Introduction to Environmental Modeling

Assessment 3

Assessing the Impact of Water Abstraction on a Scottish Marsh

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Contents

1 Introduction

1.1 Background

Wetlands are of high ecological importance globally as they provide a variety services such as filtering water, biodiversity, flood control, and climate change mitigation, yet globally they are declining as the water is abstracted for other uses and pollution discharged into it. The Ramsar Convention on Wetlands (1976) contracts the sustainable use and management of wetlands of all signing parties (RAMSAR 2014). As signatory Scotland has 51 Ramsar sites, with 393,000 hectares designated as important wetlands (NatureScot 2020). Most of Scottish wetlands have disappeared, now largely confined to the Highlands and Hebrides, as shown in Figure 1. Within the European framework, most are also designated as either Special Protection Area (SPA) or Special Area of Conservation (SAC), depending on the habitat and species present.

Figure 1: *Map of RAMSAR sites in Scotland.*

To keep its conservation value, a wetland has to maintain its ecological characteristics. The term "wetland" covers a variety of habitats such as marsh, fen, swamp and peat-bog, both temporarily or permanently flooded. The focus will be on a marsh, which can sustain submergent and floating plants but is dominated by rushed, reed, sedges and other soft-stemmed emergent plants (Ellis et al. 2003). All types of wetland are highly sensitive systems that, when stressed, start degrading, and are therefore tightly regulated by the Scottish government (HMG 2011, SEPA 2022).

Any application for abstraction has to assess the possible impacts such abstraction would have on a wetland system to ensure all steps are taken to prevent degradation of its value. To this end, a simple environmental model was created to measure the effects a water abstraction project would have on a marsh of 10 km^2.

A simple model was created in OpenModel based on previous studies and validated with an independent dataset. The model was then used to measure the effect of water abstraction on Biomass and Water Concentration to evaluate the model and the effect the abstraction would have on the marsh.

1.2 Aims

To model the effect water abstraction has on the biomass of a wetland ecosystem, the following aims are set out:

- Construct a model of the natural system.
- Validate the model with an independent data set.
- Run scenarios for different abstraction levels to determine their effects and safe abstraction levels.

2 Method

The model was disaggregated into Biomass and Water concentrations, linked through the volumetric Water Content $Theta$ (θ) (Figure 2). It can be calculated by dividing the volume of $Water$ on a given day by the volume of the $Soil$ in the wetland ($10,000,000\ m^3$):

$$\theta = \frac{vol_{Water}}{vol_{Soil}} \tag{1}$$

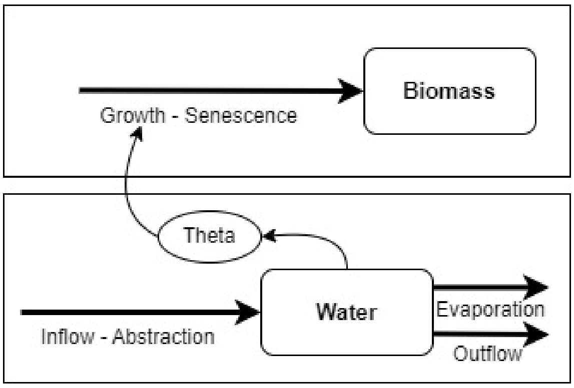

Figure 2: *Conceptual diagram of the two model aspects: Biomass and Water with their main components, linked through Theta (θ).*

2.1 Biomass

To determine the change of the biomass over time ($\Delta Biomass/\Delta time$), the senescence ($Senescence$) – plant death – of the existing Biomass ($Biomass$) has to be subtracted from the growth rate ($Growth$), this can be calculated through the differential equation:

$$Biomass = Growth - Senescence * Biomass \tag{2}$$

The plant turnover ($Senescence$) is temperature dependent ($Temp$ ($°C$)), a provided data set for 3287 days was used for this model. It is calculated for the marsh vegetation through the equation:

$$Senescence = \frac{Temp}{300} \tag{3}$$

To calculate the plant growth ($Growth$ (g/m^2)) the fraction interception of solar radiation (f_i, calculated in Equation 5) is multiplied with the conversion coefficient for solar radiation to biomass ($e_r = 1.4$ (g/MJ)), the daily solar radiation (S (MJ/m^2)) and Theta (θ, Equation 1). A provided data set for solar radiation over 3287 days was used.

$$Growth = f_i * e_r * S * \theta \tag{4}$$

As the water concentration in the soil (θ) increases the plant growth increases, up to the set limit of $\theta = 1$ (Figure 3) at which point it levels out, for the purpose of the model.

