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Infiltration Rate of Groundwater in Vadose Zone of Uplifted Carbonate Island

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Abstract: Solute contents in the vadose zone of limestone strata on Miyako Island of the Ryukyu Archipelago in Japan were measured by means of electrical conductivities (EC) of the extracted solutions of limestone core samples. A vertically nonuniform distribution of solute content was observed, which should lead to temporal variations of solute concentration in the groundwater under the water table. On the other hand, the data of chloride concentration in groundwater from 13 wells on the island was analyzed to see their long time variations. Both of these two approaches resulted in recharge rates of around 10^{-7} m s^{-1} for the vadose zone in the limestone strata of this typical uplifted carbonate island of the western Pacific Ocean.

Keywords: Groundwater, Recharge Rate, Vadose Zone, Limestone, Carbonate Island

1. Introduction

Cenozoic limestone strata constitute karstic aquifers covering much of the small islands in the tropics and the subtropics. They are the resource of groundwater which is indispensable for the inhabitants, a range of industries, and the ecosystem on the islands. It is important to understand and predict how water flows in limestone strata for sustainable use of groundwater resources, and to understand and manage contamination problems. However, monitoring water in vadose zone, especially in highly heterogeneous limestone formations, is difficult, and estimating recharge rate is one of the most complicated tasks in the hydrological cycle [1-3].

There are two primary pathways for groundwater to infiltrate through the vadose zone of karst: ‘quick flow’ which is the rapid conduit flow through the karst systems and large fractures, and ‘slow flow’ which includes fissure flow and matrix flow [4]. Rain water, when the rainfall rate exceeds evaporation, infiltrates and descends by diffuse flow through the small pore spaces of the soil and the matrices of limestone. When the rainfall rate exceeds the infiltration rate, surface water moves into closed depressions and descends rapidly through relatively open pathways to the water table, bypassing the matrices [5]. Such difference in water pathways also affects the concentration of solutes, as geometry and residence time determine the degree and characteristics of water/sediment and water/rock interaction [6].

Karst aquifers on carbonate islands are especially unique even among karst aquifers in general which do not fit standard Darcian models of groundwater flow [5]. Mylroie and Jenson [7] studied on karst in small carbonate islands of the Caribbean and western Atlantic, and established the Carbonate Island Karst Model, a general theoretical model for the unique karst that characterizes the terrain formed in young limestones on small islands. Taborosi et al. [8] reported the hydrology of the island of Guam according to this context, and emphasized the importance of ‘slow flow’ in water infiltration of carbonate island karst because of the high porosity of the young host limestones.

Miyako Island of the Ryukyu Archipelago in Japan is one of the typical uplifted carbonate islands of the western Pacific Ocean. Groundwater quality has been continuously monitored and reported by the local authority since 1980’s at dozens of wells and springs on this island for the conservation of water resources [9]. In the present study, the vertical distribution of solute contents in the vadose zone of limestone strata was observed by means of measuring electrical conductivities (EC) of the extracted solutions of the limestone core samples. As the movement of solutes should reflect the water flow, they can be used as natural tracers in order to understand the feature of water flow in the vadose zone. In addition, the reported data of chloride concentrations in well waters were analyzed to see their long time variations. Chloride has been generally used as a natural tracer in hydrological studies of groundwater [10], and is the most abundant anion in groundwater of Miyako supplied mainly from sea salt by precipitation. In contrast to some other anions like nitrate which is often originated by anthropogenic sources and gives variations specific to each well, meteorological events like typhoons give major variations of chloride input on the surface simultaneously over the island. Therefore, the comparison of the responses of groundwater qualities to such variations of chloride input at the wells with different depths should give information about the downward movement of groundwater in the vadose zone to the water table.

2. Materials and Methods

2.1. Site Description

Located in the subtropics, Miyako Island's annual average temperature is 23.6°C and annual rain fall is 2,021 mm (average of 1981-2010). This island has a plane shape and the highest altitude of 114.6 m. Surface area is 158.88 km^2 with the most part covered by the carbonate terrain overlying on the mudstone basement. There is no major river on the island, and approximately 40% of its annual precipitation is estimated to discharge as groundwater. The ridge and cuesta topography is characteristic of this island. The ridges run in parallel with a direction of NW to SE or NWW to SEE with an interval of several kilometers, and the cuestas decline gently southward [11]. According to these topographic observations and the results of boring and electric surveys, it is suggested that the island is divided into 27 groundwater aquifers (Figure 1). Fifty-seven percent of the surface is used as farms especially for sugarcane cultivation. A total of 24,000 m^3 per day of groundwater from several major wells and springs are distributed as tapped water for the 50,000 residents on the island [9].

