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Development and evaluation of wetland sustainability index for Binae Wetland, Korea

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ABSTRACT

Wetlands play a crucial role in maintaining human life and ecosystems. In order to conserve and manage wetlands in a quantitative way, their sustainability needs to be evaluated. With this background, this study assessed the sustainability of the Binae wetland, located along the Namhan River, Korea. More specifically, we developed a wetland sustainability index (WSI), taking into account water environments, hydrometeorological factors, and the plant and animal habitats in the wetland area. Sustainability of the Binae wetland was assessed based on the WSI, which showed favorable results in general. The wetland was expected to have high sustainability in water environments and hydrometeorological factors, a moderate or low sustainability for plant habitat, and very low sustainability for animal habitat. Therefore, it can be concluded that more attention and management efforts need to be paid to the wetland's animal habitats to make the region more sustainable.

Keywords: Binae Wetland; Wetland sustainability index; Wetland environments; Hydrometeorological factors; Plant and animal habitat

1. Introduction

Wetlands play many important roles in human lives and ecosystems, principally such as flood prevention, food provision, water purification, climate modification, maintaining biodiversity, and serving as places for leisure activities [1]. In addition, wetlands contain valuable ecological resources, which not only provide habitats for plants and animals but also benefit humans. With the recent growing concerns over global warming caused by climate change, wetlands are drawing more attention as current studies have demonstrated their capability to purify water and reduce greenhouse gases (i.e., they can serve as carbon sink). Wetlands are enormously complex mechanisms in terms of their functions that have diverse natural values, which is why they are considered environmentally important [2]. In Korea, since the 1970s, people started to recognize the importance of wetlands and develop positive views on them. Along with the growing international efforts to protect and sustainably use wetlands, Korea tries to conserve its wetlands and their biodiversity focusing on sustainable use by legislating the Wetlands Conservation Act. Also, there were many wetland researches in Korea such as wetland function and value evaluation [3–5]. Wetlands are

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one of the most endangered ecosystems around the world. It is important to understand that the stress on the wetland ecosystems has been intensified by the complex and cumulative effects of biogenic and anthropogenic causes including climate change. Schleupner et al. [6] pointed out that climatological and hydrological changes and land use are most responsible for the current state of wetlands and suggested a wetland sustainability index, based on which priorities for conserving wetlands were proposed. Being able to identify how wetlands evolve with time and determine whether they will be sustainable in the long run requires monitoring of the development, growth, and aging of wetland plants [7]. In particular, assessment of sustainability considering potential floods in forests near river bands in the spring season [8], estimation of the effects of management and restoration of arboretum wetlands on water quality [9], flood analysis, and water quality are considered main factors for sustainability of plant communities in wetlands. Sebastia-Frasquet et al. [10] addressed the issues of land use of western Mediterranean coastal areas and sustainability of coastal wetlands. Moreover, according to the data released at the World Wetlands Day 2015, sustainable use of water and wetlands could make a significant contribution to achieving sustainable social and economic development, adapting to climate change, and improving social cohesion and economic stability. The sustainable development goals, set by the United Nations General Assembly 2015, noted the importance of restoration and management of water resources and related ecosystems including wetlands to tackle the water scarcity crisis. In other words, using wetlands in a sustainable way is crucial and this entails the capability to evaluate whether their functions and ecosystems can be sustained in the long run. Although the need to assess sustainability of wetlands has been widely recognized, studies on wetland sustainability itself are scarce. With this background, this study aims to suggest a wetland sustainability index that can help predict future variability of a target wetland, which will be used to decide how to conserve, sustain, and manage it.

2. Wetland sustainability index

Sustainability generally refers to the ability to maintain a certain process and/or state. Now the term is mainly used in the context of biology and human life. From the ecological perspective, sustainability is defined as the ability of an ecosystem to maintain its reaction, functions, biodiversity and reproduction well into the future. With their hydraulic/hydrologic, topographic, meteorological, and ecological functions such as provision of water resources, flood control, serving as plant and animal habitats, water purification, and climate modification, wetlands provide enormous benefits to both human and environment. We evaluated to what extent the Binae wetland will be able to sustain its functions in the future by assessing its current state. However, in order to establish quantitative management measures of wetlands (e.g., to determine whether they are well managed, or they need urgent conservation efforts or functional improvement), not only their functions but also their future variability should be continuously monitored and assessed. Therefore, this study aims to suggest new assessment criteria of wetland sustainability index (WSI) as a tool to evaluate the potential variability of wetlands. The Ministry of Environment (MOE) [11] concluded that hydraulic and hydrologic conditions of water environment (e.g., water quality); topography and soil element; weather and climate change; and plant/animal habitat are four main factors that drive change in wetlands. Other studies also suggested climate, hydrology, and land use mainly affect the sustainability of wetlands [6].

3. Target wetland

The Binae wetland, located in the mainstream of the Namhan River in Chungju-si, Chungcheongbuk-to Province, consists of a river island. About 29 km away downstream from the Chungju Dam, the wetland spreads over 700,000 m^2. It went through a restoration process from 2007 to 2012 as part of the Four Major Rivers Project conducted by the Korean government, with the aim that a variety of plants could take root in the area. Therefore, we chose the Binae wetland as our study site because it represents the plant habitat conditions of the Han River mainstream and it was also considered appropriate to analyse the trend of future variability of a newly restored wetland (Fig. 1).

