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A hydraulics-based analytical method for artificial water replenishment in wetlands by reservoir operation

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ABSTRACT

As water resources have been developed, the input of water into wetlands by rivers has decreased. Thus, these wetland ecosystems are seriously threatened. The upstream reservoir must be operated in a manner that provides downstream wetlands with their ecological water requirement. Here, a method for analysing the effects of artificial water replenishment from reservoirs on wetlands is established. A hydrodynamic mathematical model was coupled by a one-dimensional longitudinal and depth-averaged two-dimensional hydrodynamic model to simulate the water replenishment process in wetlands. The results indicate that the overflow of floodwaters into wetlands may not occur if insufficient reservoir water is discharged. In contrast, if too much water is discharged, excess water will reach the wetland and cause a water shortage upstream. Furthermore, the results showed that there is a quantitative relationship between the area of water in a wetland and the flow discharged by the upstream reservoir. This analytical method provides direct data that can be used to ensure that wetlands receive enough water from reservoirs to maintain their ecological functions and to avoid wasting the water resources of upstream reservoirs.

1. Introduction

Wetlands play an important role in maintaining the local ecological balance. Due to human activities and changes in the natural environment, wetland ecosystems are suffering from structural damage, functional decline, loss of biodiversity, decreasing biological productivity, and decreased production potential. Thus, wetland resources are gradually disappearing (Han et al., 2012). The over-exploitation of water resources and the construction of reservoirs in rivers have altered the original hydrological regime. This interruption is responsible for disrupting the hydrologic balance of wetlands and is threatening the health of wetland plants and animals. Recently, many research studies have focused on the ecological water requirements of wetlands (Guo et al., 2004; Mayer and Thomasson, 2004; Cui et al., 2005; Wang et al., 2011). These studies focused on the ecological balance and normal development of wetlands, the protection of wetland hydrological functions, and the water requirements of the associated environments (Zhao et al., 2005; Ferrati and Canziani, 2005; Zacharias et al., 2005; Liu et al., 2010).

Many researchers have studied methods of improving wetland ecology (David et al., 1998; Day et al., 2012), and pointed out that the water replenishment strategy is an effective method for wetland protection. Although reservoir construction affects a river's original hydrological form, reservoirs are also used for flood regulation, which can mitigate the imbalance of water in wetlands. The provision of supplemental water to wetlands by reservoirs during emergencies was discussed by Yang et al. (2008). Several Scenarios were initiated in China to release reservoir water into adjacent wetlands. For example, water was released from the Nenjiang reservoir into the Zhalong wetlands (Zhou et al., 2007), from the Xiaolangdi hydropower reservoir into the Yellow River Delta wetlands (Cui et al., 2009b), and from the upstream reservoirs into the Tarim wetlands (Huang and Pang, 2010). A new reservoir operating model is proposed to effectively direct water supplies to wetlands, cones of depression, and humans (Yin and Yang, 2012).

However, the discharge of water from the upstream reservoir to wetlands will be attenuated and delayed across long distances. Water may not enter the wetlands if it is not discharged from the reservoir in sufficient quantity. Similarly, if too much water is discharged, excess water will reach the wetland and cause a water shortage in the reservoir upstream. Therefore, a method based on reservoir operation is needed to analyse the effects of artificial water replenishment in wetlands. Here, the water replenishment of wetlands from the operation of upstream reservoirs was

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investigated. A method was developed to analyse the artificial water replenishment of wetlands. In addition, a hydrodynamic mathematical model was used to analyse both water transmission in the river and the area of water in the wetlands. This method can characterise the relationship between the flow discharged from the upstream reservoir and the increment in water area of the wetland. The water quantity that is needed to meet the ecological requirements of the wetland was accurately calculated. In addition, the corresponding discharge requirements for upstream reservoir was determined. The results can provide scientific basis for the wetland water replenishment plan. The method proposed in the paper can be a practical tool for the researches about the protection of wetlands and reservoir operational regulation.

As a case study, we tested the method by analysing the wetland in the Hulunbuir plateau and the reservoir located 380 km upstream.

