Sustainable Use of Laura Lens during Drought

Kazuhisa Koda, Tsutomu Kobayashi

Abstract**—**Laura Island, which is located about 50 km away from downtown, is a source of water supply in Majuro atoll, which is the capital of the Republic of the Marshall Islands. Low and flat Majuro atoll has neither river nor lake. It is very important for Majuro atoll to ensure the conservation of its water resources. However, upconing, which is the process of partial rising of the freshwater-saltwater boundary near the water-supply well, was caused by the excess pumping from it during the severe drought in 1998. Upconing will make the water usage of the freshwater lens difficult. Thus, appropriate water usage is required to prevent up coning in the freshwater lens because there is no other water source during drought.

Numerical simulation of water usage applying SEAWAT model was conducted at the central part of Laura Island, including the water supply well, which was affected by upconing. The freshwater lens was created as a result of infiltration of consistent average rainfall. The lens shape was almost the same as the one in 1985. 0 of monthly rainfall and variable daily pump discharge were used to calculate the sustainable pump discharge from the water supply well. Consequently, the total amount of pump discharge was increased as the daily pump discharge was increased, indicating that it needs more time to recover from upconing. Thus, a pump standard to reduce the pump intensity is being proposed, which is based on numerical simulation concerning the occurrence of the up-coning phenomenon in Laura Island during the drought.

Keywords**—**Freshwater lens, islands, numerical simulation, sustainable water use.

I. Introduction

In the Pacific Ocean, approximately 30,000 low-latitude (i.e., between the latitudes of 30º N and 30º S) islands exist well away from continents. Among these islands, those that are sinking into the sea may accumulate coral on or around the islands, thereby forming atolls. These formations are called atoll islands.

On islands that have bedrock with low permeability, such as volcanic islands, spring water and river water can act as water sources; however, on islands that have bedrock with high permeability, such as atoll islands, water sources are limited to rainwater and groundwater [1]. On islands with a width of over several hundred meters, fresh groundwater exists in a lens shape floating over saltwater owing to the density difference between freshwater and saltwater. These underground freshwater lenses play an important role in terms of a stable supply of water resources. However, water demands are relatively high on small islands, resulting in excessive water intake and thus contraction or even elimination of freshwater lenses [1].

The presence of El Niño in the Pacific region often causes droughts on low-latitude islands. There is also concern that climate and meteorological changes caused by global warming may expand areas of drought or cause them to shift. In addition, the possible effects of sea level rise linked to global warming on freshwater lenses are of concern.

Laura is an island town situated on the western edge of Majuro Atoll, the capital of the Republic of Marshall Islands; it has an area of 1.8 km^2 and a population of approximately 2,300, with an average altitude of a few meters. This low, flat island has no rivers or lakes. The near-surface geologic framework of Laura Island consists of three layers: the top soil layer (surface to a depth of 0.6 m), the lagoon deposit formed during the interracial period of the Holocene (upper and lower deposit layers), and the limestone in which calcite was precipitated during the marine regression stage of the Pleistocene (lower limestone) [2]. As a result of population growth in Majuro Atoll, water demand on the atoll is expected to increase and put an increasing pressure on the freshwater lenses in Laura Island—the water sources of Majuro Atoll. During droughts in particular, the refill rate of the freshwater lens exceeds pumping from the lens, yet it is important to use such valuable freshwater lenses in a manner that prevents saline intrusion into the lens. In this study, a method for sustainably pumping water from a water intake plant located over the center of a freshwater lens was numerically simulated.

II. Methods

According to [3], it is possible to pump water from water wells until the level decreases from around half to one quarter of the original thickness of the freshwater lens, if water pumpage is reduced after confirming the occurrence of upconing by monitoring the movement of the saltwater-freshwater boundary of the fresh water lens. Continued water pumping even after upconing in the freshwater lens reaches the shaft will lead to the pumping of high-salinity groundwater, after which pumping will cease. Assuming that pumping can be stopped when upconing reaches the shaft, it is possible to sustainably pump the remaining freshwater from an area around the upconing that is unaffected by water pumping. Thus, the freshwater lens should be preserved by setting upconing as one preservation item with the aim of stopping upconing from reaching the shaft, and water pumping under such a condition is evaluated by monitoring the movement of the saltwater-freshwater boundary.

