Research Article

The role of groundwater outflow in the water cycle of a coastal lagoon sporadically opening to the ocean

Kazuhisa A. Chikita[a]*, Wataru Iwasaka[b], Abdullah Al Mamun[b], Kazuhiro Ohmori[b], Yo-suke Itoh[b]

[a] *Faculty of Science, Hokkaido University, Sapporo, 060-0810, Japan*
[b] *Graduate School of Science, Hokkaido University, Sapporo, 060-0810, Japan*

*Corresponding author. Tel. & fax : +81-11-706-2764
E-mail address: chikita@mail.sci.hokudai.ac.jp

Abstract

The water budget of a coastal lagoon, Oikamanai Lagoon, Hokkaido, Japan, sporadically opening to the Pacific Ocean, is estimated by establishing a bathymetric map of high accuracy (0.3m depth interval), and by monitoring the meteorology, lagoon water level and river stage. The opening to the ocean is produced by incising the sand bar from the overflow and discharge of lagoon water at the lowest site of the sand bar. The overflow results from an increase of the lagoon water level basically by snowmelt or rainfall river runoffs. As a result, the drainage by the opening to the ocean caused the lagoon to decrease the water volume up to more than 96%. The estimate of the water budget at nearly constant water level under closed condition of the lagoon suggests that, as the net groundwater output from the lagoon, the confined groundwater outflow to the ocean across the sand bar prevails. The gravelly confined aquifer was inferred to be at the similar elevation with some thickness along the grave-sand bar about 2000 m long. Meanwhile, during the regrowth of the sand bar at the outlet after the opening, the gravelly sediment first deposited near the sea level. Hence, the spatial distribution of the gravelly aquifer along the sand bar suggests that the whole sand bar was simultaneously broken in the past and then was grown up again.

Keywords: coastal lagoon; sporadic opening; sand bar; water budget; confined aquifer

1. Introduction

The ecosystem in coastal lagoons and the surrounding marsh could be affected by the climate conditions, the magnitude and frequency of seawater input, the artificial land development in the drainage basin, etc. (**Dussaillant et al., 2009**). The water budget, mass budget and associated flow characteristics of open coastal lagoons have been evaluated by the water balance method, geochemical method and hydrodynamic simulations (**Fujinawa et al., 2009**; **Gunaratne et al., 2010; Rapaglia et al., 2010**). **Fujinawa et al. (2009)** and **Rapaglia et al. (2010)** pointed out that, as a factor of interactions between the inland, lagoon and sea, a groundwater flow plays an important role in the water and mass budgets of the lagoons. Meanwhile, environmental managements of intermittently closed-open lakes or lagoons (ICOLL) are discussed in many research papers (**Haines et al., 2006**; **Czitrom et al., 2010**; **Morris and Turner, 2011**). However, the role of groundwater outflow or inflow in the water cycle is not there discussed, because their primary concern is about the seawater input and its exchange with lagoon water to improve the water quality. A coastal lake, Lake Abashiri, in Hokkaido, Japan, has the lower anoxic saline layer, which is produced by the seawater intrusion during the daily high tide. **Chikita (2000)** detailed the dynamic behaviors of the anoxic water with high sensitivity to the ecosystem.

The five coastal lagoons in southeastern Hokkaido (42°31' to 42°40'N, 143°29' to 143°37'E) are normally closed by the sand bar, but are sporadically open to the Pacific Ocean by the overflow of lagoon water across the sand bar (**Fig. 1a**). In this study, as a first step to clarify a whole system of the water cycle among the lagoons, their back marshes and drainage basins and between the lagoons and the ocean, the water budget of Oikamanai Lagoon, one of the five lagoons, is estimated by measuring the meteorology, lagoon water level and river stage.

2. Study area and field observations

2.1. Study area

Each sand bar of the five lagoons in southeastern Hokkaido was formed and at presence grows in the northeast to southwest direction by deposition of gravel and sand drifted mainly by southwestward longshore currents. The deposits were probably provided by the Tokachi River upstream of the longshore currents (**Fig. 1a**). Hence, each sand bar of the five lagoons tapers gradually from northeast to southwest along the coast. The sporadic water overflow in each lagoon occurs uniquely at the lowest and narrowest sand bar near the southwest end. The overflow of lagoon water results from the increase of water level basically by snowmelt or rainfall river runoffs. The frequency of the opening depends on the drainage area and lagoon water volume, which decide the residence time of lagoon water. Horokayanto Lagoon, neighboring to Oikamanai Lagoon, is open to the ocean once per four to five years because of the relatively small river inflow (**Fig. 1a**; **Nakao, 1990**), while the other lagoons are opened a few times per year.

The drainage basin of Oikamanai Lagoon, one of the five lagoons, mainly has three sub-basins, of which the two sub-basins finally produce a main influent river, the Oikamanai River, to control the lagoon water level or water volume (**Fig. 1b**). According to the GIS map of 1/25,000 scale in 2006 (the National and Regional Planning Bureau, Ministry of Land, Infrastructure, Transport and

Tourism, Japan: URL http://nlftp.mlit.go.jp/ksj/jpgis/datalist/_KsjTmplt-L03-b.html), Oikamanai Lagoon (surface area, 1.55 km^2 at 1.52 m amsl; **above mean sea level**) has the Oikamanai River and the other two small rivers, making up the back marsh (3.69 km^2 in area) in the east to northwest regions of the lagoon (**Fig. 1b**). The geology in drainage basins of the lagoons is mostly Miocene to Pliocene sedimentary rocks. The drainage area is 105.7 km^2 excluding the lagoon surface area, which consists of 75.2 % forest, 16.3 % farmland, 6.1 % marsh, etc. The records at a meteorological station about 15 km west-southwest of Oikamanai Lagoon indicate the mean annual precipitation of 1,178 mm (11 % snowfall) and annual mean air temperature of 5.6 °C in 1989 – 2010. The back marsh of Oikamanai Lagoon provides for habitats of rarely large corbicula (40 – 45 mm in diameter) (*corbicula japonica*) as a benthos in brackish water and the bird community of red-crowned crane (*Grus japonensis*; one of special natural treasures in Japan), yellow daylily (*Hemerocallis middendorffii*), etc. Such an ecosystem is made up by climate conditions and water and material cycles between the lagoon and its drainage basin, and between the lagoon and the ocean.

2.2. Field observations

In order to estimate the water budget of Oikamanai Lagoon, the meteorology was measured at 30 min intervals at site M and a meteorological station about 7 km southwest of the lagoon, the lagoon water level and lagoon surface temperature at 30 min interval at site L, and the river stage at 1 h interval at sites R1 and R2 in April – October 2011 (**Fig. 1b**). The time series of river discharge at sites R1 and R2 was obtained by using rating curves between river stage and frequent discharge measurement. River discharge was calculated by measuring the depth averaged velocity at about 20 sections partitioned in the cross-section and then summing the sectional discharge defined by the product of the sectional area and the depth averaged velocity. Each discharge of the northwestern two streams (**Fig. 1b**) was decided by assuming the runoff rate (discharge divided by the drainage area; mm day^{-1}) to be equal to that at site R1. The lagoon water level was obtained by two pressure gauges for air pressure and air pressure plus water pressure (HOBO water level logger; Onset Computer, Inc.; ranges of 0 – 9 m and -20 – 50 °C and accuracies of ±0.5 cm and ±0.37 °C for freshwater depth and temperature, respectively). The hourly data of sea level were provided at the Tokachi Bay 33 km southwest of Oikamanai Lagoon by the Obihiro District Development and Construction Department, the Hokkaido Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan:

Coastal lagoons in the world, most of which were fluvially incised valleys in the past, typically have a basin shape of relatively deep and narrow thalwegs and spacious shallow area, including the marsh (**Ferrarin et al., 2010**). This means that a small temporal variation of lagoon level produces large variation of the lagoon area. Hence, in order to accurately calculate a temporal change of the water volume of Oikamanai Lagoon, the bathymetric map of high resolution (0.2 m or 0.3 m depth interval) at high water level was made up by scanning 85 lines with a GPS echo sounder (model HDS-5 83/200TD, LOWRANCE, Inc.; resolution, ±0.01 m) attached to a boat in September and October 2010, and by dealing with the position and depth data from the GPS sounder on the software, “DrDepth”. Meanwhile, the shoreline of the lagoon was determined by topographic surveys with a theodolite and a portable GPS, and compared with the GIS map of 1/25,000 scale in 2006.

The surficial sediment at the lagoon bottom and on the sand bar was sampled by a Ekman-Birge grab sampler and manually, respectively, and then analyzed for grain size by the sieving method for more than 45 μm grains and the gravitational photo-extinction method for 45 μm or less grains. The sediment sampling was carried out under closed condition of the lagoon. According to the Wentworth scale of grain size, here, the sediment is classified into clay (grain size, $d \leq 3.9\,\mu$m), silt ($3.9 < d \leq 63\,\mu$m), sand ($63 < d \leq 2{,}000\,\mu$m) and gravel ($d > 2{,}000\,\mu$m). Vertical profiles of salinity and water temperature at site L were frequently obtained at 0.1 m pitch by using a TCTD (temperature-conductivity- turbidity-depth) profiler, Alec Electronics, Ltd.

