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烏石礁公園濕地水文循環之定量分析

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摘　　要

本研究是實地調查與分析宜蘭縣烏石礁公園溼地在二年間的水文環境變化情形。調查資料與研究成果將成為宜蘭縣蘭陽博物館展示的一部份，同時也做為未來研究博物館周邊生態環境，自然資源與人類文化的基礎資料。

研究步驟首先著重於博物館建築預定地及周圍區域之基礎水文資料蒐集，再將現地調查之水文資料進行分析，並推估濕地之窪蓄量、滯留時間等，再以誤差分析暸解調查資料之正確性。研究結果顯示溼地水池在一般季節〈非旱澇時期〉地下水輔助比例約佔 90%，其餘為地面水或直接降水；流出方式主要為地表水；滯留時間則隨池水體積及總流入量為 2 天至 26 天；溼地水池對較長暴雨延時且具有稽延洪峰的效果。

關鍵詞：溼地、野外調查、水文分析。

Quantification Analysis of Hydrological Process at Wu-She wetland

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Abstract

This paper reports the results of field survey and analysis of a hydrological environment in Wu-She wetland located at Ilan County in northeastern Taiwan during a 2-year period. The data collected in this study will be presented as part of the exhibition materials in the Lan-Yang Ecological Museum (LEM) project. These data will also serve as fundamental elements for other components in the LEM project such as further studies in ecological system, natural resources, and Human Cultures. As the first step, this study focuses on collecting the basic hydrologic data in the parameter around the construction site of the LEM project. Hydrologic analysis is conducted based on the data collected in the field survey. Water storage as well as residence time for a pond inside the site are estimated. Error analysis is performed, providing insight information for evaluating the accuracy of the collected data. The results show that, during regular seasons, 90% of the groundwater in the area is from the pond. For the two years analyzed, the residence time is about 2 days to 26 days. The pond is also able to reduce the peak discharge for the rivers in the area during storms.

Keywords: wetland, field survey, hydrological analysis

1. Introduction

Hydrological balance of wetland, pond, and lakes has been studied heavily in previous researches (Owen, 1995; Hughes et al., 1998; Guardo, 1999; Gilvear et al., 1993; Gerla and Matheney, 1996; Hayashi et al., 1998; Watson et al., 2001; Nath and Bolte, 1998; Braaten and Flaherty, 2000). Fewer subjects may be influenced by tidal effect due to the site. Field survey with instrumentations was processed to monitor the data related to precipitation, evaporation (or evapotranspiration), surface inflow, surface outflow, groundwater level, infiltration, and hydrological conductivity. These data constitute components of water balance in a wetland. A hydrological model of wetland is derived from the analysis of water balance to simulate water circulation condition. The extended function of wetland such as storm water storage is also acknowledged from hydrological analysis.

Owen (1995) described the hydrological budget and flow patterns of an urban wetland in south central Wisconsin, USA, for over a 2-year period. Major inflow to the wetland was precipitation and surface flow. The wetland had a large capacity for flood control, but fewer contributions to supply groundwater or stream flow. Three major patterns of horizontal shallow flow were acknowledged with insignificant path flow because shallow slope and low hydraulic conductivities were shown in the wetland area.

Hughes et al. (1998) monitored an area of mangrove and salt marsh wetland in the Hunter River estuary, Australia. In his experiment, weather condition, groundwater levels, and tidal levels were monitored over a 10-week period. Saturated and unsaturated pore water movements were predicted by a two-dimensional finite element model. The results showed that groundwater responds to tidal fluctuations significantly due to highly permeable subsurface sediments. During the drying period, tidal forcing was found to generate incoming fluxes. Rainfalls dominated the water balance at heavy rainfall periods. Hyper salinity and salt encrustation showed that evapotranspiration influenced salt concentration significantly in both the surface soil and underlying aquifer during non-rainfall season.

The Ilan County proposes a project for the construction of the first ecological museum in Taiwan, known as the Lan-Yang Ecological Museum (LEM) project. It is known that an ecological system in a site is highly correlated to its hydrological environment. A small change in the hydrological environment of wetland may cause significant shift in plant communities, even inducing loss of species. To acquire the basic information for the ecological system within the site of the LEM project, hydrological investigations in various aspects are conducted as the first step of the project, which include surveys for precipitation, evaporation, surface water, and ground water. Water-budget and wetland storage changes in the region of the site are also studied based on the data collected in the field surveys. Since there are relatively few process studies that couple wetland and groundwater hydrology (Gilvear et al., 1993), the purpose of this research was to acquire detailed and quantified information for all water inputs to and outputs from both the wetland and groundwater, and tried to find the relationship between them, which was undertaken as part of a larger investigation examining the ecological system of the Wu-She wetland.

2. Site description

The location of the LEM project is in the region of a site known as Wu-She wetland located at Ilan County in the northeastern Taiwan (Figure 1). The site is in the vicinity between highway 2 and the new Wu-She Harbor. The total area for the site is about 27 acres. This site, known as Old Wu-She Port, was once an important trade harbor and marketplace for agriculture products between Ilan area and Mainland China. In the late 19th century, a large ship accidentally sunk in the harbor. The wreckage of the ship blocked the river by changing its course and inducing sediment aggradations both in the river and the port. The function of the port was therefore lost since then. The location has now become a wetland with a pond at its eastern side and is known as Wu-She wetland today. Within the area, there are 4 natural or man-made channels connecting to outside rivers labeled as channels #1 to #4 as shown in Figure 2. Adjacent to eastern side of Wu-She wetland, a new harbor has now been constructed (New Wu-She Harbor).

Channel #1 which is connected to Wu-In Creek is a main drainage of the Wu-She wetland. The flow direction of channel #1 could be contrary when storm flows through the Wu-In Creek and pour the water into the wetland which becomes a storm storage basin. Channels #2 and #3 collect runoff from this watershed separately. Channel #3 also connects the drainage of road and drain the extra water from the ditch. The channel labeled #4 is connected to the drainage of community. The flow of channel #4 is running scarcely because of the poor design for drainage purpose.

The weather of Ilan County is strongly affected by wind direction and the landscape. With the Pacific Ocean adjacent to the east and the Snow Mountain to the west, it receives over 200 days of raining in a year. The annual accumulation depth is about 2500mm to 3000mm. However, strong regional variation is observed, in some areas the precipitation differs for as much as twice of the amount. Because of the high occurrence of rainfall, monthly-averaged relative humidity is over 83% which is the highest in of Taiwan. Also, because of the heavy cloud in the area, the average sunshine rate is just 33%. With the average temperature of 22.6^{o}C and relative humidity of 83%, the annual evaporation reaches 770.6 mm.

3. Methods for field survey

For the measurement of the groundwater elevation, seven observation wells with a depth up to 2m were installed in the site during December, 2000 through July, 2002. The locations of these observation wells are indicated in Figure 2. Pumping test and infiltration coefficient test were conducted to obtain the infiltration coefficients (K and S) at different levels. Numerical analysis was applied to construct the water balance model as well as boundary conditions for the groundwater.

Since the weather records in the area are too short to perform a reliable statistical analysis, the study adopted the rainfall and temperature data collected at the Ilan station of the Central Weather Bureau in Taiwan. The distance between the station and the subject area is just 8 kilometers and the correlation coefficient for a 5-year rainfall data of the two areas is 0.97, providing confidence for the use of long-term weather data at Ilan station for the hydrological analysis.

