Study on Dug Well Distribution and Water Balance in Teshima Island: Environmental Humanities and Hydrological Perspectives

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Ⅰ. Introduction

The islands of the Seto Inland Sea are climatically characterized by low rainfall and topographically characterized by low altitude, low-lying mountains; geologically, the region is characterized by impermeable granite that does not retain water in some regions that only have a few surface-water systems. Therefore, freshwater resources on the islands are scarce, and the islands are prone to water shortages and droughts[1)]. Notably, Teshima Island in Tonosho town (area: 14.4 km^2, Figure 1), which is our study area, has a unique water environment with abundant water resources, compared to other islands in the Seto Inland Sea; this region hosts the “Karato no Shimizu” spring that flowed even during the severe droughts in 1994 and 1995 [2)3)] (Figure 2) and large scale rice terraces that use substantial amounts of agricultural water.

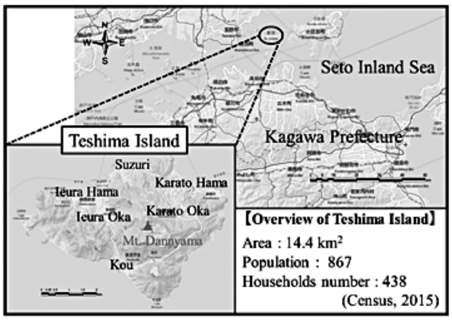

Figure 1. Map portraying of Teshima Island

Figure 2. Spring water “Karato no Shimizu”

Figure 3. Communal dug well “Maegawa”

(December 13, 2020)

On Teshima Island, dug wells were used as a source of water for daily life before the construction of a piped water supply system, owing to the abundant water resources (Figure 3). Therefore, dug well water plays an important role as a water source for life in this region. However, detailed investigations that focus on dug wells have not been conducted in this area to date. Furthermore, there are only some fragmentary descriptions of dug wells on Teshima Island, most of them in local historical literature[4)]. The distribution and number of dug wells, as well as their usage, have not been determined since the construction of the piped water supply system to the present.

Through this study, we determined the distribution of dug wells on Teshima Island, described their characteristics, and analyzed the changes in their usage. As the distribution of dug wells and their use are strongly related to the natural hydrological cycle, such as rainfall and infiltration into the ground, we estimated the water balance at one of the river basins in Teshima Island using a hydrological approach and analyzed its relationship with the island’s water use.

Ⅱ. Method

In general, there are two types of water cycles: 1) natural hydrological cycle, which includes rainfall, evaporation, and infiltration into the ground, and 2) artificial hydrological cycle, which includes the use of dug wells, piped water supply systems, and sewage treatment plants (Figure 4). The artificial hydrological cycle is synonymous with human water use, and the distribution and use of dug wells is the prime factory that drives this cycle. However, because the natural water cycle is strongly related to anthropological use, it is necessary to also consider natural water recharge. Therefore, to determine the supply from dug wells and the water balance in Teshima Island, we adopted an approach that combines two different fields, namely, environmental humanities and hydrology.

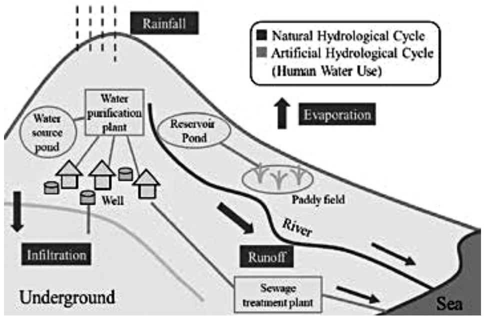

Figure 4. Interpretation of natural and artificial hydrological cycle

1. Environmental Humanities Approach

In the environmental humanities approach, we mainly focused on the distribution and use of dug wells and the related anthropological water use, including the usage of dug wells as a source for the piped water supply system. The methods applied in this approach included field surveys, interviews with residents, and the analysis of local historical literature and administrative statistics. In the hydrological approach, we focused on the natural hydrological cycle and estimated the water balance on Teshima Island using a hydrological runoff model simulation.

2. Hydrological Approach

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2.1. Hydrological runoff model

In this study, we used the Rainfall-Runoff-Inundation (RRI) model, which is a distributed runoff analysis model[5]. The RRI model simulates river runoff depending on the rainfall and flood inundation in the entire river basin in an integrated manner; notably, it even considers the inundation caused by inland rainwater in low flat basins and river branches[6]. Owing to its wide applicability, the RRI model has been applied to mountainous river basins, low flat areas in Japan, overseas river basins, and small and medium-sized rivers in Kagawa Prefecture[7].