3. Observational results

Fig. 2 shows time series of hourly lagoon water level (m amsl; above mean sea level) and total river discharge ($m^3\ s^{-1}$), and rainfall ($mm\ hr^{-1}$) for 1 April – 27 October 2011. As shown by the abrupt decreases in water level, the lagoon opened to the ocean four times at 2300h of 25 April, 1900h of 12 July, 1600h of 7 September, and 1700h of 22 September. The openings of 25 April, 12 July and 7 September finally drained 98.4 %, 96.4 % and 97.8 %, respectively, of the water volume before the openings. During the openings, the lagoon water level varied semi-diurnally following the oceanic tide, but the amplitude of the water level variation gradually decreases by the growth of the sand bar at the outlet. The third opening of 7 September occurred by the relatively large river runoff of 5 September from Typhoon No. 12. The lagoon was once closed on the night of 21 September by the growth of sand bar at the outlet. However, the large river runoff of 22 September from Typhoon No. 15 again opened the lagoon to the ocean. The second opening of 12 July was done artificially by an excavator, in order that fishermen picked the rarely large corbicula (40 - 45mm in diameter) (*corbicula japonica*; normally 10 – 15 mm in diameter) at the lowest water level. The first opening of 25 April was produced by relatively small rainfall runoffs, since the high water level was in advance provided by the snowmelt runoffs.

Fig. 3 shows temporal variations of lagoon water level, sea level and river discharge during the openings in September 2011.The overflow and outflow of lagoon water were caused by two rainfall river runoffs, which incised the sand bar at the outlet. The lagoon water level, showing the semi-diurnal variations, is at any time higher than the sea level even during the opening. The seawater intrusion into the lagoon is then done at the outlet by the breakers rolling up on the beach. Just after the openings, the lagoon water level varies in phase with the sea level. However, as the time lapses, the phase of the lagoon level variation is delayed up to 3 hrs and the amplitude gradually decreases, because the sand bar grows continually at the outlet.

The bottom topography of the lagoon exhibited a trace of the incised “valley” extending from the northwestern influent streams (**Fig. 4**). The “valley” is connected to the relatively deep regions along the sand bar, suggesting that the sporadic outflow of lagoon water is accompanied by the erosion of bottom sediment. The isopleths of water depth indicate the largest change of surface area at depths of 0.6 to 0.9 m (or the elevation of 0.62 to 0.92 m amsl). This is clearly reflected in the relation between the lagoon water level and surface area from the bathymetric map (**Fig. 5**).

The bottom sediment of the lagoon was sandy gravel on the inner steep slope of the sand bar, and silty at site L in the shallower region (**Fig. 6**). During the regrowth of the bar at the outlet after the opening, the gravelly sediment first deposited near the sea level, and then the sandy sediment was superimposed on the gravel. Thus the surficial sediment on the bar top is indeed sandy (**Fig. 6**).

The salinity under closed condition of the lagoon ranged from 0.033 to 0.67 ‰ by frequent vertical measurements at site L, thus corresponding to the salinity of freshwater (less than 0.5 ‰) or around.

4. Water budget of the lagoon

4.1. Basic equations

In order to quantify the groundwater output to the surrounding marsh and the ocean, the water budget of Oikamanai lagoon under closed condition was estimated on the daily base by the following equation.

$$\Delta V / \Delta t = \Delta h \cdot A / \Delta t = \left(P - E\right) \cdot A + Q_R - Q_G - Q_L \qquad (1)$$

where ΔV is the change of water volume, V (m^3) per time, Δt (here, a day), Δh is the change of water level (m) per Δt, A is the water surface area (m^2), P is the total precipitation (m day^{-1}) onto the water surface over the period, E is the evaporation (m day^{-1}) from the water surface, Q_R is the total river water input (m^3 day^{-1}), Q_G and Q_L are the net groundwater output (m^3 day^{-1}) to the surrounding marsh and to the ocean through the sand bar, respectively. The evaporation, E, was calculated by the bulk transfer method as follows (**Kondo, 1994**):

$$Q_E = -\lambda\left(\frac{\rho_a \varepsilon}{p}\right)\cdot(au_z)\cdot(e_z - e_0) \tag{2}$$

and

$$E = (Q_E/\lambda)\cdot(86{,}400/\rho_w)\ , \tag{3}$$

where Q_E is the latent heat flux (W m^{-2}), λ is the vaporization heat (J kg^{-1}), ρ_a is the air density (=1.2 kg m^{-3}), ε is the ratio of water vapor density to dry air density (=0.622), a is the empirical coefficient, u_z is the wind speed (m s^{-1}) at the height, z, above the water surface, p is the air pressure (Pa) at z, e_z is the vapor pressure (Pa) at z, e_0 is the saturated vapor pressure at the water surface temperature, and ρ_w is the water density (kg m^{-3}) at the surface temperature. The height of the meteorological measurement at site M was near 10 m, i.e., z =10 m in Equation (2) (**Fig. 1b**). Then, according to **Kondo (1994)**, the empirical coefficient, a, is given by 1.1×10^{-3}– 1.2×10^{-3} at 1 m s^{-1} < $u_{10} \leq 5$ m s^{-1} and by 1.2×10^{-3} – 1.3×10^{-3} at 5 m s^{-1} < u_{10} < 30 m s^{-1}. In this study, Q_R is given as the sum of river discharge at sites R1 and R2 and the stream water input into the northwestern marsh (**Fig. 1b and Fig. 4**). The parameters, λ, a, u_z, p, e_z, e_0 and ρ_w in Equations (2) and (3) were determined from the measurements of air temperature, relative humidity, wind speed and air pressure at site M and surface water temperature at site L. The vertical salinity measurements at site L under closed condition of the lagoon indicated that the salinity of lagoon water is low at 0.033 - 0.67 ‰, thus being similar to that of freshwater. Hence, the mass balance of the lagoon for salinity, connected to the water budget of Equation (1), was not here considered.

In Equation (1), the net groundwater output, $Q_G + Q_L$, is unknown, since the other terms are numerically obtained by the hydrometeorological observations and calculations, and the accurate surface area at a certain water level (**Fig. 4**). The small magnitude of Δh, not accompanied by the large change of the surface area, A, is needed to improve the estimate of $Q_G + Q_L$. because the A values are roughly given at 0.3 m depth interval (**Fig. 4**), and thus even the small change of A could produce the relatively large error in the $Q_G + Q_L$ estimate. Meanwhile, the lagoon surface area changes greatly at the water level, $H_w \leq 1.22$ m amsl (regions at depths of 0.3 m or more in **Fig. 4**) (**Fig. 5**). Hence, nine time periods of 4 days at $H_w > 1.22$ m amsl and $\Delta h \leq 0.05$m in **Fig. 2** were chosen as those for the water budget (**Table 1**).

4.2. Calculated results

Fig. 7 shows relations between the lagoon water level, H_w, minus the sea level, H_s, and the calculated net groundwater output, $Q_G + Q_L$. This exhibits the definitely linear relationship between the two parameters, i.e., the groundwater output increases linearly with increasing the water level gap or the lagoon water level because of the H_s values at almost zero m amsl (**Table 1**). This indicates that the net groundwater output is dominated by the confined groundwater output to the ocean. By hydrological observations in a neighboring lagoon, Horokayanto Lagoon, **Nakao (1990)** concluded that the lagoon water is drained into the ocean through the gravelly confined aquifer (hydraulic conductivity, $K = 0.011$ m s^{-1}) about 3 m thick below the sand bar at the outlet. The linear relationship in **Fig. 7** indicates that, in Oikamanai Lagoon, the groundwater output to the ocean occurs through the confined aquifer along the sand bar (**Fig. 8**). In **Fig. 8**, the elevation of the bar's crest at the outlet in the beginning of the overflows in April and September 2011 is obtained at about 3.5 m amsl from **Fig. 2**. Following the observation in Horokayanto Lagoon by **Nakao (1990)**, the upper boundary of the confined aquifer is located near the sea level.

