A GIS-Based Water Quality Assessment and Pollution Control Planning Approach for Lake Management (WQAPCP)

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ABSTRACT

Many lakes are receiving large volumes of contaminants from agricultural discharges, industrial emissions and municipal wastewater, which causes significant surface water pollution. The adverse environmental and health effects of lake contamination are a primary concern in environmental management. Water quality assessment methods and pollution control planning models are useful tools for researchers and decision-makers to protect ecological environments and develop local economies. Also spatial information technologies such as Geographic Information Systems (GIS) make it possible to manage water bodies with more detailed location-based information.

The goal of this thesis is to develop a GIS-based water quality assessment and pollution control planning approach for lake management (WQAPCP), which includes the following components: (1) evaluation of water quality based on four index methods with inter-comparisons; (2) pollution control planning for a lake system based on an integration of pollutant distribution simulation and optimization models along with water quality index measures; (3) GIS technology to help implementing water quality assessment and lake contamination control optimization by creating displayed maps of the study results to provide spatial support for decisions.

Several water quality evaluation methods are first presented in this thesis within the GIS framework to examine water quality index models, including the US Oregon water quality index (OWQI), the Canadian water quality index (CWQI), the Chinese

single-factor water quality index (CNWQI-S) and the Chinese comprehensive water quality index (CNWQI-C) methods. These index methods are applied to assess the water quality of a real case. The assessment results are presented in the form of GIS maps containing the spatial distribution of the water quality levels and their ranking. Through an example of sensitivity analysis and comparison of four sets of water quality assessment results, the parameters with the most significant influence on lake water quality are identified and the most suitable method of water quality evaluation is put forward to support future lake management.

Subsequently, this thesis develops a simulation-optimization approach by integrating lake water quality simulation and lake pollution control optimization. A contaminant dispersion simulation is first conducted to provide input for the optimization study. Particularly, a single-objective programming (SOP) model and a multi-objective programming (MOP) model are developed, applied, and compared to support effective lake water contamination control planning under different lake management scenarios. Three periods and a set of significant levels are considered in the real case study to provide a comprehensive dynamic modeling and optimization analysis of lake pollution control through the simulation-optimization approach. Based on the developed optimization method and the case study results, the OWQI and CNWQI-C methods are utilized to help formulating the effective measures for lake water quality management.

GIS technology is employed in this study to link the water quality assessment approaches and the lake pollution control optimization. By integrating the relevant data and creating visualized maps of the study results, GIS plays an important role in extending the modeling and assessment results for the lake water quality management with spatial geo-references.

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Table OF Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

n	number of these samples
S_n	result of single sub-index
F_1	scope
F_2	frequency
F_3	amplitude
nse	normalized sum of excursions
C	concentration
C_o	O-grade standard concentration
C_{o+1}	(O + 1)-grade standard concentration
D	distribution coefficient
A	constant of concentration dispersion equation
B	constant of concentration dispersion equation
I_0	Bessel function of the first kind
K_0	Bessel function of the second kind.
k	period 1, 2 and 3
i	a set of significant levels
p_i	a probability for the constraints
AX_{ik}	area of agricultural land with a probability level of p_i during period k
LX_{ik}	number of livestock with a probability level of p_i during period k
FX_{ik}	area of aquaculture with a probability level of p_i in period k
PX_k	number of residents during period k

ANB_k	net benefit from agricultural plantation in period k
LNB_k	net benefit from farmed livestock in period k
FNB_k	net benefit from aquaculture raised with fish in period k
AWD_k	water demand for agricultural land planted in period k
LWD_k	water demand for livestock raised in period k
FWD_k	water demand for aquaculture farmed with fish in period k
RWD_k	water demand for residents in the system during period k
EWD_k	water demand for ecological protection during period k
AP_k	amount of phosphorus generated by agricultural activities in period k
LP_k	amount of phosphorus generated by livestock in period k
FP_k	amount of phosphorus generated by fish in period k
PP_k	amount of phosphorus generated by human activities
TP_k	maximum allowable amount of phosphorus emission during period k
α_{lk}	average treatment efficiency for phosphorus discharged from livestock in period k
α_{pk}	average treatment efficiency for phosphorus discharged from resident in period k
$ANH_3\text{-}N_k$	amount of ammonia nitrogen generated by agricultural activities in period k
$LNH_3\text{-}N_k$	amount of ammonia nitrogen generated by livestock in period k
$FNH_3\text{-}N_k$	amount of ammonia nitrogen generated by fish in period k
$PNH_3\text{-}N_k$	amount of ammonia nitrogen generated by human activities
$NH_3\text{-}N_k$	maximum allowable amount of ammonia nitrogen during period k

β_{lk} average treatment efficiency for ammonia nitrogen discharged from livestock in period k

β_{pk} average treatment efficiency for ammonia nitrogen discharged from resident in period k

$ABOD_k$ amount of BOD_5 generated by agricultural activities in period k

$LBOD_k$ amount of BOD_5 generated by livestock in period k

$FBOD_k$ amount of BOD_5 generated by fish in period k

$PBOD_k$ amount of BOD_5 generated by human activities in period k

BOD_k maximum allowable amount of BOD_5 during period k

θ_{lk} average treatment efficiency for BOD_5 discharged from livestock in period k

θ_{pk} average treatment efficiency for BOD_5 discharged from residents in period k

TWi_k maximum allowable amount of water resources available with a probability level of p_i in period k