The fraction interception (fi) of solar radiation is calculated from Euler's number ($e = 2.72$), the extinction coefficient of leaf canopy ($k = 0.45$) and the canopy leaf area index (L (m^2/m^2), Equation 6):

$$f_i = 1 - e^{-kL} \tag{5}$$

For this model 0.5 of the total biomass is assumed to be leaves and the specific leaf area (SLA) for the marsh is 0.02 m^2 of leaf per gram of leaf material. The canopy leaf area index (L) can thus be calculated utilising $Biomass$ (calculated in Equation 2):

$$L = 0.5 * Biomass * SLA \tag{6}$$

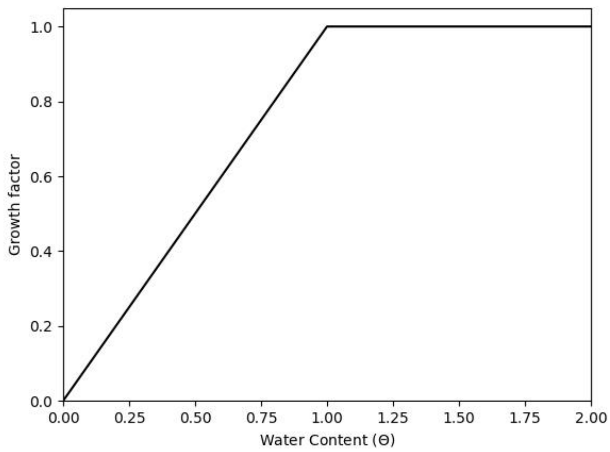

Figure 3: *The influence of Theta on the Growth factor levels out at $\theta = 1$.*

2.2 Water content

The Water Content in the wetland over time ($Water_t$) depends on water $Inflow$, $Evaporation$ and $Outflow$. The equation can be described as:

$$Water = Inflow - Evaporation - Outflow \tag{7}$$

The Inflow data was provided for this model and was used directly. Evaporation and Outflow data was also provided but used to create regression equations for the wetland.

The Evaporation data provided was gathered in a previous study, measuring the daily evaporation relative to the potential evaporation and water. It was measured in mm and therefore had to be converted to m^3 by multiplying the values with $10,000$ for the marsh model. The resulting equation for Evaporation (8) has a high R^2 value of 0.79 and low p value of $5.046e-21$ indicating a good fit (see Figure 4).

$$Evaporation = 9598 * \theta - 1222 \tag{8}$$

The Outflow data fit the equation (9) (Figure 5) with a R^2 value of 0.94 and p of $4.049e-39$, indicating a good fit too.

$$Outflow = 4819 * \theta - 2354 \tag{9}$$

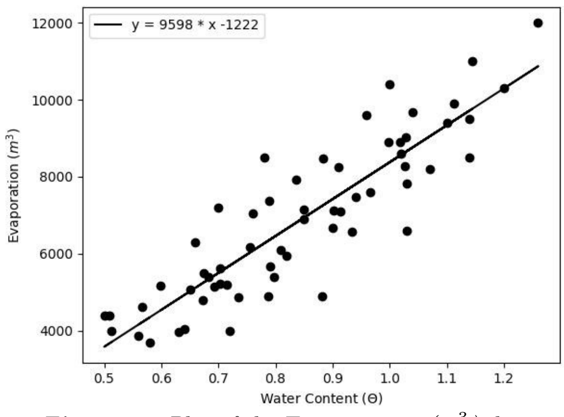

Figure 4: *Plot of the Evaporation (m^3) data and the regression line.*

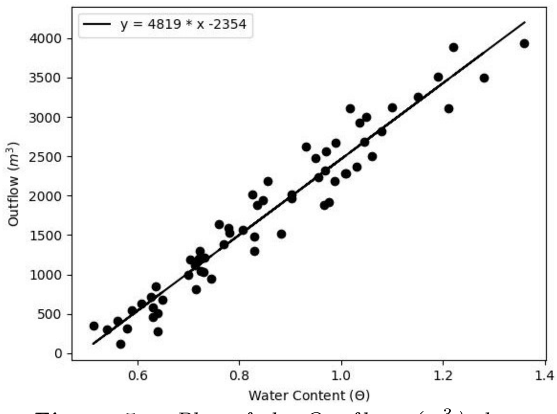

Figure 5: *Plot of the $Outflow$ (m^3) data and the regression line.*

Due to the regression lines fit no further attempt was made to create polynomial equations that might be closer to real observations beyond the point range provided for the purpose of this study.