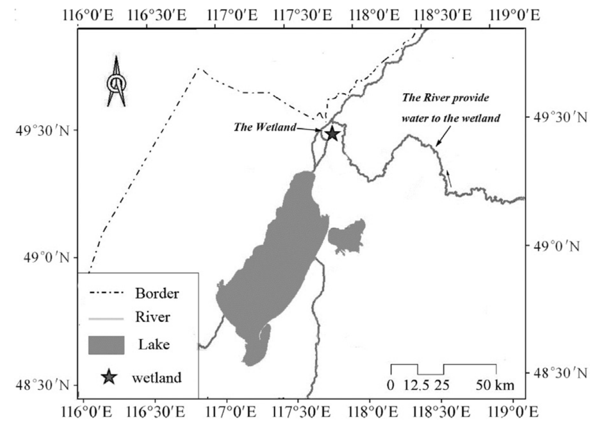

Fig. 1. The location of the wetland.

2. Mathematical model

A mathematical model, which was coupled by a longitudinal one-dimensional and depth-averaged two-dimensional hydrodynamic model, was used to simulate the water replenishment process in wetlands. The model was used to analyse the flood in the river and the overflow flood in the wetland. The longitudinal 1D model was used to simulate hydrodynamics of the flow inside the river bank. The depth-averaged 2D model was used to simulate the flood transportation in the wetland when over-bank flow occurs in the river. The flow rate over the river bank was used as the inlet boundary condition of the 2D model. The 1D and 2D model were solved coupling.

This mathematical model was validated by Zhu (2010), who used it to calculate and evaluate flood production. The result showed that the difference between the measured and simulated water levels was only 1.69%. Thus, it was concluded that the model can satisfactorily simulate the spatial and temporal distribution of water.

2.1. The longitudinal one-dimensional model

The Saint Venant equations were used to simulate the unsteady flow in the river. These equations include the continuity equation and the momentum equation.

$$\frac{\partial Q}{\partial x} + B\frac{\partial h}{\partial t} = \varphi \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial\left(\alpha(Q^2/A)\right)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2AR} = 0 \tag{2}$$

where x is the space coordinate; t is the time coordinate; Q is the cross-sectional flow rate; h is the water level; A is the wetted area of the cross-section; B is the cross-sectional width; R is hydraulic radius; g is the acceleration due to gravity; C is the Chezy coefficient, $C = (1/n)h^{1/6}$ (n is manning number); α is the vertical velocity distribution coefficient, for which the value is 1; and φ is the flanking inflow based on the river length.

The 6-point implicit central difference scheme was used to separate these equations, and the chasing method was used to obtain numerical solutions.

2.2. The depth-averaged two-dimensional model

The flow process in the wetland was simulated by the depth-averaged two-dimensional model. This model included the continuity and momentum equations.

$$\frac{\partial \xi}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0 \tag{3}$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\frac{\partial \xi}{\partial x} + \frac{gp\sqrt{p^2+q^2}}{C^2h^2} - fq = 0 \tag{4}$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\frac{\partial \xi}{\partial y} + \frac{gq\sqrt{p^2+q^2}}{C^2h^2} + fp = 0 \tag{5}$$

where ξ is the water level of the free surface, p is the unit discharge in the x-direction, q is the unit discharge in the y-direction, and f (=$2\Omega\sin\varphi$) is the Coriolis parameter (ω is the angular rate of revolution and$\varphi$is the geographic latitude).

The finite volume method was used to discrete the equations.

2.3. Roughness

Roughness is used to indicate the bed resistance. Generally, the roughness value in a river is low than that in forest land and paddy field. According to the status of the bed resistance (Wu, 2007), a different manning number was used in the model (0.035 for the wetland and 0.03 for the river).

3. Calculating the water replenishment in the wetland

A typical wetland ecosystem occurs on the Hulunbuir plateau. To maintain the ecological functions of the wetland, a stable water source is needed. The water sources for this wetland are rainfall and river flood from the east, which is the predominant source. However, due to recent increases in upstream water demands, the ability of the river to provide water to the wetland has decreased, especially in the arid season. Thus, the upstream reservoir was used to provide water to the wetland. The location of the wetland, the river networks and the reservoir are shown in Fig. 1. The associated reservoir is 380 km upstream of the wetland and can store 4.00×10^8 m^3 of water. Further details of the wetland and river are shown in Fig. 2. The wetland covers an area of 65.01 km^2 and is divided into northern and southern regions by a new national road. The combined area of the core and buffer zones, which are located on the north side of the national road, is 35.38 km^2. The