ALA_k maximum allowable area of land for agriculture during period k

ILA_k minimum area of agricultural land demanded in period k

ALS_k maximum allowable number of livestock in period k

ILS_k minimum number of livestock demanded in period k

AWF_k maximum allowable area of water for aquaculture during period k

LIST OF ACRONYMS

WQI	Water Quality Index
AWQI	National Sanitation Foundation Water Quality Index (NSF WQI)
MWQI	Multiplicative Water Quality Index
OWQI	Oregon water quality index
CCME	Canadian Council of Ministers of the Environment
CWQI	Canadian Water Quality Index
CNWQI	Chinese Water Quality Index
CNWQI-C	Chinese Comprehensive Water Quality Index
CNWQI-S	Chinese Single-Factor Water Quality Index
GIS	Geographic Information System
SOP	Single-Objective Programming
MOP	Multiple-Objective Programming
HJH Lake	Huang Jia Hu Lake
CESI	Canadian Environmental Sustainability Indicators
P	Phosphorus
TP	Total Phosphorus
NH_3-N	Ammonium Nitrogen
NO_3-N	Nitrate Nitrogen
BOD_5	Five-Day Biological Oxygen Demand
DO	Dissolved Oxygen
TSS	Total Suspended Solids

pH	Hydrogen Ion Concentration
Tur	Turbidity
T	Temperature
HUST	Huazhong University of Science and Technology

CHAPTER 1 INTRODUCTION`

1.1 Problem Statement

In recent decades, aquatic ecological deterioration and the degradation of surface water have turned into primary environmental concerns all over the world (Sánchez-Avila et al., 2009). Out of the various types of water bodies, lakes are facing a particularly significant challenge because their water quality is descending along with the growth of human populations while industry and agriculture are advancing rapidly (United Nations, 2014). Lakes inevitably receive large volumes of agricultural discharge, industrial sewage, and municipal wastewater which cause water body pollution at different levels (Jing et al., 2008). Moreover, the quantity of contaminants discharged into lakes has significantly increased, especially in developing nations (Zhao et al., 2006). These pollutants include microbiological organisms, suspended matter, biodegradable organic compounds, heavy metals, nitrates, nutrients, salts, and organic micropollutants (Helmer and Hespanhol, 2011). The degradation of lake water quality is consequently turning into an urgent issue in most countries (United Nations, 2014). Lake eutrophication, for example, has become a major pollution problem worldwide, especially in areas with high-density populations and intensive agricultural activities (Anders, 2012).

Surface water quality evaluation through multi-parameter indices plays a significant role in environmental control and management. Decision-makers can make effective policies to manage water bodies based on the results for water quality assessments. Since the last century, environmental researchers have studied and produced several water quality evaluation methods worldwide (Hurley et al., 2012). A water quality index model called the National Sanitation Foundation Water Quality Index model (NSF WQI, later named AWQI) was first proposed (Horton, 1965; Lumb et al., 2011). Brown et al. (1973) then put forward a version of NSF WQI modified using the multiplicative method (hereafter named MWQI). The Oregon Department of Environmental Quality later presented the well-known Oregon water quality index (OWQI) (Cude, 2001). This was followed by a new water quality index (CCME-WQI, abbr. CWQI) developed by the Canadian Council of Ministers of the Environment (CCME) (CCME, 2001). Finally, based on the Chinese 5-level water quality standard (GB3838, 2002), water quality evaluation approaches in China were developed including the single-factor water quality index (CNWQI-S) and comprehensive water quality index (CNWQI-C) assessment methods (Zhu et al., 2010; Li et al., 2012).

During the same period, several optimization programming techniques were also used for water contamination management and decision-making. A plant aggregation approach was presented by Zhao et al. (2009) to balance local industry and wastewater discharge. An integrated programming model was developed by Ham et al. (2010) in planning the scale of constructed wetlands to improve water quality. By the single objective method, Liu et al. (2008) proposed a linear programming model with inexact chance-constraints to optimize water pollution management. Cheng and Chang (2010) proposed a multi-objective, fuzzy genetic algorithm-based programming model to control water contamination in river basins.

The measures mentioned above have advantages and limitations as water quality assessment methods and approaches to pollution control planning. In the traditional water quality index (WQI) evaluation methods, AWQI and MWQI are arbitrary since their most significant parameters and weights were derived from the opinions of water experts based on field-test data. Due to its data requirements, CWQI is not usable for most projects. CNWQI-S is also too one-sided because of its negation of all the other better data. Both the OWQI and CNWQI-C models have more advantages and are thus employed to a greater degree in the following chapters of this thesis. In lake water quality management, there is a series of issues regarding inter-effects among the parameters such that if only a single sector is considered, the relevant results will be inexact or even incorrect, and the related conclusions will not provide useful guidance to decision-makers. Most previous optimization techniques faced difficulty in clearly illuminating the inter-reactions between all relevant elements due to the large amounts of data, competing objectives, unquantifiable factors and uncertainty during parameterization (Cheng and Chang, 2010). Researchers have to seriously consider multiple procedures with complex interrelationships.

In summary, all existing water management measures have limitations and little related research toward integrating: 1) water quality assessment methods; 2) pollution control planning models; and 3) convenient and direct methods of showing the scale of contamination of water bodies.