In order to develop a method for preserving Laura Island's freshwater lenses, a numerical simulation was performed using the SEAWAT model [4]. A numerical simulation was

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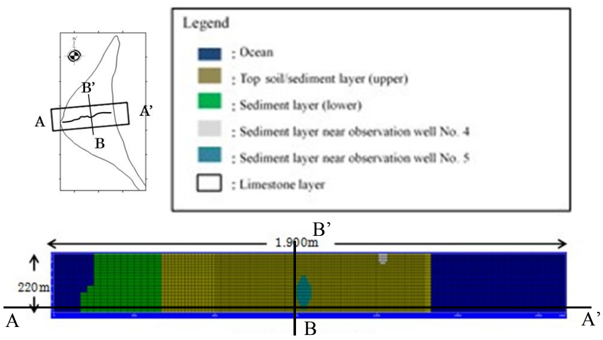
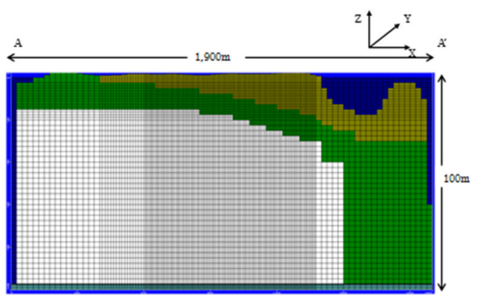
performed for a cross-section of the island near its center—the widest part of the island. The target section had a width of 220 m, a depth of 100 m, and a length of 1,900 m traversing the island (as shown in Fig. 1). The section was divided into 47 layers in the vertical direction, into 177 layers in the east–west direction, and into 19 layers in the north–south direction, and grid cell size was set to gradually decrease from the boundaries toward the center, where the freshwater lens existed. A dispersion length of 0.01 m was set for the X-, Y-, and Z-directions—standard values for water. As hydraulic characteristics, a permeability coefficient of 80,000 m/d, a specific yield of 0.99 (to ensure fluidity), and a fixed ocean salinity of 35,000 mg/l were set. The permeability coefficient and the specific yield were set based on the results of a pumping test conducted for an aquifer with a freshwater lens (in the upper sediment layer) [5]. As boundary conditions, a fixed monthly precipitation of 0 mm was set with varied pumpages. By generating saltwater upconing in the freshwater lens, a period during which water can be sustainably pumped from the lens was calculated by numerical simulation.



(a) Plan view



(b) Cross-sectional view

	Stratum	Permeability coefficient
	Deposit layer (upper)	$K_{xy} = 31$ m/d, $K_z = 2$ m/d
	Near No. 4	$K_{xy} = 31$ m/d, $K_z = 0.1$ m/d
	Near No. 5	$K_{xy} = 200$ m/d, $K_z = 2$ m/d
	Sediment layer (lower)	$K_{xy} = 350$ m/d, $K_z = 45$ m/d
	Limestone layer	$K_{xy} = 500$ m/d, $K_z = 50$ m/d

Note: Permeability coefficients were set based on the study by [6]. The boxes in the graphics are grid cells.

Fig. 1 Spatial discretization model for the cross-section near the center of Laura Island

III. Results

A freshwater lens was generated by numerical simulation in the aquifer in Laura Island over a period of approximately 20 years by setting the initial salinity of the aquifer at 35,000 mg/l, the fixed tide level at 0 m, and the recharge level at the average precipitation for the period between 1975 and 1984. As shown in Fig. 2, the thickness of the freshwater lens became constant at around 7,300 days after the start of the calculation. The shape of this freshwater lens, as shown in Fig. 2, is consistent with the shape in 1985 [7].

By varying the daily pumpage, the number of months during which water can be sustainably pumped from the freshwater lens was calculated based on the time taken for upconing saltwater to reach the shaft. As shown in Fig. 3, at zero precipitation and at a daily pumpage of 110 m^3—the average level there [8]—upconing saltwater reached the shaft after nine months. At a daily pumpage of 220 m^3, under identical climate conditions, upconing saltwater reached the shaft after six months. It was therefore shown that as the daily pumpage was increased, the time taken for upconing to occur decreased, but the total pumpage (daily pumpage × months) increased. The linear approximate expression in the figure gives sustainable pumpage levels at zero precipitation; therefore, the region under the graph represents sustainable pumping schemes.

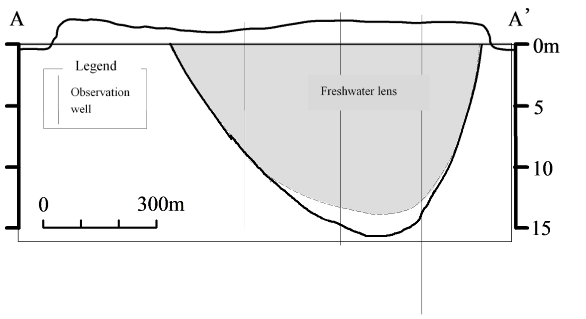


Fig. 2 A cross-section of a freshwater lens near the center of Laura Island: The broken black line indicates the border between freshwater and saltwater in 1985 [7]. The solid line indicates the simulation result and the vertical lines indicate the locations and depths of observation well. The location of the traverse line A-A' is shown in Fig. 1