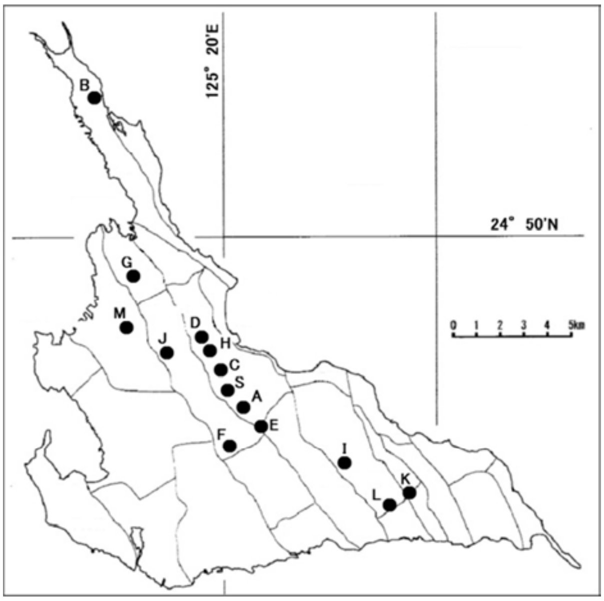

Figure 1. *Location of the Sampling Site on Miyako Island.*

2.2. EC of Extracted Solutions from Rock Samples

Core rock samples were obtained by the boring at the site S in Figure 1 held by the local authority in December 2006 for the petrologic definition of strata [12]. Soil thickness was 0.5 m, and the mudstone basement appeared at -17 m. The depth of the groundwater table was 15.8 m beneath the surface. Thirty one rock samples at different depths were subjected to analysis.

EC of the extracted solution from each rock sample was measured to assume the vertical variation of solute contents in the limestone strata, which should reflect the solute concentration in groundwater infiltrating through the vadose zone at each depth. The rock samples were picked with stainless spatulas to obtain powder samples. Five grams of powder from each rock sample was shaken with 25 mL of purified water for one hour [13]. EC of the extracted solution was measured with CM-31P EC meter (Toa-DKK, Japan).

2.3. Chloride Concentration in Well Waters

The data of chloride concentration in 13 wells (A-M in Figure 1) on the island reported by the local authority [9] from April 2005 through March 2013 were analyzed to compare their variations. These wells were selected because their water qualities had been monitored once or twice a month throughout these years and did not show immoderate fluctuation by some specific causes.

3. Results and Discussion

3.1. Underground Vertical Distribution of Solutes

Figure 2 shows EC of the extracted solution from the rock at each depth. The samples from the surface to one meter of depth showed relatively high EC, indicating the higher solute content in the surface soil in comparison with the limestone strata. The sample beneath the water table also had high EC, which should be attributed to a high content of water with the solutes in the saturated zone. EC was low and stable from two to five meters beneath surface, suggesting a low content of water with solutes in limestone in this zone.

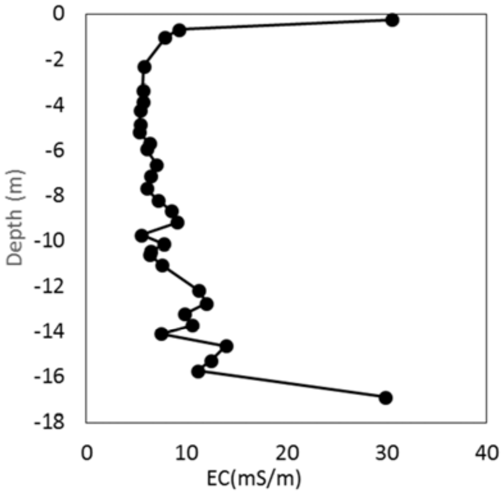

Figure 2. *EC of Extracted Solutions from Core Samples.*

In the limestone deeper than this, EC increased towards the water table with some peaks. These results indicate the existence of vertically nonuniform distribution of solutes in the limestone strata. This may be attributed to temporal variations of salt input from seawater or from human activities on the ground, and/or of concentration/dilution processes of groundwater including evaporation. It is known that evaporation from the ground or vegetative surfaces can be significant especially in tropical climates when rainfall is light [5]. As the downward movement of water in the vadose zone carries the solutes into the groundwater under the water table, vertical distribution of solute concentrations should result in temporal variations of solute concentrations in the groundwater under the water table.

