Ecological Engineering 96 (2016) 150–161

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Environmental flow management strategies based on the integration of water quantity and quality, a case study of the Baiyangdian Wetland, China

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ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form 1 November 2015
Accepted 8 December 2015

Keywords:
Environmental flow
Water quality
Ecosystem status
The Baiyangdian Wetland

ABSTRACT

Environmental flow plays an important role in sustaining or improving wetland ecosystems. There are many methods for environmental flow assessments, most of which only focus on simplistic environmental flow standards or theoretical cause–effect relations between flow regimes and target species. However, traditional assessments may not be suitable for ecosystems with severe water quality deterioration. Ignoring relationships among flow, water quality, and multi-level ecological responses in real and complex ecosystems may misguide management practices and lead to further ecosystem degradation. To investigate impacts of flow alteration on ecosystems with different pollution rates, and examine the underlying mechanisms, a two-dimensional hydraulic and ecological model was developed in this study. This model simulates flow circulation; pollutant transport; and the interactions between flow, nutrients, and holistic ecosystem characteristics. The integrated model was applied to 21 scenarios to understand ecosystem characteristics in response to various environmental flow rates and water quality standards. Finally, holistic indicators including total primary production/total respiration, total biomass/total production, eco-exergy, and structural eco-exergy are used to quantify the effects of different scenarios on ecosystem health, and provide scientific environmental flow recommendations. The proposed method was applied to Baiyangdian, the largest wetland in the North China Plain. The results indicate that the annual environmental flow should be higher than 2 m^3/s in order to prevent the Baiyangdian ecosystem from further degradation. To maintain an optimal ecosystem status, the minimum environmental flow should be kept as 5–9.5 m^3/s, and the maximum environmental flow should be kept as 9–13.5 m^3/s in different hydrological years. In addition, the water quality should be always kept at or above the Chinese class IV standard. This result can guide basic research in hydroecology and assist further implementation of comprehensive environmental flow management.

1. Introduction

Global population growth and socio-economic development has resulted in increasingly intensified problems of water shortages and water quality deteriorations in riverine and wetland ecosystems (Zeng et al., 2011). The importance of maintaining environmental flow has been widely recognized by scientists and managers (Poff and Zimmerman, 2010), and environmental flow has become one of the important components in water resource management, planning, and allocation. Recently, many restoration projects focus on restoring environmental flows to improve the integrity of aquatic ecosystems to minimize the negative impacts of reservoirs on aquatic ecosystems, and numerous approaches have been developed for determining sustainable environmental flow in different ecosystems (Yin et al., 2012).

The relationship between flow alteration and ecological response is a crucial issue in the environmental flow assessment (Chen et al., 2013). Traditional methods of environmental flow assessment can be generally grouped into two categories: (1) methods based on analysis of hydrological time series; (2) methods based on cause–effect relations between flow alteration and ecological response. Generally speaking, the first type of methods works under the hypothesis that natural hydrological conditions can effectively protect aquatic biodiversity as well as the integrity of wetland ecosystems and the management focuses on minimizing the differences between natural and current hydrological regimes (Richter et al., 1996; Wantzen et al., 2008). However, because ecological conditions are not measured, the specific

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http://dx.doi.org/10.1016/j.ecoleng.2015.12.018
0925-8574/

ecological outcomes cannot be predicted with this black-box approach. In contrast, the second type of methods takes into account quantitative flow alteration–ecological response relationships, such as hydraulic rating and habitat simulation (Anderson et al., 2006; Powell et al., 2008; Tharme, 2003). The current research on ecological responses simply focus on one or a few target species due to the data and analysis tool limitations, however, different species may respond to environmental flow in different ways due to their various habitat requirements and tolerance abilities in fact. Because complex multi-species interactions under the impact of environmental flow cannot be known, the obtained environmental flow would not satisfy the requirements of a holistic ecosystem (Suen and Eheart, 2006).

In addition, traditional environmental flow (EF) assessment methods have mainly focused on the aspect of flow regime, with the assumption that the flow regime has an overriding effect on aquatic ecosystems. However, water quality is becoming an increasingly important challenge in maintaining aquatic ecosystem health (Coops et al., 2003). Point and non-point source pollution from industrial and urban development is discharged into rivers, lakes, or wetlands, degrading water quality. Degraded water quality will modify or, if strong enough, conceal flow alteration–ecological response relationships (Buchanan et al., 2013). Previous research has shown that biota and ecological processes may respond to flow alteration either directly or indirectly through water-quality or habitat-mediated responses (Poff et al., 2010). Flow changes over different time scales can amplify the overall impact on water quality (Hofmann et al., 2008), for example, short-term increases of a wetland's water volume could improve its water quality through the dilution effect, and long-term increases can improve water quality from the combined impact of the improved self-purification ability and dilution (Yang and Yang, 2014). Much evidence also exists that flow regime plays a significant role in nutrient transport and re-suspension of organic matter, and consequently influences biological communities and productivity (Bunn and Arthington, 2002; Doyle et al., 2005). Water quality improvement can potentially ameliorate the impacts of flow alteration. In order to expand the applicable conditions and scopes of methods, water quality should be further considered in the EF assessment. Zheng et al. (2011) proposed an eutrophication model based on the WASP for assessing water quality responses under different pollution load and environmental flow scenarios. Chen et al. (2013) developed an ecological model for assessing acceptable flow regimes for lake protection at the ecosystem level.