The model was created and run in OpenModel (openmodel.info), with the initial values: $Theta = 1$, $Biomass = 85$ and $Water = 10,000,000$, signifying a very healthy ecosystem. OpenModel was selected due to familiarity with the software.

The output data was exported for analysis and visualisation in Python, using the libraries: pandas (Wes McKinney 2010), NumPy (Harris et al. 2020), Matplotlib (Hunter 2007), seaborn (Waskom 2021) and SciPy (Virtanen et al. 2020).

2.3 Validation

To validate the model an independent data set was used. The data was in 20 day time steps between days 400 and 1120. There was no metadata provided on the initial values of the test data ecosystem.

First the test and model data points were plotted in a time series and against each other for visual comparison. R^2 and p values were calculated for a best fit line between the two data sets before residuals were calculated and analysed.

2.4 Abstraction

To model the effects of water *Abstraction* on the marsh, it was included in the Water content (Equation 7). As the river flow is strongly seasonal, rather than using an absolute value, it was expressed as fraction of the inflow. The Abstraction amount in % is divided by 100, followed by subtraction from one before it is multiplied by $Inflow_t$.

$$Water = Inflow * \mathbf{(1 - \frac{\mathit{Abstraction}}{100})} - Evaporation - Outflow \tag{10}$$

Scenarios were run over 10,000 days for two *Abstraction* amounts, 20% and 40%, and at two Biomass initial amounts, 85% and 60%. This was to evaluate the effects varying abstractions would have on different systems. OpenModel loops over the given data sets, resulting in a repetitive pattern every 3287 days. Furthermore *Abstraction* scenarios were run to establish how much water could be abstracted before the wetland would become too stressed and loose its ecological characteristics.

3 Results

3.1 Validation

The natural model was validated by comparing it to an independent dataset provided for 37 points between day 400 and 1120. First they were plotted alongside the model in the time range for visual comparison (Figure 6) showing high similarity when *Biomass* is low but a high variability when *Biomass* is high.

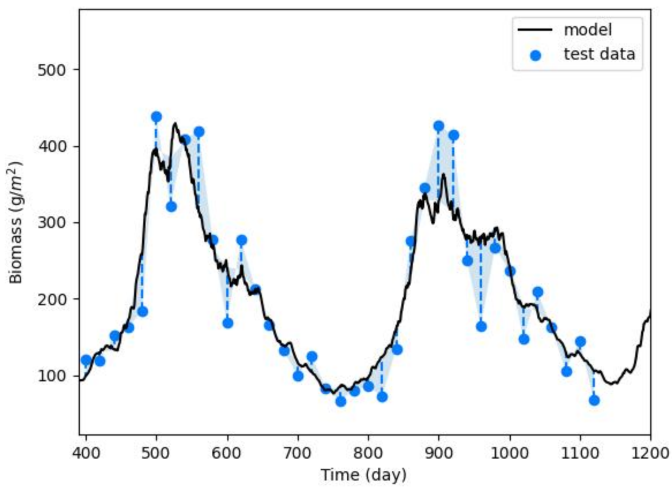

Figure 6: *Plot of the model and the test data, indicating errors in blue.*

This is confirmed when Model and Test Data were plotted against each other (Figure 7) and by looking at the Test Data residuals (Figure 8). Points above 160 have more variability from the center line. The line of best fit (blue) varies slightly from the center line (black). However, the line of best fit has a high R^2 value of 0.839 and low p value of $1.925e-15$ suggesting it describes a high level of relationship between the model and test data. The residuals plot has positive outliers, that are balanced by a larger number of negative residuals, resulting in an even spread, supporting the assumption that the linear regression in Figure 7 is appropriate.