3.2. Variations of Chloride Concentration in Well Waters

Chloride concentration in wells A-M is shown in Figure 3. Baseline chloride concentrations were around 40 mg L^{-1} in the majority of these wells. Two previous monitoring on Okinawa Island of the Ryukyu Archipelago reported 351 [14] and 675 μeq L^{-1} [15] as the volume weighted mean concentration of chloride in precipitations. As 45% of rainwater is estimated to evaporate, the concentrations in groundwater calculated from these data are 22 and 43 mg L^{-1}, respectively. The observed baseline concentrations are harmonic to these values, indicating that chloride in groundwater of this island is predominantly supplied by precipitations.

In the cases of the wells B, C, and G, of which the depths of water table were less than 10 m beneath the ground surface, annual cycles of chloride concentration were observed. Decreased chloride concentrations appeared often in April or May for B, from September to November for C, and in July or August for G. Any anthropogenic cause to explain such cycles of chloride concentration was found on the island, and seasonal change of rainfall (Figure 4) was not uniform every year to explain them, neither. One possible explanation of this phenomenon is that seasonal change of temperature and/or sunlight radiation, as these were much more uniform for every year than rainfall (Figure 5), may have been affecting the evaporation and concentration of solutes in water near the surface. These annual cycles appeared in different seasons for each of these three wells, suggesting that it took months or more period of time for the fluctuations of concentration near the surface to reach the groundwater under water table at each site. As the core rocks for the EC measurement were sampled at the site S close to the well C (500 m in distance) in December 2006, and the water table in C was -5 m beneath the surface, the peaks in the vertical EC distribution of the core samples (Figure 1) deeper than -5 m (-7.0, -9.1, -12.0 and -13.9 m) may correspond to the annual variations of concentration in the well water at C prior to the boring, e.g., from 2003 through 2006. The average of the vertical intervals of these EC peaks was 2.7 m, and this value may be interpreted as the annual recharge rate of groundwater, which equals to 0.9×10^{-7} m s^{-1}.

In addition, almost all the wells showed variations of chloride concentration with a cycle of several years, and these variations tended to delay corresponding to the depth of water table at each well. For example, data for the wells A, C, D, E and H, which are located in a same aquifer, showed a similar peak during 2008 through the beginning of 2011. The maximum concentration at each of these wells during this period appeared in different time depending on the depth of water table (Figure 6), and the recharge rate is calculated as approximately 0.2 m per month (1×10^{-7} m s^{-1}). On the other hand, the deeper wells, F, I, J, K and M, commonly showed a similar long term variation of chloride concentration, and the minimum concentration of each well among the data in Figure. 3 appeared with delays well correlating to the depths of water table (Figure 7), giving the recharge rate of approximately 1.2 m per month (5×10^{-7} m s^{-1}). The water in the deeper vadose zone without the influence of evaporation on the surface may have moved faster than in the shallower zone.

Tracers such as fluorescent dyes and environmental isotopes in the vadose zone of karst at many sites showed recharge rates ranging 2×10^{-7}–2×10^{-6} m s^{-1} [4], while Bottrell & Atkinson [16] recorded tracer peaks in cave drips up to six years after tracer injection into sinkholes and fractures. The recharge rates estimated above are close to these values and also in accordance with the rate (3 m $year^{-1}$) once estimated on the basis of the delay of nitrate concentration trend in groundwater compared with the trend of nitrogen input on this island [17].

4. Conclusions

EC of the extracted solution from the core samples of Miyako Island indicated the existence of vertically nonuniform distribution of solutes in the limestone strata, which should lead to temporal fluctuations of solute concentration in the groundwater under the water table. The data of chloride concentration in groundwater from the wells on this island were analyzed to see their long time variations. The recharge rates estimated from these results were of around 10^{-7} m s^{-1}, which were in accordance with the rates of 'slow flow' in various karst sites in the world, for the vadose zone in the limestone strata of this typical uplifted carbonate islands of the western Pacific Ocean. The results in the present study, as well as those former studies, indicate the importance of 'slow flow' in vadose zone for groundwater quality of the islands.