Accordingly, this research presents a GIS-based water quality assessment and pollution control planning approach for lake management (WQAPCP). This measure is effective for managing lake-related data, facilitating the application of water quality index methods and contamination control optimization models, and helping to communicate complex information, including indices of examined results and optimization data, to a wide range of groups through map-oriented visualizations. In this thesis, there are comparisons based on the four traditional water quality evaluation methods and SOP and MOP models as well as further comparisons of two index-assessment measures based on the same planning results. GIS technology shows strong advantages in its recent application to environmental projects to integrate water management measures through the efficient handling of pollutant distribution, water quality parameters, socioeconomic data and geophysical features. With powerful functions for visualizing data and analyzing results, GIS can help decision-makers achieve a better balance between water pollution control and economic development (Debaine and Robin, 2012). The integration of GIS, water quality assessment and contamination control optimization synthesizes their functions and advantages and makes conclusions more acceptable to a variety of stakeholders. To validate the practicability of this study, a real case, named Huang Jia Hu Lake (abbr. HJH Lake) and located in Central China, was employed in the research.

1.2 Research Objectives

This thesis aims to develop a GIS-based water quality assessment and pollution control planning approach for lake management (WQAPCP) which includes water quality assessment methods, pollution control planning models, and GIS technology. The results for water quality evaluation and lake optimization are presented in maps which clearly show the differences between a diversity of compared approaches. Moreover, WQAPCP is performed in detail according to the following steps:

(1) To evaluate water quality assessment methods based on comparison and analysis using OWQI, CWQI, CNWQI-S and CNWQI-C index models, where key water quality parameters are considered.

(2) To develop a modeling approach for lake pollution control planning based on certain objectives and a number of environmental, social and economic constraints with a comparison between SOP and MOP models. Based on the same planning results, OWQI and CNWQI-C methods are respectively applied in a real case study to identify a better method of index evaluation of water quality.

(3) To propose a new lake management approach integrating water quality assessment, lake contamination control optimization models and a GIS framework. The case studies are all conducted on the same real case.

(4) To evaluate trade-offs between economic benefits, lake water quality and other factors and provide feasible options to decision-makers through the integrated approach.

1.3 Thesis Organization

Six chapters are organized in this thesis:

Chapter 1 shows the research background, states the research problems, specifies the research objectives and briefly presents the research methodologies.

Chapter 2 provides an extensive literature review regarding water quality assessment, optimization modeling, and the integration of Geographical Information Systems.

Chapter 3 describes the theories and methodologies regarding the development of a lake management approach, including water quality assessment methods and lake pollution control optimization models. The evaluation and planning models are integrated with the ArcGIS Engine and databases.

Chapter 4 provides a real case study wherein four water quality assessment methods are applied within a GIS framework. Based on widely-used index measures (OWQI, CWQI, CNWQI-S, and CNWQI-C), the water quality results for the evaluation clearly present the diversity of results obtained by using these evaluation methods in different water areas. Additionally, an example of sensitivity analysis is presented to discover the controlling parameters which exert a significant influence on lake water quality.

Chapter 5 depicts the same case, wherein water quality simulation and lake pollution control planning are applied based on GIS technology. Firstly, contaminant dispersion simulation plays a significant role in validating the probability of the following lake optimization. Then, two planning approaches for modeling lake systems, the SOP model and the MOP model, are presented and compared in order to identify a more acceptable approach for lake planning. Finally, there is a modeling comparison between the OWQI and CNWQI-C methods based on MOP optimization under two probabilities and two periods.

Chapter 6 exhibits the conclusions and research contributions as well as recommendations for future work.

CHAPTER 2 LITERATURE REVIEW

This chapter provides an overview of several water quality assessment methods, water pollution control optimization models, and water quality management-based geographical information systems. These evaluation measures, planning models, and spatial data techniques are partly used in this thesis to validate their feasibility and put forwards thoughtful options regarding lake protection and contamination control to decision-makers.

2.1 Water Quality Assessment

2.1.1 Water quality index methods

In 1848, German experts proposed the concept of water quality to classify water levels based on grades of pureness or contamination (Sladecek, 1973; Dojlido and Best, 1993). Meanwhile, the significance of the connection between human health and water quality was discovered in Britain and Snow identified poor water quality as the cause of the spread of cholera (Snow, 1854).

Since the introduction of the concept of water quality, scientists have spent more than 100 years advancing the technology used to evaluate it. In 1965, Horton applied the measure of digital indices to assess water quality in the Ohio River, and a numerical system for the water quality index (WQI) was used to categorize water quality through the selection and integration of relevant physical, chemical and biological water parameters based on certain proportions. An improved water quality index model called the National Sanitation Foundation Water Quality Index (NSF WQI, later named AWQI) model was used. The sub-index ranges from 0 to 100, the weighting factors have a range of 0-1, and the results rise from the sum of the relative values. Although the AWQI model was easy to use and calculate, it had the limitation of sensitivity insufficiency in the case of a single parameter overpassing its guideline on the WQI. Therefore, Brown et al. (1973) presented a multiplicative model based on the NSF WQI (later called MWQI). These two measures were widely verified at dozens of stations in several American states (McClelland, 1976a, 1976b; Steinhart et al., 1981). Afterwards, the models and concepts derived from the NSF were adjusted or modified for use in rating the quality of surface water all across the USA (Dunnette, 1979; Steinhart et al., 1982).

In the past couple of decades, the Oregon Water Quality Index (OWQI) method was used extensively to evaluate surface water quality worldwide. In the OWQI model, aggregate amounts are integrated to build a score representing different quality graduations to assess water quality (Cude, 2001). The employment of the OWQI measure markedly developed the technology of water quality evaluation in the 1970s (Dunnette, 1979). Subsequently, the advanced OWQI was used in 1995 to show the status and tendency of water quality to policy makers and the public (http://www.deq.state.or.us/lab/WQM/WQI/wqimain.htm). The OWQI model integrated into a large number of environmental indicators has become a tool for providing traditional reports including water quality status descriptions and water quality assessment analysis (Cude, 1999). Moreover, the OWQI approach was also used and amended to build other water quality indices in Australia (Richard, 1997). Until now, the OWQI method has been accepted worldwide for application in surface water management and extensively adopted in daily environmental communications on water quality.

