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Strategies for Managing Environmental Flows Based on the Spatial Distribution of Water Quality: A Case Study of Baiyangdian Lake, China

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ABSTRACT. Water shortages and deterioration of water quality become more serious as a result of industrial development and urbanization, but both can be mitigated by optimal management of environmental flows. In this paper, we used Baiyangdian Lake as a case study of this form of management. We divided the lake into 13 sub-areas using GIS software, and analyzed water-quality processes in each sub-area using an eutrophication model based on the WASP 7 software. The model considered the dissolved oxygen content, the nitrogen and phosphorus cycles, and phytoplankton growth. We used monitoring data for Baiyangdian Lake to parameterize and validate the model. Using the model, we then analyzed water quality variations for different non-point-source pollution load scenarios and artificial water release scenarios to reveal the relationships between water quality and these factors. We found that return water such as industrial wastewater and domestic sewage with a large organic load worsened eutrophication, whereas reducing pollutant loads, transferring water into the lake, or a combination of the two approaches improved water quality. The detailed spatial distribution of water quality supplied key information to support further analysis of ecological water demand and water allocation. Our simulation revealed environmental flows of 3.87×10^8, 3.70×10^8, and 3.23×10^8 m^3/a, respectively, for scenarios with pollutant load reductions of 30, 50, and 90% under various water-release strategies. On this basis, we propose optimal water quality management strategies for Baiyangdian Lake to improve its water environment.

Keywords: Baiyangdian Lake, eutrophication, environmental flows, lake management strategy, WASP model, water quality simulation

1. Introduction

Water shortages and quality deterioration are serious dilemmas for lake managers, as both problems sharply decrease the ecosystem services and functions provided by a lake. Lake water that is allocated and made available for maintaining ecological processes and particular ecological characteristics in a desirable state is referred to as the "environmental flows" for a lake (O'Keefe, 2000; Smakhtin et al., 2006). Assessing the environmental flows for a lake can provide a scientific basis for water management, so this approach has received the attention of many researchers since the 1990s (e.g., Sherrard, 1991). The existing calculation methods for environmental flows are mostly based on research for rivers, and can be divided into four types: hydrological, hydraulic, habitat, and synthetic methods (Arthington, 1998). Based on this previous research, the water balance, ecological water level, relative curve, and functional methods are typically used to assess the environmental flows for lakes, and have recently been adopted for use in China (e.g., Cui et al., 2005). However, most of the research on environmental flows has focused on water quantity, but has neglected water quality and its spatial distribution. This has caused the theory of environmental flows to diverge from the practice, and has made it difficult to effectively protect aquatic ecosystems (Kashaigili et al., 2005; Gupta, 2008; Yang and Mao, 2011).

As a result of industrial and urban development, large quantities of sewage are discharged into lakes, thereby degrading the water quality (Ping et al., 2010). Water quality problems, and especially eutrophication, are becoming an increasingly important challenge in the management of lake water (Forsythe et al., 2010), thus water quality has become one of the basic factors that must be considered when determining environmental flows and environmental water allocation. Giardino et al. (2008) considered that sustainable use of lake water requires the coupling of water quality assessment with water allocation management. Wu and Suo (2007) established an optimal allocation model that also considered water quality and quantity, but accounted for economics and for social, environmental, and ecological factors. Despite these advances, it is also important for lake managers to account for the spatial distribution of water quality throughout a lake. Some researchers have adopted existing water quality modeling software to simulate water quality in lakes (Furia et al., 1995; Vuksanovic and Smedt, 1996; Thomas et al., 1997; McIntyre and Wheater, 2004; Gurkan et al., 2006). However, there has been no approach that combines a consideration of water quantity and quality together with its spatial distribution in the management of environmental flows.

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In this study, we simulated the spatial distribution of water quality using version 7 of the WASP model (http://www.epa.gov/athens/wwqtsc/html/wasp.html), and analyzed water quailty variations in scenarios with different non-point-source pollution loads and different artificial water releases into the lake to reveal the relationships between water quality improvement and various combinations of water treatment and artificial water allocation. Using a shallow freshwater lake in China (Baiyangdian Lake) as a case study, we demonstrate how this simulation approach is a useful tool for adaptive management of lake water quality and quantity.