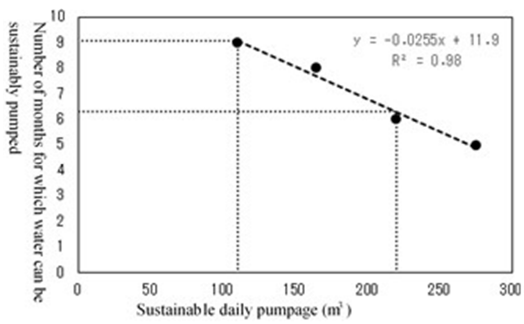


Fig. 3 Sustainable pumping period at zero precipitation

On the spatially discretized boundary surface of the central part of Laura Island, the numerical simulation software automatically sets a no-flow border. To prevent the border from influencing the groundwater flow vector, the range of spatial discretization in the north-south direction was increased from 220 m to 360 m. The influenced zone of the separation flow line is shown in Fig. 4. A sustainable amount of recharge is calculated by dividing the daily pumpage at which upconing occurs by the square measure of the influenced zone calculated from the separation flow line. Assuming a daily pumpage of 110 m^3, which is the average level, the recharge amount is approximately 17 times the monthly average during the period in which the freshwater lens is generated; assuming a 50% recharge rate, 137.5 mm is available until upconing occurs. The ratio of this available quantity to the average recharge amount (monthly) is almost equal to the ratio of the influenced zone to the submerged area of the freshwater lens of Laura Island.

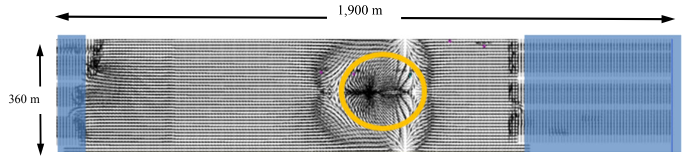
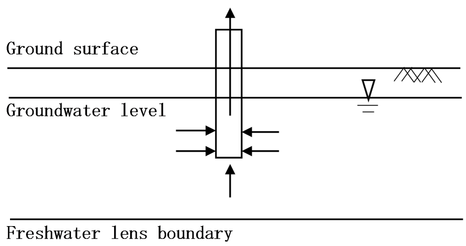
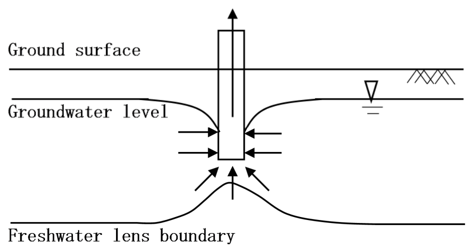


Fig. 4 The influenced zone of Laura lens: The light blue areas indicate the ocean; the yellow circle indicates influenced zones; the arrows indicate the flow direction of the groundwater table.

The mechanism by which upconing develops within the freshwater lens was clarified. Initially, the groundwater table is lowered when groundwater is pumped from the water wells. Then, groundwater from the surrounding area moves to the water well. When groundwater moves from the lower part of the water wells, the saltwater-freshwater boundary of the freshwater lens rises due to the influence of the freshwater-saltwater balance. Only rainwater in the influenced zone is pumped from the water wells.



(a) Start of pumpage



(b) Occurence of upconing

Fig. 5 The mechanism of upconing

IV. Conclusion

For its sustainable use as a water resource, the freshwater lens of Laura Island, a common property precious to the citizens of Majuro Atoll, must be handed down to the next generation in good condition by keeping it safe, secured, and stable in terms of both water quantity and quality.

Periods during which water can be sustainably pumped from the freshwater lens in Laura Island were calculated by numerical simulation assuming zero precipitation (i.e., drought). By parametrically giving daily pumpage, sustainable pumping periods for the freshwater lens were calculated based on the time taken for upconing saltwater to reach the shaft. It was shown that as the daily pumpage was increased, the time taken for upconing to occur decreased, but the total pumpage (daily pumpage × months) increased. To conserve a freshwater lens, it is important to allow time to recover from upconing; thus, it is desirable to implement low pumping intensity at wells.

In order to mitigate upconing, it is important to carry out dispersed pumping by increasing the number of pumping wells and reducing the pumpage in each well; this method should be utilized to propose a new groundwater water intake system for Laura Island, which is shown in Fig. 6. Water-supply well No.4 needs to be reactivated if the land-use problem can be resolved. Otherwise, it will be important to construct a new water supply well between well No.3 and well No.5 because there is a fair distance between them.

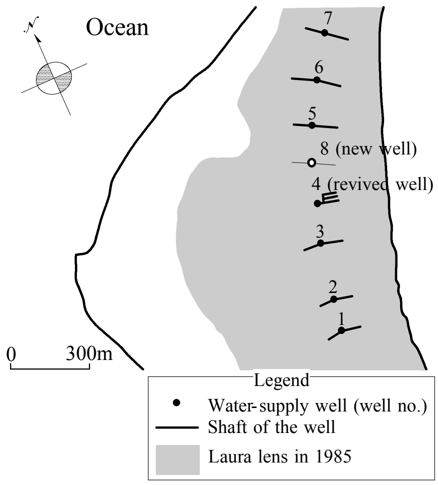


Fig. 6 New groundwater intake system in Laura Island

Acknowledgment

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