For the measurement of evaporation, it is found not appropriate to use evaporation pan for data collection, since the area is well-covered by varieties of plants so that the accuracy of evaporation pan might be affected by transpiration due to these plants. The study thus utilized another approach to estimate the evaporation. By applying Thronthwaite's method, the possible evapotranspiration was first obtained using the monthly-averaged temperature data. Calculation shows that, in Ilan area, the possible evapotranspiration (Etp) is the same as the reasonable evapotranspiration (Eta). The evaporation is thus estimated as 0.7 times of the possible evapotranspiration in this study. The precipitation and evaporation data are measured as follows: annual average rainfall in the area is 2360.5 mm; the annual average possible evapotranspiration is 1062.8 mm; the annual average actual evapotranspiration is about 748.2 mm.

The infiltration coefficient of the pond was measured using a 2.5-inch diameter plastic tube drilled into the bottom of the pond for 40 cm. The water elevation inside the tube is kept higher than the water elevation of the pond outside of the tube. The infiltration coefficient was obtained by recording the water drop in the tube with the frequency of a week. Experiments show that the seepage of the soil at the pond bottom is about 1.0×10^{-6}cm/sec which falls in the range of fine-sand soil.

4. Field survey of hydrologic environment

4.1. Precipitation and Evaporation

Figure 3 shows the daily accumulation depth for the rainfall during November, 2000 and July, 2002. As shown in the figure, due to the passing of the typhoon Xangsane and Bebinca, there were continuous rain fall over three days (150 mm) during November, 2000. The maximum daily depth reached 231mm. The monthly rainfall depth is 995.5 mm in November, which is much higher than the monthly average rainfall of 412 mm for the past 10-year records. The precipitation was very low in December. From January to July of 2001, except a few days in May reached 100 mm due to the passing of typhoon Cimaron, the rainfall was generally low. The rainfall reached 334 mm in September due to typhoon Nari and Lekima. During October, 2001 and October, 2002, except the passing of Rammasun and Nakri in July 2002, the rainfall was generally lower than the average amount for the past 10-year records, which might possibly be a sign of the phenomenon of El Nino.

Figure 4 shows the Daily evaporation at Ilan station during November, 2000 to July, 2002. The annual average evaporation is 770.6 mm. A maximum of 114.7 mm appeared in July. In general, the evaporation is low when the precipitation goes high.

4.2. Surface water

The inflow of Wu-She wetland includes few channels (labeled #2, #3, and #4) that discharge runoff water into pond. Channel #1 is a drainage channel in general condition except when storm water of the Wu-In Creek flows into Wu-She wetland. The channels labeled #2 and #3 are the main channels with significant flow while channel #4 is neglected for its insignificant flow. Channel #2 constitutes the most amount of inflow into Wu-She wetland which is shown in Figure 5.

Figure 6 gives the surface water inflow to and outflow from the pond. As seen in the figure, the outflow was radically over-high during late 2000 and early 2001, which might be due to some erroneous measurements of the drainage flow. The dry season in 2002 is also clearly seen in the figure. The flow of outflow that is greater than that of inflow may be resulted in the added amount of groundwater.

4.3. Ground water

Figure 7 gives the measured groundwater elevation in the site during the period of November, 2000 to July, 2002. It is observed that the groundwater elevation decreases following the sequence of wells #4, #5, #3, #7, and #2. Wells #4 and #5 are located in the high land at the northwestern side of the pond. These elevations of groundwater are higher than the rest of the wells located in the lower land, i.e. wells #2 and #3, or at location near the pond, i.e. well #7. Figure 8 shows the comparison of the water elevation between groundwater and the pond. Strong correlation between these elevations is clearly seen in the figure indicating that the groundwater flows mainly to the pond from the watershed at the western side of the pond and from the Wu-In Creek at the South-Western side.

Figure 9 shows the groundwater level contour measured on January 13, 2001. It also shows that the flow direction is mainly from the mountain side at the west to the coast side at the east, which suggests that the Wu-In creek at the west may be an ideal resource for groundwater recharging.

5. Estimation of groundwater recharge

To estimate the groundwater recharge, the infiltration coefficient is roughly set to be the same as coarse sand as $K = 0.015$m/sec since the measurement of the infiltration coefficient is undertaken at that time. The boundary conditions are set as the water elevations of well #5 and the pond. The ground water recharging is estimated by using the following equation (McCuen, 1998):

$$q = \frac{K}{2L}(h_1^2 - h_2^2) \qquad (1)$$

where q is the recharge per unit length (cms/m), K is the infiltration coefficient, L is the distance between well #5 to the pond, h_1 is the relative water depth of well #5, and h_2 is the water depth of the pond.

The simulation was then verified by comparing to the water elevation in well #7 using the following relation

$$h^2 = h_1^2 - \frac{x}{L}(h_1^2 - h_2^2) \qquad (2)$$

The result shows that the correlation coefficient is about 0.75. The estimated groundwater recharge provided the basic information for the evaluation of the hydrologic balance of the pond.

6. Relationships of hydrology circulation

Figure 10 shows the inflow hydrograph for water from various sources including channel #2, channel #3, and ground water. It is seen in the figure that the inflow from channel #2 is lower than that from channel #3 although the size of the water basin for channel #2 is twice as that of channel #3. Field survey shows that there are underground flows from channel #2, indicating that the water is recharged to the groundwater and, therefore, inflow to the pond is reduced. Also, since channel #3 is connected to the drainage channel of Highway 2, part of the water from the drainage channel also flows into the pond through channel #3.

Figure 11 gives the components for the inflow of the pond. It is seen in the figure that the inflow from groundwater was reduced in September, 2001, because the water elevation in the pond was higher than that of the groundwater due to a typhoon at that time. However, due to some missing records in 2002, 90% of the inflow for the pond is found to be from groundwater.

7. Hydrological system analysis

7.1. Hydrological balance model

The hydrological balance in a wetland is dominated by three factors: surface water balance, geological variation, and conditions of the groundwater. By considering these factors, a hydrological balance model in a wetland can be constructed as follows (Mitsch and Gosslink, 1993):

$$\frac{\Delta V}{\Delta t} = P_n + S_i + G_i - ET - S_0 - G_0 + T \qquad (3)$$

where V is the water stored in the wetland; $\Delta V / \Delta t$ is the rate of change in water storage; P_n is net precipitation; S_i is surface water inflow; G_i is ground water inflow; ET is evaporation; S_0 is surface water outflow; G_0 is ground water outflow; and T is tidal inflow or outflow. The seepage is included in the groundwater item.

This hydrological balance model described in Figure 12 indicates that the water in a wetland comes from several sources including rainfall, runoff, groundwater, and possibly some inflow from tide. There are also several factors responsible for the loss of water including evaporation from the surface, outflow to the surface water, infiltration to the groundwater, and possibly some outflow due to the tide.

Investigations show that the surface area of the pond is related to rainfall and evaporation. Since there are just little plants grow in the pond, the transpiration can be neglected. The surface water flows from 3 channels labeled as channels #2, #3, and #4 as shown in Figure 2. Water at the northwestern side of the area is collected and carried into the wetland through channels #2 and #3. The amount of water in channel #2 depends significantly on the rainfall. In most of the time, there is no water in the channel except after a heavy rainfall. On the other hand, channel #3 can retain low discharge even during the dry season. Channel #4 is a natural stream connected to the local drainage system. However, the discharge is very low.

