

## A Study of the Sealing Effect in the Observation Well of the Freshwater Lens at Laura Island, Republic of the Marshall Islands

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### Abstract

The authors have been conducting research with the aim of developing methods to preserve and effectively use groundwater resources. This research has been ongoing since 2008 with the focus on Laura Island, Majuro Atoll, Republic of the Marshall Islands. Examination of the groundwater level potentials in pre-existing observation wells at Site No. 6, named by the United States Geological Survey (USGS), showed no difference in the groundwater level potential along the depth. Accordingly, observation well No. 6-N was established by boring to accurately observe the profiles of electric conductivity (EC) of groundwater. However, salt water intrusion occurred, contrary to the observed results for the groundwater level potential. Accordingly, the depth of the salt water intrusion was identified by developing a double packer, observation well No. 6-N was partially sealed and the sealing effect on the observation well was confirmed. This paper will discuss 1) the measures against salt water intrusion which occurred in the observation well, 2) the groundwater flow in an observation well, which was established to measure electric conductivity (EC) profiles of the groundwater, and 3) the depth of the groundwater path estimated by measuring EC profiles with a double packer in the observation well.

**Discipline:** Agricultural Environment

**Additional key words:** double packer, electric conductivity, groundwater flow, groundwater level potential

### Introduction

The global population has reached approximately 7 billion and is projected to reach 8 billion by 2025, more than three times that of the 20<sup>th</sup> century<sup>10</sup>. Because the population growth means increased water usage, water resources are key to 1) sustainable growth, 2) alleviation of poverty, and 3) adequate global food supplies, particularly for developing countries.

There are approximately 30,000 islands in the Pacific Ocean, approximately 1,000 of which are inhabited, and most of which are considered developing countries. Among these islands, atolls are characterized as low-lying with

small areas, and fragile water resources. Because they consist of small islands, these countries have highly unusual geographical conditions; they consist of land scattered over a broad area, are small-scale, and situated far from other countries, meaning they endure disadvantageous conditions. Moreover, these island countries face issues such as erosion and flooding due to climate change and rising sea levels associated with global warming<sup>7</sup>.

Located in areas with islets, “freshwater lenses” are lenticular fresh water pools that float on top of salt water aquifers due to the difference in density between both kinds of water<sup>9</sup>. Freshwater lenses develop in the limestone aquifers of the islands in the Pacific Ocean. As no surface water exists on these islands as a stable and secure fresh water

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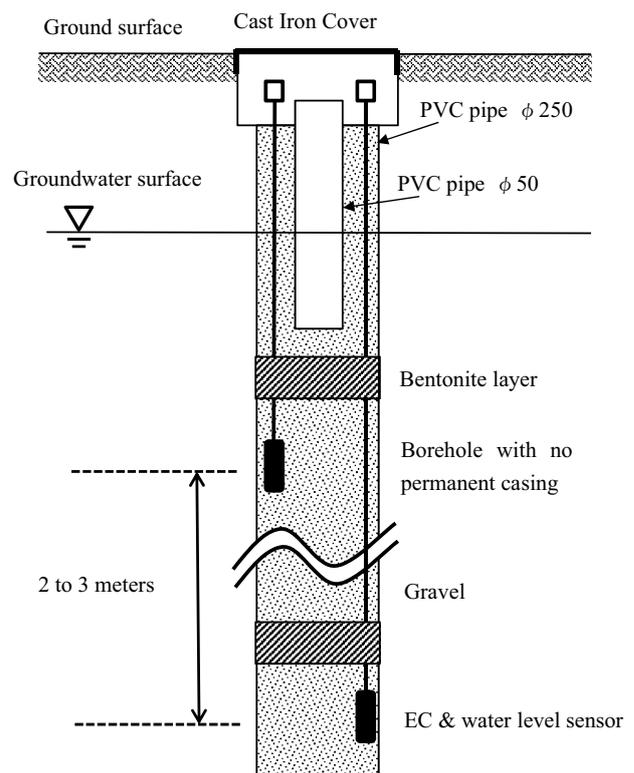
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resource, the fresh water in the freshwater lenses is withdrawn from wells as groundwater for use as drinking water<sup>5</sup>, whereupon the pressure in the vicinity of the wells decreases. Accordingly, if excessive groundwater is withdrawn, a wedge of salt water intrudes from the bottom end of the aquifer (up-coning), which eventually turns the well-water saline<sup>3,9</sup>. Once this happens, salt water remains in the microscopic spaces between the aquifer particles, and channels for salt water intrusion are formed. Thus, in cases where the groundwater environment cannot recover<sup>4,6</sup>, there is an urgent need to stop the salt water intrusion into fresh water aquifers. Freshwater lenses are therefore fragile water resources, and research and development are needed into 1) the impact on groundwater of groundwater withdrawal from the freshwater lenses and 2) conservation of freshwater lenses.

Against this background, the authors have been conducting research and targeting methods to conserve and effectively use groundwater resources on an ongoing basis since 2008 with the focus on Laura Island, Majuro Atoll, Republic of the Marshall Islands. On Laura Island, horizontal wells have been constructed to withdraw groundwater from a freshwater lens that extends over a broad area. However, Presley<sup>8</sup> reported that up-coning occurred due to excessive groundwater withdrawal from the freshwater lens. The salt water that intruded into the aquifer due to this up-coning remains within the aquifer<sup>9</sup>. Furthermore, Mimura et al.<sup>7</sup> suggested that the combination of 1) a shrinking of freshwater lenses due to rising sea levels and 2) changes in rainfall patterns due to climate change would fatally affect the water resources of the republic, suggesting the urgent need to conserve groundwater resources in this country.

The thickness of freshwater lens can be estimated by the vertical EC profile in the observation well, which is monitored to manage the amount of groundwater withdrawal from freshwater lens. A mass balance model to estimate the groundwater budget of seawater-intruded island aquifers was developed to make a suggestion on the groundwater abstraction in the Penghu islands, Taiwan<sup>2</sup>. The observations of groundwater level potential and EC are the basic key method, while a multi-level borehole monitoring system to measure the EC and groundwater level potential at different depths in a freshwater lens has been used in the small islands<sup>11</sup> (Fig. 1).

It is necessary to increase the observation depths to observe the accurate EC profile. However, it is currently impossible to do so, given the lack of observation depths in pre-existing observation wells for a site. It is also important that the effectiveness of the partial-sealing method in the observation be verified as a deterrent in case of salt water intrusion from wells. However, the effectiveness of the partial-sealing method in the pre-observation well cannot be verified because the strainer is installed only at the deepest



**Fig. 1. Multi-level borehole (additional description to White<sup>11</sup>)**

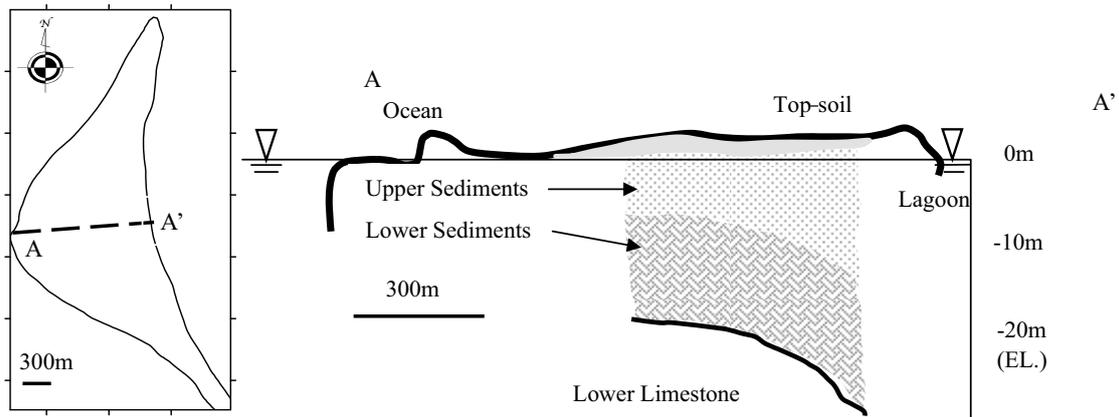
short section of the pre-existing observation well. The research objectives include 1) to increase the observation depths to observe the accurate EC profile in the observation well, and 2) to verify the effectiveness of the partial-sealing method in the observation well as a deterrent in case of salt water intrusion from wells.

The groundwater observation was conducted by installing a new observation well. The groundwater data obtained in the observation well was compared with that in existing observation wells. A double packer was developed to identify the salt water intrusion depth and the observation well was partially sealed. The research schedule is described in Table 1.

This paper will discuss 1) the groundwater flow in an observation well, which was established to measure the EC profiles of groundwater, 2) measures against salt water intrusion having occurred in the observation well, and 3) the depth of the groundwater path; estimated by measuring EC profiles with a double packer in the observation well etc.