Then, Q_L in Equation (1) is calculated by a simple two-phase equation of confined groundwater outflow from the lagoon to the sea:

$$Q_L = BD \cdot K(H_w \rho_w - H_s \rho_s)/(\rho_w L), \qquad (4)$$

and $$Q_L \approx BD \cdot KH_w / L, \quad \text{if } H_s \approx 0 \text{ for a time period,} \qquad (5)$$

where B is the horizontal width (m) of the confined aquifer along the sand bar, D is the thickness (m) of the aquifer, K is the hydraulic conductivity (m s^{-1}) of the aquifer, H_s and H_w are the sea level and lagoon water level (m amsl), respectively, and L is the length (m) of the aquifer across the sand bar. Here, assuming that the $Q_G + Q_L$ values in **Table 1** are equal to Q_L from Equation (5), the gravelly aquifer thickness, D, averaged along the sand bar is numerically obtained by setting L = 50 m from the topographic survey across the sand bar and B = 2,000 m from **Fig. 4**. The hydraulic conductivity, K = 0.011 m s^{-1} after **Nakao (1990)** was then applied. Relations between the calculated aquifer thickness, D, and the lagoon level, H_w, are shown in **Fig. 9**. At H_w less than ca. 1.9 m, the thickness, D, is converted into the value of 1.35 ± 0.16 m (mean $\pm$ standard deviation) (black circles in **Fig. 9**). This indicates that the thickness, D, averaged along the sand bar, is inherent in the gravelly confined aquifer along the sand bar. The increase of the D values at H_w more than ca. 2.0 m means that the net groundwater output to the back marsh then increases. By applying D = 1.35 m to Equation (5), each of Q_G and Q_L can be recalculated for the budget periods (**Table 1, Fig.**

10). The two regression lines of Q_G in **Fig. 10** indicate that Q_G increases linearly at H_w more than ca. 1.8 m and nearly zero at H_w less than ca. 1.8 m. In order to ascertain the hydrological characteristic of the confined groundwater outflow to the marsh, it is necessary to investigate the relationship between lagoon water level and groundwater level in the marsh. A comparison among Q_L, Q_G and the other hydrological parameters in **Fig. 11** and **Table 1** shows that the role of the confined groundwater outflow on the water budget of the lagoon is very important because of the magnitude comparable to the river inflow, Q_R. The residence time, RT (day), of the lagoon water is here estimated by $RT = V_4/(Q_L+Q_G)$ or V_4/Q_L, where V_4 is the 4-day averaged water volume (m^3). As a result, the residence time ranged from 13 to 20 days, which were much shorter than the closed time periods (69 days of 4 May to 12 July and 53 days of 16 July to 7 September) in Fig. 2, in which the lagoon water level did not vary diurnally. Thus, it is seen that the confined groundwater outflow to the ocean and marsh controls the water cycle of the lagoon. After the opening, the bar grows again at the outlet by first depositing gravelly sediment and then sandy sediment. Hence, the spatial distribution of the gravelly confined aquifer restricted to the similar elevation near the sea level with some thickness along the sand bar suggests that the whole sand bar was broken simultaneously in the past and then was built up for a short period, probably in a few years.

5. Conclusions

The five coastal lagoons on the southeastern coast of Hokkaido, Japan, commonly produce the sporadic water outflow to the Pacific Ocean. The water cycle system of such a coastal lagoon, exemplified by Oikamanai Lagoon, was clarified by exploring the hydrological conditions of the lagoon. The estimate of the water budget under closed condition of the lagoon at almost constant water level revealed that the confined groundwater output to the ocean through the sand bar plays the important role on the water budget of the lagoon. The existence of the gravelly confined aquifer along the sand bar about 2000 m long suggests that the whole sand bar was simultaneously broken possibly by a giant tsunami in the past and then was built up again. The careful assessment of the ecosystem in the lagoon and the back marsh is needed at presence and for the future, because the ecosystem is sensitive to both the climate change and tsunami attack.

References

Chikita, A., 2000. Dynamic behaviours of anoxic saline water in Lake Abashiri, Hokkaido, Japan. Hydrological Processes 14, 557-574.

Czitrom, S., Penié, I., de la Lanza, G., Osuna, V., 2010. Management Proposal for an Intermittently Closed Coastal Lagoon Using a Wave-Driven Seawater Pump and a Volume–Salinity Box Model. Journal of Coastal Research 26, 947-956.

Dussaillant, A., Galdames, P., Sun, C., 2009. Water level fluctuations in a coastal lagoon: El Yali Ramsar wetland, Chile. Desalination 246, 202-214.

Ferrarin, C., Cucco, A., Umgiesser, G., Bellafiore, D., Amos, C. L., 2010. Modelling fluxes of water and sediment between Venice lagoon and the sea. Continental Shelf Research 30, 904-914.

Fujinawa, K., Iba, T., Fujihara, Y., Watanabe, T., 2009. Modeling interaction of fluid and salt in an aquifer/lagoon system. Ground Water 47, 35–48.

Gunaratne, G. L., Tanaka, N., Amarasekara, P., Priyadarshana, T., Manatunge, J., 2010. Restoration of Koggala lagoon: Modelling approach in evaluating lagoon water budget and flow characteristics. Journal of Environmental Sciences 22, 813–819.

Haines, P. E., Tomlinson, R. B., Thom, B. G., 2006. Morphometric assessment of intermittently open/closed coastal lagoons in New South Wales, Australia. Estuarine, Coastal and Shelf Science 67, 321-332.

Kondo, J., 1994. *Meteorology in Aquatic Environments*. Asakura Publication, Inc., Tokyo, 350pp.

Morris, B. D., Turner, I. L., 2011. Morphodynamics of intermittently open–closed coastal lagoon entrances: New insights and a conceptual model. Marine Geology 271, 55–66.

Nakao, K., 1990. Hydrological evaluation of breaking frequency of coastal lakes dammed by a sand bar and environmental changes of Lake Oikamanai-numa and Lake Horokayanto-numa, Tokachi, Hokkaido. The Memoirs of the Geological Society of Japan 36, 89-102.

Rapaglia, J., Ferrarin, J., Zaggia, L., Moore, W. S., Umgiesser, G., Garcia-Solsona, E., Garcia-Orellana, J., Masque, P., 2010. Investigation of residence time and groundwater flux in Venice Lagoon: Comparing radium isotope and hydrodynamical models. Journal of Environmental Radioactivity 101, 571–581.

Acknowledgements

We are indebted to the Government of the Taiki-city and Fishermen's Union at Hama-Taiki Village for the kind permission of our field observations in Oikamanai Lagoon. We express our gratitude to the farmers, Messrs. Takahashi and Mori, at Seika Village for the frequent water sampling.

Figure Captions

Fig. 1. Location of (a) five coastal lagoons in southeastern Hokkaido, Japan, and their sporadic outflow, and (b) observation sites in the drainage basin of Oikamanai Lagoon. The river stage was measured at sites R1 and R2, the lagoon water level at site L, and the meteorology at site M.

Fig. 2. Temporal variations of hourly lagoon water level (m amsl), total river discharge (m^3 s^{-1}) and rainfall (mm h^{-1}) for 1 April to 27 October 2011.

Fig. 3. Response of the lagoon water level to total river discharge and sea level for the two openings in September 2011.

Fig. 4. Bathymetry (0.3 m depth interval) of Oikamanai Lagoon at water level of 1.52 m amsl (above mean sea level).

Fig. 5. Relation between lagoon water level (m amsl) and surface area (km^2).

Fig. 6. Cumulative grain size distributions of lagoon sediment and bar deposits. The sediment classification by grain size follows the Wentworth scale.

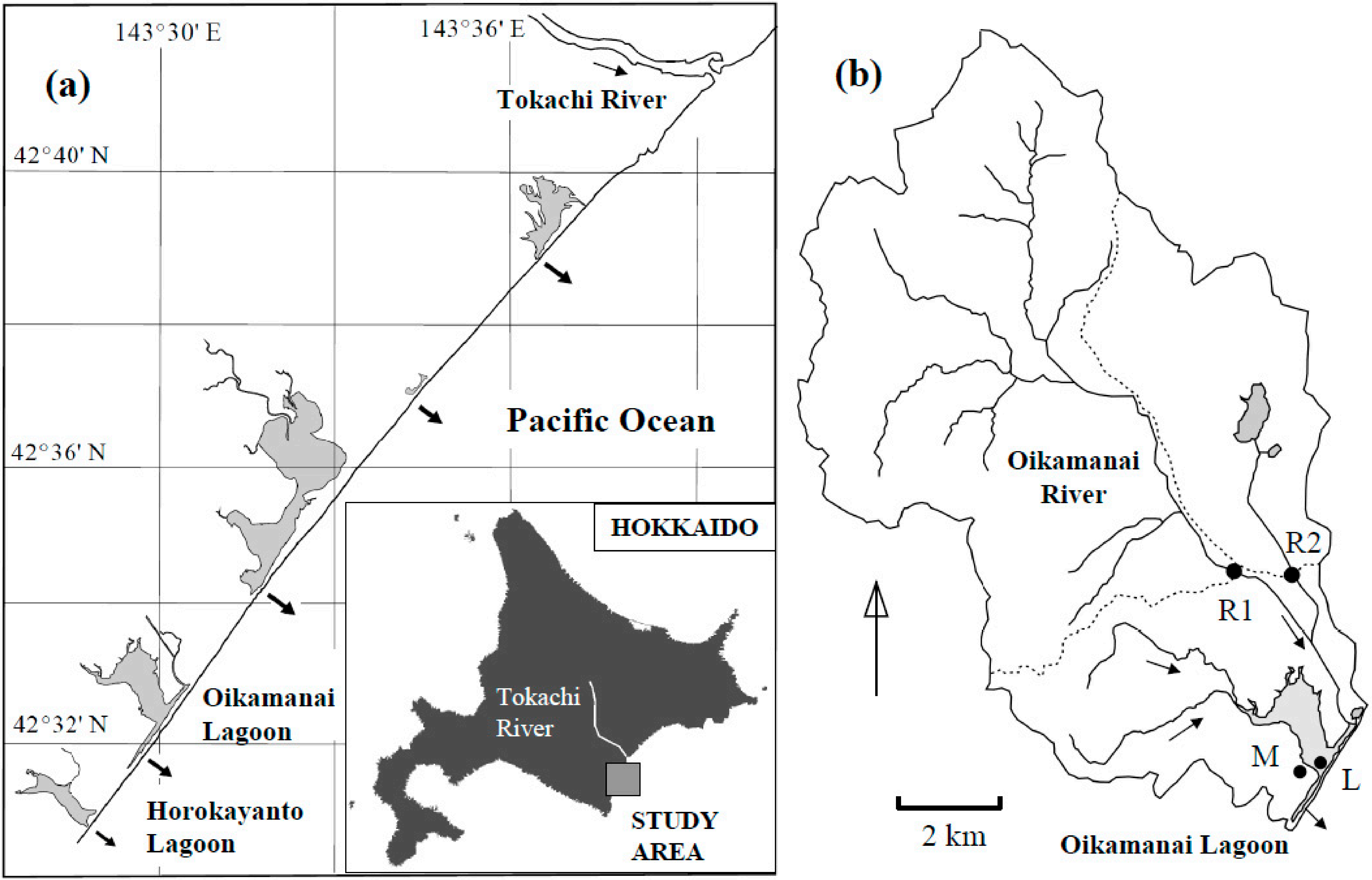
Fig. 7. Relation between the lagoon water level, H_w, minus the sea level, H_s, and the net groundwater output, $Q_G + Q_L$.