4. Factors of the WSI

Four major factors that are known to affect wetlands include water environment, topography and soil, weather and climate, and plant and animal habitat [11]. We sorted through all the factors to decide, which ones will be applied to the development of the WSI. It was found that monitoring data related to water environment, weather and climate, and plant and animal habitat of the Binae wetland had been accumulated for several years and their future values can be simulated via modeling, while there had been only 1 y of monitoring data for the wetland's topography and soil, and this short monitoring period makes it difficult to simulate future values. Based on these considerations, the three factors of water environment; weather and climate; and plant and animal habitat were selected to assess the sustainability of the wetland, and each factor was set according to the corresponding criteria by the MOE. The level of sustainability for each factor was scored as 0 (no possibility), 1 (moderate possibility or expected to remain in the current state), and 2 (sufficient possibility). The calculated factors were weighted and combined to derive the comprehensive wetland sustainability index.

4.1. Water environment

In this study, inundation depth, water quality, and flow velocity were considered in terms of water environment. However, flow velocity will be discussed later in the Plant and Animal Habitat section since it is also related with fish habitat.

4.1.1. Inundation depth

Inundation depth (ID) is an important parameter to see whether a wetland will be sustainable or not. Plants

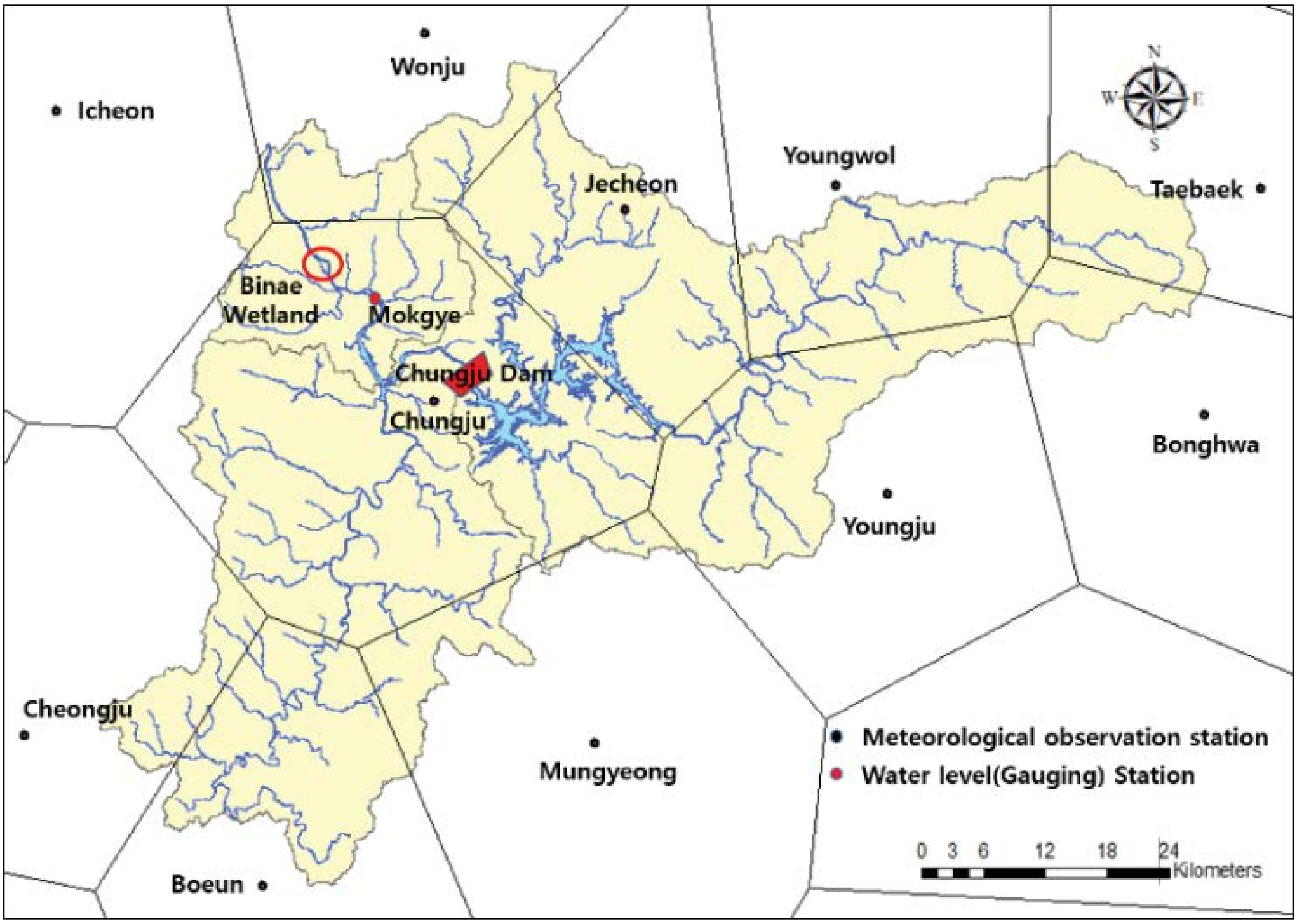

Fig. 1. Map of the Binae wetland.

and fish are largely affected by the inundation depth. Only plants were used when evaluating the sustainability of the inundation depth because fish do not live inside Binae wetland. In particular, as the sustainability of plants is highly dependent on inundation depth, ID of the plant habitats need to be assessed. Kim [12] analyzed that the Binae wetland has dynamic vegetation communities and the inundation depth should be no higher than 0.8 m in order for the plants to survive. This indicates that ID of 0.8 m or less makes the wetland highly sustainable in terms of water environment. Moreover, the Ministry of Land, Infrastructure and Transport [13] defined the ID limit as 2 m. Therefore, 0.8 m < ID ≤ 2 m refers to moderate sustainability because the wetland can still be sustainable although it is uninhabitable for plants. If ID is over 2 m, the wetland is considered unsustainable. And then if it has no inundation, wetland plants cannot live. So if it is not flooded, the wetland is also considered unsustainable (Table 1).