In addition, as the pre-existing observation method embeds the materials and equipment in an observation well to observe the groundwater level potential and EC at different depths as described in Fig. 1, it is not easy to continuously and regularly maintain and operate them. Our groundwater survey method can overcome these problems by installing a strainer pipe in the bored hole.





**Fig. 3. Geological structure of Laura Island**

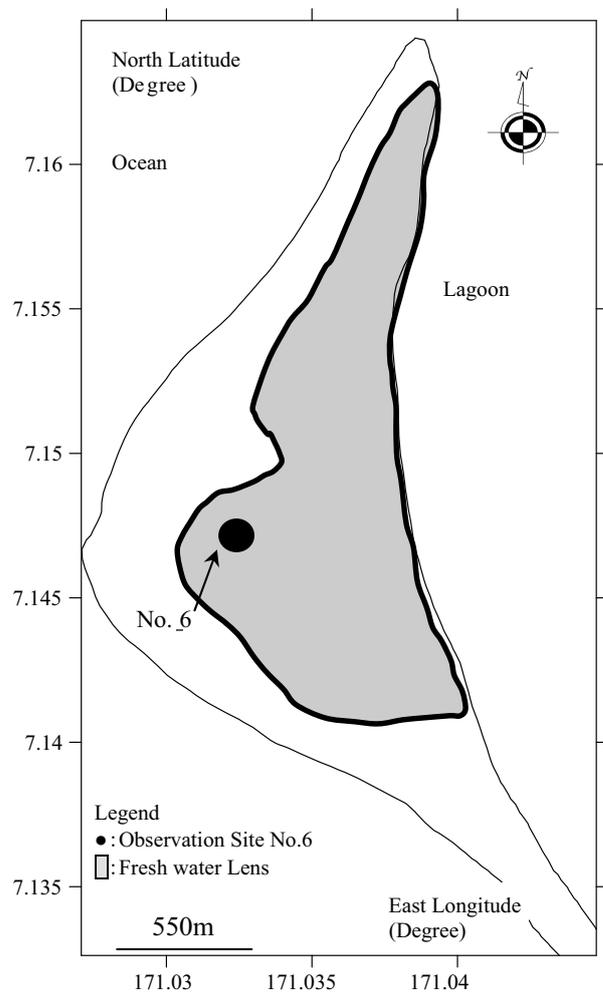
been used to the present day<sup>8</sup>. This research will describe the observation well at Site No. 6 (hereafter observation well No. 6-N), the location of which is illustrated in Fig. 4

**2. Installation of an observation well and measurements of the groundwater level potential and EC**

To carry out research into the dynamics of the fresh-water lens at Laura Island, an observation well No. 6-N was created on the center section of the freshwater lens. Site No. 6 has easy access from downtown to transport materials and equipment on wide asphalt-paved roads and enough space to keep them. As there was no objection to constructing the observation well at Site No. 6, the local landowner system did not hinder the works. The surface elevation of the site with the observation well is approximately 2 m. There are two pre-existing observation wells located within 2 m of the observation well No. 6-N.

**(1) Installation of the observation well**

The observation well was constructed from June 25-29, 2009. Boring was performed with a water supply, creating a borehole diameter of about 86 mm, and a casing pipe was inserted into the bored hole to protect the walls. The water used in the boring operation rose upward along with the dirt. After removal of sand and gravel from this water, it was pumped up and reused. Because the hole was being bored underwater in sandy ground and its walls were prone to collapse, a thickener, namely Rester (Telnite Co., Ltd., Japan), was used to protect the wall of the bored hole. The main constituent of Rester is plant polysaccharide, which is a white powder. When a small amount is added, even groundwater containing salt water becomes viscous. The viscosity disappears over time, meaning the groundwater reverted to its original state just a few days after the construction work. After completion of the boring operation, a strainer pipe was inserted. Subsequently, the casing pipe was pulled out, and filter materials were poured into the



**Fig. 4. Location map of observation well No. 6-N**

space between the wall of the hole and the strainer pipe. After the bored hole had been cleaned out, the near-surface portion of the hole was cement-plastered as protective waterproofing treatment .

The strainer pipe consisted of a polyvinyl chloride

(PVC) pipe of diameter 51 mm with a screened surface as shown in Fig. 5. The bottom of the observation well was set at a depth of approximately 15 m, after investigating pre-existing wells in the vicinity to ensure that the observation well would not break through the lower limestone and cause salt water intrusion. The difference between the observation well and the pre-existing observation well is mainly structural. The observation well consists entirely of a strainer, which can observe an accurate vertical EC profile and groundwater flow, because the EC and groundwater level can be measured at any depth.

(2) Use of a pre-existing observation well

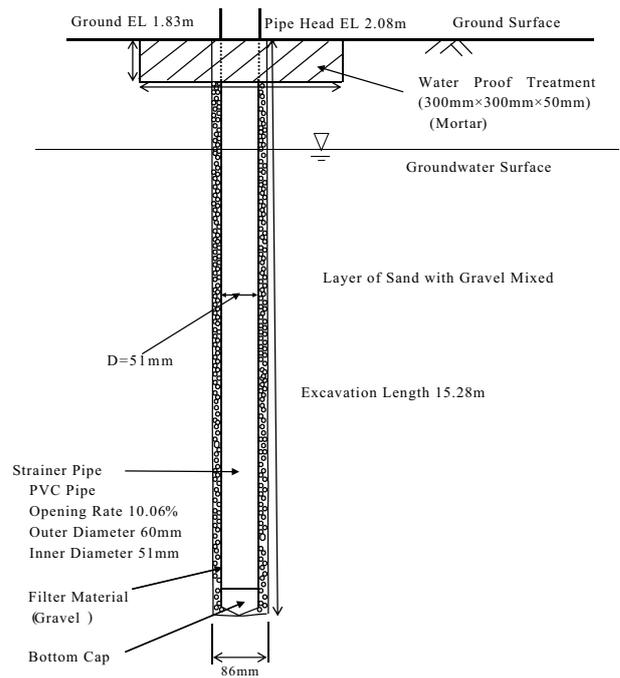
Site No. 6 with the bored observation well No. 6-N includes pre-existing observation wells that were installed by USGS during the drought of 1998 and are equipped with strainers<sup>8</sup> at different depths. The pre-existing observation wells, Nos. 6-33 and 6-48 still exist today, and were used to measure the values of groundwater level potential and EC in this research. Fig. 6 shows the structure of the pre-existing observation wells used for the groundwater measurements.

(3) Groundwater level potential and EC measurements

To achieve the research objective, the groundwater level potential and EC were observed in pre-existing observation wells and the observation well. The groundwater observation method is classified into continuous mechanical observation and manual observation. Continuous mechanical observation uses three self-recording data loggers to perform a virtual observation well-sealing experiment fixed with a double packer at specified depths. As for manual observation, a water level meter and EC meter were used during the project.

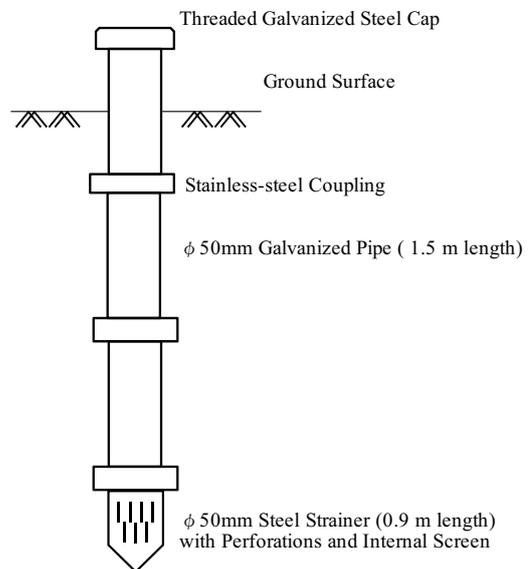
Continuous mechanical observations of EC were conducted using a Diver groundwater level and conductivity sensor/recorder (DIK-603B-B1; Schlumberger Ltd., USA). The sensor was deployed at specified depths of the observation well No. 6-N, which were then automatically measured at 15 min intervals. The observation results were used to estimate the depth of the groundwater path.