Fig. 8. Schematic of the lagoon water outflow to the ocean through the gravelly confined aquifer below the sand bar.

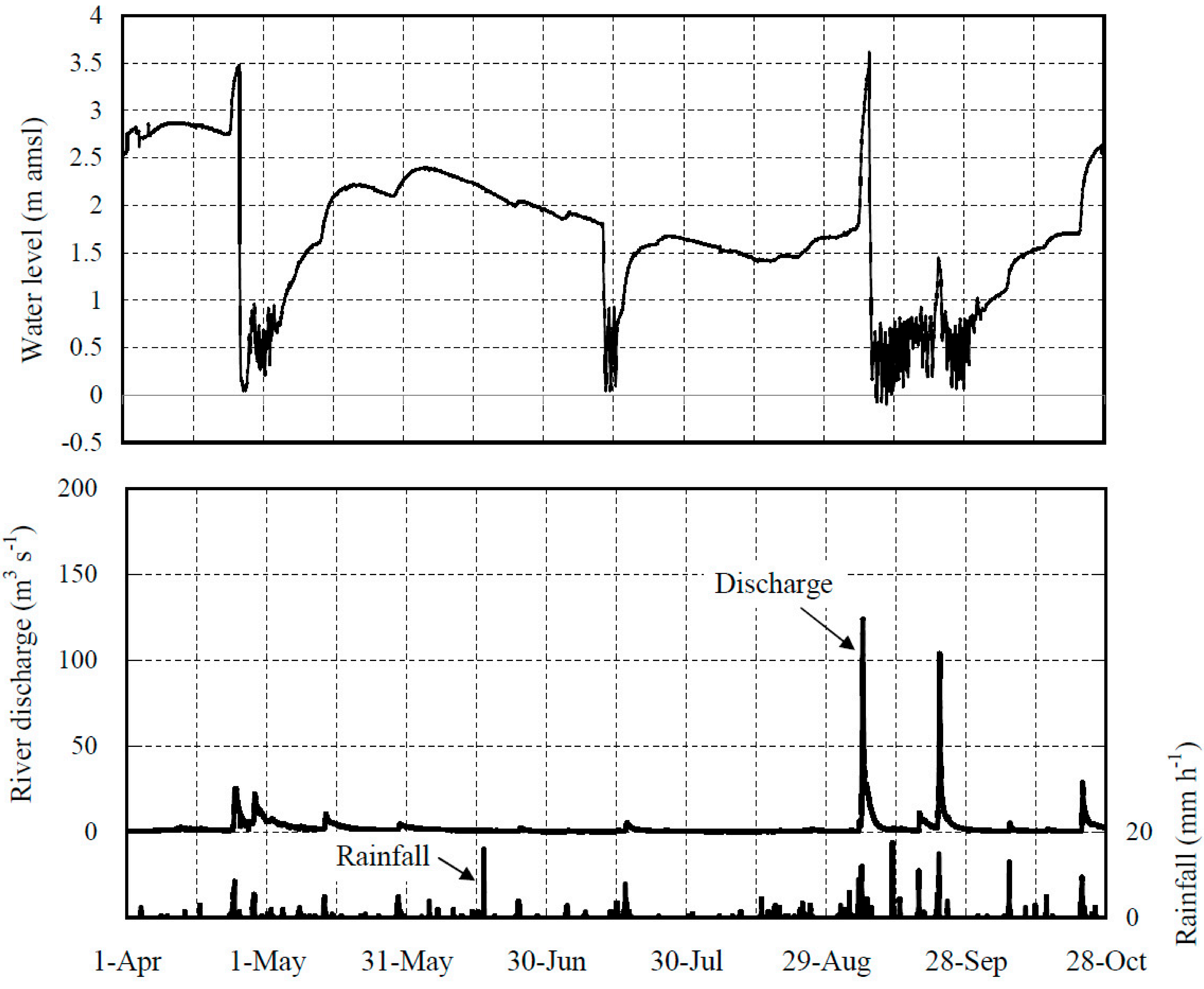
Fig. 9. Relations between the calculated confined-aquifer thickness, D (m), and lagoon water level, H_w (m amsl).

Fig. 10. Relations between the lagoon water level, H_w (m), and recalculated Q_L and Q_G.

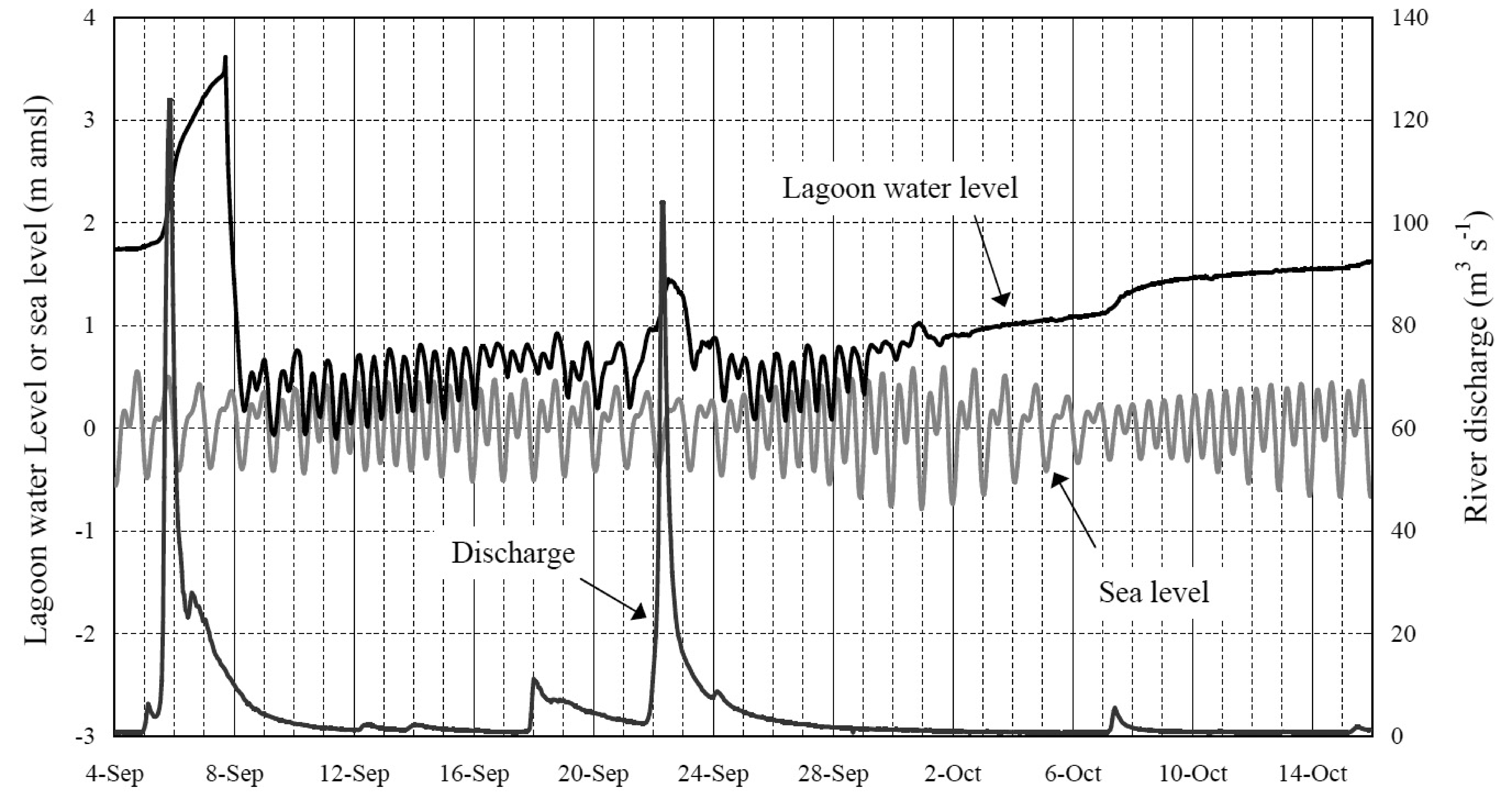
Fig. 11. Comparison among the five hydrological terms in Equation (1) for the nine time periods under closed condition of the lagoon. The values in each time period are mean values for four days (**Table 1**).