A new measure was proposed in the late 1990s in the form of the Canadian Council of Ministers of the Environment (CCME) Water Quality Index (CWQI). It was entirely different from the index based the NSF concept. The CWQI model is a necessary tool to guide users in collecting sufficient water quality data from sampling stations and putting them into index values. According to a series of technical reports across Canada, the index was improved to be the ultimate measure after the study was completed in the province of British Columbia (Rocchini and Swain, 1995; B.C. Ministry of Environment, 1996). The CWQI has been employed to determine the water quality status in the provinces of British Columbia, Newfoundland and Alberta (Newfoundland Department of Environment, 2001), as well as in the city of Edmonton and the Toronto Region Conservation Authority (City of Edmonton, 2003; Forester, 2000). In the city of Halifax, a workshop was established to help researchers obtain practical experience with the CWQI in 2003 (Environment Canada, 2003). This index measure was employed in the workshop as an available tool to share water quality results arising from a large amount of complex sampling data. Using the CWQI model, the Canadian government created the Canadian Environmental Sustainability Indicators (CESI) for reporting on environmental information including air quality, water quality, and greenhouse gas emissions (CESI, 2008). Furthermore, the CWQI method was able to show the distribution of nutrients, pesticides, bacteria and metals in water bodies through sub-indices (AEP, 2016). The United Nations Environmental Program regards the CWQI model as a valuable measure for evaluating the quality of drinking water worldwide (Rickwood and Carr, 2009).

As one of the most advanced Asian countries, China has unique measures to water quality assessment. In most of central and southern China, the primary source of drinking water is surface water because of its low cost and convenience. Based on the Chinese secure guarantee plan for public drinking water resources, some concepts were defined to present a security assessment of municipal drinking water resources. By using a method integrating water quality, water quantity, risk resistance capability and the security assessment indicator system, Zhu et al. (2010) conducted a safety assessment of general drinking water resources in China. Based on the results for the water quality security evaluation, the water quantity and risk-resistance capability of water resources in cities were assessed in their research. Water quality assessment was the first step toward the protection and management of water bodies. On the basis of "Chinese Surface Water Environment Quality Standard" (GB3838, 2002), the water quality evaluation index was classified into five levels, 1 to 5, respectively representing 5 types of water quality classes: excellent, good, medium, poor, and very poor. There are two methods for evaluating the quality of surface water resources, namely the single-factor assessment (abbr. CNWQI-S) method and the comprehensive assessment (abbr. CNWQI-C) method. For CNWQI-S, the maximum individual index is treated as the water quality assessment index for the relevant projects. The results for CNWQI-C need to be computed based on the relevant equations and requirements (Li et al., 2012).

2.1.2 Other water quality assessment studies

In addition to the above index assessment methods to assess water quality management, there are several other evaluation methods in water-focused environmental fields. They include the fuzzy-set method, Multi-variate statistical techniques, the biological-indicator measure, etc.

Examining many types of uncertainties and vagueness in the studies of water quality assessment, Lotfi A. Zadeh established fuzzy logic as a perfect measure to tackle these problems (Zadeh, 1999). Since then, the risk evaluation connected with environmental issues has been discussed in many reports according to the fuzzy set theory. In 1995, Smith presented a fuzzy aggregation method for the assessment of environmental quality. A method integrating fuzzy risk evaluation was proposed by Chen et al. (1998) to assess environmental risk from petroleum-polluted stations. They (2003) then advanced a fuzzy random risk-evaluation method to examine uncertainties regarding water quality requirements and assessment regulations for groundwater systems. Rehana and Mujumdar (2009) provided a fuzzy-set-based model for waste load distribution to deal with uncertainties due to the lack of data regarding hydrological parameters. The fuzzy synthetic assessment approach was employed by Zheng et al. (2007) in a waste-dumping area where the classification of the sea water quality was based on the maximum membership principle. A developed fuzzy system assessment method was presented by

Liu et al. (2012) to evaluate the water quality in the Three Gorges region. The researchers achieved more reliable results by using the weighted average principle to replace the maximum membership policy.

Multivariate statistical techniques have been used in recent decades to assess the unique temporal variations in water quality. As space and time often change, water quality is difficult to interpret precisely in a sampling program. Representativeness and reliability are needed to present the water quality assessment of water bodies (Dixon and Chiswell, 1996). Several techniques including cluser analysis, primary ingredient analysis, and element analysis are applied to easily describe the water quality and environmental states of the researched systems, to identify the probable factors which impact water bodies and to provide a suitable tool for pollution control and water management (Vega et al., 1998; Lee et al., 2001; Wunderlin et al., 2001; Reghunath et al., 2002). In 2009, Pejman et al. provided a method using multivariate statistical techniques to assess the variations of water quality across various spaces and seasons. They collected water quality data from 8 monitoring sites in the Haraz River Basin across four seasons from 2007 to 2008. Based on cluster analysis, primary ingredient analysis, and element analysis, these researchers drew the conclusion that the consideration of the temporal changes of parameters is necessary for the quality evaluation of surface water (Pejman et al., 2009).