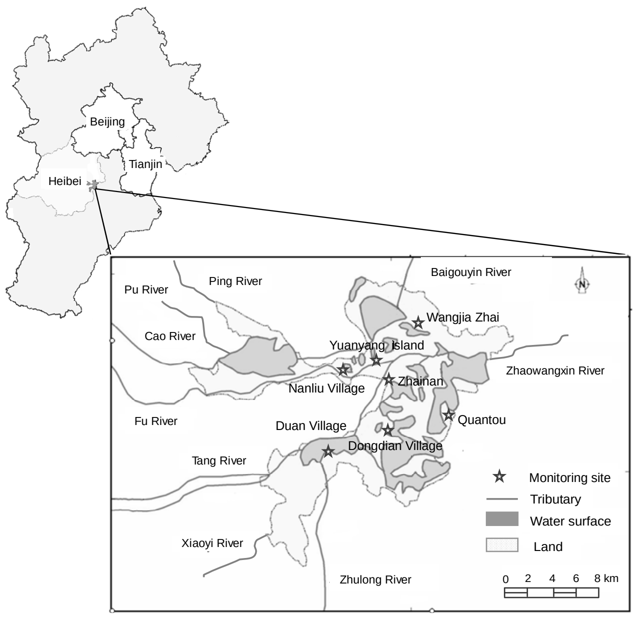

Figure 1. Regional map showing the location of Baiyangdian Lake and the associated rivers.

2. Methods and Models

2.1. Study Area

Baiyangdian Lake (38°43′ to 39°02′ N, 115°45′ to 116°07′ E), which is located in An'Xin County of Hebei province, comprises one of the largest freshwater wetlands in northern China (Figure 1). The total area of Baiyangdian Lake is 362.8 km^2. However, rather than being a single lake, it is a network of interconnected lakes with extensive areas of emergent and submerged aquatic vegetation, and small changes in water level can dramatically alter this system. The lake plays an important role in providing habitat for plant and animal species, protection against floods, water purification, and amenities and recreational opportunities for the residents of northern China. However, water interception by upstream dams during the last 20 years and excessive water use by humans have dramatically decreased water levels in Baiyangdian Lake, decreasing its ability to provide ecosystem services and functions. Realizing the importance of maintaining the lake ecosystem's health, managers have attached increasing importance to management of its environmental flows, which means that additional water must be supplied to recharge the lake, raise the water level, and restore the deteriorated wetlands (Cui et al., 2010). Because of the importance of the eutrophication problem in the lake, we defined the environmental flows in terms of four key pollution parameters underlying the eutrophication problem (see section 2.3 for details).

At present, only water from the Fu River flows into Baiyangdian Lake, and before the water enters the lake, it runs through a detention and treatment pond to reduce the pollutant load. Nitrogen and phosphorus also enter the lake from the surrounding villages. This includes a total of 39 villages in raised fields and 84 other villages, whose population totals 271, 000. Domestic sewage, excrement, livestock wastewater, and aquaculture waste flow into the lake, which leads to severe eutrophication (Table 1).

Table 1. Pollutant Load Entering Baiyangdian Lake*

Source	Pollutant load (t/a)			
	COD	BOD	TN	TP
Industrial wastewater	10976.3	1520.5	476.28	28.69
Domestic sewage	9366.1	1155.9	706.45	74.67
Farm runoff and livestock wastewater	1588.3	365.7	368.09	5.16
Atmospheric precipitation	-	-	41.17	3.04
Recreational activities	1309.2	-	510.58	60.75
Aquaculture	-	-	20.15	3.07
Total	23239.9	3042.1	2122.72	175.4

* COD, chemical oxygen demand; NH_3-N, ammonia nitrogen; TN, total nitrogen; TP, total phosphorus; Data were obtained from the environmental protection bureau of An'xin County.

Table 2. Pollutant Load at Several Monitoring Sites*

Location	Pollutant load (mg/L)			
	COD	NH_3-N	TN	TP
Inlet of Fu River	25.3	12.6	13.6	1.27
Wangjiazhai Village	26.7	2.34	4.68	0.822
Duan Village	21.3	0.241	2.12	0.183
Nanliu Village	18.9	12.4	12.6	1.54
Zhainan Village	25.7	0.27	2.50	0.526
Yuanyang Island	34.1	10.8	12.4	1.54
Quantou Village	2.1	0.306	1.78	0.114
Dongdian Village	34.4	0.091	1.05	0.094

*COD, chemical oxygen demand; NH_3-N, ammonia nitrogen; TN, total nitrogen; TP, total phosphorus.