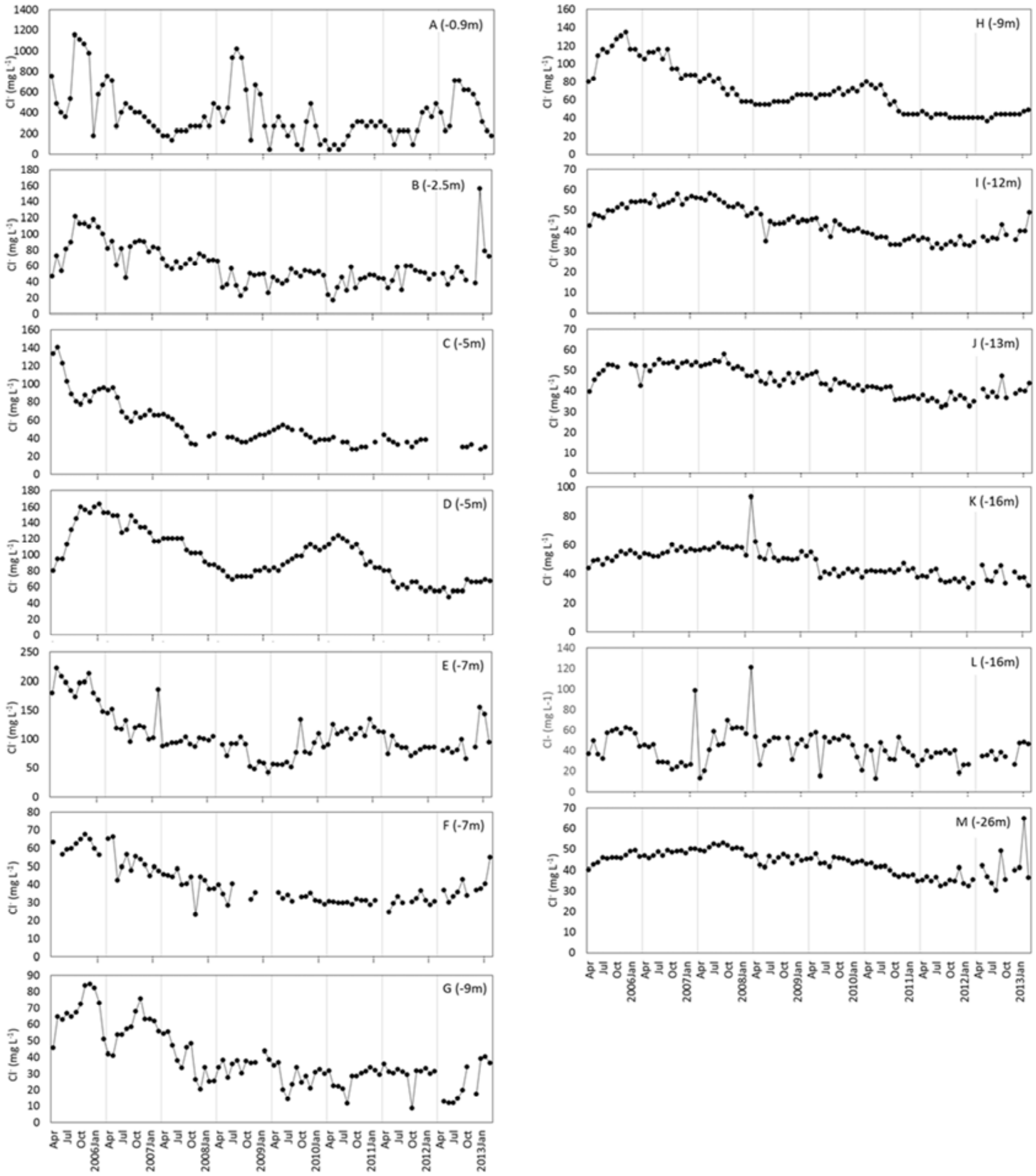

Figure 3. Chloride Concentration of Groundwater from the Wells in Miyako Island. Depth of Water Table at each well is Described in Parentheses.