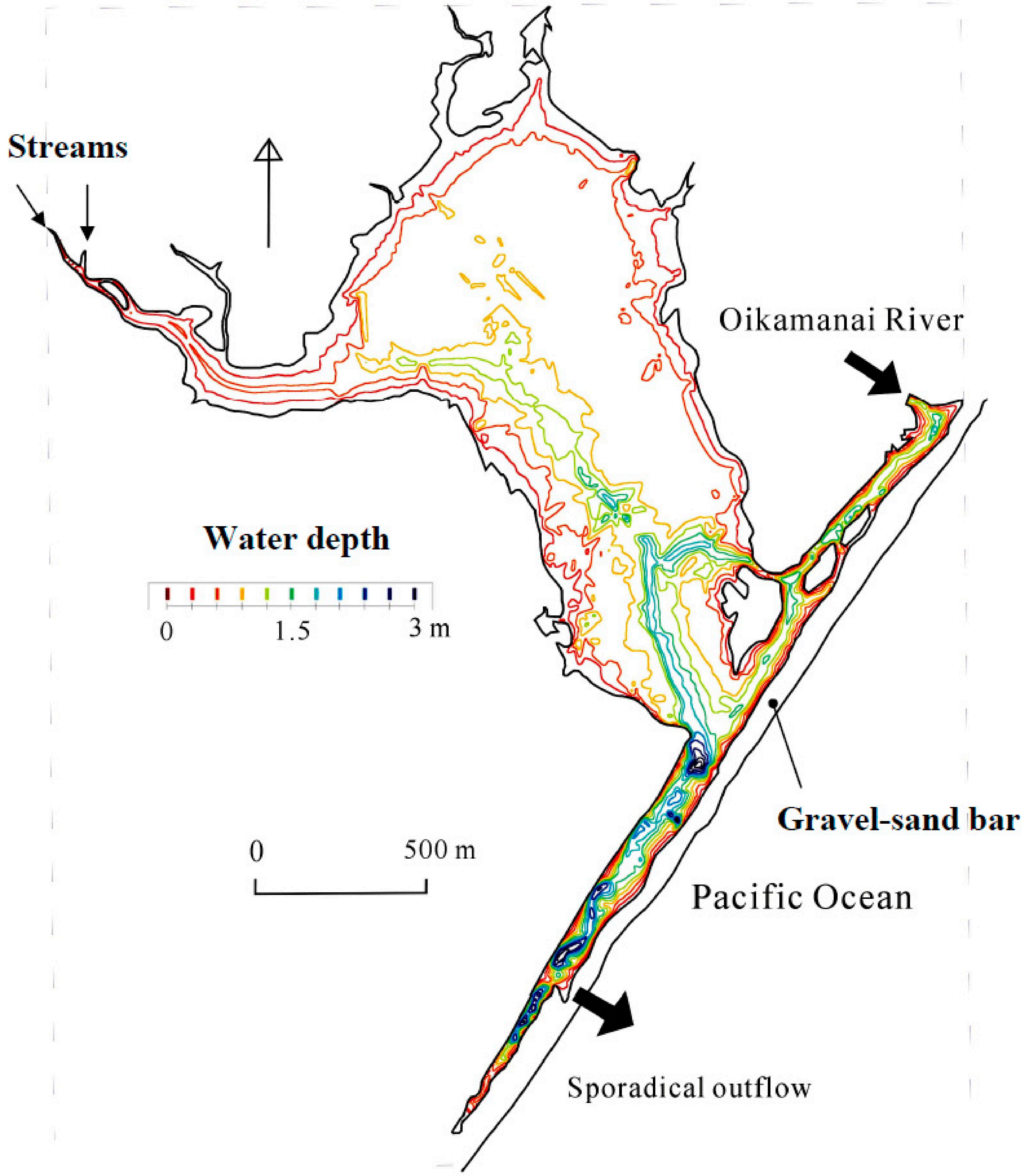
143°30' E
143°36' E
(a)
Tokachi River
42°40' N
Pacific Ocean
42°36' N
HOKKAIDO
Tokachi
River
Oikamanai
Lagoon
42°32' N
Horokayanto
Lagoon
STUDY
AREA
(b)
Oikamanai
River
R2
R1
M
L
2 km
Oikamanai Lagoon

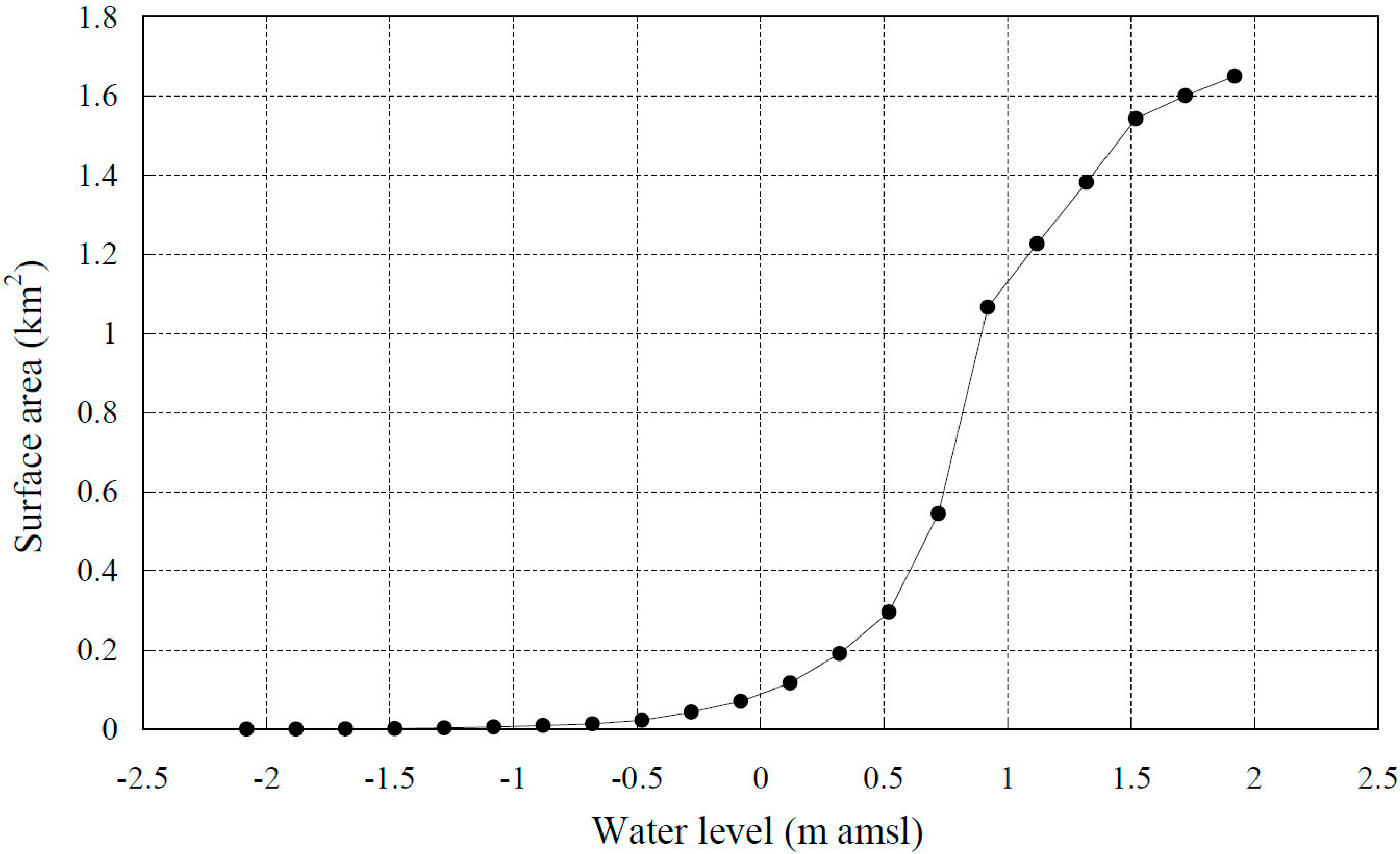


Water level (m amsl)
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
River discharge ($m^3 s^{-1}$)
200
150
100
50
0
Discharge
Rainfall
Rainfall ($mm h^{-1}$)
20
0
1-Apr
1-May
31-May
30-Jun
30-Jul
29-Aug
28-Sep
28-Oct