In observation well No. 6-N, the EC values were also manually measured at multiple depths. To measure the EC, an EC meter (Cond315i; Wissenschaftlich-Technische Werkstätten GmbH, Germany) was used. The measurements were performed by lowering a conductivity-measuring cell (TetraCon325; Wissenschaftlich-Technische Werkstätten GmbH, Germany) to measurement points at intervals of 1 m and using the pipe head as a reference. The cell was lowered about 1 m for 10 seconds. If the reading was stable for 10 seconds, the reading was recorded. Otherwise, if the reading was stable for more than 5 seconds, then the 4<sup>th</sup> reading was recorded. The reading after two minutes was recorded if it was not stable at all. Manual observation of the groundwater level potential was conducted using a groundwater level potential meter (Million Water Level Measure - PVC



No.	Ground EL (m)	Crown EL (m)	Strainer Depth (m)	Sensor EL (m)
6-N	1.83	2.08	All in depth direction	-2.92, -7.92, -12.92

Fig. 5. Structure of observation well No. 6-N



No.	Ground EL (m)	Pipe Head EL (m)	Strainer EL (m)	Sensor EL (m)
6-33	1.83	1.91	-7.99	-7.99
6-48	6-33	1.86	-12.54	-12.54

Fig. 6. Structure of pre-existing observation well at Laura Island (additional description to Presley<sup>8</sup>)

Coated Fiberglass Tape Combined with Probe WL50M, Yamayo Measuring Tools Co. Ltd.). In addition, the values of the groundwater level potential and EC were measured at the strainer depths in pre-existing observation well Nos.

6-33 and 6-48 with the same measurement tools as in observation well No. 6-N. Fig. 7 shows the location of the data logger and EC sensor.

**3. Identification of salt water intrusion depth and partial-sealing section in observation well No. 6-N**

**(1) Investigation of a measure against salt water intrusion**

The observation well should be partially sealed to verify the effectiveness of the partial-sealing method in deterring salt water intrusion from wells. The salt water intrusion depth in the observation well was identified for the partial sealing from the bottom to the salt water intrusion depth in the observation well.

Because the EC values of the groundwater inside the pre-existing observation wells after the installation of observation well No. 6-N increased from those during the pre-installation period, the depth of salt water intrusion needed to be identified by measuring the depth-dependent EC to examine the causes. Since the freshwater lens is the source of drinking water on Laura Island, this excluded the possibility of using tracers to measure the groundwater layer. Accordingly, a packer was created to be used in the field.

The device known as a packer consists of an air tube, which can stop the upward and downward flow of groundwater inside an observation well. A single packer can prevent groundwater intrusion from lower layers, while a double packer can prevent groundwater intrusion between the packers.

**(2) Structure of a double packer**

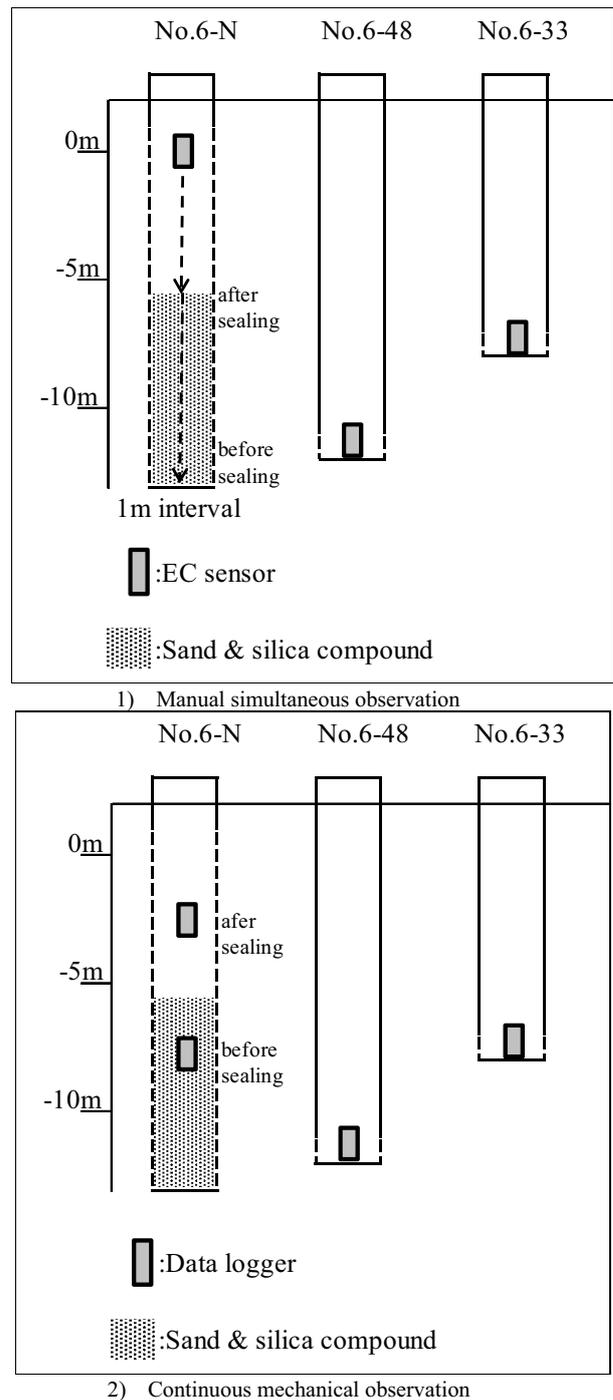
As Fig. 8 shows, a double packer was created to examine the cause of the unexpected increase in EC of the groundwater in the observation well. Once its two air tubes are filled with air, a double packer can be used to seal off a section of an observation well, while an EC sensor in the sealed section can be used to measure the EC at that depth. Measurements of the EC using a double packer at multiple depths allow 1) identification of the depth of salt water intrusion and 2) estimation of the condition of the observation well when partially sealing it down to the depth of the salt water intrusion.

**(3) Observation-well-sealing experiment with the use of a double packer**

It is important to conduct the observation-well-sealing experiment to confirm the effectiveness of the partial-sealing method. Accordingly, a double packer was developed and used in this experiment to identify the salt water intrusion depth in the observation well.

Observation well No. 6-N was virtually and partially sealed with the double packer from February 5-10, 2011. During this experiment, a data logger was deployed at elevations of -2.92, -5.92, and -10.92 m; while the double packer was deployed within the elevation range -6.92 to -4.92 m.

The EC values were measured in observation well No.

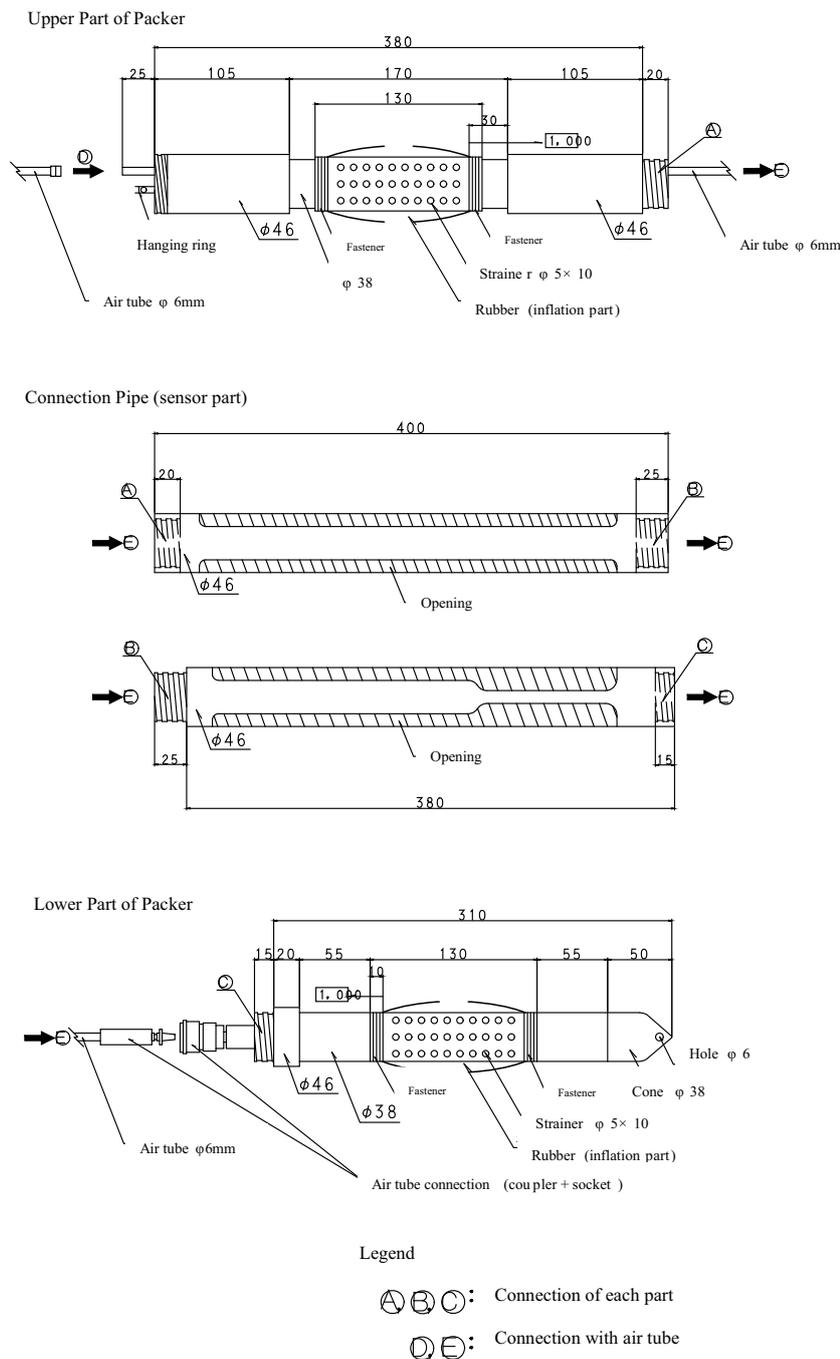


**Fig. 7. Location of the data logger and EC sensor**

6-N from February 5-10, 2011, during the virtual observation-well-sealing experiment. After a section of the well had been sealed by the double packer, the EC was measured for each deployment depth of the data logger.