Outflow is mainly from channel #1 located at south, which then merged into the Wu-In creek. However, because of heavy aggradations in the channel, flow discharge is very low. During flood seasons, the direction of the flow in channel #4 may even reverse. Flood in Wu-In Creek flows into the wetland through the channel and the wetland becomes a storage pond.

Abundant groundwater is found in this area, which is believed to be due to the geological condition of the area. Our investigation revealed that most of the inflow to the wetland is from groundwater. However, it is observed that the groundwater is decreased after the construction of the New Wu-She Harbor, which might be caused by increasing the infiltration layers at the area. Since the pond in the wetland does not connect to the new harbor, investigations showed no significant correlation between the water elevation in the pond and the tide in the harbor.

7.2. Water storage

Figure 13 gives the precipitation, evapotranspiration, and water depth in the pond. As the figure shows, the depth varies between 0.3 m and 2.0 m. It appears that the water depth in the wetland is rising suddenly to about 2 m after a typhoon with heavy rainfall. Most of the year, the elevation of the pond is between 0.5 m to 1.0 m unless during the typhoon season and dry season from March to May of 2002.

Figure 14 gives the amount and area of water storage in the wetland collected from November, 2000 to July, 2002, which can be used to determine the water storage providing the water elevation in the wetland.

7.3. Hydrologic balance of the pond

Comparing to the inflow from surface water, groundwater and precipitation as shown in Figure 15, the time lag between rainfall and runoff is obvious from the figure. The peak of the surface water usually happens following the appearance of peak rainfall. It appears that groundwater is the major source for the inflow. The figure also shows that the inflow from the precipitation is a little higher than that from the surface water. Figure 16 gives the measured outflow of surface water, seepage, and evaporation of the pond from December, 1990 to July, 2002.

According to water balance, water in the pond should satisfy the following relation:

$$I - O = \Delta S / \Delta t \quad (4)$$

where I is the inflow (cms); O is the outflow (cms); and ΔS is the variation of the water volume in the pond (m3).

To evaluate the accuracy of the collected data, the deficiency of the water balance is estimated using $I\Delta t - O\Delta t - \Delta S$. The result is shown in Figure 17. Positive value suggests that probably some outflow seem to be overlooked. On the other hand, negative value signifies some missing inflows.

It is found in the figure that the fluctuation during late 1990 and early 2001 is related to the anomaly of surface water inflow and outflow at that time. After mid 2001, the inconsistency is found to be related to some anomaly in groundwater. However, the figure also shows that the accumulation curve of the defect completes just a hydrologic balance cycle if using $\Delta t = 8$ months for the calculation. This phenomenon might probably be a coincidence since the pond is not a closed system. Long-term observation is required for further understanding of this phenomenon.

8. Summary and conclusions

Based on the data collected from the field survey for the 2-year period, it is found that 90% of the water in the pond is from groundwater during regular seasons (not dry or wet season). The rest is from surface water and rainfall. The outflow is mainly through surface water. Water depth of the pond varies between 0.3m and 2m. Analyses show that the residence time is about 2 days to 26 days, depending on the volume of the pond and the amount of inflows.

For storms with longer duration, the pond is functions as a storage pond and is able to reduce the peak discharge. However, as the depth of the pond rises high, the effect for reducing the peak discharge is decreased.

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Table 1 Estimated residence time

Month	Averaged area(m^2)	Averaged water storage (m^3)	Total inflow (m^3 /month)	Total inflow (m^3 /day)	Residence time(day)
Dec-00	31486	16471	278629	9288	2
Jan-01	33957	18916	337006	11234	2
Feb-01	25719	11051	136034	4534	2
Mar-01	24325	9434	98797	3293	3
Apr-01	26332	11825	62081	2069	6
May-01	25604	10910	119245	3975	3
Jun-01	26926	12613	129583	4319	3
Jul-01	24102	9193	105812	3527	3
Aug-01	22560	7654	67055	2235	3
Sep-01	78329	41072	194460	6482	6
Oct-01	55017	29164	159563	5319	5
Nov-01	27817	13868	133321	4444	3
Dec-01	28560	14984	80816	2694	6
Jan-02	22707	7791	53807	1794	4
Feb-02	23371	8436	39686	1323	6
Mar-02	14101	2478	39854	1328	2
Apr-02	5640	715	1593	53	13
May-02	13408	2245	2632	88	26
Jun-02	24277	9381	35936	1198	8
Jul-02	37392	22113	56704	1890	12