According to the Chinese environmental quality standards for surface water (GB3838-2002), concentrations of cyanide, fluoride, sulfide, volatile phenolics, oil, and most heavy metals in Baiyangdian Lake meet the criteria for class II water quality; this means that the water is suitable for irrigation, but not for drinking. However, the values of ammonia nitrogen (NH_3-N), total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD) mostly fail to meet the requirements for class III water quality; this means the water is not suitable for irrigation

(Tables 2 and 3). Based on an analysis of pollutant loads and actual water quality, we chose the dissolved oxygen (DO) content, NH_3-N, organic nitrogen (Org-N), and organic phosphorus (Org-P) as the variables in our simulation (see sections 2.3 and 2.4 for details).

Table 3. Chinese Environmental Quality Standards for Surface Water (mg/L, except for DO)*

Index	Class III	Class IV	Class V
DO	5	3	2
COD	20	30	40
NH_3-N	1	1.5	2
TN	1	1.5	2
TP	0.05	0.1	0.2

*DO, dissolved oxygen; COD, chemical oxygen demand; NH_3-N, ammonia nitrogen; TN, total nitrogen; TP, total phosphorus;

2.2. Spatial Distribution of Water Quality

To examine the spatial distribution of water quality, we used version 13 of the ArcInfo GIS software (ESRI, Redlands, CA) to divide the lake into 13 sub-areas based on whether standing water was present throughout the year, or only during the rainy season (Figure 2). We also considered administrative divisions, the distribution of monitoring stations, and water environment functional zones (e.g., water bird habitat, fish protection, reed cultivation). The borders between these sub-areas were initially based on administrative divisions, and were then revised to account for the aforementioned factors.

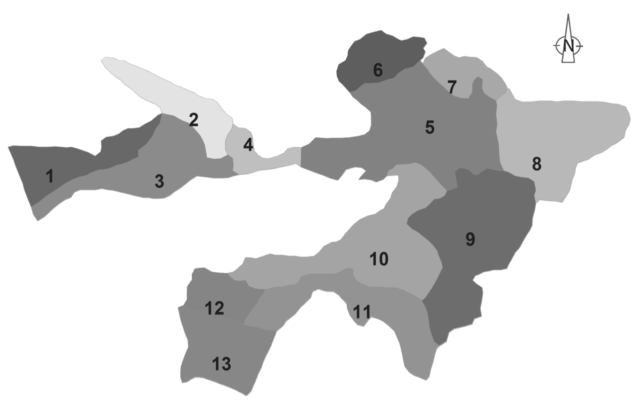

Figure 2. Ecological and administrative divisions (sub-areas) of Baiyangdian Lake.

2.3. Parameterization of the Water Quality Model

We used the WASP7 model for our simulation of water quality. To simulate the abovementioned pollutant loads, we used the EUTRO sub-model. EUTRO consists of four interacting systems: dissolved oxygen, the nitrogen cycle, the phosphorus cycle, and phytoplankton kinetics. Using these systems, EUTRO can simulate the transport of pollutants and transformations of up to eight state variables: DO, carbonaceous biological oxygen demand (CBOD), nitrate nitrogen (NO_3^-), inorganic phosphorus (PO_4^{3-}), chlorophyll-a, NH_3-N, Org-N, and Org-P (Figure 3). We used net flows instead of total flows to facilitate calculation of the impact of changes in flows of water and individual pollutants. We selected the Euler method provided by EUTRO as the solution technique, since this is the traditional approach that has been used in WASP since its inception. We considered impact factors such as temperature, wind speed, daily solar radiation, the light extinction coefficient, sediment oxygen demand, and phytoplankton in the WASP simulation. Data for these parameters were provided by the Environmental Protection Agency Monitoring Station of Baoding City.

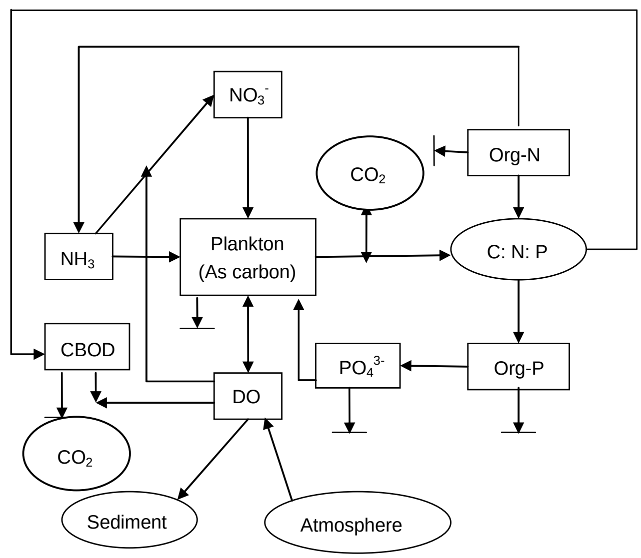

Figure 3. Structure of the EUTRO sub-model of the WASP software (Ambrose et al., 1993).