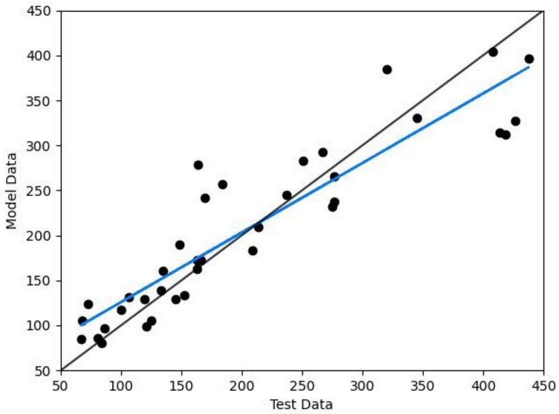

Figure 7: *Test and Model data plotted against each other, with a black center line and blue best fit line.*

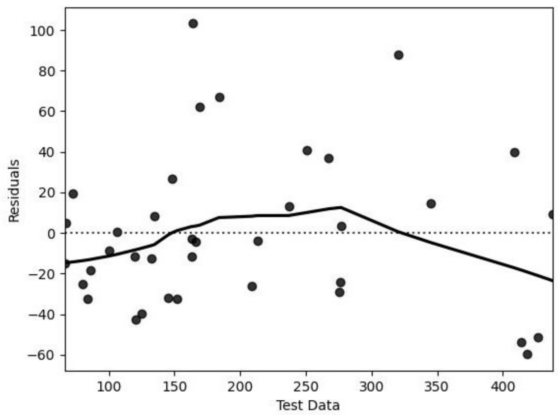

Figure 8: *Residuals plot for the test data.*

3.2 Abstraction

The inflow data was analysed to establish estimations for possible water abstraction (Table 1). Due to seasonal weather, the water inflow is highly variable (Figure 9) reaching from a maximum of $18,563$ m^3 to a minimum of $3,787$ m^3. With an average inflow of $11,507$ m^3, the average abstraction at 20% would be $2,301$ m^3 and at 40%, $4,603$ m^3. In reality, the true abstraction value would have to be bound by the extreme values, between 757 m^3 and $7,425$ m^3.

Table 1: *Statistical summary of the water inflow and water abstraction at* 20% *and* 40%.

	mean	min	median	max
water inflow	11,507	3,787	11,925	18,563
20%	2,301	757	2,385	3,713
40%	4,603	1,515	4,770	7,425

Due to this variability in the water inflow, the *Biomass* also shows high variability (Figure 10). There are also occasional extreme low or high values in the yearly rotations. In good years, the Biomass reaches 554 g/m^2, while in dry years, it only peaks at 293 g/m^2, with most low points below 100 g/m^2. When overlaying the natural model, in which the initial Biomass is set at 85, with that of the abstraction model at -20% and -40%, there is no visual or statistical difference within the time window.

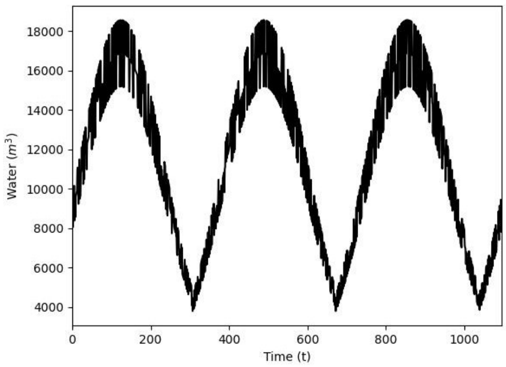

Figure 9: *Water inflow over three 3 years.*

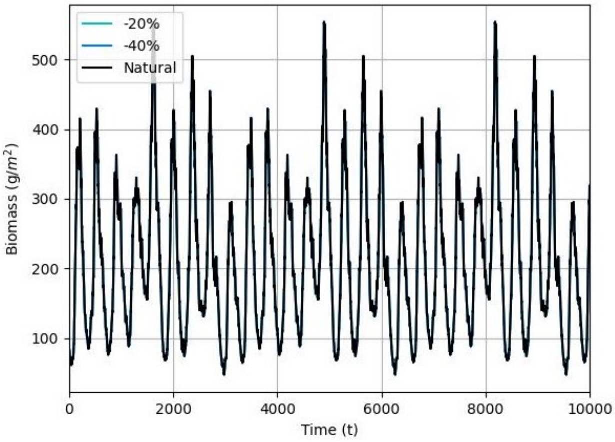

Figure 10: *Biomass (initial value 85) over time compared to that of a system with* 20% *and* 40% *Abstraction.*

In the model with the initial Biomass set at 60, the impact becomes visible after the second year for both abstraction levels (Figure 11). The impact on Biomass in the 20% abstraction model is small compared to that of the 40% abstraction model. After the fifth year, Biomass at 40% abstraction does not reach 300 g/m^2 anymore, reaching less than 100 g/m^2 in dry years.