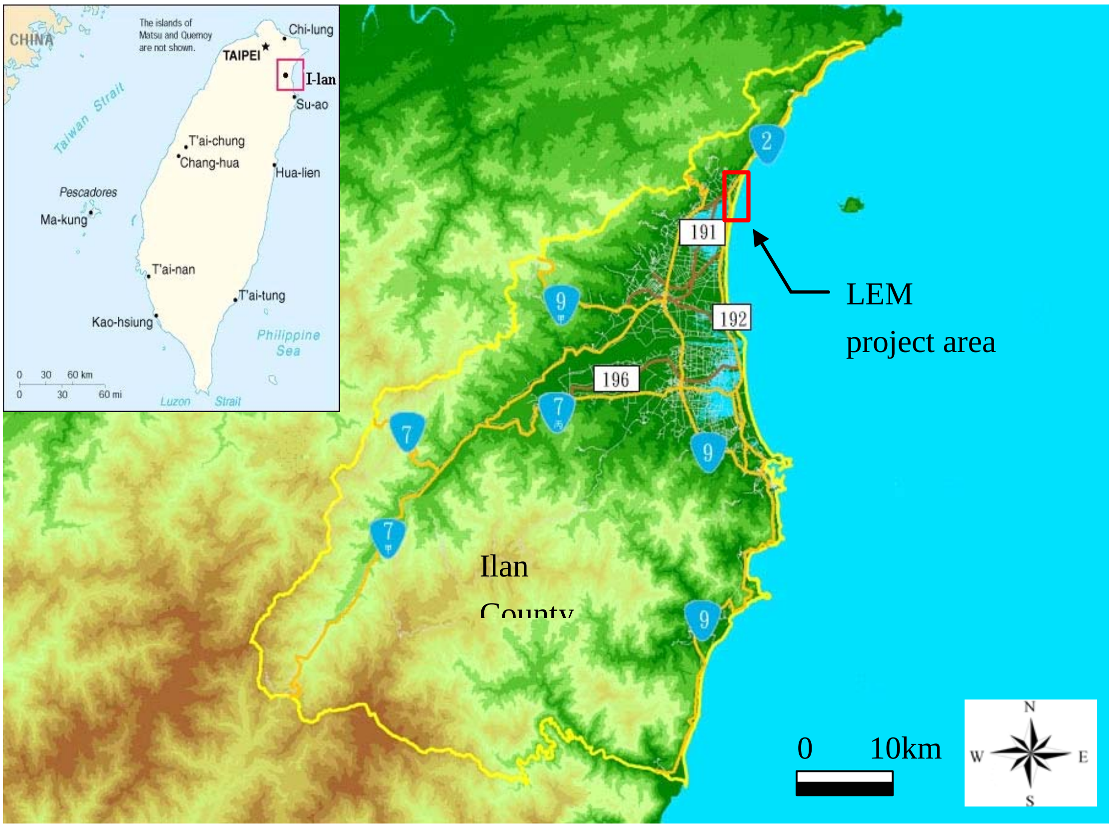

Figure 1. Location of the Lan-Yang Ecological Museum (LEM) project

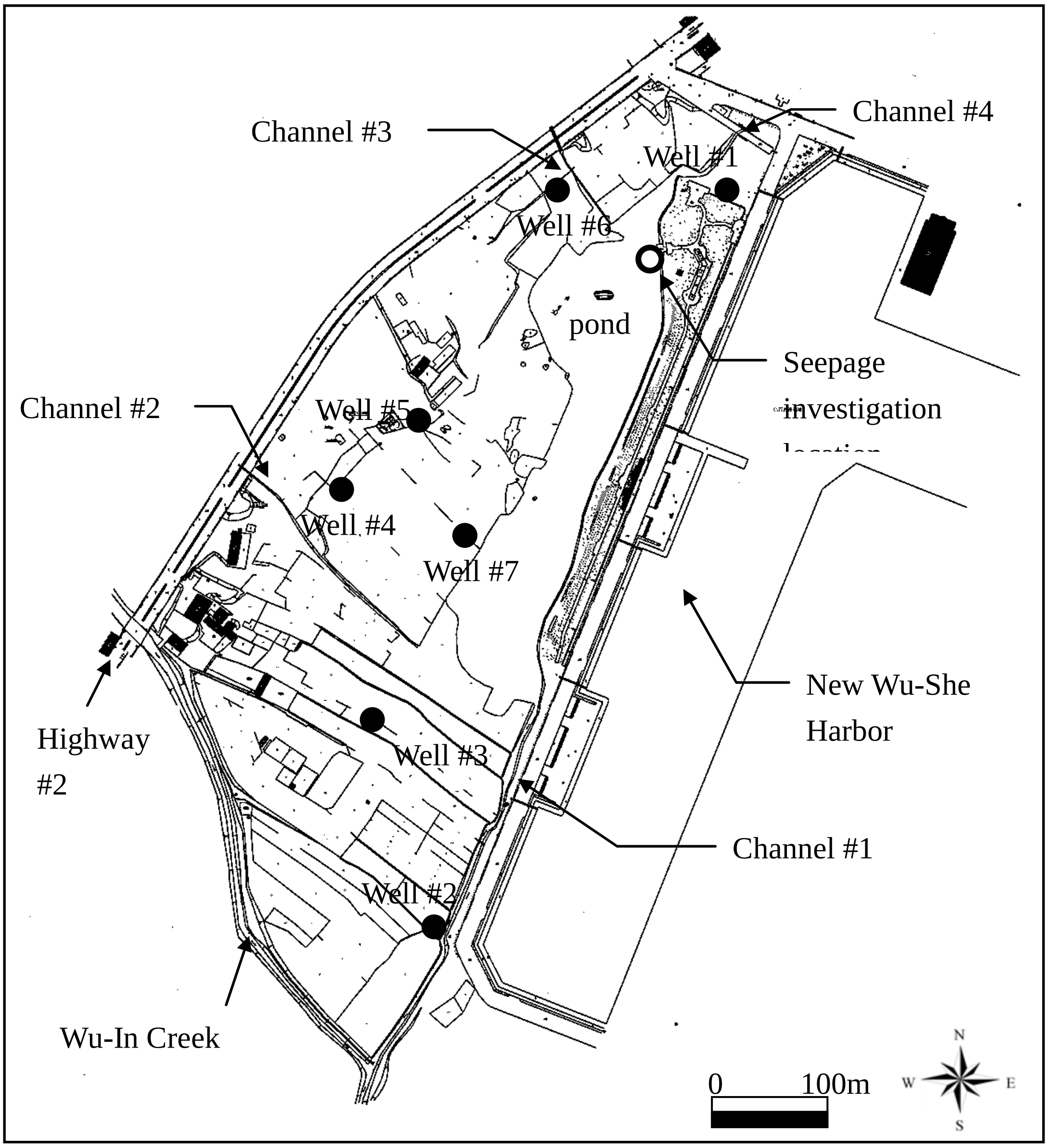

Figure 2. Map of wetland area and location of the observation wells

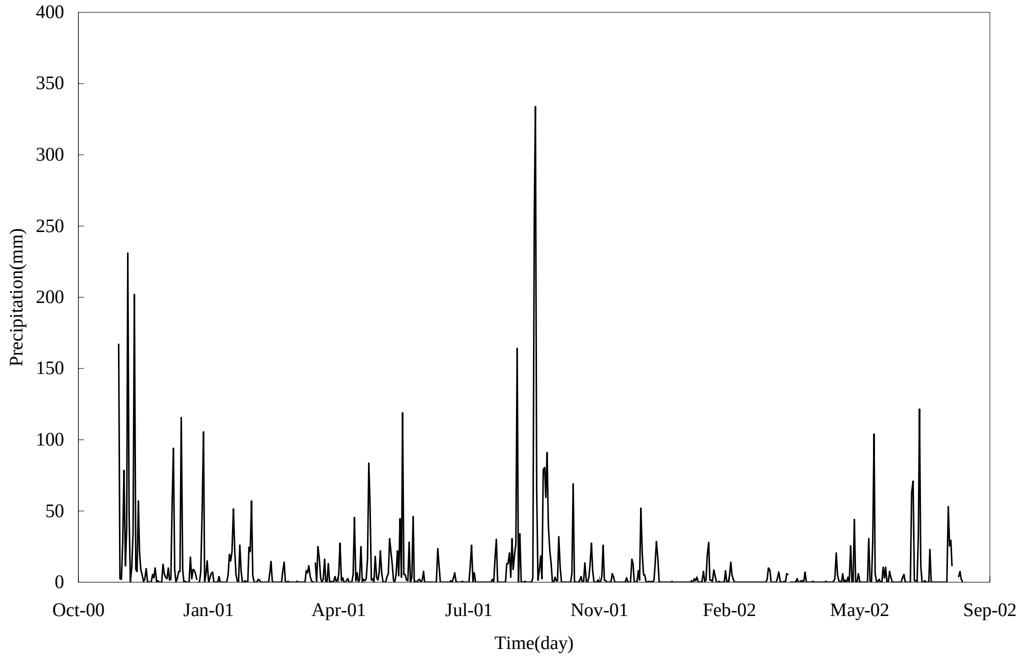

Figure 3. Daily rainfall depth (Data source: Central Weather Bureau in Taiwan)