2.2. Datasets

The RRI model uses elevation (digital elevation model, DEM), land cover classification (land cover), soil classification (soil), and rainfall data (Table 1). In our study, the Japan flow direction map (JFDM) was used as the elevation data[8]. The JFDM is a surface flow direction map of Japan with a grid size of approximately 1 s (approximately 30 m). Land cover classification data (land cover), collected by the MODerate resolution Imaging Spectroradiometer (MODIS) in 2008, were obtained from the International Steering Committee for Global Mapping (ISCGM) (Terra and Aqua)[9] and soil texture classification data (Soil) were acquired from the Food and Agriculture Organization (FAO)[10] to include as defaults in the RRI model, with spatial resolutions of 15 s (approximately 380 m) and 5 min (about 7.6 km), respectively. For the rainfall data, we used the observations from a rain gauge installed at the top of Mt. Danyama (34.48168 ° N, 134.07820 ° E; elevation: 339 m; Figure 1), which is the highest peak on Teshima Island, by the river and sediment control division of the civil engineering department in Kagawa Prefecture.

Table 1: Input data set used in RRI model in our study

	Name	Data Source	Spatial Resolution
Elevation data (DEM)	Japan Flow Direction Map (JFDM) ver.1.31	Yamazaki, 2018 [8]	1 sec. (30 m)
Land cover classification data (Land cover)	The Global Land Cover by National Mapping Organizations (GLCNMO) ver.2	ICGCM [9]	15 sec. (380 m)
Soil classification data (Soil)	Digital Soil Map of the World (DSMW) ver.3.6	FAO [10]	5 min. (7.6 km)

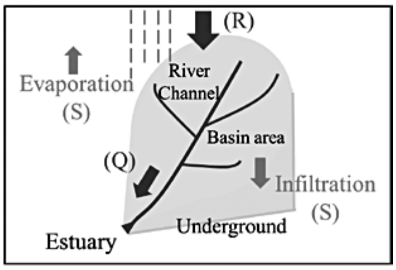

Figure 5. Concept of water balance

2.3. Concept of water balance

As a case study, the water balance, $R-Q=S$, was estimated to evaluate the natural hydrological cycle on Teshima Island, especially with respect to groundwater storage (Figure 5). In the equation, R is the total amount of rainwater, which is equal to precipitation × basin area, Q is the total amount of runoff from rivers, and S is the difference between R and Q (Table 2). In our study, S included the amounts of evaporation and storage (groundwater). For the calculation of Q, the discharge at the downstream end of the river was obtained using the RRI model.

Table 2: Parameters of water balance equation "R-Q=S"

"R"	"Q"	"S"
Precipitation × Basin area (m^3)	Total Discharge (m^3)	R-Q (m^3)

2.4. Target river basin

In our study, we selected Kasuga River, which has the largest basin area (1.96km^2) on Teshima Island, for our case study to estimate the water balance (Figure 6). The Kasuga River flows through the northern part of Teshima Island and traverses Ieura, which is the most populated area on the island, from south to north. The river channel and basin area were simulated using ArcGIS Pro ver.2.8.3 (Esri Inc.) using the elevation data acquired from JFDM.

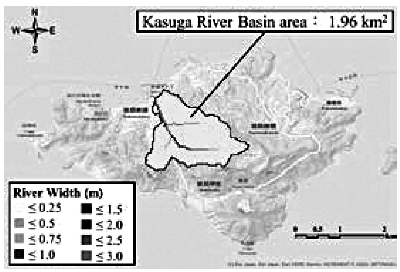

Figure 6. River channel and basin area in Kasuga River

2.5. Calculation period

The simulation was conducted for one year from 00:00h on January 1, 2015, to 00:00 h on January 1, 2016. The reason for selecting this period was because the average annual precipitation (1150mm) in the past 30 years (from 1990 to 2020) observed at Takamatsu of the Japan Meteorological Agency, Automated Meteorological Data Acquisition System (AMeDAS), is similar to the annual precipitation in 2015[11]. Notably, the annual precipitation at the top of Mt. Dannyama on Teshima Island in 2015 was 1257 mm.