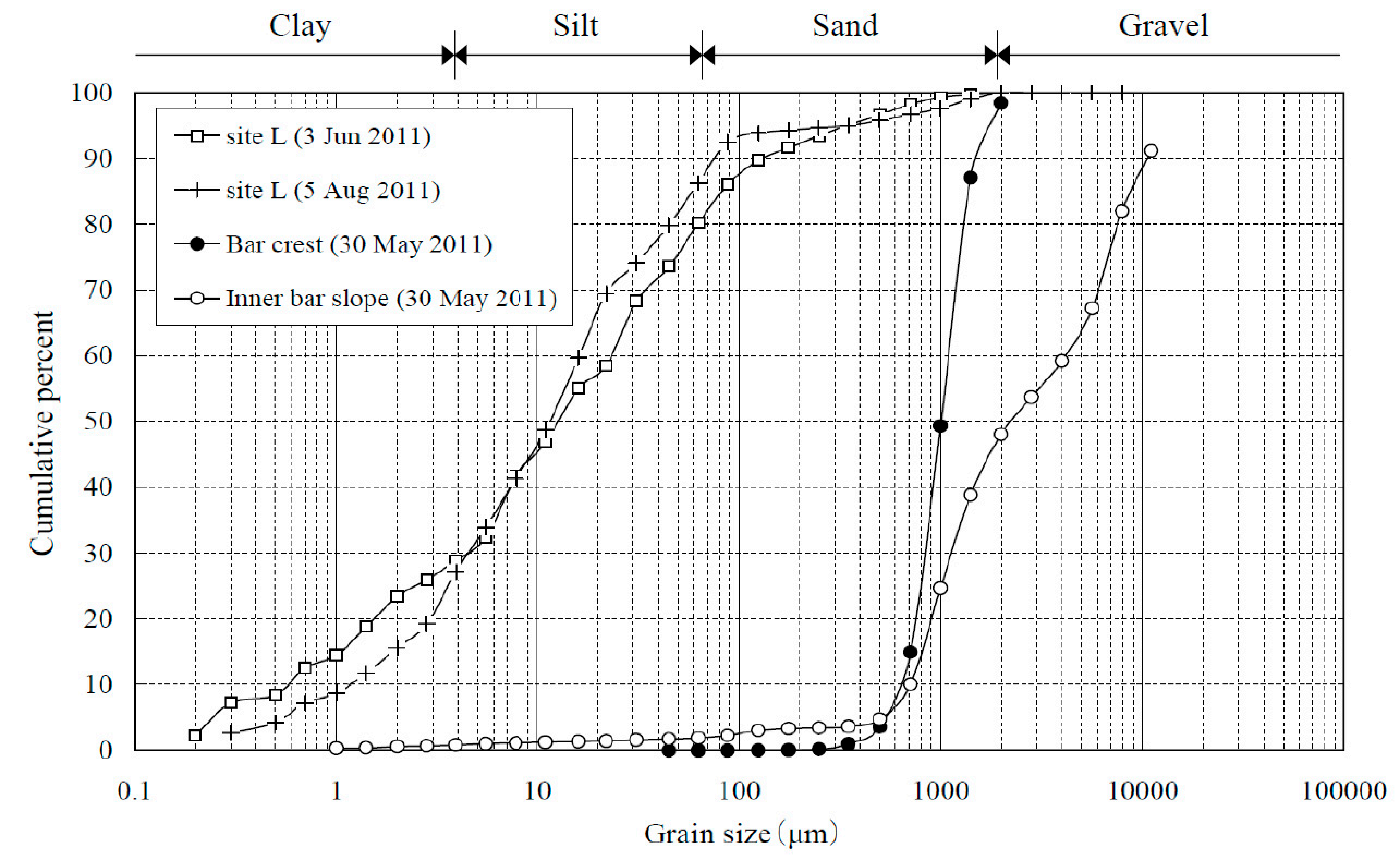


Lagoon water Level or sea level (m amsl)
River discharge (m^3 s^{-1})
Lagoon water level
Discharge
Sea level
4
3
2
1
0
-1
-2
-3
140
120
100
80
60
40
20
0
4-Sep
8-Sep
12-Sep
16-Sep
20-Sep
24-Sep
28-Sep
2-Oct
6-Oct
10-Oct
14-Oct

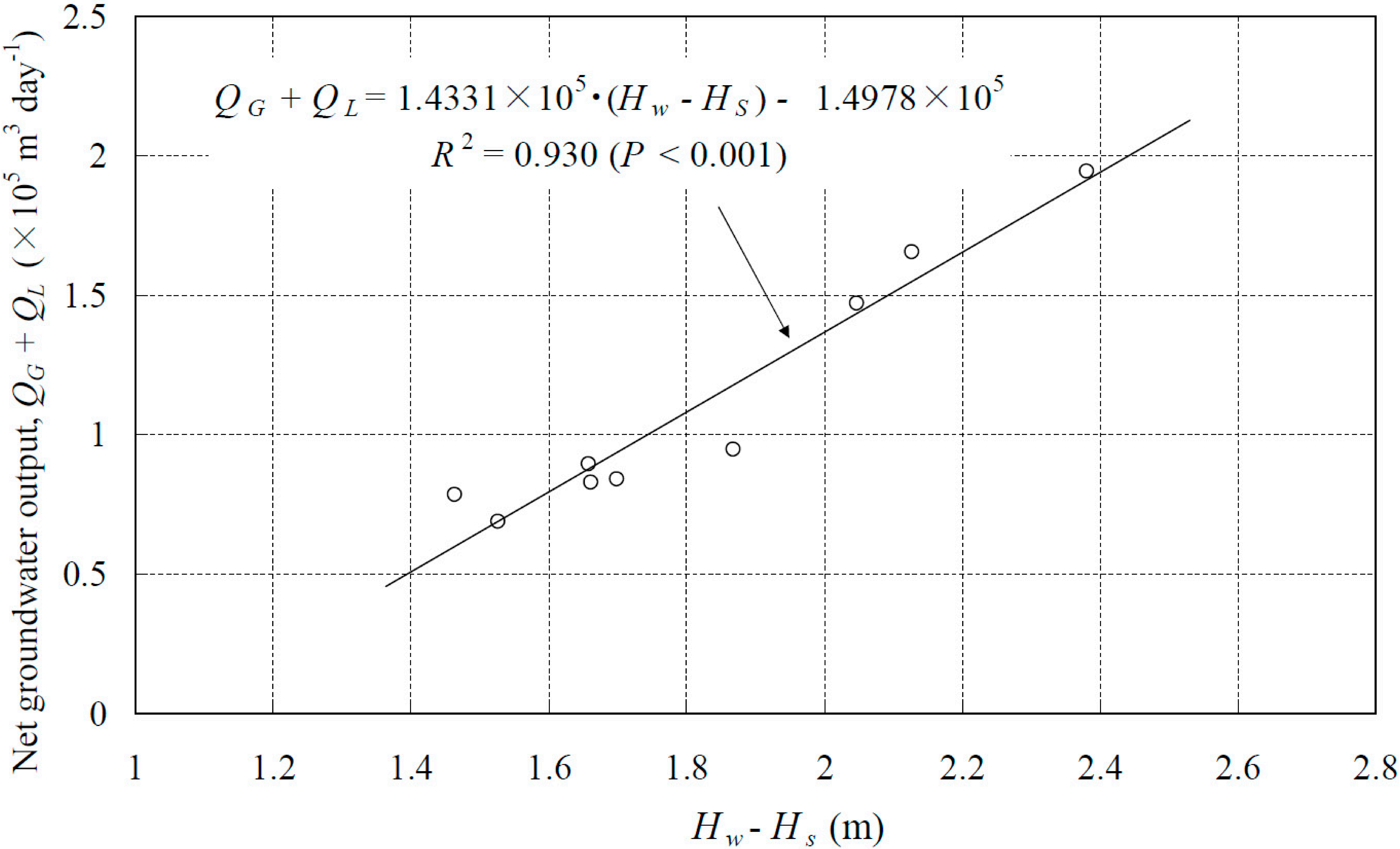

Streams
Oikamanai River
Water depth
0
1.5
3 m
Gravel-sand bar
0
500 m
Pacific Ocean
Sporadical outflow