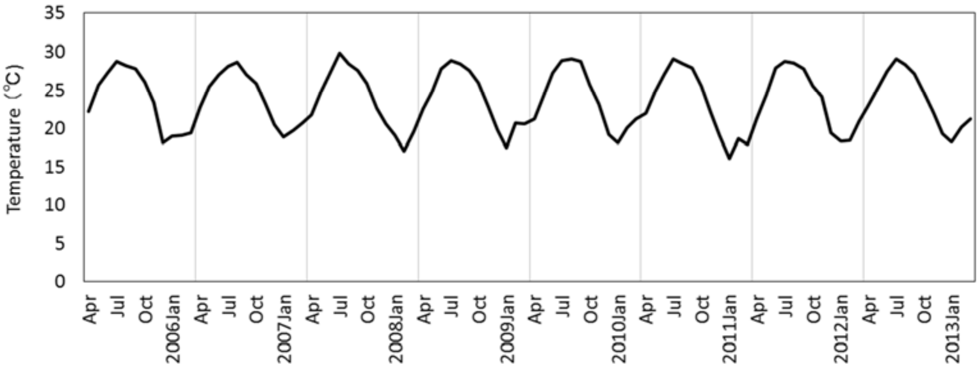

Figure 4. Monthly Rainfall on Miyako Island (Data from Miyako Island Meteorological Station).

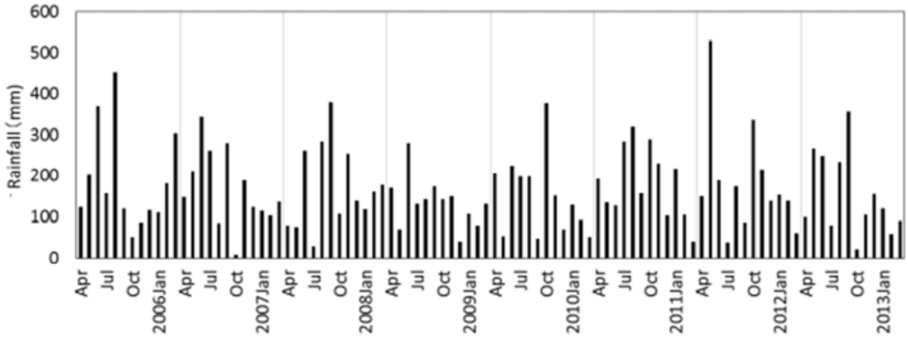

Figure 5. *Monthly Average Temperature on Miyako Island (Data from Miyako Island Meteorological Station).*

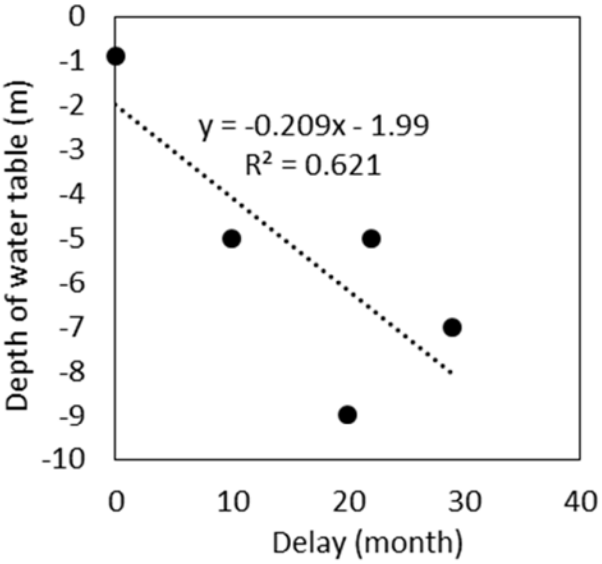

Figure 6. *Correlation Between the Delay of the Maximum Concentration from August 2008 Through January 2011 at Wells C, D, E and H Relative to A and the Depth of Water Table at each well.*

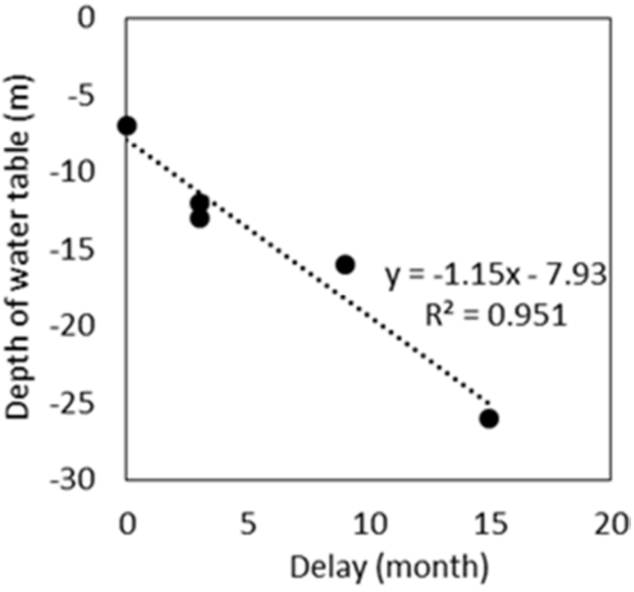

Figure 7. *Correlation Between the Delay of the Minimum Concentration from April 2005 Through March 2013 at Wells I, J, K and M Relative to F and the Depth of Water Table at each well.*