Table 1
Criteria of sustainability related to inundation depth

Parameter	Criteria	Scores
Inundation depth (ID)	ID ≤ 0.8 m	2
	0.8 < ID ≤ 2 m	1
	No inundation or ID > 2 m	0

4.1.2. Water quality

Out of many water quality related parameters, BOD was chosen for this study since it can be quantitatively assessed. Given the fact that fish species are classified according to the BOD levels, the fish that live in the Binae wetland can be seen as an indicator of the wetland's sustainability in terms of water quality. It was estimated that about 89% of the fish species in Korea, except some such as *Rhodeus notatus*, carp, and *Acanthorhodeus macropterus*, known as highly resistant to organic pollutants, live in water with a BOD level of 0–2 ppm. This means fish are particularly sensitive to BOD among other water quality parameters and most species inhabit water with a BOD ≤ 2 ppm [14]. The monitoring results showed that the average BOD of the Binae wetland was 1.9 ppm and the fish inhabiting there were indicator species of the second grade or lower water quality (BOD ≤ 3 ppm). Overall, it can be seen that BOD ≤ 2 ppm is a criterion for the wetland to be sustainable. If BOD rises to over 3 ppm, the wetland will be hardly sustainable because the fish species will not be able to survive in the polluted water (Table 2).

4.2. Hydrometeorological factors

Since 2012, the water levels have been measured once per season in Binae wetland but there are no data on infiltration or subsurface runoff. Therefore, it is difficult to evaluate the hydrological sustainability of the wetlands of Binae wetland. To overcome these limitations, precipitation and evaporation were considered in this study for the wetland sustainability assessment in terms of HF. MOE [11] defined that precipitation, temperature, humidity, insolation, cloud cover, and wind velocity are main HF parameters that affect wetland variability. We decided that precipitation and evapotranspiration can serve as good hydrometeorological indicators of wetland sustainability. When it comes to wetlands, a certain amount of water must be retained across the area all the time. According to a water balance equation, water inflows and outflows are calculated by measuring precipitation and stream flows, and the difference between inflow and outflow is referred to as evapotranspiration for a certain long-term period (e.g., a season) [15]. In other words, stream flow equals the difference between precipitation and actual evapotranspiration A positive difference indicates that the wetland is more likely to be sustainable, while a negative difference means the opposite (Tables 3 and 4). Even if precipitation minus evapotranspiration is greater than 0, the score is 0 when the inundation depth exceeds 2 m, and the score is 1 when the inundation depth is between 0.8 and 2 m.

Table 2
Criteria of sustainability related to water quality

Parameter	Criteria	Scores
Water quality (WQ)	BOD ≤ 2 ppm	2
	2 ppm < BOD ≤ 3 ppm	1
	BOD > 3 ppm	0

Table 3
Criteria of sustainability related to precipitation

Parameter	Criteria	Scores
Precipitation (PR)	PR – ET > 0, PR > Reference	2
	PR – ET > 0, P < Reference	1
	PR – ET < 0	0

Table 4
Criteria of sustainability related to evapotranspiration

Parameter	Criteria	Scores
Evapotranspiration (ET)	PR – ET > 0, ET < Reference	2
	PR – ET > 0, ET > Reference	1
	PR – ET < 0	0

4.3. Plant and animal habitat

We considered plant habitat and animal (fish) habitat separately in assessing the wetland sustainability in terms of plant and animal habitat.

4.3.1. Plant habitat

Sustainable wetlands require sustainable wetland plants. If the plant habitat is stable, the species will become more diverse, whereas disturbance of the habitat could damage the plant communities, resulting in increased bare ground. Evaluation of plant habitat entails analysis on how the plants evolve in the wetland environment. In particular, whether the wetland vegetation (both submerged and emergent) has increased or decreased should be evaluated because it has a huge impact on the stability of the plant habitat. In order for a wetland to be sustainable, the plants that live there should prosper. Therefore, we concluded that an increase in the wetland vegetation indicates high sustainability and decreased vegetation implies no sustainability (Table 5).

4.3.2. Animal habitat

This study considered fish as an indicator of the wetland sustainability with respect to animal habitat. The advantage of monitoring fish is that the quantitative assessment of parameters affecting their habitats can be conducted easily compared with other animal groups. Kang [16] suggested that water depth (WD) and flow velocity (FV) are the most important parameters for fish habitats because the habitat suitability index (HSI) for fish is estimated based on the two parameters. Following this guideline, we used water depth and flow velocity as the key parameters to assess the sustainability of the wetland's animal habitat. It was also important to select a representative species for the assessment. Dominant species in the Binae wetland include *Tridentiger brevispinis*, *Zacco platypus*, *Pungtungia herzi*, *Acheilognathus yamatsute* MORI, and *Rhinogobius brunneus*. In addition, an important protected species of *Gobiobotia macrocephala* was found to inhabit this area. MOE [11] also mentioned that more attention needs to be paid to endangered and protected species from a sustainability perspective. In this regard, we chose *Gobiobotia macrocephala* as the representative species for this study with the understanding that its sustainability will help keep the wetland more sustainable. Moreover, the HSI for fish developed by

Table 5
Criteria of sustainability related to plant habitat

Parameter	Criteria	Scores
Plant habitat (PH)	Increase in wetland vegetation	2
	Constant level of wetland vegetation	1
	Decrease in wetland vegetation	0

Kang [16] was also used in assessing the sustainability of the Binae wetland. The HSI was derived for each species by water depth and flow velocity, based on monitoring measurements of fish species (including endangered ones) that lived in the Han River and Geum River water systems. The HSI for *Gobiobotia macrocephala* is illustrated in Fig. 2. Lee et al. [17] defined HSI of 0.5 as the baseline to determine whether a habitat of interest is suitable for habitation. Therefore, we suggest that *Gobiobotia macrocephala* shows the highest sustainability at the water depths (WDs) and flow velocities (FVs) with HSI of 1, moderate sustainability at the WDs and FVs with HSI ranging from 0.5 to 1, and no sustainability at the WDs and FVs with HIS < 0.5 (Table 6).