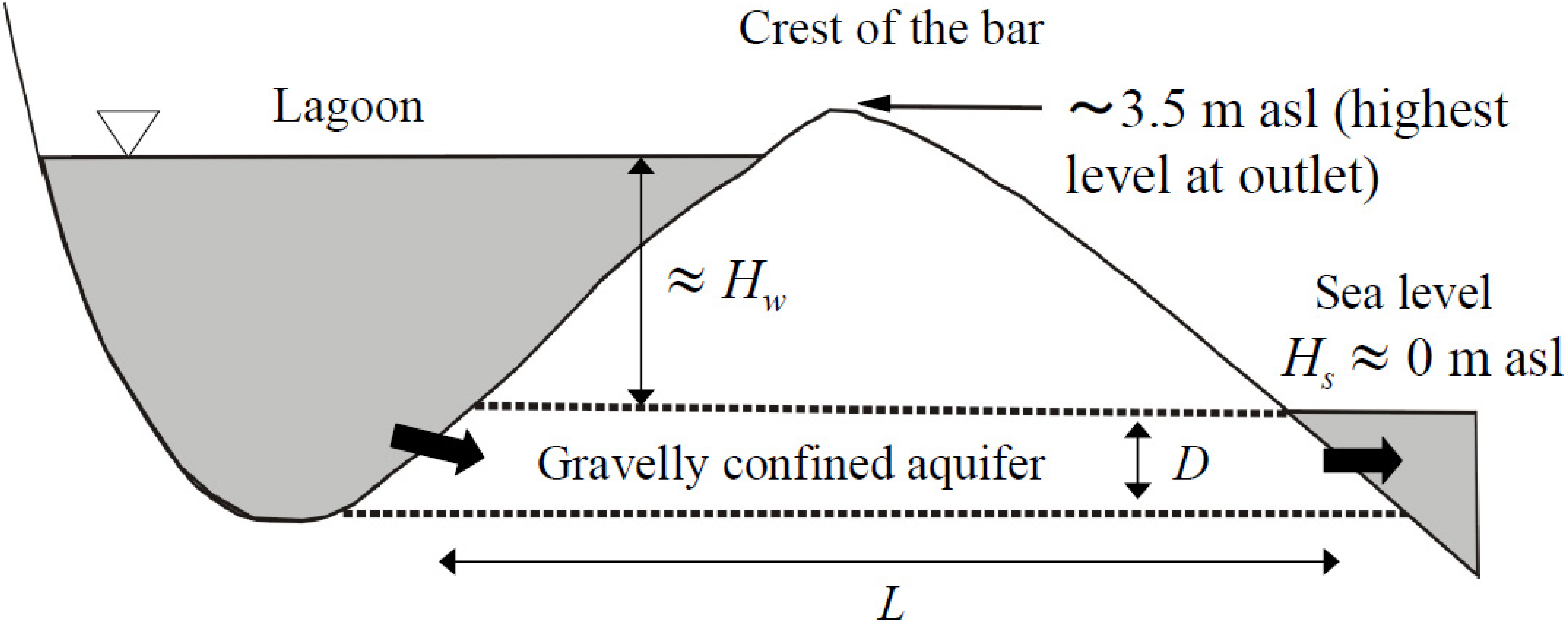
Surface area (km^2)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
Water level (m amsl)

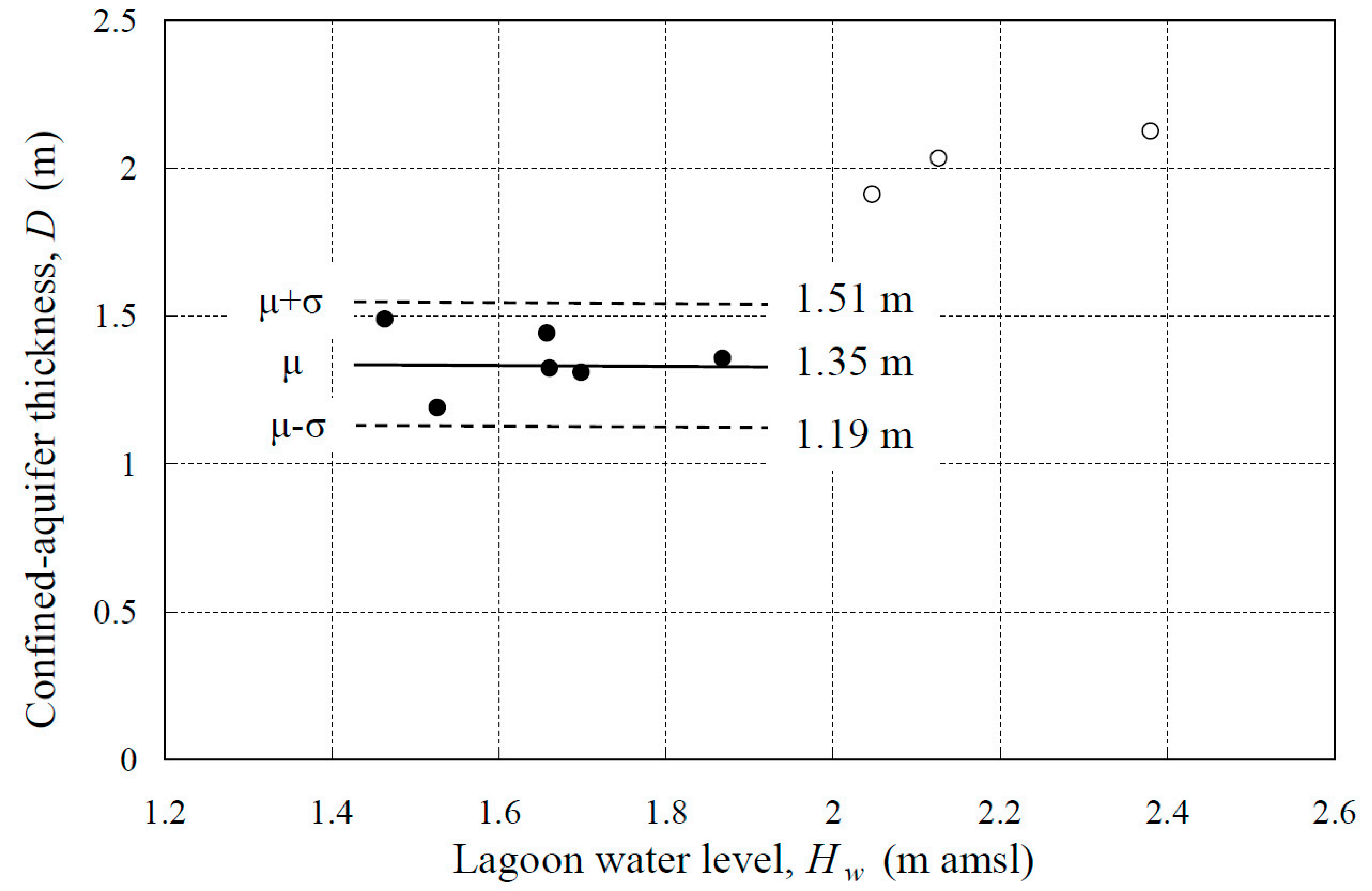


Clay
Silt
Sand
Gravel
site L (3 Jun 2011)
site L (5 Aug 2011)
Bar crest (30 May 2011)
Inner bar slope (30 May 2011)
Cumulative percent
0
10
20
30
40
50
60
70
80
90
100
0.1
1
10
100
1000
10000
100000
Grain size (μm)

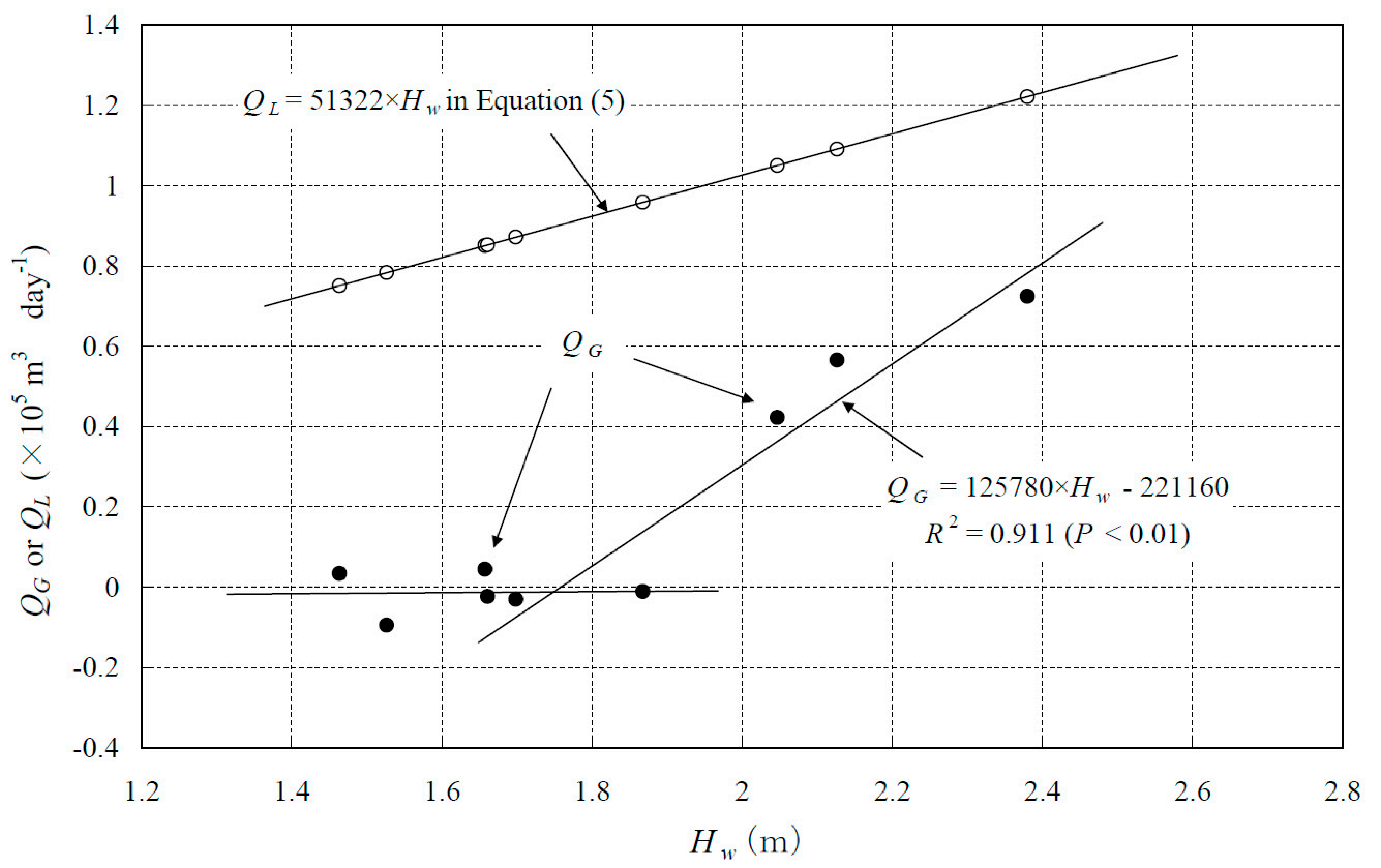


$Q_G + Q_L = 1.4331 \times 10^5 \cdot (H_w - H_S) - 1.4978 \times 10^5$
$R^2 = 0.930$ ($P < 0.001$)
Net groundwater output, $Q_G + Q_L$ ($\times 10^5$ m^3 day^{-1})
$H_w - H_s$ (m)
0
0.5
1
1.5
2
2.5
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8