2.6. Topographical conditions of target basin

The land cover classification data acquired from the Global Land Cover by National Mapping Organizations (GLCNMO) used in the RRI model had a total of 20 classification patterns. In the case of Teshima Island, most grids could be classified as mountainous land areas, such as forests (mainly, green or orange color), except for flat cultivated land (pink) in the lower Kasuga River basin (Figure 7).

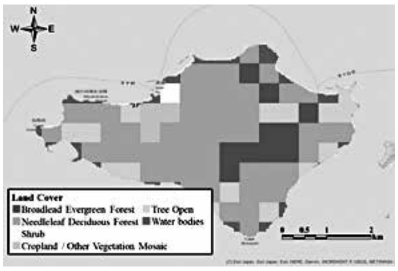

Figure 7. Map of land cover of Teshima Island using data acquired from GLCNMO

The soil classification data used in the RRI model, acquired from the digital soil map of the world (DSMW), indicated that clay was distributed over the entire area of Teshima Island; notably, clay has small inter-particle pore spaces and low permeability.

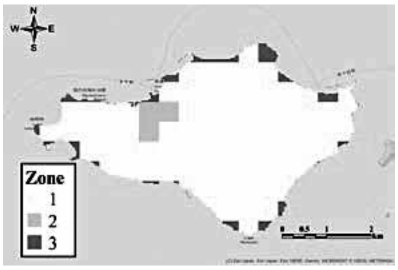

Figure 8. Set Parameter (Zone)

2.7. Calculation conditions for RRI model

In the RRI model, the land cover classification data were used to determine the infiltration models through the application of Darcy's law in mountainous areas and the Green-Ampt model in flatland areas. The soil classification data could delineate the parameter values for the infiltration model.

Table 3: Calculation parameters of RRI model (default)

Zone	1	2	3
Infiltration Model	Darcy's law	Green-Ampt Model	Green-Ampt Model
Soil	Clay	Clay	Clay
Diff or Kinem (Diffusion Wave or Kinematic Wave)	Diff	Diff	Diff
ns slope ($m^{-1/3}s$) (Manning's roughness on slope cells)	3.000d-1	3.000d-1	3.000d-1
soil depth (m) (soil layer depth)	1.000d0	1.000d0	1.000d0
gammma (effective porosity)	3.850d-1	3.850d-1	3.850d-1
ksv (m/s) (vertical saturated hydraulic conductivity)	0.000d0	1.670d-7	0.000d0
sf (m) (the suction at the wetting front)	3.163d-1	3.163d-1	3.163d-1
ka (m/s) (lateral saturated hydraulic conductivity)	1.670d-3	0.000d0	0.000d0

The application of Darcy's law for mountains areas does not allow the use of vertical saturated hydraulic conductivity (ksv) in the calculation, and the application of the Green-Ampt model for flatlands does not allow the use of lateral saturated hydraulic conductivity (ka). Therefore, according to Darcy's law, water only infiltrates in the lateral direction and not in the vertical direction, whereas the Green-Ampt model assumes that water infiltrates only in the vertical direction and not in the lateral direction.

In the case of Teshima Island, the entire area was classified into three parameter sets or zones (Zone 1, Zone 2, and Zone 3) (Figure 8). The infiltration model and calculation parameters for each zone are presented in Table 3.

Ⅲ. Result of Environmental Humanities Approach

1. Distribution of Dug Wells and Their Characteristics

A total of 57 dug wells were confirmed throughout Teshima Island by conducting field surveys twice in September and December, 2020 (Figure 9). To portray the characteristics of the dug well location clearly, the layers of dug well location, land use, elevation (JFDM), and landslides were visualized and overlaid. For the land use layer, we used the land use subdivision mesh provided by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) (grid size: 100 m)[12]. It was clear that most of the dug wells were located in residential areas. This means that dug well water was used as a source of water for daily life (Figure 10).

