Island has an area of 1.8 km^2. Fig. 3 shows the monthly precipitation, the total storage volume of the freshwater lens, cumulative permeation volume, and cumulative water-pumping volume; the values indicated here were obtained by dividing the measured values by the area of the island. The cumulative water-pumping volume was less than the cumulative permeation volume. The total storage volume of the freshwater lens did not vary greatly. These findings suggest that most of the groundwater that seeped into the freshwater lens had drained out into the ocean.

IV. Discussion and Conclusion

We observed variations in the shape of the freshwater lens on Laura Island and estimated its total storage volume. Based on the relationship between EC and altitude of the opening at each monitoring-well site, the depth of the interface of the freshwater lens was calculated by interpolation. When the depth of the interface was shallower than the highest-altitude opening of the monitoring wells or deeper than the lowest-altitude opening, the depth of the interface was determined as the upper limit or lower limit, respectively, of the altitudes of the openings. This explains why the interface sometimes did not vary greatly. This result may have been influenced by the limited number of monitoring wells used in this study; it is, therefore, necessary to increase the number of openings in the wells to be used for monitoring in the future.

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