2.4. Water Quality Simulation Scenarios

We first simulated the water quality in Baiyangdian Lake in a "do-nothing" scenario, with no change from the current situation (Tables 1 and 2), and then repeated our simulation for different pollutant discharge and water-release scenarios. Based on the simulation results, we defined additional scenarios that coupled water quantity with water quality (Figure 4).

3. Model Calibration and Validation

Before performing the simulations using the water quality model, it is necessary to calibrate the model and verify its ability to simulate the system being studied using data for the system. Monitoring data for Baiyangdian Lake were obtained from the State Environmental Protection Agency monitoring stations surrounding the lake and were used for calibration of the model's parameters and validation of the model's outputs. Monthly continuous observations of the lake's water quality have been performed since 2005, and seven monitoring sites have been established to cover most of the lake (Figure 1). We divided the available data into two parts: calibration samples and validation samples. The calibration samples were used to calibrate the model before running the simulations, and the validation samples were used to check whether the prediction performance of the calibrated WASP model was acceptable.

Table 4. Main Parameters in the WASP Model

Parameter	Units	Value
Nitrification rate (20°C)	day^{-1}	0.08
Temperature coefficient for nitrification	—	1.08
Half-saturation constant for nitrification oxygen limitation	mg O_2/L	2
Denitrification rate (20°C)	day^{-1}	0.09
Temperature coefficient for denitrification	—	1.04
Half-saturation constant for denitrification oxygen limitation	mg O_2/L	0.1
Dissolved org-N mineralization rate	day^{-1}	0.1
Dissolved org-N mineralization temperature coefficient	—	1.07
Dissolved org-P mineralization rate	day^{-1}	0.27
Dissolved org-P mineralization temperature coefficient	—	1.07
Phytoplankton maximum growth rate	day^{-1}	0.19
Phytoplankton endogenous respiration rate	day^{-1}	0.03
Phytoplankton respiration temperature coefficient	—	0.04
Phytoplankton death rate	day^{-1}	0.04
Phytoplankton zooplankton grazing rate	day^{-1}	0.09

Table 5. The Relative Error Values for the Water Quality Simulated Using WASP 7*

	DO	NH_3-N	Org-N	Org-P
RE (%)	24	-0.9	6.4	5.4

*DO, dissolved oxygen; NH_3-N, ammonia nitrogen; Org-N, organic nitrogen; Org-P, organic phosphorus.

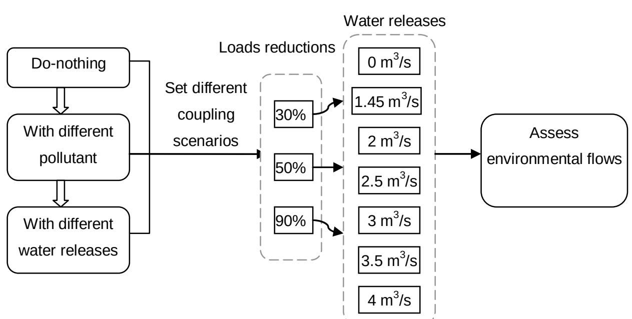

Figure 4. Summary of the simulation scenarios investigated in this study.

We defined the preliminary parameters for WASP using previously published values (Tufford and McKellar, 1999; Wang et al., 1999). We then ran the simulation using the calibration data and compared the outputs with values measured at the monitoring sites around the lake. If necessary, we adjusted the input parameters until the simulation results were close to (within 0.5 SD of) the measured values, and Table 4 shows the final calibrated parameters. After the calibration process, we applied the same parameters to verify the model against the validation dataset. The mean relative error (RE) was calculated to as follows:

$$RE = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\frac{C_i - C_{0i}}{C_{0i}}\right)^2} \times 100\% \qquad (1)$$

where N is the number of samples, C_i is the simulated value at location i in the lake, and C_{0i} is the measured value at location i.

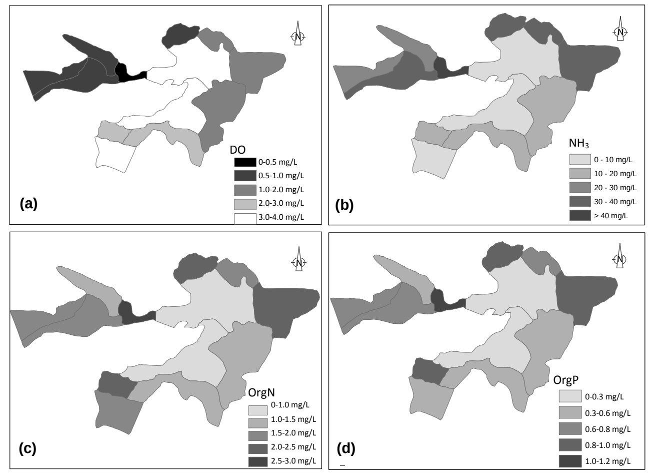

Figure 5. Spatial distribution of a) DO, b) NH_3-N, c) Org-N, and d) Org-P with the status in quo.