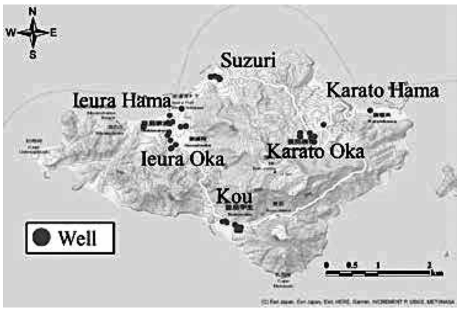

Figure 9. Distribution of dug wells on Teshima Island

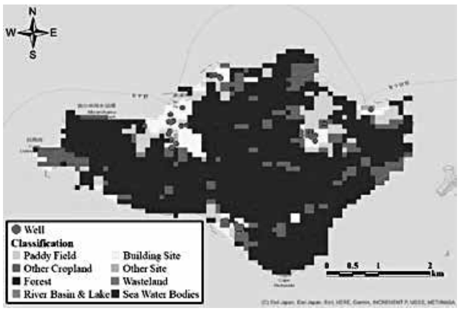

Figure 10. Distribution of dug wells with land use

In most areas, the altitude at which the dug wells were located was less than 10 m above the mean sea level (MSL), except in the Karato Oka area. The dug wells in the Karato Oka area were located at much higher elevations, between 101 and 150 m above the MSL (Figure 11). Furthermore, the location of these high-altitude dug wells overlapped with the topography of landslides (Figure 12)[13]. Notably, most of the dug wells, along with the spring "Karato no Shimizu" and rice terraces, are located near the landslide topography around Karato Oka. It was assumed that the landslide topography strongly contributes to the rich storage of groundwater in the region.

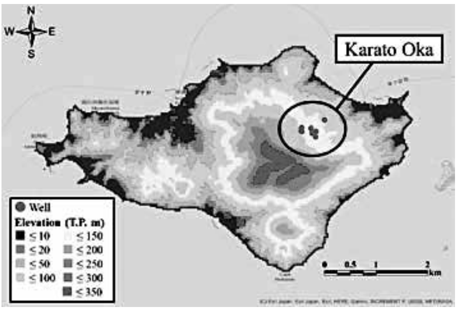

Figure 11. Distribution of dug wells and elevation

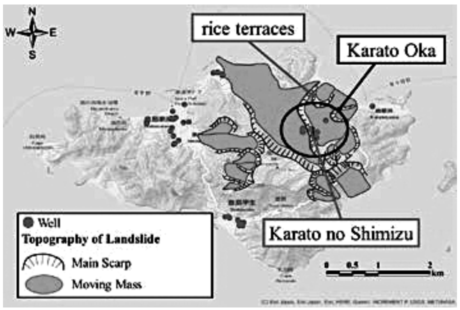

Figure 12. Distribution of dug wells and topography of landslide

2. Changes in Dug Well Use and Purpose of Usage

The introduction of piped water supply on remote islands in Japan progressed as part of the "Light and water on remote islands" project which was a part of the Remote Islands Development Act implemented in 1953[1]. The construction of the piped water supply system started in 1955 on Teshima Island, the year that the island's jurisdiction was merged with Tonosho (Table 4)[14]. During this time, piped water supply was introduced in the Ieura area, which is the most populated region on Teshima Island.

Table 4: History of piped water supply system on Teshima Island

	History of piped water supply system in Teshima Island
1953	Enactment of remote Islands development act with the keyword "Water and Light for the Islands"
1955	Completion of the Teshima Ieura piped water supply system, triggered by the merger with Tonosho town
1965	Completion of the Teshima Karato piped water supply system
1976	Completion of the Teshima Kou piped water supply system
2001	Integration of piped water supply system in Ieura and Karato area

However, in 1970, 15 years after the introduction of the first piped water supply system, the water supply coverage rate remained at 44.6%, and more than half of the population still used dug well water (Figure 13)[15]. In 1980, the water supply coverage rate rapidly increased to 95%. Corresponding to the increase in the piped water supply coverage rate, opportunities for using dug wells decreased, and ever since, their use as a source of water for daily life has been declining.

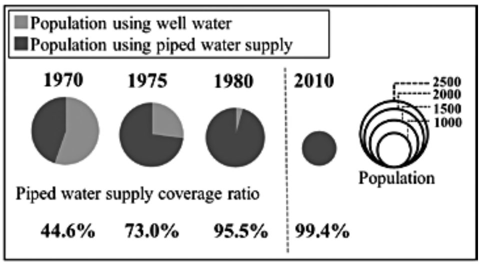

Figure 13. Changes in population using dug wells water and piped water from 1970 to 2010

Based on our interviews with local residents about the current use of the dug wells, we obtained testimonies that they no longer used the dug wells as a source of drinking water because of the easy access to safe water via the piped water supply system. However, some households still use dug wells, albeit only for outdoor water use, e.g., for watering plants and vegetables and cleaning purposes. Thus, residents use different water sources according to their needs.