Acknowledgements

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References

[1] B. R. Scanlon, Evaluation of methods of estimating recharge in semiarid and arid regions in the Southwestern U.S., in: Groundwater recharge in a desert environment: the Southwestern United States, American Geophysical Union, 2013, 235–254.

[2] I. Željković and A. Kadić, Groundwater balance estimation in karst by using simple conceptual rainfall-runoff model, Environ. Earth Sci., 74, 2015, 6001-6015.

[3] K. Mahmud, G. Mariethoz, A. Baker, P. C. Treble, M. Markowska, and E. McGuire, Estimation of deep infiltration in unsaturated limestone environments using cave lidar and drip count data, Hydrol. Earth Syst. Sci., 20, 2016, 359–373.

[4] N. A. Sheffer, M. Cohen, E. Morin, T. Grodek, A. Gimburg, E. Maga, H. Gvirtzman, M. Nied, D. Isele and A. Frumkin, Integrated cave drip monitoring for epikarst recharge estimation in a dry Mediterranean area, Sif Cave, Israel, Hydrol. Process., 25, 2011, 2837–2845.

[5] J. M. U. Jocson, J. W. Jenson and D. N. Contractor, Recharge and aquifer response: Northern Guam Lens Aquifer, Guam, Mariana Islands, Journal of Hydrology, 260, 2002, 231-254.

[6] A. F. Tooth and I. J. Fairchild, Soil and karst aquifer hydrological controls on the geochemical evolution of speleothem-forming drip waters, Crag Cave, southwest Ireland, Journal of Hydrology, 273, 2003, 51–68.

[7] J. E. Mylroie and J. W. Jenson, The carvonate island karst model applied to Guam, Theoretical and Applied Kastology, 13, 2000, 57-61.

[8] D. Taborosi, J. W. Jenson and J. E. Mylroie, Karst features of Guam Mariana Islands, Technical Report No. 104, Water & Environmental Research Institute of the Western Pacific, University of Guam, 2004.

[9] Miyakojima City Office, “FY 2005-2013 Reports on groundwater quality conservation monitoring in Miyakojima City” (in Japanese), 2007-2015.

[10] Y. Arbel, N. Greenbaum, J. Lange and M. Inbar, Infiltration processes and flow rates in developed karst vadose zone using tracers in cave drips, Earth Surf. Process. Landforms 35, 2010, 1682–1693.

[11] H. Furukawa, Quaternary geologic history of the Ryukyu Islands, Bulletin of Science & Engineering Division, University of Ryukyus, 27, 1973, 99-161.

[12] Miyakojima City Office, "FY 2007 Report of Groundwater Conservation Committee of Miyakojima City" (in Japanese), 2008.

[13] K. Kamewada, 1:5 water extraction method for electronic conductivity (in Japanese). In Analytical Methods of Soil Environment, Editorial Committee for Analytical Methods of Soil Environment (ed), Hakuyusha, Tokyo, 1997, 202-204.

[14] H. Sakihama, M. Ishiki and A. Tokuyama, Chemical characteristics of precipitation in Okinawa Island, Japan, Atmospheric Environment, 42, 2008, 2320-2335.

[15] Network Center for EANET, "Data report on the acid deposition in the East Asian region, 2004", 2005.

[16] S. H. Bottrell and T. C. Atkinson, Tracer study of flow and storage in the unsaturated zone of karstic limestone aquifer. In Tracer Hydrology, H. Hötzl and A. Werner (eds), Balkema, Rotterdam, 1992, 270–277.

[17] Y. Tashiro and K. Takahira, Long term trend of nitrogen emission and nitrogen concentration of groundwater in Miyako Island, Okinawa (in Japanese with English abstract), Journal of Japan Society of Water Environment, 11, 2001, 733-738.