The mean relative errors for the simulated NH_3-N, Org-N, and Org-P were less than 10% (Table 5). The DO error was slightly more than 20%, largely because this parameter fluctuates greatly in response to many factors. The results generally showed acceptable reliability and suggest that the calibrated model could be applied in our simulations.

4. Results

4.1. Do-nothing Scenario

In this scenario, we simulated the changes in DO, NH_3-N, Org-N, and Org-P from August to September 2009 with no change from the current situation. DO decreased rapidly during the first 10 days, and then varied slightly. However, the DO in each sub-area was less than 5 mg/L, which meets the criterion for Class III water quality. NH_3-N in each sub-area increased as a result of the large pollutant loads. Org-N showed different patterns of variation in each sub-area during the first 3 days. Most segments showed decreases caused by mineralization, followed by increases due to the high pollutant load. Org-P showed a gradual increase as a result of the large pollutant load. Figure 5 shows that the pollution was worst in sub-area 4, which includes Nanliu Village and is near the inlet of the Fu River. Here, NH_3-N, Org-N, and Org-P concentrations were highest, reaching 68.18, 2.94, and 1.2 mg/L, respectively. If no mitigation measures are adopted, water quality in the lake would continue to decrease sharply, so the lake managers must act immediately to improve the water environment and protect the lake ecosystem. Based on our initial analysis, sub-area 4 was most severely polluted, so we chose it as a typical area for further analysis.

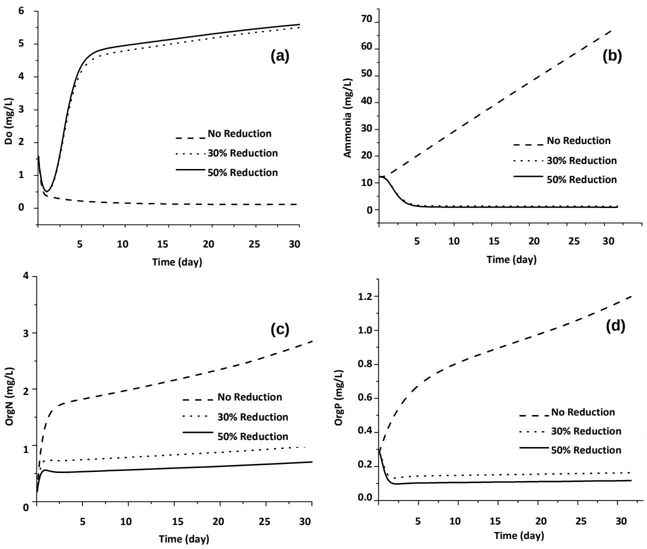

Figure 6. Changes in a) DO, b) NH_3-N, c) Org-N, and d) Org-P in sub-area 4 with different pollutant load reductions.

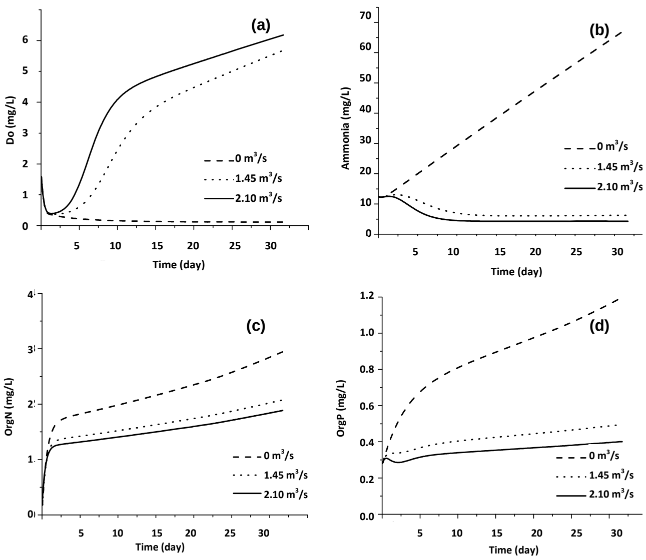

Figure 7. Changes in a) DO, b) NH_3-N, c) Org-N, and d) Org-P in sub-area 4 with different water-release levels.