Although multiple models for water quality or ecological analysis have been considered in recent studies, there are very limited studies that have tried to integrate hydraulic and ecological models for identifying the comprehensive interrelations among flow regime, water quality, and aquatic ecology (Dong et al., 2013; Zhao et al., 2014). This may make the environmental flow results diverged from the actual conditions and make it difficult to protect aquatic ecosystems successfully (Yang and Mao, 2011; Buchanan et al., 2013). Integrating the hydraulic and ecological models in environmental flow assessment has gradually gained its significance in management strategies and ecosystem restoration. Hydraulic model is widely used to simulate the flow circulation, temperature dynamics, contaminant transport and advanced eutrophication processes (Nepf, 2012). It has also been applied in the simulation and decision support analysis of surface water such as lakes, reservoirs, bays, wetlands and estuaries (Shucksmith et al., 2011; Wu and Chen, 2014; Wang and Chen, 2015). By comparison, ecological models can simulate a variety of ecological processes, dynamics across multi-species at different trophic levels, and can be used to establish a quantitative linkage between external nutrient loading, internal water quality condition and holistic ecosystem response.

In this study, an integrated hydraulic and ecological model was developed to investigate impacts of flow alteration on ecosystems with different water qualities and examine the underlying mechanisms. The model simulates flow circulation; pollutant transport; and the interactions among flow, nutrients, and ecosystem status. Scenario analysis was conducted to understand holistic ecosystem health in response to various environmental flow amounts and nutrient load intensities, and ecosystem health was described as a series of robust ecosystem indicators. When the method was applied to the Baiyangdian Wetland (North China), the results showed that this approach is useful for decision making about environmental flow, especially in ecosystems with deteriorated water quality.

2. Materials and methods

2.1. Study area

Baiyangdian Wetland (38°43′–39°02′N, 115°38′–116°07′E), the largest plant-dominated freshwater wetland in the North China Plain (Fig. 1), was selected as the study area for this research. Relative to sea level, the average elevation of the wetland bottom is 5.5 m, and the greatest surface area is approximately 366 km^2. Historically, eight rivers flowed into Baiyangdian Wetland, offering many irreplaceable services, such as regulating the water cycle, supporting biodiversity, and maintaining the ecological balance of its surroundings. However, over the last decades, continuous droughts and flow regulation by upstream reservoirs (such as Xidayang Reservoir, Wangkuai Reservoir, and Angezhuang Reservoir) have profoundly altered the hydrology of the Baiyangdian catchment. Most rivers in this catchment have become seasonal or are persistently dried out. The average annual inflow to Baiyangdian Wetland decreased from 1.94 billion m^3 in the 1950s to 0.065 billion m^3 in the 2000s. Low or no inflows caused decreases in water level and area of the wetland. The wetland has disappeared four times since the 1960s (Yang et al., 2014). Currently, the Fu River is the only inflow river, and it carries a large quantity of pollutants, causing serious eutrophication and biodiversity reduction.

2.2. Data resources

Daily meteorological data used for hydraulic model establishment were obtained from China Meteorological Data Service System and included wind velocity, precipitation, and evaporation (http://cdc.cma.gov.cn). Daily hydrological records for Xinan and Duancun Hydrological Monitoring Stations were obtained from the Water Conservancy Office of Baoding City, Hebei Province and used to calibrate and validate the hydraulic model. Water quality data from 2009 to 2010 for 14 monitoring sites in Baiyangdian Wetland were obtained from the Municipal Environmental Protection Bureau (Fig. 1). Biomass data for aquatic macrophytes, phytoplankton, zooplankton, and zoobenthos were obtained from four field samplings carried out from August 2009 to July 2010, which can reflect seasonal changes in Baiyangdian Wetland. The detailed methodology of sample collection and analysis was mentioned in Yang and Chen (2013). The brief introduction of the sampling sites was presented in Table 1.

2.3. Building hydraulic foundation

To understand hydrodynamics of the study area, the Environmental Fluids Dynamics Code (EFDC) was selected as the computational platform for simulating the distribution of flow amount, flow velocity, water level, and water depth in the Baiyangdian Wetland. EFDC is a widely used, multi-task, highly