5. Development of the WSI

For a statistical prediction of the future, a relatively short period of about 10 y is considered appropriate to produce reliable results [18–20]. With this in mind, we estimated the WSI of the Binae wetland for the year of 2024, 10 y after 2014 when the monitoring started.

5.1. WSI for water environment

5.1.1. Inundation depth

The SLURP (semi-distributed land use-based runoff processes) and HEC-RAS models were used to make hydrologic analysis considering effects of climate change. For the SLURP model, it can be applied to both watersheds and river basins [21], and it is also known to be appropriate to evaluate the hydrological behavior in wetlands using climate change scenarios. HEC-RAS is one of the most commonly used models to predict water depth. These explain why this study relied on the two models to conduct the hydrologic analysis.

In this study, the runoff of the Binae wetland was simulated by applying the meteorological data of 11 meteorological stations (Fig. 1) and topographic data to SLURP model. It is difficult to calibrate using the runoff data of Binae wetland due to the lack of runoff data. So, calibration and validation were performed using the runoff data of Mokgye gauging station near the Binae wetland. According to a study by Ladson [22], the model can be used if NSE

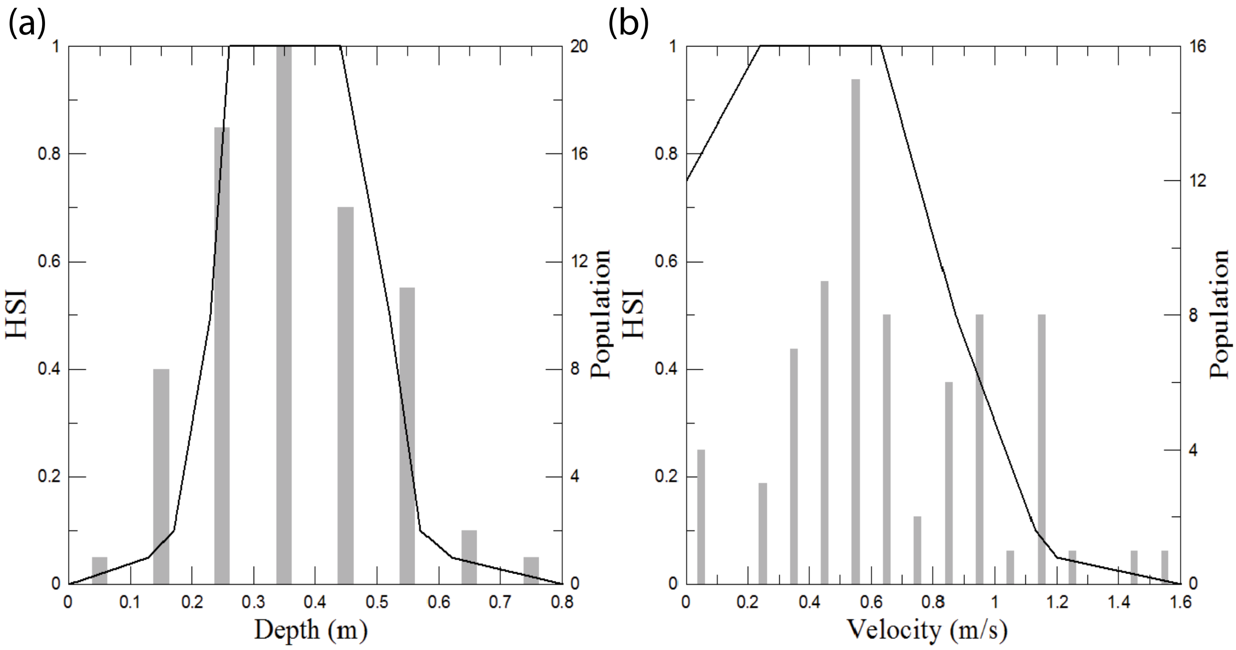

Fig. 2. Habitat sustainability index for *Gobiobotia macrocephala* (Kang, 2010): (a) water depth and (b) flow velocity.

Table 6
Criteria of sustainability related to animal habitat

Parameter			Criteria	Scores
Animal (Fish) habitat)	*Gobiobotia macrocephala*	FV	0.25–0.63 m/s	2
			0–0.25 m/s or 0.63–0.86 m/s	1
			>0.86 m/s	0
		WD	0.25–0.43 m	2
			0.22–0.25 m or 0.43–0.51 m	1
			Rest	0

(Nash–Sutcliffe efficiency) is above 0.6 when model is calibrated and above 0.3 when model is validated. Therefore, it is determined that the SLURP model in this study is usable (Table 7).

The HEC-RAS model was used to simulate the inundation depth of Binae wetland. To simulate the inundation depth of future, the impact of the 'Four Major Rivers Project' must be considered. The cross section of river around the Binae wetland was constructed from the data of the Han river master plan (Supplementary) (Paldang dam – Chungju dam) report [23]. This report is a supplementary report taking into account the changed riverbed due to 'Four Major Rivers Project'. In this study, HEC-RAS model was calibrated using the data of inlet and outlet of river. HEC-RAS model is considered reliable because the correlation between the simulated and observed values is high and the RMSE (relative root mean square error) is small (Table 8).

The modeling of inundation depth of the Binae wetland predicted the average inundation depth would be 0.346 in 2024. This results in WSI of 2 for inundation depth, according to the criteria in Table 1.