Ⅳ. Result of Hydrological Approach

1. Default Topographic Conditions (Darcy's Law)

Using the RRI model under the default conditions (Table. 3), we considered the runoff at the downstream end of the Kasuga River in 2015 as the output and calculated the water balance (Table 5). For the given amount of rainfall (R), 90% was observed as the runoff (Q) from the river; 10% was the residual difference (S). The Q estimated in our study exceeded the estimates calculated in previous studies that estimated the water balance of Ishima Island, which is located to the west of Teshima Island; notably, our estimate did not reflect the actual situation.

Table 5: Water balance in Kasuga River basin (default condition)

	"R" Rainfall × Basin area (m^3)	"Q" Total Discharge (m^3)	"S" R-Q (m^3)
Clay	2469883 (100%)	2242970 (90.8%)	226913 (9.2%)
Sand	2469883 (100%)	229058 (90.3%)	240825 (9.7%)

To address this issue, the soil cover classification of the region was changed to sand, which has a higher hydraulic conductivity than clay and is known to have a higher permeability (Table 6). The water balance was calculated again using the calculation conditions listed in Table 6. The results were the same as those obtained for clay, where Q accounted for 90%, and S for 10% of total R (Table 5).

The reason why Q accounted for 90% was because of the similar infiltration conditions in each zone. The default infiltration model uses Darcy's law over a wide area of Teshima Island (Tables 3, 6, and Figure 8). In Darcy's law, rainwater does not infiltrate vertically and only laterally, regardless of soil conditions. Therefore, it was considered that most of the given rainwater did not infiltrate into the ground and flowed into the river.

Table 6: Caluculation parameters of RRI model (sand)

Zone	1	2	3
Infiltration Model	Darcy's law	Green-Ampt Model	Green-Ampt Model
Soil	Sand	Sand	Sand
Diff or Kinem (Diffusion Wave or Kinematic Wave)	Diff	Diff	Diff
ns slope ($m^{-1/3}s$) (Manning's roughness on slope cells)	3.000d-1	3.000d-1	3.000d-1
soil depth (m) (soil layer depth)	1.000d0	1.000d0	1.000d0
gammma (effective porosity)	4.170d-1	4.170d-1	4.170d-1
ksv (m/s) (vertical saturated hydraulic conductivity)	0.000d0	6.540d-5	0.000d0
sf (m) (the suction at the wetting front)	4.950d-2	4.950d-2	4.950d-2
ka (m/s) (lateral saturated hydraulic conductivity)	6.540d-1	0.000d0	0.000d0

2. Changes in Infiltration Conditions (Green-Ampt Model)

To reduce Q, the Green-Ampt model was used as the infiltration model for all zones in the Kasuga River basin (Table 7). Notably, in the Green-Ampt model, water infiltrates in the lateral direction and not in the vertical direction. Generally, when the soil layer is saturated with water and infiltration exceeds the limit, excess infiltration is discharged as surface flow.

Table 7: Calculation parameter of RRI model (Green-Ampt model)

Zone	1, 2, and 3	
Infiltration Model	Green-Ampt Model	
Soil	Clay	Sand
Diff or Kinem (Diffusion Wave or Kinematic Wave)	Diff	Diff
ns slope ($m^{-1/3}s$) (Manning's roughness on slope cells)	3.000d-1	3.000d-1
soil depth (m) (soil layer depth)	1.000d0	1.000d0
gammma (effective porosity)	3.850d-1	4.170d-1
ksv (m/s) (vertical saturated hydraulic conductivity)	1.670d-7	6.540d-5
sf (m) (the suction at the wetting front)	3.163d-1	4.950d-2
ka (m/s) (lateral saturated hydraulic conductivity)	0.000d0	0.000d0

The water balance using the Green-Ampt model for the Kasuga River basin indicated that when the soil type was clay, approximately 60% of the water was discharged from the river as Q, and the remaining 40% was S (Table 8). However, when the soil type was changed to sand, although the R/Q ratio was slightly (2.5%) different from that when the soil type was clay, approximately 60% of the water was discharged from the river as Q and 40% was S, similar to that observation for the model that considered the soil cover to be clay.