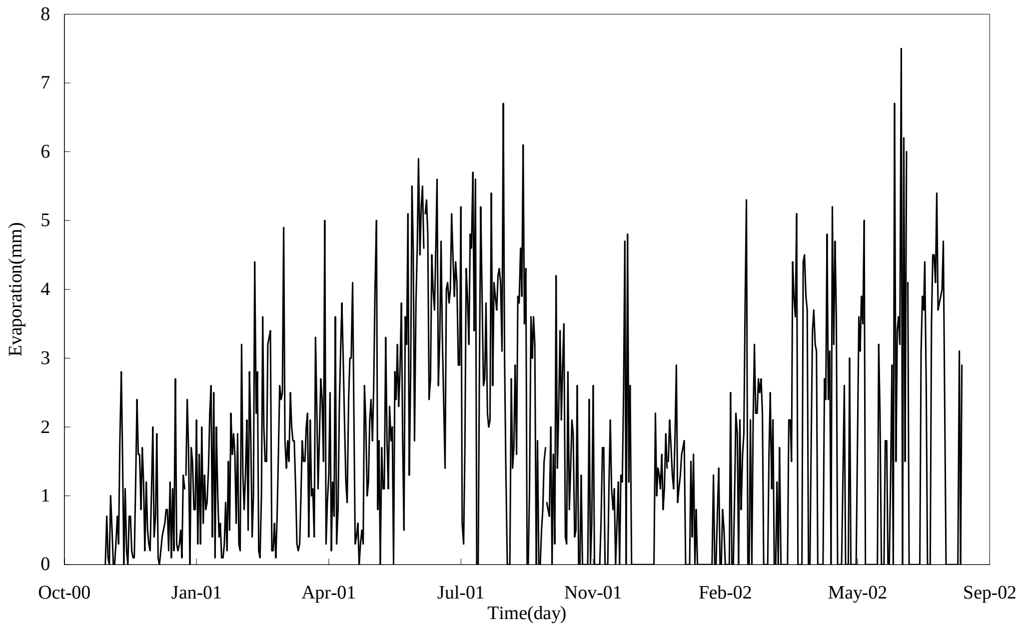

Figure 4. Daily evaporation at Ilan station (Data source: Central Weather Bureau in Taiwan)