5.1.2. Water quality

An artificial neural network (ANN) was used in predicting water quality of the Binae wetland. Globally, there have been a number of studies on water quality prediction using ANNs [24–27] and some researchers also suggest that ANN-based water quality prediction produces more accurate results than the multiple regression analysis does [26]. We predicted BOD of the Binae wetland for 2024 using ANN-based modeling. The accuracy of the ANN was evaluated by statistical analysis of the predicted BOD from 1997 to 2014 and the observed BOD of the same period. As a result of evaluating the accuracy of the ANN, the Pearson correlation coefficient increased from 0.371 to 0.642 and the model efficiency increased from 0.0794 to 0.4821. It can be seen that the accuracy of the ANN has improved (Table 9).

The result was that BOD would range from 0.849 ppm (June) to 1.254 ppm (April) (Fig. 3). With the prediction of BOD < 2 ppm all year round in 2024, WSI for water quality can be estimated as 2, implying that the current fish species (endangered ones included) inhabiting the Binae wetland are expected to be highly sustainable.

5.2. WSI for hydrometeorological factors

The analysis of the wetland's precipitation using the SLURP model showed that the average precipitation was 900.45 mm in 2014 and would be 1,047.8 mm in 2024 (Fig. 4).

Evapotranspiration was calculated via the widely used Penman–Monteith method. Penman developed the Penman equation by combining the energy balance with evaporation parameters including wind that affects evapotranspiration. Many of the evapotranspiration related equations stemmed from this equation and then were further modified and developed. The original Penman equation, however, does not consider aerodynamic resistance and vapor transport related surface resistance. Now the Penman–Monteith equation that reflects these factors are most

Table 8
Calibrated result of HEC-RAS

	Inlet	Outlet
Simulated water level (EL.m)	47.74	45.89
Observed water level (EL.m)	48.62	46.14
Correlation coefficient	0.998	
RMSE	0.65	

Table 7
Calibrated and validated result of SLURP

	Calibration		Validation	
	Before calibration	After calibration		
Period (Year)	2011–2012		2015	2017
Simulated average daily runoff (m^3/s)	251.58	312.77	38.2	121.25
Observed average daily runoff (m^3/s)	323.56		39.7	158.48
Mean error	–71.982	–10.789	–5.482	–14.421
Mean error/observed average daily runoff	–0.22	–0.03	–0.14	–0.09
NSE	0.36	0.62	0.67	0.54

Table 9
Calibrated result of ANN

	Pearson correlation coefficient	Mean error	Mean absolute error	Root mean square error	Relative root mean square error	Model efficiency
Before calibration	0.371	0.0362	0.357	0.547	48.432	0.0794
After calibration	0.642	0.0163	0.307	0.414	34.927	0.4821

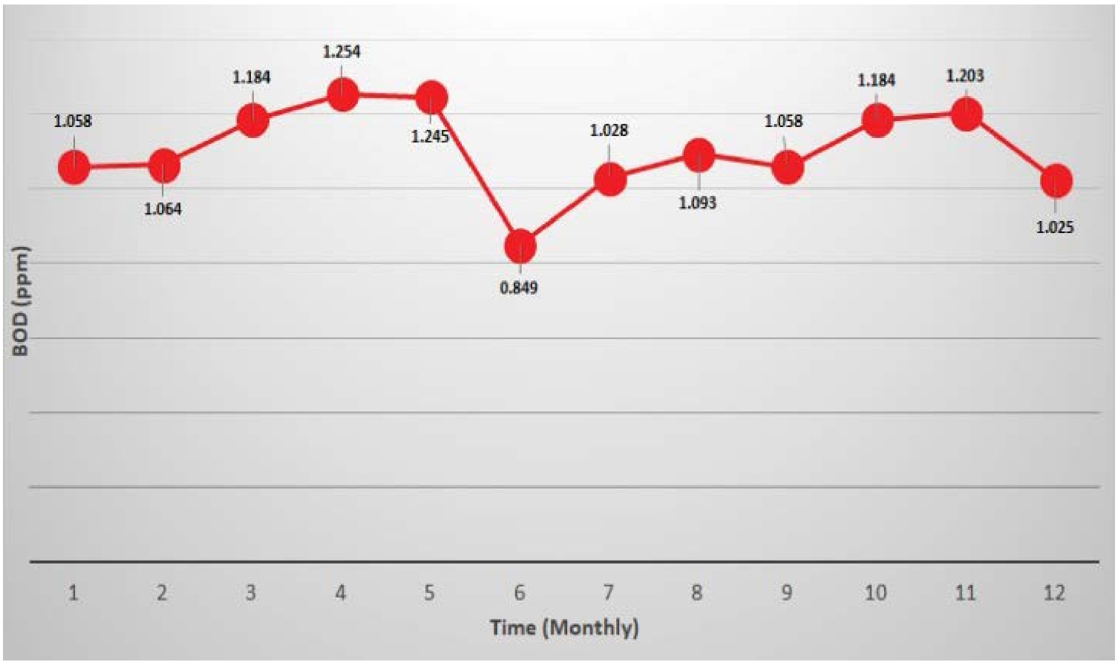

Fig. 3. BOD of the Binae wetland (for the year 2024).