Table 8: Water balance in Kasuga River basin (Green-Ampt model)

	"R" Rainfall × Basin area (m^3)	"Q" Total Discharge (m^3)	"S" R-Q (m^3)
Clay	2469883 (100%)	1448561 (58.6%)	1021322 (41.4%)
Sand	2469883 (100%)	1386171 (56.1%)	1083712 (43.9%)

Next, the temporal variations in river discharge under clay and sand cover were compared. Although there was no significant difference in Q over one year, the maximum discharge and temporal variations in the discharge differed depending on the soil type. For example, in April, the maximum discharge for clay soil was 1.75 m^3/s, while that for sandy soil was 0.21 m^3/s, more than 8 times greater than that for clay soil (Figure 14a) . Notably, clay has a low infiltration capacity, and with time, water can infiltrate the subsurface; however, when it rains continuously, it is difficult for water to infiltrate into the subsurface in a short time. Therefore, in the case of clay, most rainfall does not infiltrate the ground and flows out as surface flow. As a result, river discharge can be expected to increase. In contrast, in the case of sand, the soil pore sizes are large and the permeability is high; thus, rainwater can easily infiltrate the ground.

In April, there was no excess water infiltration, and the amount of water flowing into the river as surface flow was less because rainwater infiltrated into the ground. Moreover, with respect to the data for June, there was almost no difference in the maximum discharge and temporal variation of the flow rate between clay and sand (Figure 14b). The reason for this was that both clay and sand were saturated with water in June, and the precipitation that exceeded the saturation level did not infiltrate into the ground and flowed out to the river as surface flow.

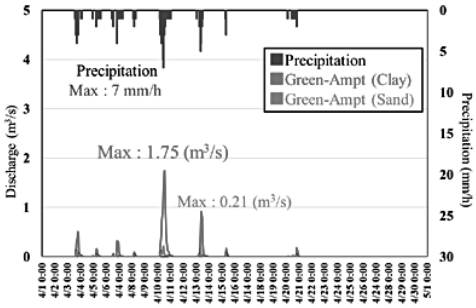

Figure 14a. Hyetograph and hydrograph（April, 2015）

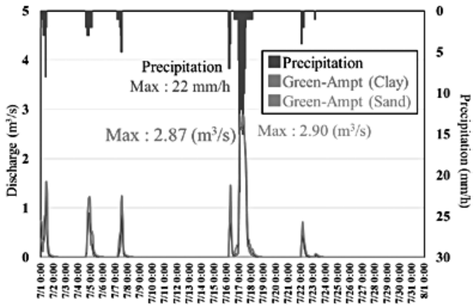

Figure 14b. Hyetograph and hydrograph（June, 2015）

Ⅴ. Conclusion and Future Scope

In this study, the distribution and locations of dug wells on Teshima Island were clarified using environmental humanities and hydrological approaches. It was found that dug wells are still used as a source of water for outdoor use other than drinking, 60 years after the construction of the piped water supply system, even though the piped water supply coverage ratio was almost 100% during our study period.

The hydrological runoff model was used to calculate the water balance in the Kasuga River basin. The water balance equation revealed that Q significantly changed because of the different infiltration conditions considered by Darcy's law and the Green-Ampt model; furthermore, we deduced that the soil conditions largely contributed to the temporal variations in river discharge.

Notably, the residents informed us that there may be dug wells inside old houses, and it is highly possible that a greater number of dug wells may exist than the 57 dug wells determined in this study. In addition to the usage of dug wells, we obtained information on the characteristics and quality of the dug well water, such as changes in the water level of the dug wells and the water salt content. In the future, we would like to identify the number of existing dug wells throughout Teshima Island, study the changes in their water level, and analyze the water quality. The provisional water balance was estimated using the RRI model, but the accuracy of the simulation results was not determined because of the lack of observational data. A3L（low cost, long life, and localized）water level gauge was recently installed in the middle part of the Kasuga River by the Kagawa prefectural government[17], and this could be used to calibrate the output of the river discharge.

In this study, we only calculated the water balance and did not estimate the specific groundwater flow and storage in Teshima Island. Notably, groundwater flow and storage are considered to be closely related to the distribution and use of dug wells. In a future study, we would like to clarify the relationship between the groundwater flow/storage and the distribution and use of dug wells in the region using higher-resolution land cover and soil data, along with a hydrological cycle simulation model specialized for groundwater flow.

Ⅵ. Acknowledgement

This work was supported by the Japan Society for the Promotion of Science（JSPS）KAKENHI, Grant-in-Aid for Scientific Research（B）（Grant. No. JP20H01523）.

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