**(4) Partial sealing of the observation well with a silica compound and prevention of salt water intrusion**

Based on the results of the partial-sealing experiment, observation well No. 6-N was sealed down to the salt water intrusion depth. The partial-sealing method is described as follows:



**Fig. 8. Structure of double packer groundwater prospecting device (unit: mm)**

As a coagulating agent, a silica compound (Permarock ASF-II, to prevent liquefaction; MTEC Co., Ltd., Japan) was used. By mixing this compound with sand from the site, the observation well No. 6-N was partially sealed. The result of the trial examination shows that approximately 1h after mixing, the mixture of the silica compound and sand starts coagulating, and within 4h of mixing, the mixture coagulates completely. Permarock ASF-II is an active complex silica grout, and since the viscosity of the grouting liquid is almost equivalent to that of water, it permeates well into fine-grained soil. Because the grout maintains its impervi-

ousness and solidity for an extended period, it can be applied to sandy ground and permanently improve it.

There was concern at salt water intrusion having occurred through the filter materials and channels created within the ground during the boring operation for the observation well. Accordingly, the ground around the observation well needed to be permeated and filled with the silica compound. To ensure that the silica compound could easily permeate into the ground around the observation well, the procedure for implementing partial sealing of the observation well was conducted during the outgoing tide, namely

the transition from high to low tide. Partial sealing was implemented over a depth of 0.5 m at a time. Assuming the silica compound would infiltrate the surroundings of the observation well, 7.5 liters and 1 liter at a time of the silica compound were respectively injected into the surrounding area of and inside the observation well No. 6-N.

(5) Method of observations made after application of the silica compound

During the one-week period from February 13-19, 2011, the observation well was partially sealed, using the silica-compound-sand mixture, from the bottom of the well to a depth of 7.5 m (elevation of -5.42 m). The values of the groundwater level potential and EC were measured every 15 min inside the partially sealed observation well No. 6-N (deployment elevation of EC sensor: -2.92 m) and inside the pre-existing observation well No. 6-33 (deployment elevation of EC sensor: -7.99 m).

In addition, the EC values at the strainer depths of pre-existing observation wells were simultaneously monitored eight times during the period from March 2011 to August 2011. On May 15, 2011, the EC was also measured in a farmhouse well at a distance of 45m from observation well No. 6-N. The data collected at the farmhouse revealed that the salt water intrusion observed inside observation well No. 6-N did not adversely affect its surroundings. Fig. 9 shows the location of the farmer's well and Site No. 6.

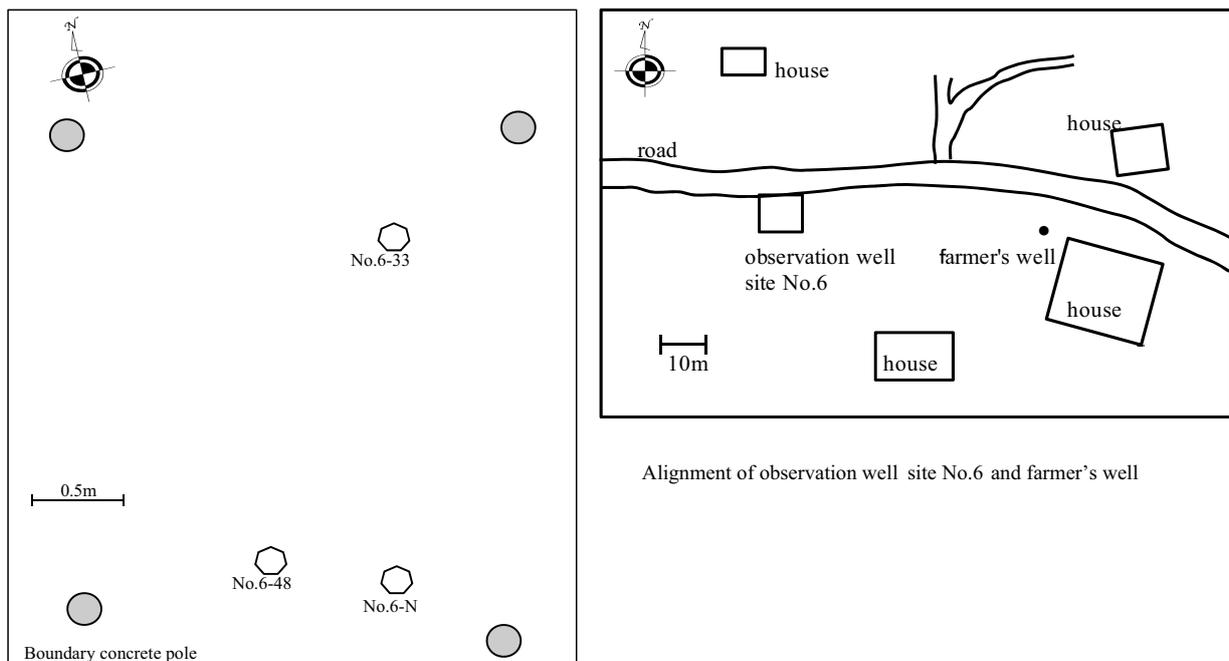
## Results

### 1. Groundwater level potential and EC

Table 2 summarizes the EC values and groundwater level potential, respectively, measured in Nos. 6-33 and 6-48, 1) in January and December, 2008, and from June 22-24, 2009 (daily), 2) from June 25-29, 2009 (daily during the boring period), and 3) in the post-boring period.

As for the groundwater observation results prior to the boring operation, the difference in the groundwater level potential between Nos. 6-33 and 6-48 was 0.20 m on average, and the value of the groundwater level potential in No. 6-33 exceeded that in No. 6-48 in all measurements. Furthermore, the EC values in No. 6-33 were less than 200 mS/m, which indicates that the opening depths of No. 6-33 were located inside the freshwater lens boundary<sup>1</sup>.

As for the groundwater observation results after boring of the observation well, the difference in the groundwater level potential was 0.16 m on average. The values of the groundwater level potential ranged from -0.06 to 0.51 m in No. 6-33 and -0.26 to 0.36 m in No. 6-48. Most of the groundwater level potential in No. 6-33 exceeded that in No. 6-48. The ranges of EC values in Nos. 6-33 and 6-48 were 71 to 5,840 and 961 to 3,190 mS/m, respectively, suggesting that the EC is larger at EL -7.99 m than at EL -12.54 m. Moreover, the EC at EL -7.99 m increased, from the seventh day after the boring operation. The fluctuations in EC



1) Alignment of observation well No.6-N, and pre-existing observation well Nos. 6-33 and 6-48

**Fig. 9. Alignment of observation well Nos. 6-33 and 48, pre-existing observation well No. 6-N, and farmer's well**

**Table 2. Manual observation results of EC and groundwater level potential in pre-existing observation well Nos. 6-33 and 6-48 (unit: mS/m)**

## (1) EC of Groundwater (mS/m)

## 1) Preliminary Observation

Date	1/21/08	12/16/08	6/22/09	6/23/09	6/24/09
No. 6-33	79	75	67	70	71
No. 6-48	1,572	236	632	698	224

## 2) During Construction

Date	6/25/09	6/26/09	6/27/09	6/28/09	6/29/09
No. 6-33	55	68	81	75	63
No. 6-48	3,090	3,040	2,090	2,900	2,830

## 3) After the Installation of the Observation Hole

Date	6/30/09	7/1/09	7/2/09	7/3/09	7/4/09	7/5/09	7/6/09	7/7/09
No. 6-33	71	75	78	80	73	104	2,300	1,041
No. 6-48	2,770	2,580	2,380	2,590	2,420	2,300	1,041	2,230

Date	7/8/09	7/9/09	7/10/09	7/11/09	7/12/09	7/31/09	8/5/09	8/10/09
No. 6-33	1,700	1,627	2,580	855	3,030	3,100	2,420	2,360
No. 6-48	2,600	2,480	2,190	1,942	2,100	2,170	2,000	1,245

Date	8/13/09	8/15/09	8/21/09	8/22/09	8/24/09	8/25/09	8/26/09	8/27/09
No. 6-33	1,990	2,080	1,759	1,663	1,690	2,060	2,310	2,500
No. 6-48	1,950	2,080	1,827	1,772	1,760	1,960	1,656	1,738