The biological indicator method is often used in water quality assessment due to the information organisms reveal about their environment. While the indicator concept has a long history dating back as far as the time of Aristotle, it has increasingly become the focus of modern environmental study. Not only can it describe and classify ecosystems and express the impact of human activities, it can also show the status of environmental recovery (Johnson, 1995). In 2010, Resende et al. used macroinvertebrates and periphytic diatoms as biological indicators to evaluate the water quality of the UI River in Portugal. Based on the assessment results, they concluded that the river did not have the ideal requirements for establishing a fluvial beach. Macroinvertebrates and periphytic diatoms were suitably applied as biological indicators to assess the water quality in the UI River (Resende et al., 2010).

2.2 Modeling for Lake Water Management

2.2.1 Lake water quality modeling

The method of employing digital simulations for water quality assessment, prediction and management is popularly accepted due to its positive effects. At present, many researchers use the modeling method to attain promising results regarding water quality, hydrodynamics, sediments, toxicants and heavy metal loads in surface water. Moreover, decision-makers also rely on the results for numerical modeling to establish environmental policies and plans (Gong, 2016). Although water bodies provide human beings with pleasant environments, there has not yet been wide academic attention paid to levels of water quality due to the lack of real simulation case studies. Compared with other types of surface water, lakes are more vulnerable due to their particular geographical locations and the difficulties in preserving their ecological environments and implementing restoration measures. Lake ecosystems are often impacted by human activities. They are easily destroyed by accepting large volumes of pollutants from agricultural discharge, industrial sewage, and municipal wastewater. In recent years, lake water has been facing a major challenge. Its water quality is descending along with the growth of human populations and the rapid advance of industry and agriculture (United Nations, 2014). For example, Lake East in the city of Wuhan, Lake Kunminghu in the city of Beijing and Lake Dianchi in the province of Yunnan (Gao et al., 2005; Jing et al., 2008; Yang et al., 2007) all suffer contamination problems which are likely to affect the functions of the lake water.

Currently, there are a few studies which focus on the changes undergone by lake water systems under the influence of industry, agriculture, rearing and climate (Miller et al., 2014). David (2000) provided a near-shore mixing model to simulate pollutant dispersion in great water bodies. Silva et al. (2011) employed zero-dimensional and one-dimensional models to describe the status of lakes as a part of a regional water system. In some studies, arguments arose about the establishment of more elaborate numerical modeling for lakes to resolve ecosystem issues including the interactions between water quality parameters, the availability and demand for hydrodynamic procedures, and the environmental heterogeneity of the ecosystems (Missaghi et al., 2013).

2.2 .2 Optimization for water quality management

Over recent decades, several optimization programming techniques have been employed for water quality management and related decision-making. For example, an aggregation approach for plants was presented by Zhao et al. (2009) to assess the spatial arrangement of local industry development and the relevant pollutant-laden wastewater discharge. In planning the scale of constructed wetlands, an aggregated programming model was developed by Ham and al. (2010) to control contaminant loads and improve water quality. Aiming to minimize the total cost, Liu and al. (2008) proposed an inexact chance-constrained linear programming model to optimize water quality management at the watershed scale. Based on optimal environmental and economic conditions, Zhang et al. (2013) discussed a particular risk interval linear programming model in the lake Fuxin watershed. In another Chinese lake named Qionghai, Liu and al. (2011) presented a similar programming model for reducing nutrient load in the aquatic ecosystem. Spanou and Chen (2001) discussed an objective orientation method to control point-source contamination in river ecosystems. In a planning system, Cheng and al. (2003) proposed the approach of improving local water quality to support decision-making. Chen and Chang (1998) addressed a multi-objective fuzzy genetic algorithm-based programming model to treat water pollution in the river basin.

The previous researchers presented various problems related to water bodies and provided several measures to manage them and control their level of pollution. However, it is difficult for most of them to clearly illuminate the interrelations between all the relevant elements due to the large amounts of data, applicable sub-models, competing objectives, unquantifiable factors and uncertainty during parameterization (Chen and

Chang, 1998). Imperatively, the aquatic environment provides a clean water supply and various habitats for marine life, wildlife, and human beings (Zedler and Kercher, 2005). Therefore, when beginning to select the parameters of the optimization programming model, researchers should seriously consider multiple procedures with complicated and real interrelationships. In each water-based ecological environment, one or more of the most significant objectives, such as total net benefits, direct and indirect costs of water pollution control, water quality improvement and the effective utilization of water resources should be chosen and taken into account after elaborative comparisons. Simultaneously, a larger number of constraints need to be incorporated into programming models due to the uncertainties and complications based on data availability, programming simulation, and calculation processes in the system (Liu et al., 2012). For example, the net benefit of agricultural cultivation always varies according to the price of crop products and the cost of investment, including labor and fertilizer, and the amount of available water resources is greatly impacted by weather conditions such as drought or waterlog seasons. Although the system's factors create many uncertainties and complexities by themselves or in tandem with each other, a probability distribution can be proposed in programming models to resolve the above problems (Huang et al., 1992).

In the optimization process, the first step is always the selection of objectives within the parameters, such as maximum net benefits, minimum cost, maximum reality and minimum risk, etc. There are often two important methods to choose from, such as the single-objective programming (SOP) model and the multi-objective programming (MOP) model. The SOP model uses the most significant parameter as a single objective or lumps several objectives into a single one. However, it can hardly present a series of accurate solutions with these diverse objectives under inter-reaction and restriction. On the other hand, the MOP model provides a set of selectively integrated solutions due to the consideration of conflicting goals. During the period of model design or stage planning, the MPO model shows three primary developments in the optimization process to help make decisions (Cohon, 1978; Bandyopadhyay and Saha, 2013):

- The MOP model provides a bigger scope of alternatives to support more reasonable suggestions.
- During the period of MOP-based model planning, the researchers and decision-makers play roles in their respective working ranges. The former builds alternative solutions while the latter has the responsibility of making decisions according to the generated solutions.
- When considering many objectives, the procedure and the results for the MOP model are more acceptable for the different relevant groups, particularly the public.