4.2. Changing the Pollutant-discharge Strategies

To help the lake managers adopt reasonable management solutions, we simulated the water quality in scenarios that were based on reducing pollutant loads by 30 and 50% of the actual load. Using sub-area 4 as a representative area, we compared the results with the no-reduction scenario. DO increased obviously in the scenarios with 30 and 50% reductions of the pollutant loads, whereas DO continued to decrease in the non-reduction scenario (Figure 6a). The final simulated DO values in the two reduction scenarios were 5.55 and 5.64 mg/L, respectively, versus a near-zero value in the no-reduction scenario. In the 30 and 50% scenarios, NH_3-N decreased rapidly during the first 5 days, and then stabilized (Figure 6b). The final simulated concentrations in the two reduction scenarios were 1.2 and 0.86 mg/L, respectively, compared with 68.18 mg/L in the non-reduction scenario. The Org-N concentration tended to stabilize in the two reduction scenarios (Figure 6c), with the simulated concentrations reaching 1.0 and 0.72 mg/L, respectively, for the 30 and 50% reductions, whereas the concentration continued increasing (to values greater than 3 mg/L) in the non-reduction scenario. The Org-P concentration decreased rapidly in the first few days of the two reduction scenarios, and then stabilized (Figure 6d). The final simulated concentrations were 0.16 and 0.11 mg/L, respectively, in the 30 and 50% reductions, whereas Org-P continued to increase (above 1.1 mg/L) in the no-reduction scenario. Based on these results, water quality could be improved greatly by reducing the pollutant loads.

4.3. Water-release Scenarios

To determine the effects of increasing water transfers into the lake, we chose transfer rates of 1.45 and 2.1 m^3/s and used the model to compare the results with a scenario in which no water transfer occurred.

In the two water-transfer scenarios, DO increased obviously (Figure 7a), reaching values of 5 mg/L on 4 September (1.45 m^3/s) and 24 August (2.1 m^3/s), so that both met the Class III water quality criteria, versus a value of 1.58 mg/L in the non-transfer scenario. The NH_3-N concentration gradually decreased and then stabilized (Figure 7b), but did not meet the Class III criteria because of the high pollutant load. The final simulated concentrations were 6.24 and 4.31 mg/L, respectively. Figures 7c and 7d show that the Org-N and Org-P concentrations continued to increase, but much more slowly than in the no-transfer scenario. Org-N in the water-transfer scenarios decreased to 2.07 mg/L (1.45 m^3/s) and 1.87 mg/L (2.1 m^3/s), versus 2.94 mg/L in the no-transfer scenario. The effect of water transfers on Org-N was smaller than the effect on DO and NH_3-N. The Org-P concentration decreased to 0.49 and 0.40 mg/L, respectively, in the water-transfer scenarios, versus a value greater than 1.2 mg/L in the no-transfer scenario.

In summary, increasing the water transfer mitigated the water deterioration to some extent, but was less effective than reducing pollutant loads. Based on these results, the quantity of the water transfer required to mitigate the pollution problems would probably be unrealistically high for the study area given current constraints on water availability. We did not consider the ideal water transfer to fully meet the ecological water demand, but simply diluting the return water entering the lake seems unlikely to solve the pollution problem.

4.4. Scenarios that Combine Changes in Water Quality and Quantity

Based on the results of our simulations of the effect of pollution reductions and increased water releases, we developed additional scenarios that combined changes in both water quality and quantity. We then estimated the ecological water requirements for Baiyangdian Lake. Since primary treatment could remove 30% of the organic pollutant load, adding a secondary treatment stage could remove 90% of the organic pollutant load,

Table 6. Environmental Flows Based on Different Pollution Treatment Rates and Water Releases into the Lake (10^8 m^3).

	Optimal scenarios			No considera-tion of water quality*
	(30%, 3.5 m^3/s)	(50%, 3 m^3/s)	(90%, 1.45 m^3/s)	
Monthly	0.961	0.947	0.908	0.870
Yearly	3.87	3.70	3.23	2.870

*Results from Zhong et al. (2008).

and the wastewater treatment efficiency of urban areas surrounding the lake should be no less than 50%, we set targets of 30, 50, and 90% reductions in pollutant loads as the simulated treatment rates. For each treatment rate, we also set a sub-series of 0, 1.45, 2.0, 2.5, 3.0, 3.5, and 4.0 m^3/s water releases into the lake to estimate the ecological water requirement.