Date	8/28/09	8/29/09	8/30/09	8/31/09	9/1/09	9/2/09	9/13/09	9/19/09
No. 6-33	2,500	2,510	2,330	2,340	2,330	2,470	2,370	2,030
No. 6-48	1,738	1,685	1,594	1,557	1,575	1,260	1,510	1,340

Date	9/27/09	10/11/09	10/12/09	10/14/09	10/15/09	10/19/09	10/26/09	10/31/09
No. 6-33	2,090	1,731	1,559	1,551	1,534	1,524	1,526	2,490
No. 6-48	1,260	2,080	2,050	2,080	2,050	1,987	1,841	1,746

Date	11/2/09	11/3/09	11/16/09	11/28/09	12/9/09	12/17/09	12/26/09	1/2/10
No. 6-33	2,290	2,210	2,090	1,270	1,280	1,190	815	778
No. 6-48	1,755	1,788	1,260	1,510	1,420	1,720	1,633	1,690

Date	1/10/10	1/18/10	2/8/10	2/16/10	2/23/10	2/27/10	2/28/10	3/1/10
No. 6-33	634	614	587	585	5,840	1,477	784	1,512
No. 6-48	1,544	2,010	2,370	2,430	2,670	2,810	2,840	3,040

Date	3/3/10	3/5/10	3/7/10	3/11/10	4/16/10	4/17/10	4/28/10	7/29/10
No. 6-33	1,672	1,784	1,341	1,778	1,772	1,759	1,938	769
No. 6-48	3,110	1,873	2,960	2,920	3,170	3,020	3,180	1,741

Date	9/23/10	10/1/10	10/7/10	10/9/10	10/16/10	10/26/10	11/7/10	11/21/10
No. 6-33	831	1,298	970	1,282	1,115	1,103	1,275	1,565
No. 6-48	2,180	1,978	1,594	1,411	1,382	1,605	1,632	1,510

Date	1/9/11	1/23/11	3/1/11	4/27/11	5/3/11	5/5/11	5/6/11	6/23/11	7/26/11	8/22/11
No. 6-33	1,414	1,368	1,525	354	1,082	1,004	916	83	255	204
No. 6-48	2,430	1,455	2,600	2,720	2,880	2,920	3,190	1,920	2,370	1,985

## (2) Groundwater level potential (elevation, m)

## 1) Preliminary Observation

Date	1/21/08	12/16/08	6/22/09	6/23/09	6/24/09
No. 6-33	0.07	0.21	0.22	0.06	0.01
No. 6-48	0.05	0.03	0.04	-0.16	-0.38

## 2) During Construction

Date	6/25/09	6/26/09	6/27/09	6/28/09	6/29/09
No. 6-33	0.27	0.23	0.11	0.31	0.09
No. 6-48	0.13	0.13	0.06	0.47	0.08

## 3) After the Installation of the Observation Hole

Date	6/30/09	7/1/09	7/2/09	7/3/09	7/4/09	7/5/09	7/6/09	7/7/09
No. 6-33	0.25	0.10	0.18	0.18	0.08	0.22	0.27	0.06
No. 6-48	0.26	0.11	0.22	0.13	-0.02	0.26	0.23	-0.10

Date	7/8/09	7/9/09	7/10/09	7/11/09	7/12/09	7/31/09	8/5/09	8/10/09
No. 6-33	0.03	0.10	0.12	-0.06	0.21	0.19	0.11	0.29
No. 6-48	-0.12	0.0	0.06	-0.01	0.27	0.10	-0.15	0.26

Date	8/13/09	8/15/09	8/21/09	8/22/09	8/24/09	8/25/09	8/26/09	8/27/09
No. 6-33	0.19	0.19	0.01	0.11	0.22	0.02	0.03	0.03
No. 6-48	0.19	0.19	0.10	-0.06	0.10	-0.10	-0.08	-0.05

Date	8/28/09	8/29/09	8/30/09	8/31/09	9/1/09	9/2/09	9/13/09	9/19/09
No. 6-33	0.06	0.10	0.07	0.23	0.03	0.16	0.21	0.09
No. 6-48	-0.02	0.06	-0.04	0.17	-0.14	0.11	0.15	-0.22

Date	9/27/09	10/11/09	10/12/09	10/14/09	10/15/09	10/19/09	10/26/09	10/31/09
No. 6-33	0.31	0.14	0.14	0.18	0.16	0.31	0.32	0.21
No. 6-48	-0.22	-0.05	-0.05	-0.12	-0.15	-0.22	0.09	0.08

Date	11/2/09	11/3/09	11/16/09	11/28/09	12/9/09	12/17/09	12/26/09	1/2/10
No. 6-33	0.22	0.09	0.31	0.24	0.26	0.29	0.21	0.28
No. 6-48	0.10	-0.19	-0.22	0.25	-0.02	0.05	0.17	0.07

Date	1/10/10	1/18/10	2/8/10	2/16/10	2/23/10	2/27/10	2/28/10	3/1/10
No. 6-33	0.17	0.19	0.14	0.16	0.27	0.03	0.12	0.16
No. 6-48	0.20	-0.06	0.10	0.14	0.30	-0.24	-0.20	-0.06

Date	3/3/10	3/5/10	3/7/10	3/11/10	4/16/10	4/17/10	4/28/10	7/29/10
No. 6-33	0.22	0.10	0.18	0.22	0.10	0.15	0.04	0.16
No. 6-48	0.16	-0.10	0.20	0.05	-0.26	-0.17	-0.11	-0.02

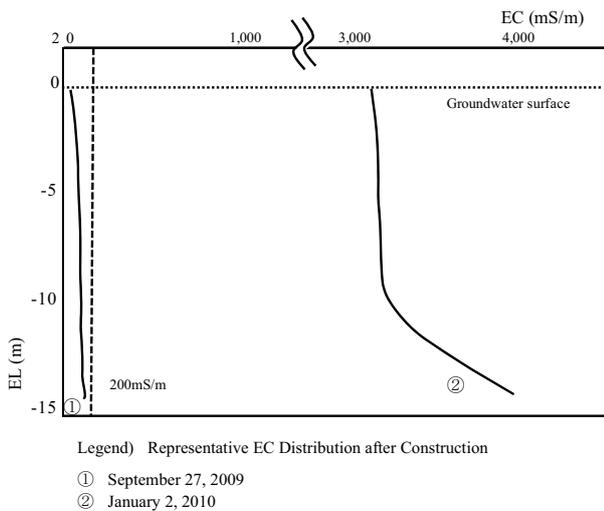
Date	9/23/10	10/1/10	10/7/10	10/9/10	10/16/10	10/26/10	11/7/10	11/21/10
No. 6-33	0.37	0.34	0.51	0.19	0.21	0.12	0.48	0.48
No. 6-48	-0.17	0.25	0.14	0.01	0.18	-0.11	-0.01	0.25

Date	1/9/11	1/23/11	3/1/11	4/27/11	5/3/11	5/5/11	5/6/11	6/23/11	7/26/11	8/22/11
No. 6-33	0.35	0.38	0.41	0.31	0.11	0.19	0.22	0.31	0.48	0.14
No. 6-48	0.07	0.06	0.12	0.34	-0.12	0.20	-0.09	0.36	0.07	-0.07

at EL -7.99 m exceeded those at EL -12.54 m. Although the EC values fluctuated, it started increasing on July 5, 2009 (sixth day after the boring operation) and reached 3,000

mS/m on July 12, 2009 (13<sup>th</sup> day after the boring operation).