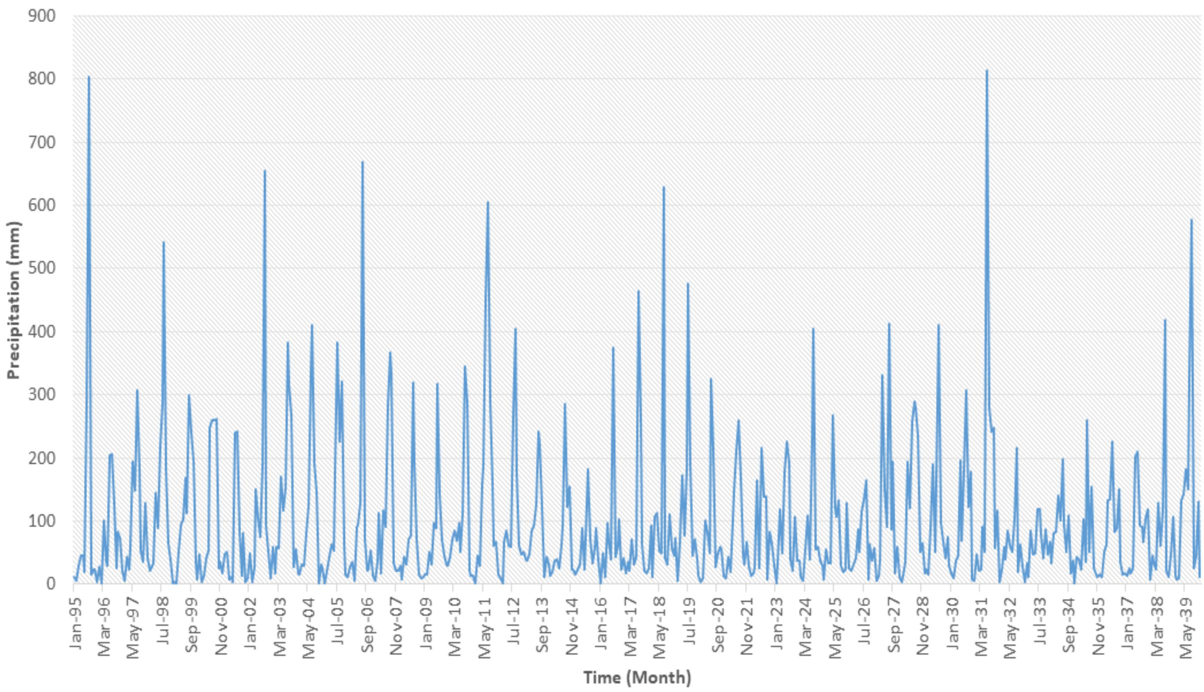

Fig. 4. Precipitation of the Binae wetland.

widely used not only in research but also in real-world applications [15]. Thus, this study employed the method that calculates evapotranspiration using the Penman–Monteith equation [15]. Potential evapotranspiration does not explain the hydration level of plants and soil. Potential evapotranspiration refers to evapotranspiration when there is no limit on the amount of water, which is why potential evapotranspiration is generally estimated larger than the actual value. To estimate actual evapotranspiration, we used a crop coefficient, which depends on crop type, meteorological conditions, and region. In real-world application, actual evapotranspiration is usually calculated by multiplying the potential evapotranspiration by a crop coefficient of 0.7 [15]. Our estimation result was that the actual evapotranspiration was 654.1 and 648.3 mm in 2012 and 2024, respectively (Fig. 5).

The difference between the precipitation and actual evapotranspiration simulated for the year 2024 is (+) 399.5 mm, which implies that if no external factors are involved, the Binae wetland will have a sustainable water balance. In addition, the expectation that the wetland's precipitation will increase and evapotranspiration decrease in 2024 compared against the baseline year of 2014 also means the water balance will consistently be stable. In 2024, the average inundation depth is 0.346 (see Inundation depth section). So, the inundation depth did not exceed 2 m. Combining the results above, we obtain a WSI of 2 for both precipitation and evapotranspiration.

5.3. WSI for plant and animal habitat

5.3.1. Plant habitat

The simulation of the plant habitat in the Binae wetland shows that the vegetation area is expected to take up 97.64% of the total area (bare ground excluded), a similar level of 97.65% in 2014. The communities of *Miscanthus sacchariflorus* and *Phragmites japonica* Steud., both of which are aquatic plants, were also simulated to remain at the similar levels for the 10-y period from 2014 to 2024 (Table 10). We suggest that this consistency of the wetland vegetation can be attributable to the assumption the inundation frequency driven by variation in water depth is stable for the simulation period. With the prediction of the constant vegetation area, the WSI for plant habitat can be scored as 1.

5.3.2. Animal (fish) habitat

Our understanding is that the wet season with increased precipitation raises the water flow in the Binae wetland, which makes it harder for *Gobiobotia macrocephala* to live in, and during the seasons with the normal flow, the wetland is considered habitable but not favorable for the fish. On the other hand, in the dry season, the flow velocity becomes favorable for the representative species. Collectively, it can be estimated that the average flow velocity in the Binae wetland will be 0.73 m/s in 2024, based on which the WSI for FV is 1. From the wet to dry seasons, the average water depth was estimated too high for *Gobiobotia macrocephala* to live in. Although there are a few areas with water depths of 0.25–0.43 m, a favorable condition for their inhabitation, the overall water depth of the wetland is expected to become unsustainable for the species and thereby the WSI for water depth is scored as 0.

5.4. WSI of the Binae wetland

Estimation of a sustainability index requires determination of weights for assessment indicators. Weighting methods can be broadly divided into two categories: (1) ordinal

Table 10
Areas of aquatic plant communities in the Binae wetland (%)

Community	2014	2024
Miscanthus sacchariflorus	24.79	24.83
Phragmites japonica Steud.	14.41	14.44