Table 6 summarizes the results of this analysis, and compares them with the results of a previous study (Zhong et al., 2008) that did not consider water quality. Based the simulation of water quality, we proposed optimal scenarios (30% plus 3.5 m^3/s, 50% plus 3 m^3/s, and 90% plus 1.45 m^3/s) to improve the water environment of Baiyangdian Lake. Note that here, we have defined "optimal" to mean that the results met the Chinese water quality criteria; we did not attempt to determine globally optimal solutions. Because the ability to release water into the lake is severely constrained, we chose the lower of the three water-release scenarios for further analysis. Figure 8 shows the water quality distribution in Baiyangdian Lake with a 90% reduction in pollution load and a water release of 1.45 m^3/s. It is important to note that the choice of a target treatment efficiency level depends on many factors, including the treatment cost and the types and distributions of the pollutants.

Figure 8. Spatial distribution of a) DO, b) NH_3-N, c) Org-N, and d) Org-P with 90% reduction in pollutant load and water releases of 1.45 m^3/s.

5. Discussion

Our results show that considering only water quantity is unlikely to solve the pollution problem in Baiyangdian Lake, particularly in dry years when water releases would be severely constrained. To mitigate pollution problems in the lake, managers not only must consider natural factors such as the ecological structure and function of each sub-area of the lake and the value of the natural environment, but also should consider the value of improved water quality, especially in areas that are experiencing pollution-induced water shortages. Water consumption and the quality and quantity of the return water are key factors in determining environmental flows, and improving these factors requires improvements in water-utilization efficiency, as well as the calculation of appropriate dilution ratios for the return water. Research on the effects of pollutant loads in the return water on water quality in the lake can help managers to determine the lake's required environmental flows and develop appropriate water management and allocation scenarios.

In this paper, we simulated DO, NH_3-N, Org-N, and Org-P in Baiyangdian Lake using version 7 of the WASP model, combined with the EUTRO sub-model, and analyzed changes of water quality in several scenarios for reduction of pollutant loads, increased water releases into the lake, and combinations of the two approaches. We found that return water such as industrial wastewater and domestic sewage with a large organic pollutant load would worsen the eutrophication problem in Baiyangdian Lake, whereas reducing pollutant loads combined with transferring water into the lake could improve the water quality to a greater degree. Our predictions of water quality variations using the WASP model showed that with appropriate calibration and validation, this model can provide reliable information to support water treatment and allocation decisions. By using the model to calculate reasonable environmental flows and to optimize the water distribution, managers could increase water-utilization efficiency and decrease the organic loads entering the lake. Our results also show that predicting changes in water quality can help managers calculate environmental flows, but this is not the final objective of water management. Managers must also use the results to learn how to optimize water allocation and how to reduce pollutant loads entering the lake.

6. Conclusions

Using Baiyangdian Lake, a shallow freshwater lake in northern China, as a case study, we simulated the spatial distribution of water quality by focusing on four key pollutants that are responsible for eutrophication. To do so, we used version 7 of the WASP model and the EUTRO eutrophication sub-model to analyze changes in water quality in scenarios based on different non-point-source pollutant loads and different artificial water releases into the lake, thereby revealing the relationships between water quality improvement and artificial water allocation. Based on our modeling results, we proposed optimal scenarios that combined a reduction in pollutant loads with increased water releases to improve the lake's water environment (30% reduction plus 3.5 m^3/s water release, 50% plus 3 m^3/s, and 90% plus 1.45 m^3/s). The results show that this simulation approach provides a useful tool to support adaptive management of the lake's water quality and environmental flows.

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References

Ambrose, R.B., Wool, T.A., and Martin, J.L. (1993). *The water quality analysis simulation program, WASP5.* Part A: model documentation. U.S. Environmental Protection Agency, Center for Exposure Assessment Modeling, Athens, GA.

Arthington, A.H. (1998). Comparative evaluation of environmental flow assessment techniques: review of holistic methodologies. Report OP26/98. Land and Water Resources Research and Development Corporation, Canberra.

Cui, B.S., Zhao, X.S., and Yang, Z.F. (2005). Eco-hydrology based calculation of the minimum ecological water requirement, *Acta Ecologica Sinica*, 25(7), 1789-1795.