Fig. 10 shows the vertical EC profiles in observation well No. 6-N on September 27, 2009 (90<sup>th</sup> day after the bor-

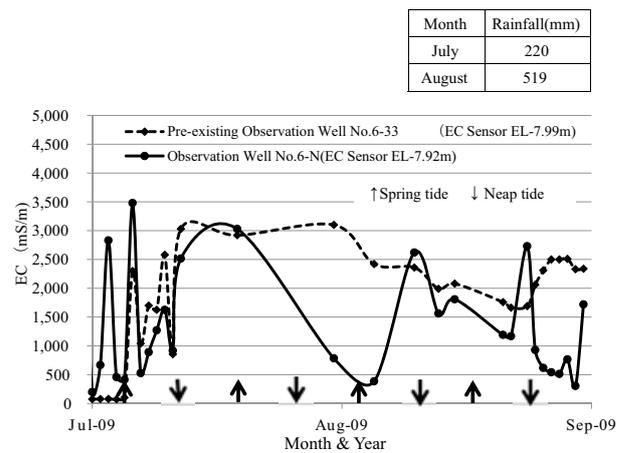


**Fig. 10. EC profile in observation well No. 6-N (manual observation)**

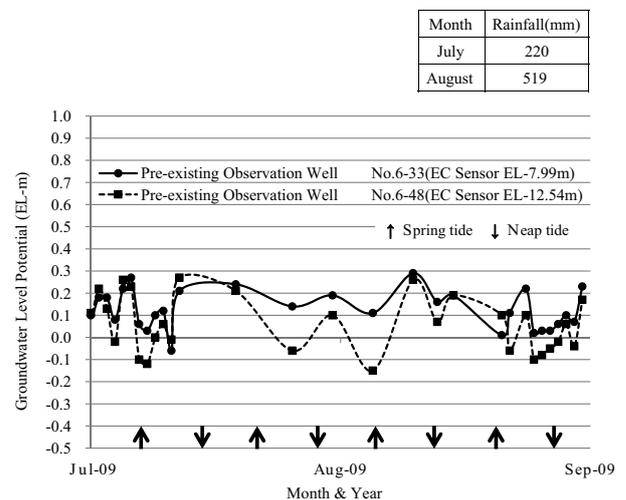
ing operation) and January 2, 2010 (188<sup>th</sup> day after the boring operation). On the 90<sup>th</sup> day after the boring operation, the EC near the groundwater surface was 68mS/m, rising gradually with increasing depth and attaining a value of 135 mS/m at an elevation of -12.92 m. On the 188<sup>th</sup> day after the boring operation, the EC remained at around 3,180 mS/m from the groundwater surface to an elevation of -8.92 m, and then rose with increasing depth below that elevation, attaining a value of 4,420 mS/m at an elevation of -12.92 m.

Fig. 11 shows the measurement results for the EC from observation well No. 6-N (EL -7.92 m) and pre-existing observation well No. 6-33 (EL -7.99 m) between June 30 and August 31, 2009. The EC fluctuated within the range 193 to 3,480 mS/m at an elevation of -7.92 m in observation well No. 6-N. The EC in pre-existing observation well No. 6-33 fluctuated within the range 71 to 3,100 mS/m, but tended to decrease gradually from mid-July to August, 2009 because the rainfall, which exceeded 500 mm for a month, entered from the shallow zones into the No. 6-N. In both Nos. 6-N and 6-33, the influence of the tidal level on the EC could not be clearly observed. The EC and water level, which were manually observed at observation time, differed from the average values at the time because they were affected by monthly neap and spring tides as well as daily low and high tides. As we could obtain only the monthly rainfall data, the influence of the rainfall is not discussed.

Fig. 12 shows the groundwater level potentials measured in pre-existing observation well Nos. 6-33 and 6-48 between June 30 and August 31, 2009. The groundwater level potentials in Nos. 6-33 and 6-48 fluctuated within the elevation ranges -0.06 to 0.29 m and -0.15 to 0.27 m, respectively. For almost the entire observation period, the values of the groundwater level potential for No. 6-33



**Fig. 11. EC in observation well No. 6-N and pre-existing observation well No. 6-33 (manual observation)**

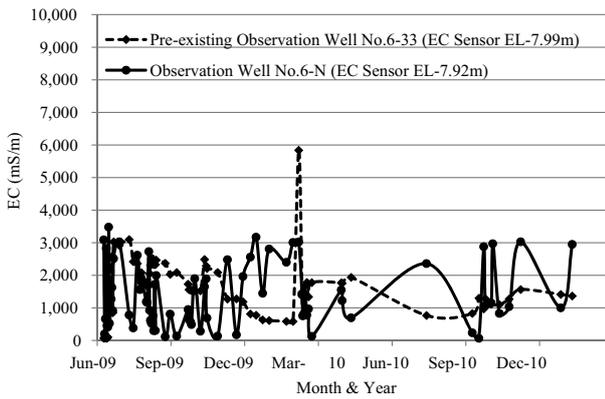


**Fig. 12. Groundwater level potential in pre-existing observation well Nos. 6-33 and 6-48 before and after the construction of observation well No. 6-N (manual observation)**

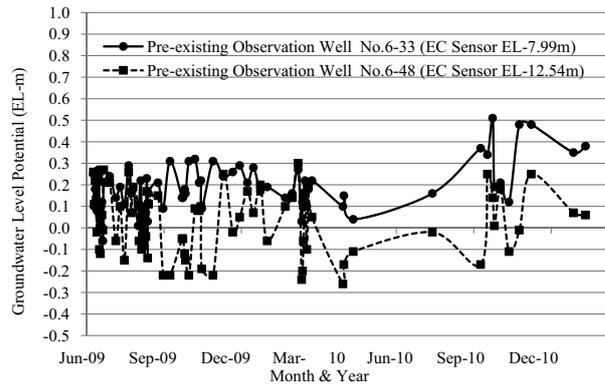
exceeded those in No. 6-48, with a mean difference of 0.06 m. As we could obtain only the monthly rainfall data, the influence of the rainfall is not discussed.

**2. Conditions inside the observation well No. 6-N and pre-existing observation well No. 6-33 prior to the partial-sealing operation in No. 6-N**

Fig. 13 shows the EC measurement results in well Nos. 6-N (EL -7.92 m) and 6-33 (EL -7.99 m) from June 30, 2009 to January 13, 2011, a period prior to partially sealing the observation well No. 6-N. The EC values at an elevation of -7.92 m inside observation well No. 6-N fluctuated within the range 64 to 3,480 mS/m. Inside pre-existing observation well No. 6-33, the EC values fluctuated within the range 71 to 5,840 mS/m. Although the maximum value of 5,840 mS/m was observed in February 2010, the EC values gradually decreased over the entire measurement period.



**Fig. 13. EC in observation well No. 6-N and pre-existing observation well No. 6-33 until partial sealing of No. 6-N (manual observation)**



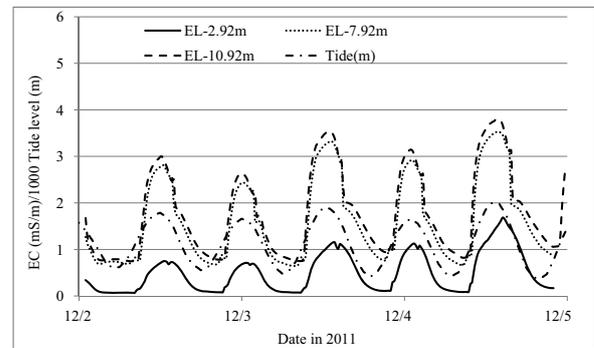
**Fig. 14. Groundwater level potential in pre-existing observation well Nos. 6-33 and 6-48 until the partial sealing of observation well No. 6-N (manual observation)**

Fig. 14 shows the measurement results of the groundwater level potential in pre-existing observation well Nos. 6-33 and 6-48 from June 30, 2009 to January 23, 2011, which fluctuated within the elevation ranges -0.06 to 0.51 and -0.26 to 0.30 m, respectively. During most of the observation period, the values of the groundwater level potential in No. 6-33 exceeded those in No. 6-48, with an average difference of 0.15 m.

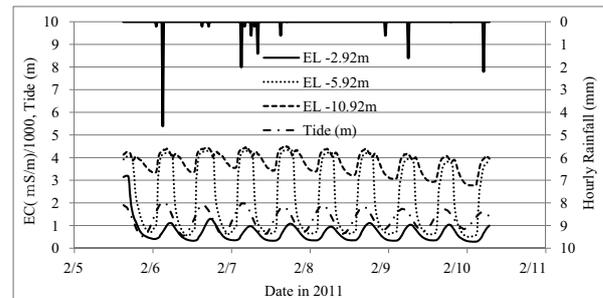
**3. EC with a double packer attached and identification of partial-sealing section in observation well No. 6-N**

As for the observation-well-sealing experiment with the use of a double packer, the measured EC values differed from one deployment depth to another as shown in Fig. 15. The difference in the measured EC values between elevations of -2.92 and -10.92 m was 3,127 mS/m on average. In all measurements, the EC values were higher at an elevation of -10.92 m than at -2.92 m. At elevations of -10.92, -5.92, and -2.92 m, the EC values fluctuated within the ranges 2,767 to 4,499, 500 to 4,334, and 285 to 3,198 mS/m, respectively. The EC values at an elevation of -5.92 m were between those at elevations of -10.92 and -2.92 m.

Fig. 15 1) shows that when the height of the connection pipe was -7.92 m, the EC at the lower packer and connection pipe was duplicated, which indicates upward movement of the high EC groundwater was unhindered. However, Fig. 15 2) shows that when the height of the connection pipe was -5.92 m, EC at three parts was not duplicated, which indicates hindered upward movement of the high EC groundwater. At an elevation of -2.92 m the EC values exceeded 3,000 mS/m until February 6, 2011 but were subsequently less than 1,000 mS/m after the double packer was installed. The existence of the groundwater path affected the EC at the connection pipe because the double packer could halt the groundwater flow in the observation well where the permeability was very high. EC at -5.92 m



1) EC change in case the double packer is installed between EL -7.42 and -8.42 m



2) EC change in case the double packer is installed between EL -5.42 and -6.42 m

Remark: Tide level is obtained by Australian BOM. As for the reference point, the height is 1.01m.