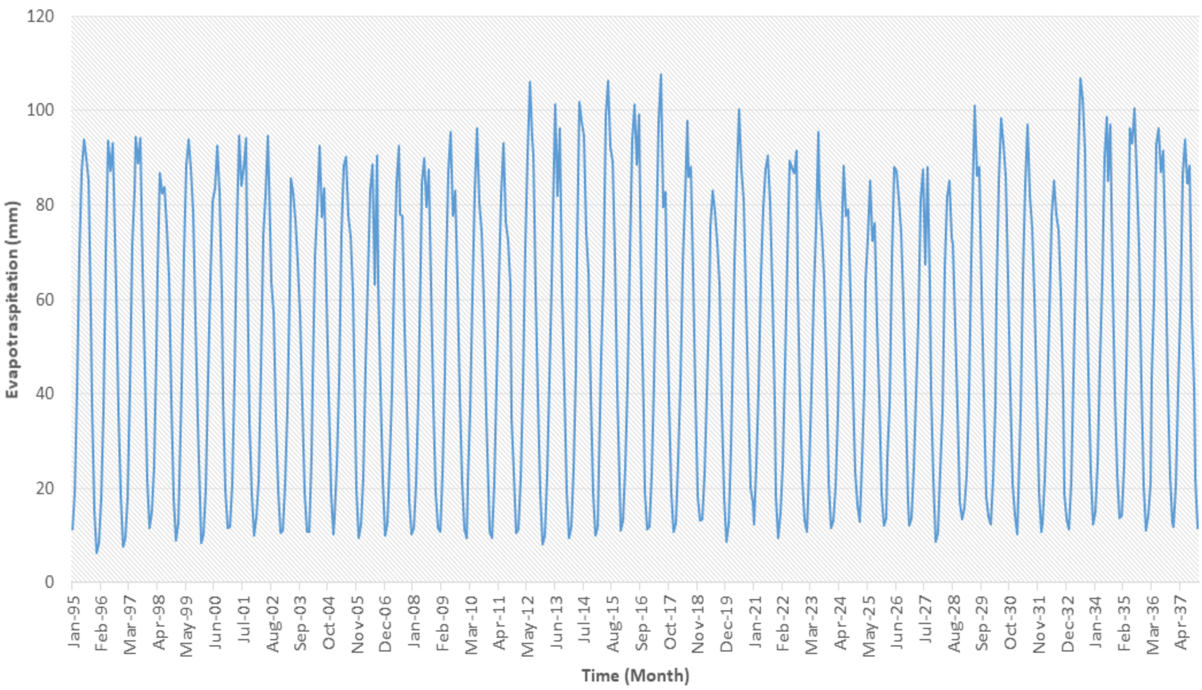

Fig. 5. Actual evapotranspiration of the Binae wetland.

comparison-based approaches such as matrix evaluation, three-grade evaluation, and raking; and (2) cardinal comparison-based approaches including the eigen vector method, weighted least squares method, and entropy method. In particular, the analytical hierarchy process (AHP) is widely used in determining weights of assessment indicators as it provides relatively high objectivity and consistency; easy application processes; and the theoretical foundation for weight calculation [28]. Thus, this study also used the AHP to determine a weight, or a relative importance, of each assessment parameter. To do this, a hierarchical structure of the AHP was established in the process as follows: first, listing the important elements through brainstorming; second, identifying redundant areas; and third, grouping common elements. The hierarchical AHP structure comprises three tiers as depicted in Fig. 6. The priority of each tier is determined according to the responses to a pairwise comparison questionnaire. For this study, 35 researchers with a master's degree or higher in hydrology, meteorology, or ecology participated in the questionnaire survey. For the AHP-based group decision making, typically two approaches are used.

The first approach is the aggregation of individual judgments (AIJ), where the priority vectors of a group are derived by creating pairwise comparison matrices based on the geometric means of individual matrices. The other approach is called the aggregation of individual priorities that first produces the priority vectors for individual respondents and then estimates the priority vectors of the group by obtaining the weighted arithmetic means of the individual priority vectors. AIJ is used when empirical data and preceding studies about decision making are not sufficient or when a group of non-experts with less information make decision, while AIP is more appropriate when the opinions of individual evaluators are reflected in the group decision making. However, AIP has a limitation that individual deviations affect the weights because the determination considers the final priority vectors only. Use of geometric means is recommended to achieve more sophisticated group decision making [29].

But each of the approaches still needs further studies to be proven reliable. This study adopted AIJ to estimate the weights considering the fact that this approach maintains better consistency when comparing a large number of matrices and calculates the geometric means of the respondents' judgment matrices from a technical perspective. In the AHP method, consistency verification is required prior to the determination of the weights. A consistency ratio of over 0.1 implies that the questionnaire survey is unreliable. In such a case, the questionnaire should be reviewed through feedback. In this way, the weights of the parameters were calculated as described in Table 11.

WSI was calculated considering the score and weight of each parameter. The equation for WSI of the Binae wetland is expressed as Eq. (1).

$$\text{WSI} = \sum Z_i \times W_i = 0.390\text{WE} + 0.283\text{HF} + 0.326\text{P} \quad (1)$$

The Tier 1 parameters of water environment (WE), Hydrometeorological factors (HF), and plant and animal