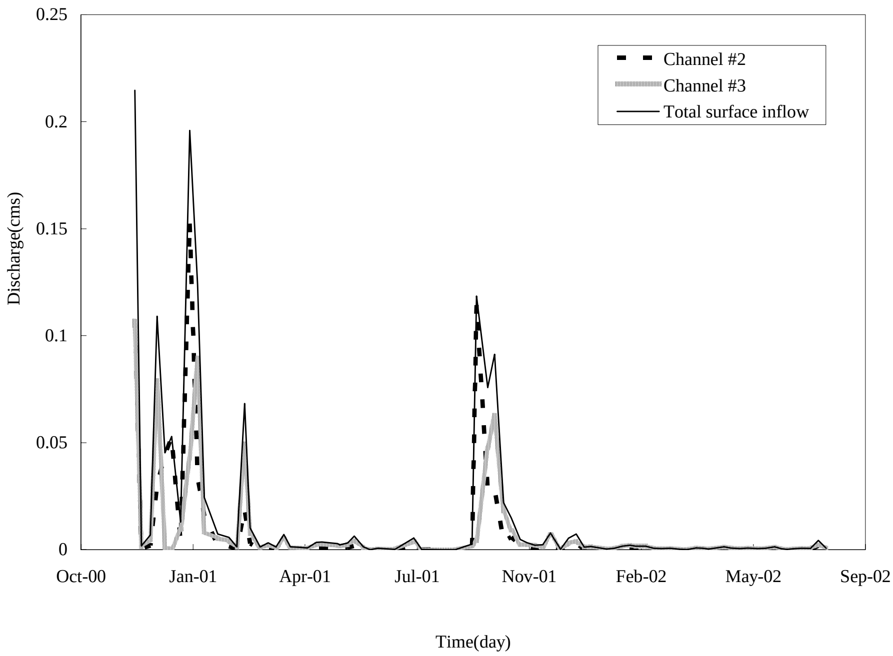

Figure 5. Surface water inflow of the pond

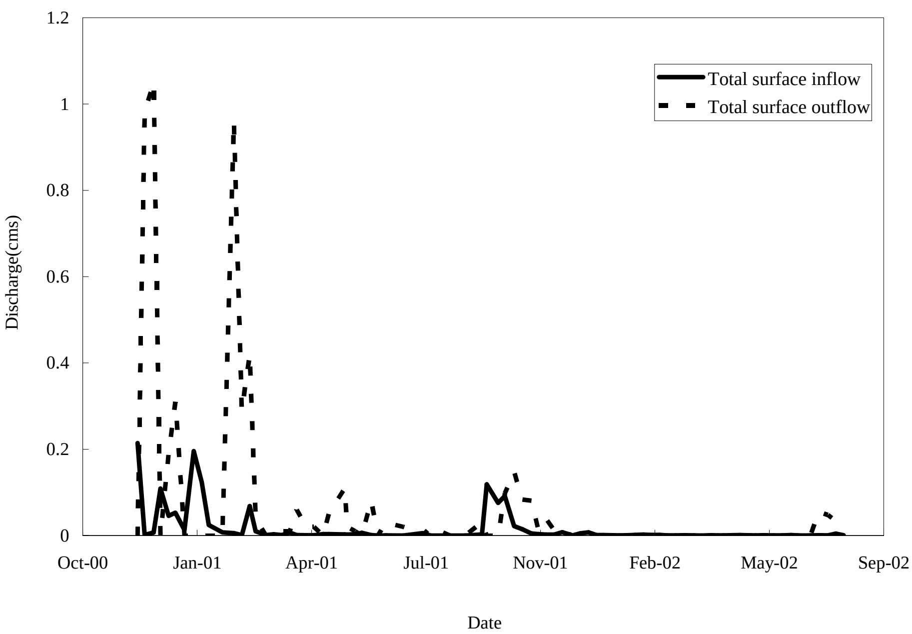

Figure 6. Surface water inflow and outflow of the pond

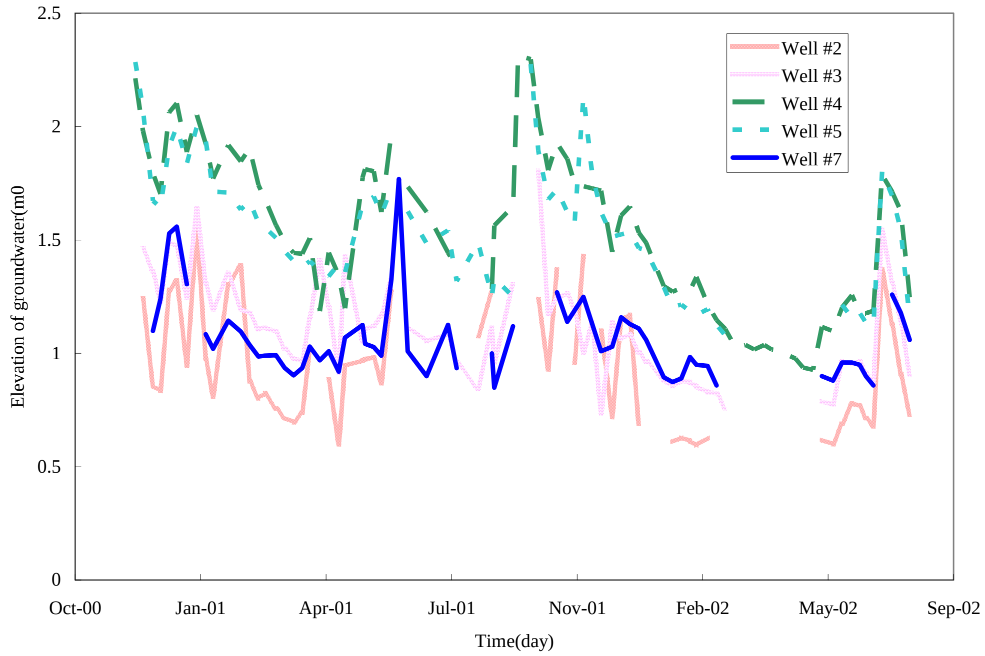

Figure 7. Groundwater elevation at Well#2 to #7

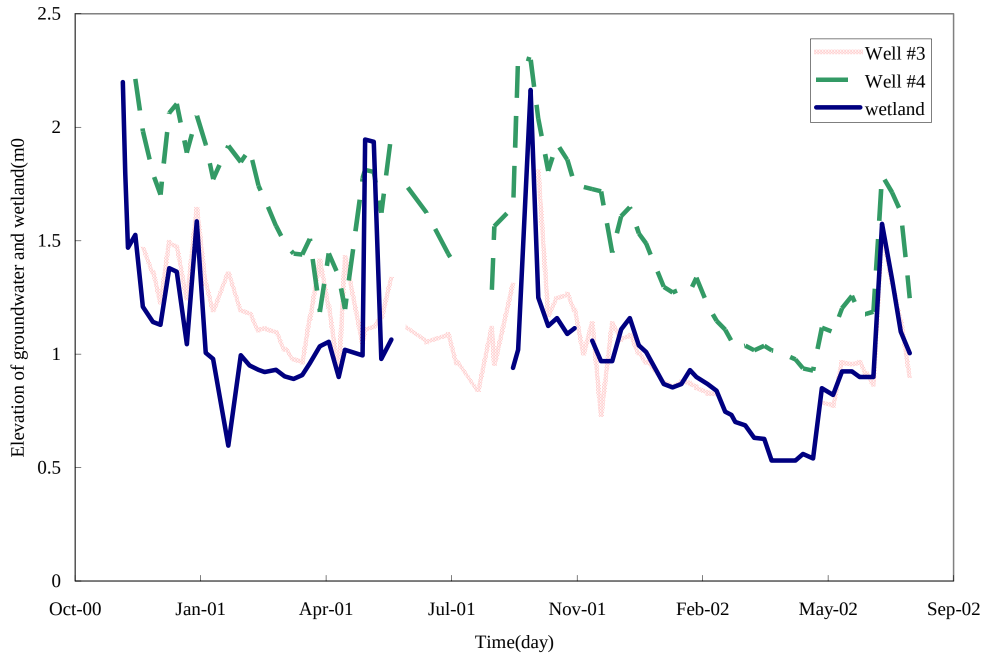

Figure 8. Water elevation at Well#3, Well#4, and the pond.