**Fig. 15. Results of the virtual-well-sealing experiment in observation well No. 6-N (continuous mechanical observation)**

changed closer to EC at -2.92 m at low tide as the high EC groundwater, which dispersed at high tide, was diluted by the surrounding aquifer, and moved back through the groundwater path at low tide.

#### 4. Conditions inside the observation well No. 6-N and pre-existing observation well No. 6-33 after the partial-sealing operation in No. 6-N

The temporal changes in EC values inside the pre-existing observation well Nos. 6-33 and 6-N are described.

##### (1) Pre-existing observation well

As Table 2 shows, the EC values observed in pre-existing observation well No. 6-33 decreased gradually after the partial-sealing operation in observation well No. 6-N on February 19, 2011. On August 22, 2011, the continually measured EC values from well No. 6-33 decreased to approximately 200 mS/m.

##### (2) Observation well bored for this research

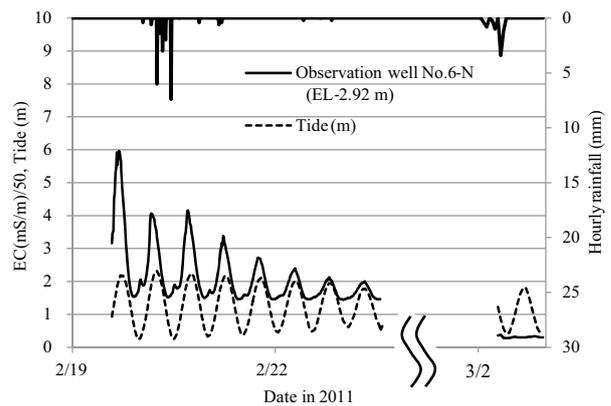
As Fig. 16 shows, the EC values inside observation well No. 6-N (deployment elevation of EC sensor: -2.92 m) decreased from 300 mS/m prior to the partial-sealing operation to 20 mS/m after the operation. Similarly, the magnitude of daily fluctuations in EC after the partial-sealing operation decreased to less than one-tenth of that prior to the operation.

## Discussion

### 1. Evaluation of the groundwater measurement results

The measurements prior to the boring operation for the observation well show that the groundwater level potential was lower in No. 6-48 than No. 6-33 (Table 2). From this result, it was determined that the groundwater flow at this site was likely to show a steady decline with increasing elevation, and construction of an observation well consisting entirely of a strainer could cause salt water intrusion from deep down. The EC values measured inside observation well No. 6-N rose with increasing depth (Fig. 8) and significantly exceeded those measured inside the pre-existing well No. 6-33 just after the boring operation (Fig. 9). These observations suggest that salt water intrusion occurred from deep down within observation well No. 6-N. At the same time, the EC values in the pre-existing observation well No. 6-33 increased gradually, starting on the sixth day after the installation of observation well No. 6-N and subsequently fluctuating at around 3,000 mS/m (Fig. 9). These results indicate that the salt water that intruded into observation well No. 6-N reached pre-existing observation well No. 6-33, which is located at a distance of 2m.

Although the inconsistency between the groundwater level potentials measured in the pre-existing observation wells prior to the boring operation and the salination of the groundwater in well No. 6-N remains unexplained, this research proceeded to investigate salt water intrusion and countermeasures to the same, as discussed in the next section, to 1) investigate the origin of the salt water in observation well No. 6-N in terms of depth and 2) to use the observation well for its purpose by preventing salination.



Remark: Tide level is obtained by Australian BOM. As for the reference point, the height is 1.01 m.

**Fig. 16. EC in observation well No. 6-N after the partial sealing of No. 6-N (continuous mechanical observation)**

### 2. Effects of the measure against salt water intrusion

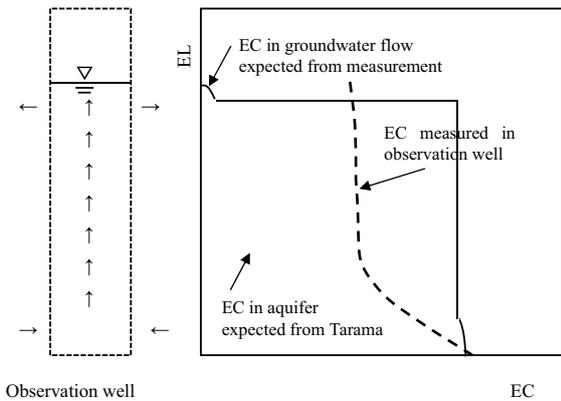
After the introduction of the measure against salt water intrusion in observation well No. 6-N on February 19, 2011, the magnitude of the daily fluctuations in EC associated with the tidal level decreased from approximately 220 to 20 mS/m (Fig. 16). The upward movement of salt water due to the effects of the tidal level, through the observation well and the filter materials around it, was prevented with immediate effect following the application of the silica compound. The EC values of the groundwater in observation well No. 6-N decreased to approximately 20 mS/m in March 2011.

In addition, prevention of salt water intrusion into the observation well caused the EC values inside the nearby pre-existing observation well No. 6-33 to decrease to approximately 200 mS/m in August 2011. Thus, as the high EC groundwater in the observation well affected the groundwater in pre-existing observation well nearby, the measure against the salt water intrusion in observation well No. 6-N was considered effective.

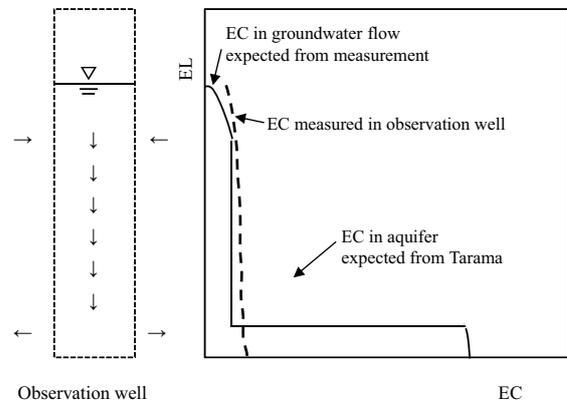
### 3. Estimation of the groundwater flow

It was assumed that the use of an observation well with strainers along its entire length would allow effective observation of the vertical EC profiles. However, the use of such structure disturbed the low and high EC groundwater in the observation well, so there was often little difference in EC in the vertical direction. When the upward groundwater flow from the deep layer reaches the shallow layer, the EC of the groundwater in the observation well increases. Conversely, the downward groundwater flow from the shallow layer reaches the deep layer, the fresh water located around the observation well moves into the observation well and the EC of the groundwater in the observation well slightly

(Upward groundwater flow)



(Downward groundwater flow)



**Fig. 17. Schematic view of the groundwater flow and vertical EC profile in observation well No. 6-N (additional description to Ishida et. al.<sup>4</sup>)**

decreases. A schematic view of the groundwater flow and EC profile is shown in Fig. 17.

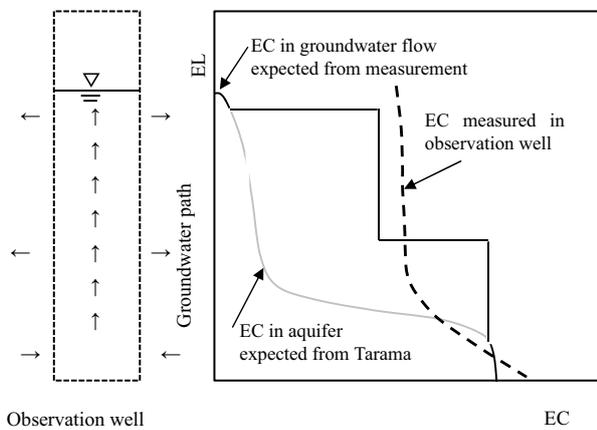
**4. Estimation of the depth of groundwater path**

The salt water may originate not only from the bottom of the observation well but also the groundwater path. It is important when partially sealing the observation well to identify the depth of the groundwater path where the salt water enters. The groundwater flow inside the observation well, which was caused by the tidal level, affected the vertical profile of the EC. Fig. 18 shows a schematic view of the groundwater flow and EC profile in case the groundwater path exists. When the upward groundwater flow occurred, part of the salt water escaped through the groundwater path outside the observation well No. 6-N. Conversely, when

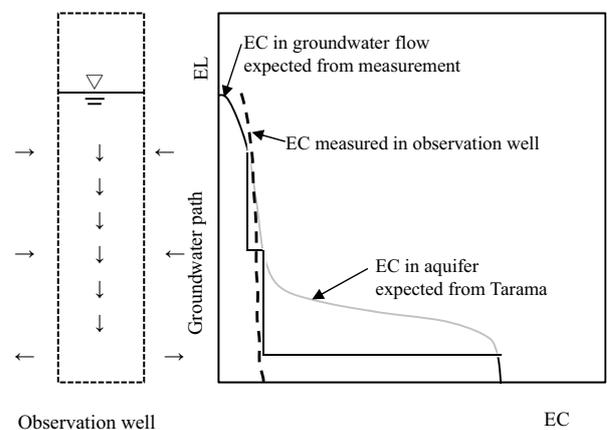
downward groundwater occurred, the salt water, which was slightly diluted by the surrounding fresh water, came into the observation well through the groundwater path.