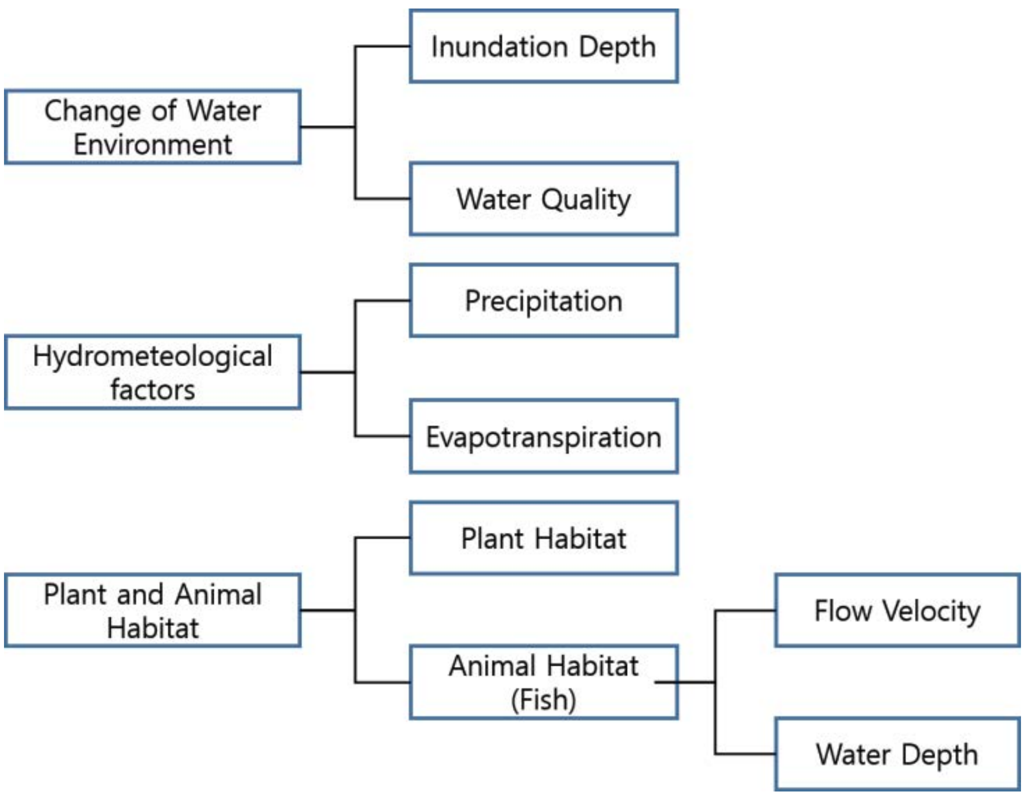

Fig. 6. Hierarchy of parameter for weighting.

Table 11
Weighting results

Tier 1	Tier 2	Tier 3	Weights	Composite weights
Water environment			0.390	
	Inundation depth		0.558	**0.218**
	Water quality		0.442	**0.173**
Hydrometeorological factors			0.283	
	Precipitation		0.554	**0.157**
	Evapotranspiration		0.446	**0.126**
Plant and animal habitat			0.326	
	Plant habitat		0.564	**0.184**
	Animal (fish) habitat		0.436	0.142
		Flow velocity	0.522	**0.074**
		Water depth	0.478	**0.068**

Table 12
WSI of the Binae wetland for the year 2024

Tier 1	Tier 2	Tier 3	Scores	Composite weights	Weighed score
Water environment					
	Inundation depth		2	**0.218**	
	Water quality		2	**0.173**	
Hydrometeorological factors					
	Precipitation		2	**0.157**	
	Evapotranspiration		2	**0.126**	**1.674**
Plant and animal habitat					
	Plant habitat		1	**0.184**	
	Animal (fish) habitat				
		Flow velocity	1	**0.074**	
		Water depth	0	**0.068**	

habitat (PA) are calculated by the standardized values and weights of Tier 2 parameters as shown in Eqs. (2)–(4).

$$\text{WE} = 0.558\text{ID} + 0.442\text{WQ} \quad (2)$$

$$\text{HF} = 0.554\text{PR} + 0.446\text{ET} \quad (3)$$

$$\text{PA} = 0.564\text{PH} + 0.436\text{AH} \quad (4)$$

Now, the Tier 2 parameters of animal habitat (AH) are estimated using the standardized values and weights of Tier 3 parameters as expressed in Eq. (5).

$$\text{AH} = 0.522\text{FV} + 0.478\text{WD} \quad (5)$$

Combining all of them above leads to the final WSI equation as written in Eq. (6),

$$\text{WSI} = 0.218\text{ID} + 0.173\text{WQ} + 0.157\text{PR} + 0.126\text{ET} + 0.184\text{PH} + 0.074\text{FV} + 0.068\text{WD} \quad (6)$$

where ID, WQ, PR, ET, PH, FV, and WD mean inundation depth, water quality, precipitation, evapotranspiration, plant habitat, flow velocity and water depth, respectively. According to the last equation, WSI of the Binae wetland is calculated as 1.647 (Table 12), which implies that the wetland is highly likely to be sustainable in the future.

6. Discussion and conclusion

In order to quantitatively evaluate the variability of wetlands and determine whether they can be sustainable in the future, this study aims to suggest a new assessment tool called the WSI. To make a WSI, we set out three major factors such as water environment; change of hydrometeorological factors; and plant/animal habitat.

From the water environment perspective, it was predicted that the Binae wetland has high sustainability as its inundation depth is expected to remain lower than 0.8 m and BOD under 2 ppm.

In terms of hydrometeorological factors, the difference between precipitation and actual evapotranspiration was simulated as positive (+) with the prediction of an increase in precipitation and a decrease in evapotranspiration. Therefore, it is reasonable to conclude that the wetland will be highly sustainable if no external factors are involved, and the water balance will remain favorable.

The evaluation of the wetland's plant habitat showed relatively constant inundation depth and period for the 10–y period (2014–2024), implying that the vegetation will also remain at the similar level. This indicates moderate sustainability. For animal (fish) habitat, it was predicted that both flow velocity and water depth will become unfavorable for the protected fish species to live in the future, leaving the relevant index at 0, or no sustainability.

A weight for each of the factors discussed above was determined, based on which the total WSI of the Binae wetland was estimated as 1.674. Therefore, it can be concluded that the Binae wetland has high sustainability.

With the growing recognition around the world of the importance of protection and sustainable use of wetland resources, we believe that this study is timely and meaningful in that it suggests a tool to evaluate sustainability of wetlands, that is, to determine whether their functions will be sustainable in the long run. The results are expected to be used as baseline data in other sustainability-related studies. However, in order to produce more reliable prospect for sustainability of wetlands, continuous monitoring of the hydrologic, meteorological, and ecological parameters should be conducted and data on topography and soil also need to be obtained in the future.

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