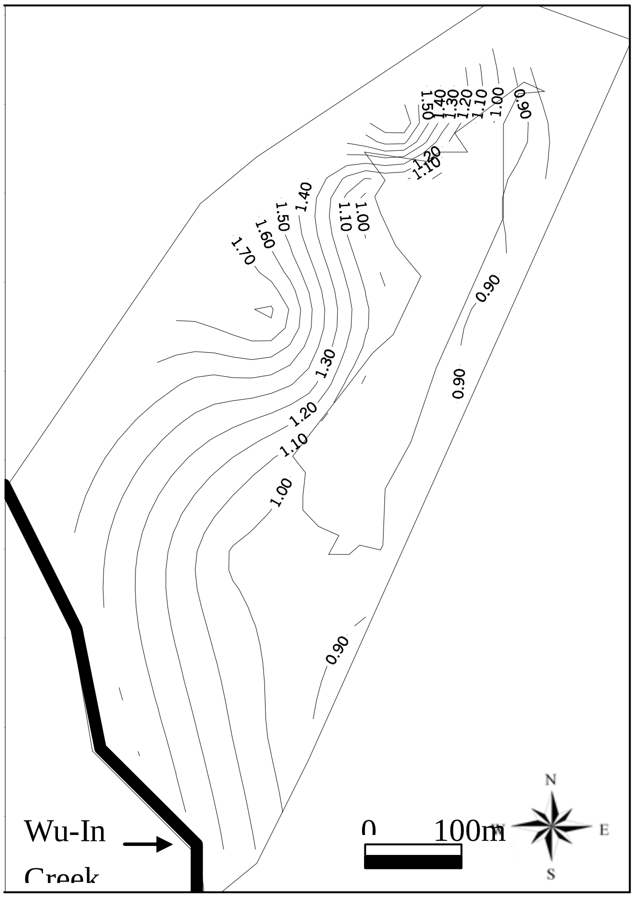

Figure 9. Groundwater level (m) on January 13, 2001

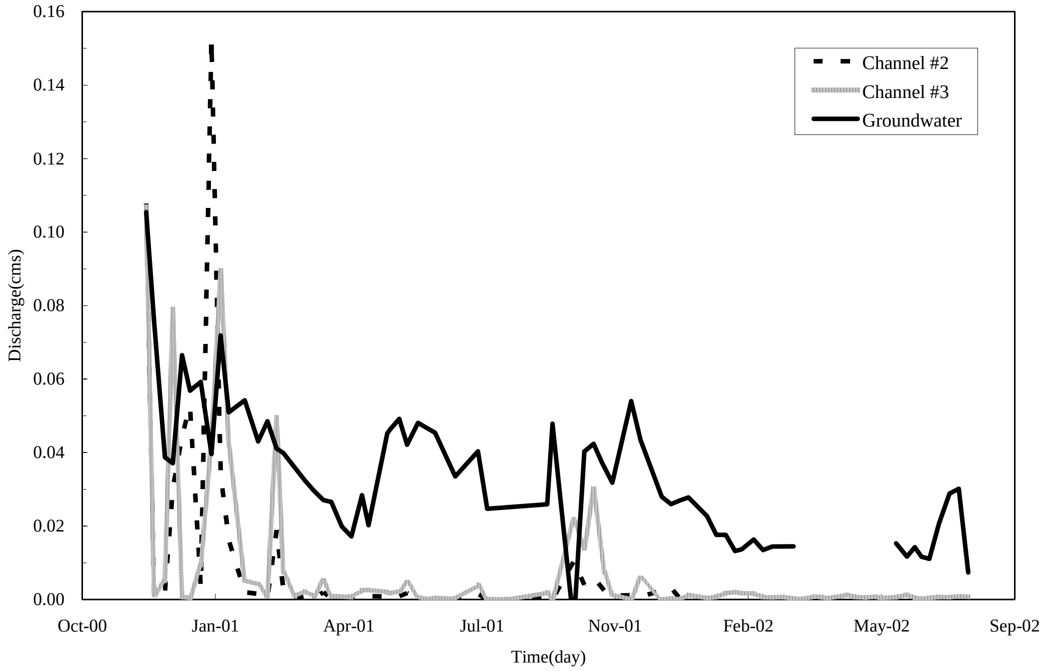

Figure 10. Discharge of Channel#2, Channel #3, and ground water

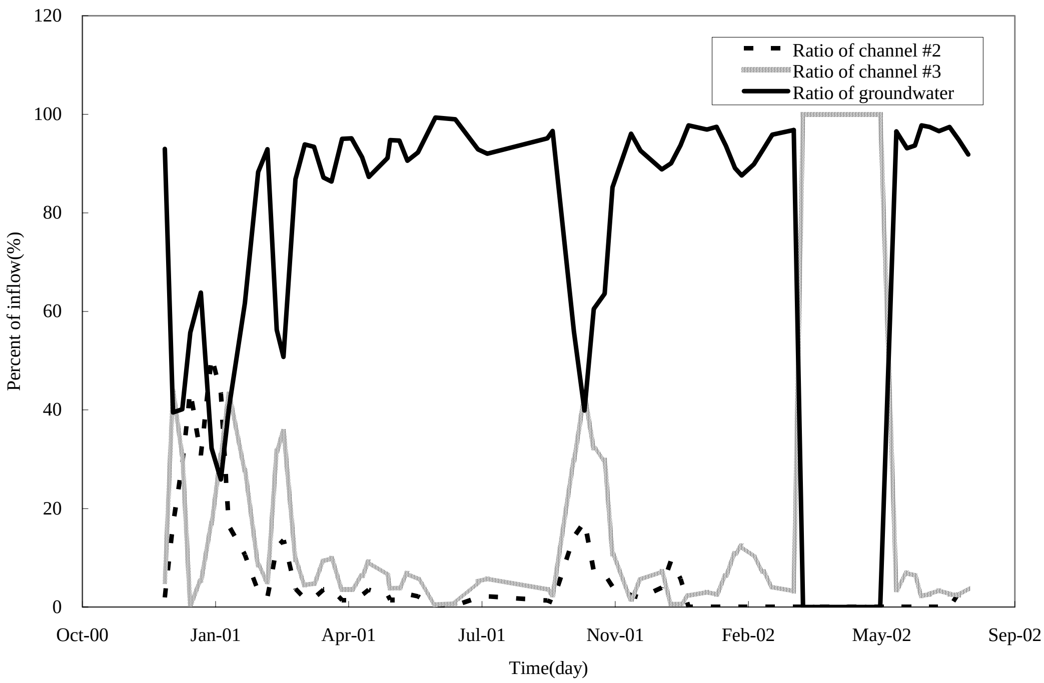

Figure 11. Inflow to the pond from Channel#2, Channel #3, and ground water

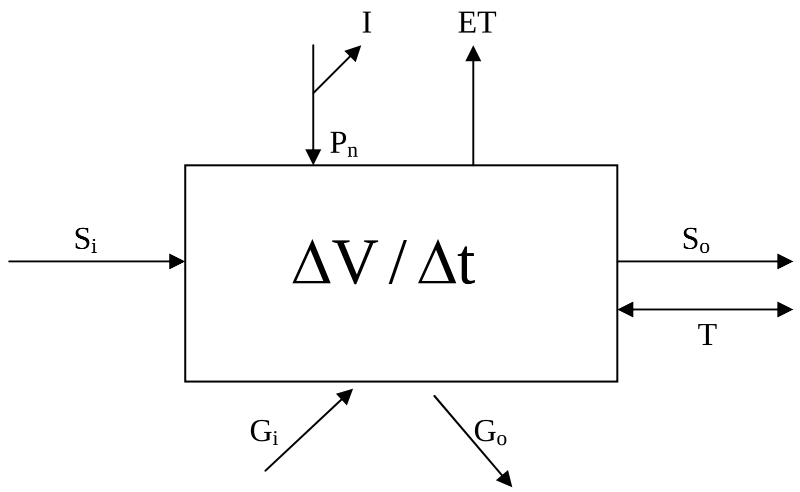

Figure 12. Water budget in the hydrological balance model for a wetland (Mitsch and Gosslink, 1993)

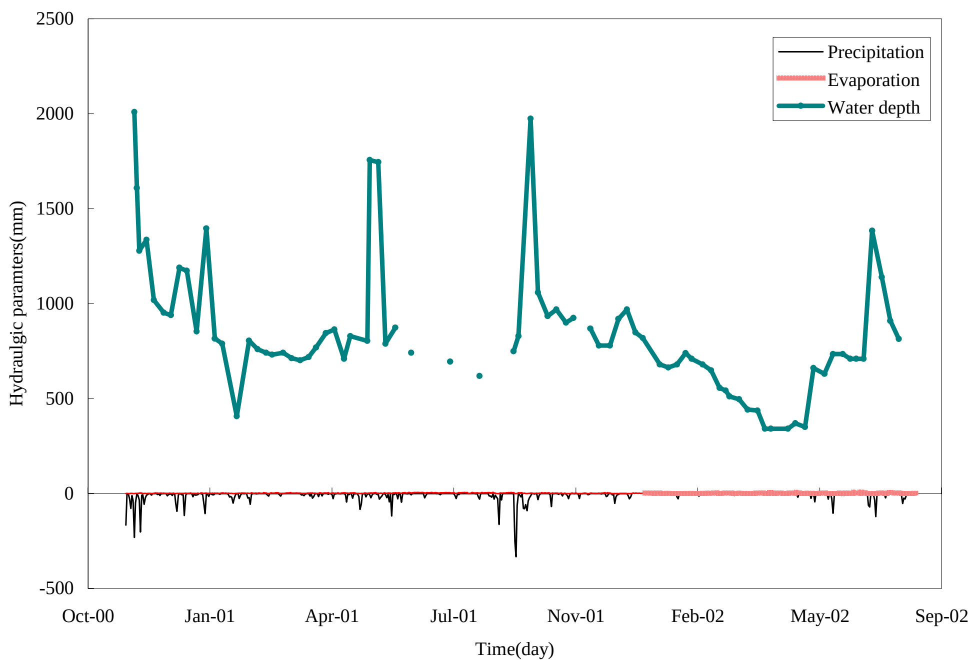

Figure 13. Water depth, precipitation, and evaporation at the wetland.