It was also effective to provide fresh water from the bottom to the surface of the observation well to roughly determine the depth of salt water intrusion and groundwater path by conducting manual EC observation in observation well No. 6-N as swiftly as possible. It was, however, necessary to use the double packer to monitor the EC change to confirm the depth of the groundwater path. Fig. 19 shows a schematic view of the vertical EC profile and the depth of the double packer attached with three data loggers. Fig. 15 1) shows the result when the groundwater path is located above the connection pipe of the packer and Fig. 15 2) at the connection pipe. If the groundwater path is located

(Upward groundwater flow)

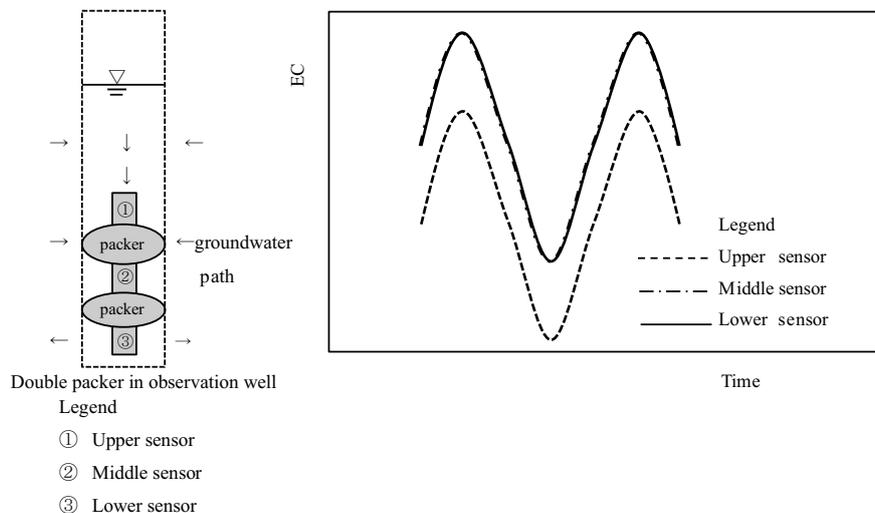


(Downward groundwater flow)

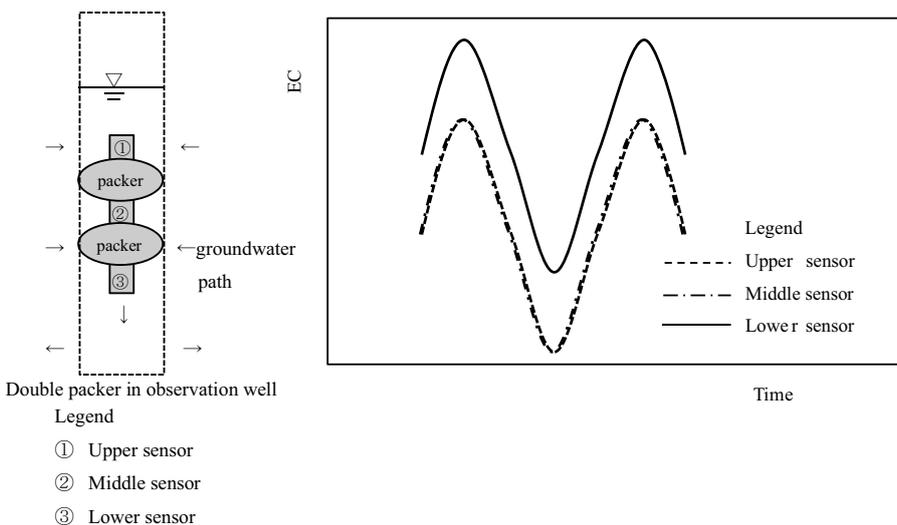


**Fig. 18. Schematic View of groundwater flow and vertical EC profile with the groundwater path in observation well No. 6-N (additional description to Ishida et. al.<sup>4</sup>)**

In case the double packer is lower than the groundwater path



In case the double packer is higher than the groundwater path



In case the double packer is almost the same depth as the groundwater path

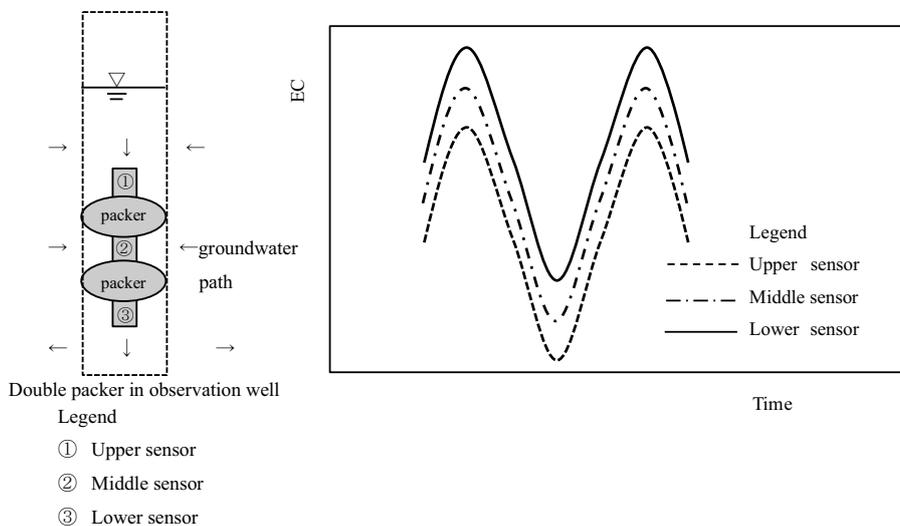


Fig. 19. Schematic view of the vertical EC profile and the depth of double packer in observation well No. 6-N

below the connection pipe, the adverse result is analogized by 1). In other words, if the packer is installed above or below the groundwater path, the EC profile will be overlapped. Only when the packer is installed at the groundwater path is the EC profile fully separated.

### 5. Estimation of the freshwater lens boundary

The influence of the tidal level caused the salt water to move upward and downward within the observation well, which hampered estimation of the freshwater lens boundary, since the vertical EC profile did not display that in the aquifer located around the observation well. In such cases, we must use the pre-existing observation wells to estimate the freshwater lens boundary.

### 6. Structure of the observation well

Up-coning occurs at a site if a difference exists between the groundwater pressures at the shallow and deep parts of the aquifer of the site. For such sites, the use of an observation well with a strainer at a particular depth is therefore appropriate. Conversely, if no groundwater pressure difference exists between the shallow and deep parts of the aquifer at a site, the use of an observation well consisting entirely of a strainer is appropriate for the site; since this would allow accurate assessment of the transition zone between fresh water, brackish water, and sea water.

### Conclusion

Examination of the groundwater level potential in the pre-existing observation well Nos. 6-33 and 6-48 showed slightly higher groundwater level potential in No. 6-33 than No. 6-48 and downward groundwater flow along the depth was estimated. Accordingly, observation well No. 6-N was considered, by boring, to be accurately observing the freshwater lens boundary. However, salt water intrusion occurred even in an unconfined aquifer, in which the groundwater has free surface, contrary to the observed results for the groundwater level potential. Accordingly, the depth of the salt water intrusion was examined by conducting a virtual-sealing-experiment with a double packer developed, and observation well No. 6-N was partially sealed. Subsequently, fixed-depth observation was performed by installing a data logger at an elevation of -2.92 m in observation well No. 6-N and -7.99 m in pre-existing observation well No. 6-33 after partial sealing down to the depth of salt water intrusion (elevation of -5.42 m) in observation well, EC reduction was observed not only in observation well No. 6-N but also pre-existing observation well No. 6-33. The partial sealing reduced the permeability inside observation well No. 6-N and of the surrounding ground, hence the

effectiveness of the partial-sealing method could be confirmed.

Pre-existing observation wells can be used to monitor the freshwater lens boundary. The local organization in charge of managing the groundwater resources will be able to appropriately recognize the vertical EC profile by considering the groundwater flow in the observation well.

### Acknowledgements

We would like to acknowledge the contributions of the following organizations which supported the on-site investigations: our partner institution, the Ministry of Resources & Development, Republic of the Marshall Islands, and associated government agencies, including the Majuro Water and Sewage Company, which assisted by providing a water supply for the boring operation.

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