In the statistical summary of the Biomass data from the model (Table 2), the impact of abstraction becomes clear: the mean, min and median for the 40% abstraction system dropping below half the natural Biomass. The data shows how resistant Biomass of the wetland system is to extreme weather with speedy recovery after particularly dry years.

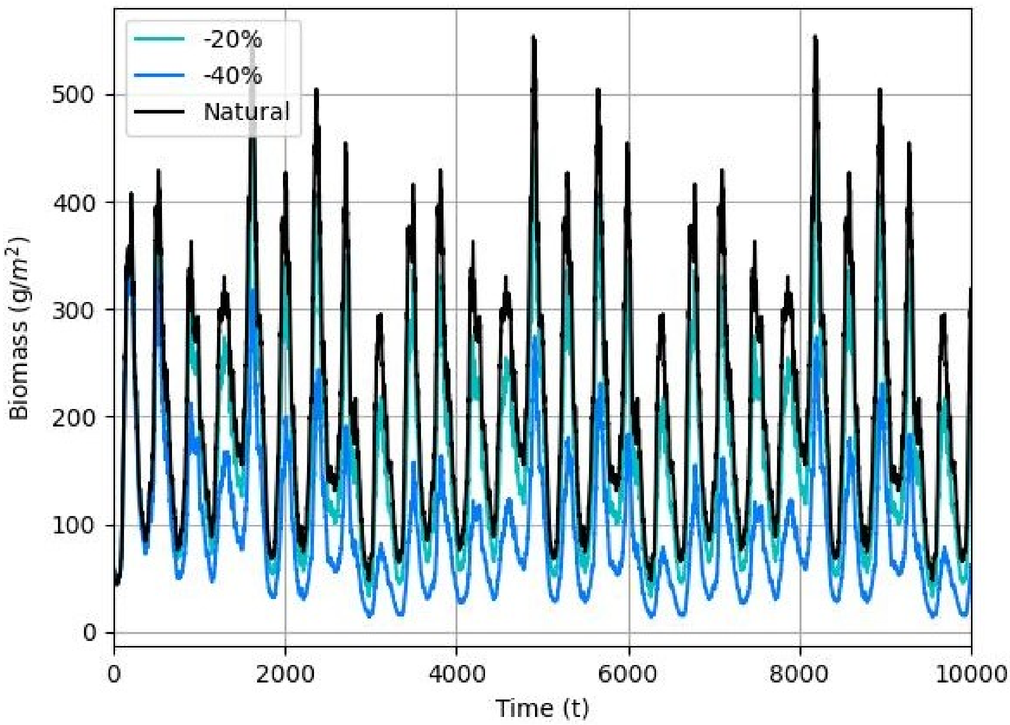

Figure 11: *Biomass (initial value 60) over time compared to that of a system with* 20% *and* 40% *abstraction.*

Table 2: *Statistical summary of the Biomass in the model with initial Biomass value of 60.*

	mean	min	median	max
natural	210	44	192	554
20%	165	34	147	464
40%	90	14	72	385

Using Biomass to describes the effects on a wetland is very general, therefore, the $Water$ concentration over time was analysed as well. When visualised the water content increases for the natural system at a steady rate. On the other hand, the drop for the two abstraction values modelled is considerable, leveling out soon after 3000 days (Figure 12).

As the wetland has to be flooded for at least some time of the year – to be considered a wetland – θ has to stay above 1 for at least some time of the year. For a wetland of the size $10,000,000\ m^3$ the $Water$ limit is therefore $10,000,000\ m^3$ to obtain $Theta$ of 1. Both abstraction models are below that level. After modelling several scenarios, the model with an $Abstraction$ of 7% $Theta$ was closest to the center, staying above 1 for half of the time (Figure 13).