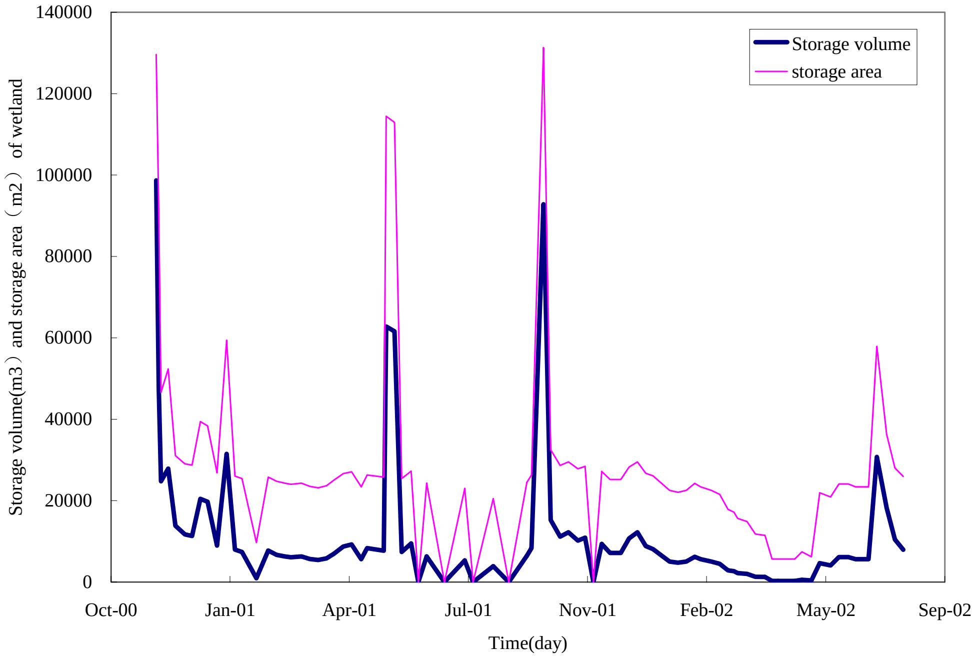

Figure 14. Water volume and storage area of the wetland

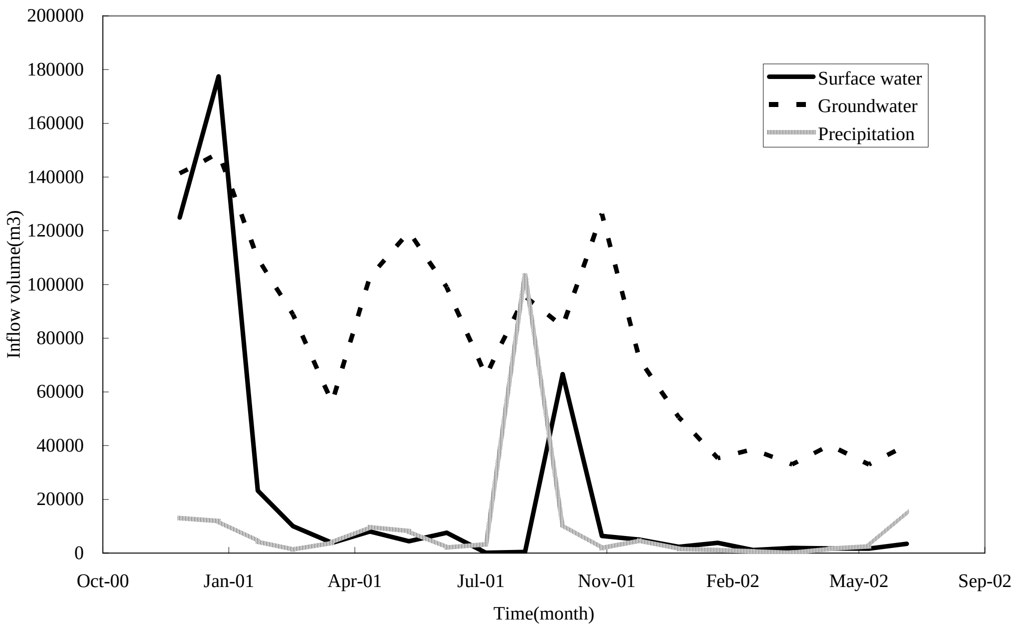

Figure 15. Inflow of the pond contributed from surface water, groundwater and precipitation.

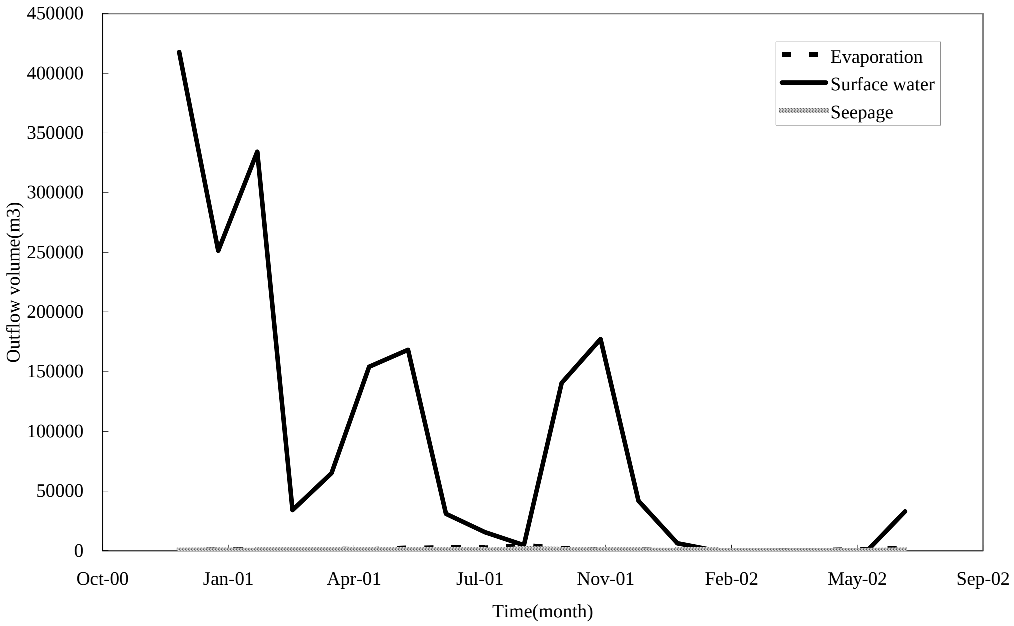

Figure 16. Outflow of the pond due to evaporation, surface water, and seepage.

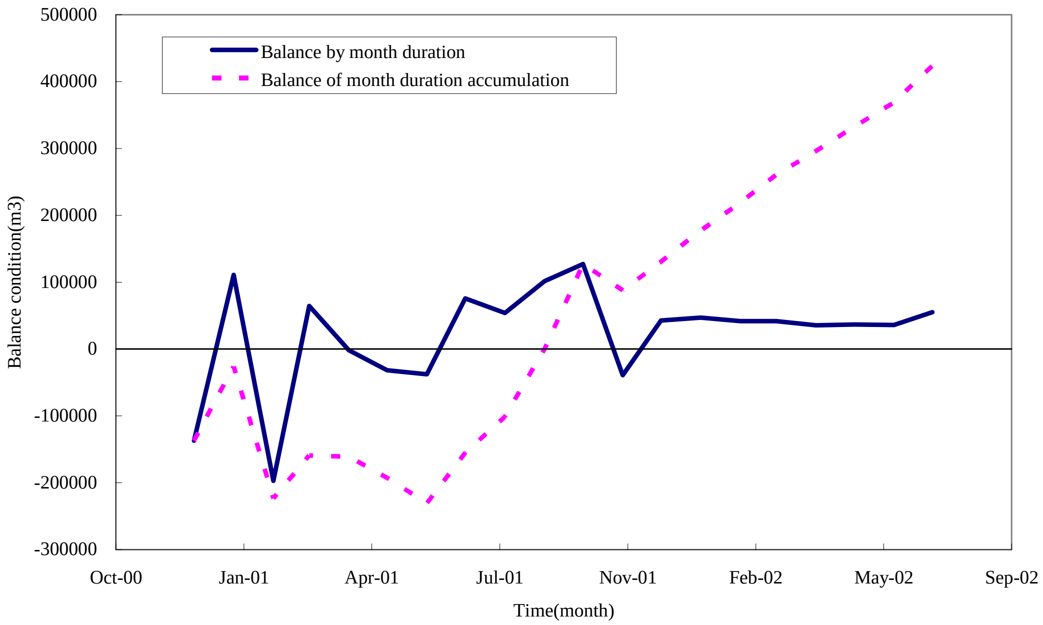

Figure 17. Shortage of the water balance in the pond