Cui, B.S., Li, X., and Zhang, K.J. (2010). Classification of hydrological conditions to assess water allocation schemes for Lake Baiyangdian in North China, *J. Hydrol.*, 385, 247-256. http://dx.doi.org/10.1016/j.jhydrol.2010.02.026

Forsythe, K. W., Paudel, K., and Marvin, C. H. 2010. Geospatial Analysis of Zinc Contamination in Lake Ontario Sediments. *J. of Env. Inform.*, 16(1), 1-10. http://dx.doi.org/10.3808/jei.201000172

Furia, L.D., Rizzoli, A., and Arditi, R. (1995). Lakemaker: A general object-oriented software tool for modelling the eutrophication process in lakes, *Environ. Software*, 10(1), 43-64. http://dx.doi.org/10.1016/0266-9838(94)00016-Z

Giardino, C., Brando, V.E., Dekker, A.G., Strombeck, N., and Candiani, G. (2008). Assessment of water quality in Lake Garda (Italy) using Hyperion, *Remote Sens. Environ.*, 109, 183-195. http://dx.doi.org/10.1016/j.rse.2006.12.017

Gupta, A.D. (2008). Implication of environmental flows in river basin management, *Phys. Chem. Earth* , 33, 298-303.

Gurkan, Z., Zhang, J.J., and Jørgensen, S.E. (2006). Development of a structurally dynamic model for forecasting the effects of restoration of Lake Fure, Denmark, *Ecol. Model.*, 197(1-2), 89-102. http://dx.doi.org/10.1016/j.ecolmodel.2006.03.006

Kashaigili, J.J., Kadigi, R.M.J., Lankford, B,A., Mahoo, H.F., and Mashauri, D.A. (2005). Environmental flows allocation in river basins: Exploring allocation challenges and options in the Great Ruaha River catchment in Tanzania, *Phys. Chem. Earth,* 30(11-16), 689-697.

McIntyre, N.R., and Wheater, H.S. (2004). A tool for risk-based management of surface water quality, *Environ. Model. Software*, 19 (12), 1131-1140. http://dx.doi.org/10.1016/j.envsoft.2003.12.003

Ping, J., Chen, Y., Chen, B., and Howboldt, K. (2010). A Robust Statistical Analysis Approach for Pollutant Loadings in Urban Rivers. *J. of Env. Inform.*, 16(1), 35-42. http://dx.doi.org/10.3808/jei.2010 00176

O'Keefe, J. (2000). Environmental flow assessments: background and assumptions. In: King, J.M., Tharme, R.E., and De Villiers, M.S. (Eds.), *Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology*. Water Research Commission, Report No. TT131/00, Pretoria, South Africa.

Sherrard, J.J. (1991). Complex response of a sand bed stream to upstream impoundment, *Regulated Rivers: Res. Manage.*, 6, 53-70.

Smakhtin, V.U., Shilpakar, R.L., and Hughes, D.A. (2006). Hydrology-based assessment of environmental flows: an example from Nepal, *Hydrol. Sci. J.*, 51 (2), 207-222. http://dx.doi.org/10.1623/hysj.51.2.207

Thomas, R.T., James, M., Wool, T., and Wang, P.F. (1997). A sediment resuspension and water quality model of Lake Okeechobee, *J. Am. Water Resour. Assoc.*, 33(3), 661-680. http://dx.doi.org/10.1111/j.1752-1688.1997.tb03540.x

Tufford, D.L., and McKellar, H.N. (1999). Spatial and temporal hydrodynamic and water quality modeling analysis of a large reservoir on the South Carolina (USA) coastal plain, *Ecol. Model.*, 114, 137-173. http://dx.doi.org/10.1016/S0304-3800(98)00122-7

Vuksanovic, V., and Smedt, F.D. (1996). Transport of polychlorinated biphenyls (PCB) in the Scheldt Estuary simulated with the water quality model WASP, *J. Hydrol.*, 174, 1-18. http://dx.doi.org/10.1016/0022-1694(95)02759-9

Wang, P.F., Martin, J., and Morrison, G. (1999). Water quality and eutrophication in Tampa Bay, Florida, *Estuar. Coast. Shelf Sci.*, 49, 1-20.

Wu, Z.N. and Suo, L.S. (2007). Model and its application for integrated optimal distribution of water quality and quantity based on ecology economy, *J. Irrigation Drainage,* 26(2), 1-6.

Yang, Z.F., and Mao, X.F. (2011). Wetland system network analysis for environmental flow allocations in the Baiyangdian Basin, China, *Ecol. Model.*, 222(20-22), 3785-3794. http://dx.doi.org/10.1016/j.ecolmodel.2011.09.013

Zhong, P., Yang, Z.F., Cui, B.S., and Liu, J.L. (2008). Eco-environmental water demands for the Baiyangdian Wetland, *Frontiers of Environmental Science & Engineering in China*, 2(1), 73-80. http://dx.doi.org/10.1007/s11783-008-0015-y