The main characteristic of the SOP model is its ability to ascertain an optimal single goal. It can also be utilized in the MOP process except in a situation where various objectives are merged into a single one. One target among all the considered parameters is regarded as the single goal, while the others are listed in the constraints in the planning procedure. Although these limitations are allocated as constraints with specific requirements, they all play their objective roles with different degrees of acquirement (e.g.

maximum reliability levels) or run to gain results satisfying several areas of the public. Nevertheless, most real case studies meet these alternatives, which are difficult to classify into precise values. Therefore, in most cases the MOP model is more useful in dealing with complex problems due to its wider scope of alternatives. In optimization projects, there are usually many actors and stakeholders. If the opinions and suggestions of all participants are considered, the whole procedure becomes complicated, potentially even to the point that it cannot be carried out. Thus, the process of planning models needs to be simplified so that it simply involves two primary actors: modelers and decision-makers. Modelers have the professional capability to present technical information about an issue to decision-makers. The techniques of optimization modeling are applied by these experts to show the processes and results for planning models to the managers in detail. In the MOP model, all designed objectives are agreed upon by both modelers and decision-makers so that the responsibilities of both participants are balanced. However, the SOP model places too great a burden on the shoulders of the model runners due to its single-objective format (Dragan, 2008).

2.3 GIS-Based Water Quality Management

The GIS plays a significant role in water quality management, including water quality assessment and pollution control, due to its powerful capacity for analyzing and displaying a large amount of spatial data. It shows data and analysis results to researchers and decision-makers via clear visualization (Debaine and Robin, 2012). In the field of water management, many scientists have discussed and analyzed relevant measures based on GIS (Huang and Jiang, 2002; Halls, 2003; Jiang et al., 2012; McKinney and Cai, 2002). Within the GIS framework, two extreme types of matching, loose and tight, were studied. Loose matching is conducted to transmit the database between the GIS platform and the modeling program. It helps to exploit the cartographic abilities of GIS and allows model researchers to flexibly select the most suitable models. The principal disadvantage of loose matching is the requirement of further implements for the proper formation of data files (Santini et al., 2010). In tight matching, analytic functions and a macro language are employed to develop the models entirely within the GIS framework. However, strong computer programming skills are necessary for the application of this approach due to its complexity (Al-Sabhan et al., 2003). In addition, several common methods were used in the employment of GIS. A five-class pyramid approach was provided by Brandmeyer and Karimi (2000) to represent the gradually advancing classes with integration. The five levels are one-way transfer, loose coupling, share coupling, joined coupling and tool coupling respectively. Based on a shared database, this measure presents functions and tools to calculate data and manage sources within multiple models.

2.4 Summary

In recent decades, water quality assessment methods and water pollution control planning models have been widely employed and improved in the realm of surface water management. The majority of the methods used in previous studies can be improved in terms of WQI-based management, effective lake pollution control based on optimization, spatial information management, and practicability. Moreover, the evaluation of water quality and contamination control planning for water resources were limited when studied in isolation as water systems are complex due to the interrelation of their hydraulic, physical, chemical and biological factors. The results generated by water quality assessment methods and pollution control optimization modeling of water bodies contain limited spatial distribution information, which may be insufficient to use for the protection and management of surface water. Spatial data management, lake water quality assessment methods, and pollution control planning models can be extended by using GIS. It would have a powerful capacity for water quality evaluation, pollution control planning and visualization of data results. The results would be clear and easy to compare, and better decisions would likely follow. This thesis plans to build a practical approach for integrating lake quality index methods and pollution control planning models with GIS technology to manage lake water. The details of the GIS-based lake management approach will be elaborated upon in the next chapter.

CHAPTER 3 METHODOLOGY

3.1 Methodology Overview

The major methodologies of the GIS-based water quality assessment and pollution control planning approach for lake management (WQAPCP) applied in this thesis are shown in Figure 3-1. These methods included three components as follows:

- Water quality assessment using four index methods, such as OWQI, CWQI, CNWQI-S and CNWQI-C, to describe the water quality status in the real case shown in Chapter 4.

- Pollution control planning based on the simulation and validation of pollutant distribution, the first comparison between the single-objective programming model and the multi-objective programming model, and the further comparisons between the OWQI and CNWQI-C methods according to the same planning results. A more acceptable approach to lake optimization is provided in Chapter 5.

- The use of GIS technology to create visual maps of the study results and integrate water quality evaluation and contamination control optimization for lake management to provide recommendations for local administration.