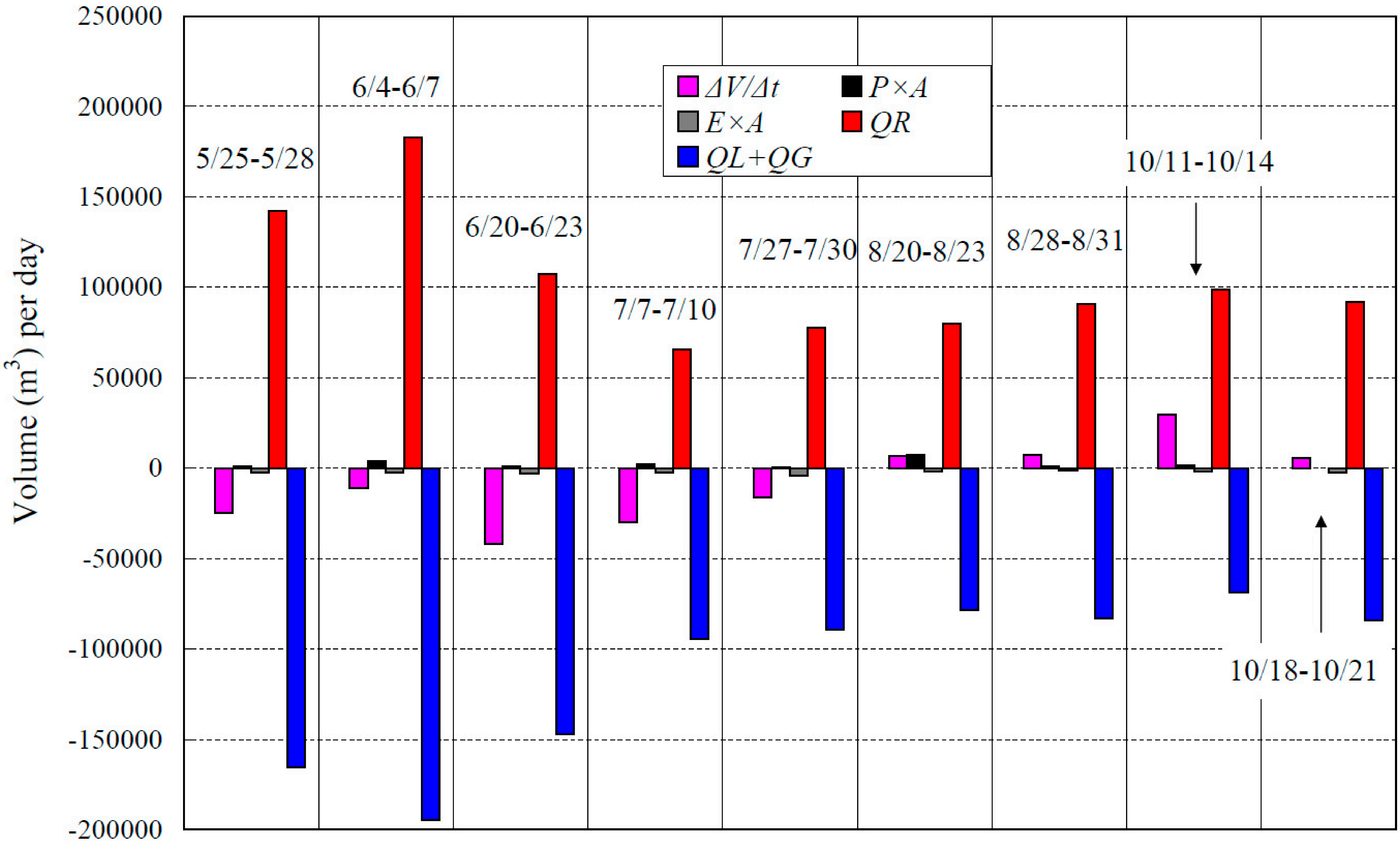

Crest of the bar
Lagoon
~3.5 m asl (highest level at outlet)
≈ H_w
Sea level
H_s ≈ 0 m asl
Gravelly confined aquifer
D
L



Confined-aquifer thickness, D (m)
Lagoon water level, Hw (m amsl)
2.5
2
1.5
1
0.5
0
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
μ+σ
μ
μ-σ
1.51 m
1.35 m
1.19 m



$Q_L = 51322 \times H_w$ in Equation (5)
Q_G
$Q_G = 125780 \times H_w - 221160$
$R^2 = 0.911$ ($P < 0.01$)
Q_G or Q_L ($\times 10^5$ m^3 day^{-1})
H_w (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8



250000
200000
150000
100000
50000
0
-50000
-100000
-150000
-200000
Volume (m3) per day
ΔV/Δt
P×A
E×A
QR
QL+QG
5/25-5/28
6/4-6/7
6/20-6/23
7/7-7/10
7/27-7/30
8/20-8/23
8/28-8/31
10/11-10/14
10/18-10/21

Table 1. Periods, lagoon water level, H_w, sea level, H_s, calculated four parameters, $\Delta V/\Delta t$, $P\times A$, $E\times A$, and Q_R, in Eq. (1) and calculated net groundwater output, $Q_L + Q_G$, Q_L and Q_G for the water budget of Oikamanai Lagoon. The values of the four parameters are averaged for the four days of each period. The Q_L values were obtained by assuming D = 1.35 m at constant. The residence time, RT (day), was obtained by $V_4/(Q_L+Q_G)$ or V_4/Q_L (values in parenthesis), where V_4 is the 4-day averaged water volume (m^3). At $H_w >\approx$ 2.0 m, the net unconfined groundwater output, Q_G, to the back marsh clearly appears.

Periods	H_w Mean (m amsl)	H_w Range (m amsl)	H_s Mean (m amsl)	$\Delta V/\Delta t$ (m^3 day^{-1})	$P\times A$ (m^3 day^{-1})	$E\times A$ (m^3 day^{-1})	Q_R (m^3 day^{-1})	V_4 (m^3)	$Q_L + Q_G$ (m^3 day^{-1})	Q_L (m^3 day^{-1})	Q_G (m^3 day^{-1})	RT (day)
25 – 28 May	2.13	2.10– 2.15	-0.02	-2.48×10^4	0.963×10^3	-2.18×10^3	1.42×10^5	2.09×10^6	1.66×10^5	1.10×10^5	0.56×10^5	13 (19)
4 – 7 June	2.38	2.37– 2.39	-0.03	-1.09×10^4	3.66×10^3	-2.76×10^3	1.83×10^5	2.48×10^6	1.94×10^5	1.24×10^5	0.71×10^5	13 (20)
20 – 23 June	2.05	2.01– 2.09	0.02	-4.20×10^4	1.16×10^3	-3.05×10^3	1.07×10^5	1.97×10^6	1.47×10^5	1.04×10^5	0.43×10^5	13 (19)
7 – 10 July	1.87	1.84– 1.89	0.02	-3.01×10^4	1.93×10^3	-2.62×10^3	0.654×10^5	1.69×10^6	0.95×10^5	0.94×10^5	0	18 (18)
27 – 30 July	1.66	1.64– 1.67	0.03	-1.61×10^4	0.385×10^3	-4.33×10^3	0.775×10^5	1.36×10^6	0.90×10^5	0.84×10^5	0.06×10^5	15 (16)
20 – 23 Aug.	1.46	1.46– 1.47	0.07	0.645×10^4	6.94×10^3	-1.98×10^3	0.800×10^5	1.06×10^6	0.78×10^5	0.71×10^5	0.07×10^5	14 (14)
28 – 31 Aug.	1.66	1.65– 1.66	0.02	0.723×10^4	0.771×10^3	-1.16×10^3	0.906×10^5	1.37×10^6	0.83×10^5	0.85×10^5	-0.02×10^5	16 (16)
11 – 14 Oct.	1.53	1.50– 1.55	0.01	2.96×10^4	1.54×10^3	-1.90×10^3	0.988×10^5	1.16×10^6	0.69×10^5	0.78×10^5	-0.09×10^5	17 (15)
18 – 21 Oct.	1.70	1.69– 1.70	0.01	0.550×10^4	0	-2.54×10^3	0.922×10^5	1.43×10^6	0.84×10^5	0.87×10^5	-0.02×10^5	17 (16)