This would be the maximum amount of abstraction possible while retaining its wetland characteristics. At the set limit of 7% water $Abstraction$, the average water that could be abstracted would be $805\ m^3$, ranging between $265\ m^3$ to $1,299\ m^3$.

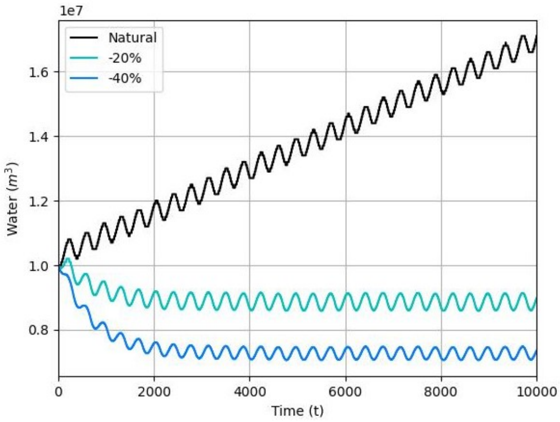

Figure 12: *Natural Water content compared to that of a system with* 20% *and* 40% *abstraction.*

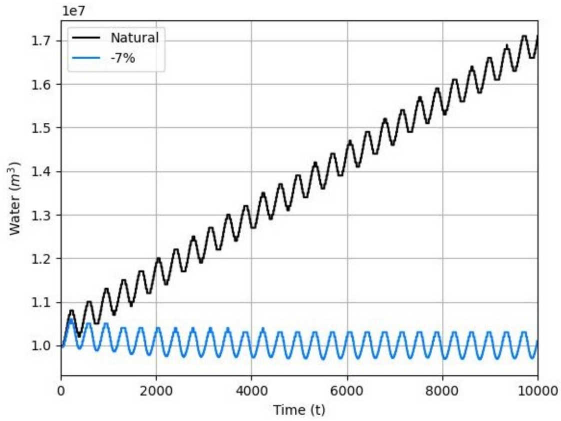

Figure 13: *Natural Water content compared to that of a system with* 7% *abstraction.*

4 Discussion

In the model, a wetland with high initial Biomass shows little change when water is abstracted even at higher levels. Even at longer time duration there was no visual change. In a system with lower initial Biomass, however, the effects quickly become substantial.

A detailed initial survey to establish exact Biomass, and close monitoring, would be required to ensure the abstraction amount is appropriate and is adjusted if the wetland health declines. This would also ensure stress is kept at a minimum and ecological characteristics of the marsh are retained.

Water content seems a more appropriate indicator for the wetland health as it indicates the water saturation in the soil and therefore if the ecosystem is still a functioning wetland. Abstraction should not go beyond 7% of inflow as water concentration would drop below saturation for the majority of the year otherwise.

Measuring the abstraction as percentage of the inflow for this simple model worked to a limited degree, but a more detailed model would be required to determine the constant value which could be abstracted, ideally only during the wetter half of the year.

Additionally, $Theta$ and $Evaporation$ would have to be changed to reflects reality more accurately. $Theta$ would not level out but decrease as the water level rises, drowning marginal plants. Representing $Evaporation$ in the calculated linear equation with a fixed surface is not a good representation for the real world either, even though the equation fit the given points well. Furthermore the water would spread horizontally, and therefore increase the surface area of evaporation. Ground water level might also have an impact on the marsh, if the water company is abstracting in the area.

The model fits well when validated with the given data set, however, no contextual data was given on the initial Biomass of the study area of those control points, or time when they were taken. With climate change, the system could already be under stress compared to when the measurements were taken. Additionally, looping over the same data over a long period without taking climate change or extremes into account could negatively affect the real world outcome for the wetland, as was demonstrated by the model with initial $Biomass$ of 60.

5 Conclusion

The simple model demonstrated high impacts of water abstraction on Biomass in a wetland when it is not at high initial Biomass levels. The abstracted amount should not be more than 7% of the inflow, and ideally only be taken during wetter seasons. With climate change, wetlands are getting exposed to an increasing amount of stress and this should be accounted for when estimating the impact of abstraction. As high water concentration is important for the sustainability of ecological characteristics, it is a better indicator for the wetland, compared to Biomass, which can be misleading due to non-wetland species taking over drier areas. Close monitoring is advised to ensure the stability of the wetland is maintained.

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