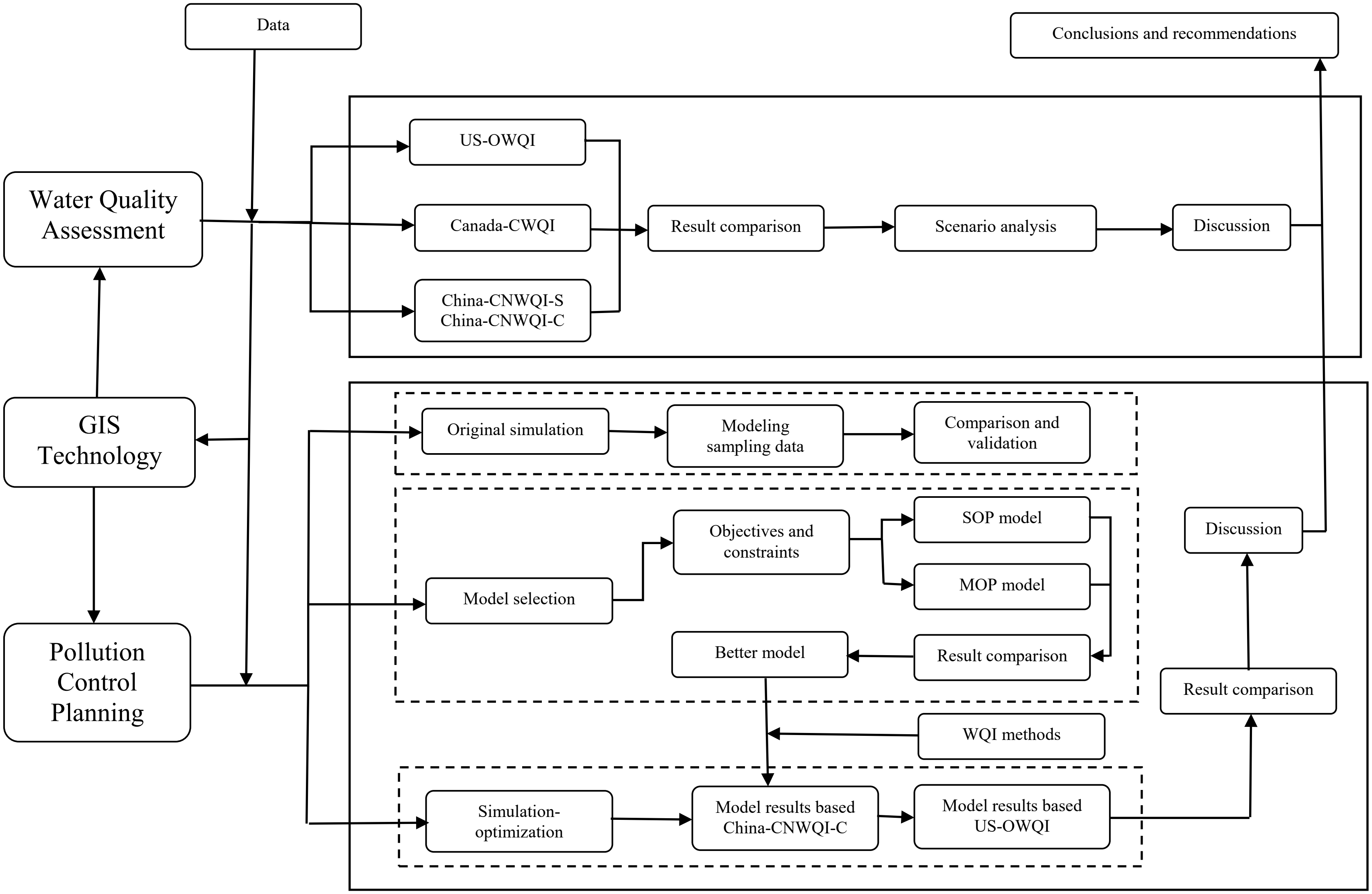


Figure 3-1 Overview of the proposed approach of WQAPCP

3.2 Water Quality Assessment Methods

3.2.1 US Oregon water quality index (OWQI) method

The OQWI method is based on the AWQI and MWQI models and overcomes their respective disadvantages by processing the theory of equal weights (=1/n) for each sub-index (Lumb et al., 2011). The core equation is shown as:

$$OWQI = \sqrt{n \ / [(1/S_1^2) + (1/S_2^2) + (1/S_3^2) + \ldots + (1/S_n^2) \ ]} \qquad (3\text{-}1)$$

where OWQI is the Oregon water quality index, n is the number of sampled parameters, $S_{1,2,3,\ldots\ldots n}$ is the result of a single sub-index of the parameters, respectively.

The first step in applying the index formulae was to calculate the sub-index value S_i for each parameter by using the following equations:

Sub-index for phosphorus (P), S_P (Cude, 2001)

$$P \le 0.25 mg/l: \ S_P = 100 - 299.5 \times P - 0.1384 \times P^2;$$

$$P > 0.25 mg/l: \ S_P = 10 \qquad (3\text{-}2)$$

where P is phosphorus in ppm (or mg/l) and S_P is the result of sub-index of phosphorus.

Sub-index for ammonium nitrogen (NH_3-N), $S_{NH3\text{-}N}$ (Wepener et al., 1992)

$$NH_3 - N \leq 0.02: S_{NH_3-N} = 100;$$
$$0.02 < NH_3 - N \leq 0.062: S_{NH_3-N} = -500 \times NH_3 - N + 110;$$
$$0.062 < NH_3 - N \leq 0.5: \ S_{NH_3-N} = 40 / (\ NH_3 - N + 0.65)^2;$$
$$NH_3 - N > 0.5: \ S_{NH_3-N} = -5.8 \times NH_3 - N + 32.5. \qquad (3\text{-}3)$$

where NH_3-N is ammonium nitrogen in ppm (or mg/l) and $S_{NH3\text{-}N}$ is the result of sub-index of NH_3-N.

Sub-index for nitrate-nitrogen (NO_3-N), $S_{NO3\text{-}N}$ (Dinius, 1987)

$$S_{NO_3-N} = 125 \times NO_3 - N^{-0.2718} \qquad (3\text{-}4)$$

where NO_3-N is nitrate-nitrogen in ppm (or mg/l) and $S_{NO3\text{-}N}$ is the result of the sub-index of nitrate-nitrogen.

Sub-index for 5-day Biochemical Oxygen Demand (BOD_5), S_{BOD5} (Cude, 2001)

$$BOD_5 \leq 8mg/l: \ S_{BOD_5} = 100 \times exp\left(BOD_5 \times \left(-0.1993\right)\right);$$
$$8mg/l < BOD_5: \ S_{BOD_5} = 10. \qquad (3\text{-}5)$$

where BOD_5 is 5-day Biochemical Oxygen Demand in ppm (or mg/l) and S_{BOD5} is the result of the sub-index of 5-day Biochemical Oxygen Demand.

Sub-index for Dissolved Oxygen (DO), S_{DO} (Cude, 2001)

$$DO\ saturation\ (Dos)\ \leq 100\%:$$

$$DO\ concentration (DO_C)\ \leq 3.3 mg/l : S_{DO} = 10;$$

$$3.3 mg/l < DO_C \leq 10.5 mg/l:\ S_{DO} = -80.29 + 31.88 \times DO_C - 1.401 \times DO_C^{\ 2};$$

$$10.5 mg/l < DO_C:\ S_{DO} = 100.$$

$$100\% < DOs \leq 275\%:\ S_{DO} = 100 \times exp((DOs - 100)\ \times (-1.197E-2)).$$

$$275\% \leq DOs:\ S_{DO} = 10. \tag{3-6}$$

where DO is Dissolved Oxygen in ppm (or mg/l) and S_{DO} is the result of the sub-index of Dissolved Oxygen.

Sub-index for Total Suspended Solids (TSS), S_{TSS} (Cude, 2001)

$$TSS \leq 40 mg/l:\ S_{TSS} = 100;$$

$$40 mg/l < TSS \leq 220 mg/l:\ S_{TSS} = 142.6 \times exp\left((TSS)\ \times \left(-8.862E-3\right)\right);$$

$$220 mg/l < TSS:\ S_{TSS} = 10. \tag{3-7}$$

where TSS is Total Suspended Solids in ppm (or mg/l) and S_{TSS} is the result of the sub-index of Total Suspended Solids.

Sub-index for pH, S_{pH} (Cude, 2001)

$$pH \le 4:\ S_{pH} = 10;$$

$$4 < pH \le 7:\ S_{pH} = 2.628 \times exp\left(0.5200\, pH\right);$$

$$7 < pH \le 8:\ S_{pH} = 100;$$

$$8 < pH \le 11:\ S_{pH} = 100 \times exp(-0.5188(pH - 8));$$

$$pH > 11:\ S_{pH} = 10. \tag{3-8}$$

where pH is a numeric scale to specify the acidity or basicity of a solution and S_{pH} is the result of the sub-index of pH.

Sub-index for Turbidity, S_{Tur} (Wepener et al., 1992)

$$S_{Tur} = -220 \times ln(0.001 \times ln\left(Tur\right) + 30) - 689 \tag{3-9}$$

where NTU is the unit of Turbidity and S_{Tur} is the result of the sub-index of Turbidity.

Sub-index for temperature, S_T (Cude, 2001)

$$T \le 11°C : S_T = 100;$$

$$11°C < T \le 29°C: S_T = 76.54 + 4.172 \times T - 0.1623 \times T^2 - 0.0020557 \times T^3;$$

$$T > 29°C: S_T = 10. \quad (3\text{-}10)$$

where T is temperature in ℃ and S_T is the result of the sub-index of temperature.

3.2.2 Canadian water quality index (CWQI) method

In the CWQI model, three factors for evaluating the water quality index are established by the Canadian Council of Ministers of the Environment (CCME, 2001). The details are shown as follows:

Scope (F_1): the number of parameters with which objective limits are not met, or, in other words, the frequency, expressed as a percent value, with which variables fail to fulfill their goals at least once within a limited time. Such variables are referred to as "failed variables". The relative equation is presented in (3-11):

$$F1 = (number\ of\ failed\ variables / total\ number\ of\ variables) \times 100 \quad (3\text{-}11)$$

Frequency (F_2): the frequency with which objectives are not met, which shows the percentage of individual tests not meeting objectives ("failed tests"). The equation is expressed in (3-12):

$$F2 = \left(number\ of\ failed\ tests\ /\ total\ number\ of\ tests\right) \times 100 \quad (3\text{-}12)$$

Amplitude (F3): the amount by which the objectives are not met, which represents the value of the tests which did not meet their targets. The computation has three steps:

The number of times by which individual concentration is greater than (or less than when the objective is a minimum) the goal is referred to as an "excursion" which can be expressed as follows. The test value must not exceed the aim.

$$excursion_i = \left(Failed\ Test\ Value_i / Objective_i \right) - 1 \quad (3\text{-}13)$$

For cases in which the test value must not fall below the objective:

$$excursion_i = \left(Objective_i /\ Failed\ Test\ Value_i \right) - 1 \quad (3\text{-}14)$$

By integrating the computation of the excursions of individual tests with the total number of tests which do and do not meet their goals, the total amount by which individual tests are not within the range can be determined. The calculation of the normalized sum of the excursions (nse) is defined as

$$nse = \sum\nolimits^{n}_{i=1} excursion_i /\ \#of\ tests \quad (3\text{-}15)$$

F_3 is computed by nse with a range between 0 and 100.

$$F3 = [\, nse / (0.01nse + 0.01)] \tag{3-16}$$

The CWQI is finally expressed as:

$$CWQI = 100 - \sqrt{(F_1^2 + F_2^2 + F_3^2) / 1.732} \tag{3-17}$$

3.2.3 Chinese water quality index (CNWQI) methods

When using the "Chinese Surface Water Environment Quality Standard" (GB3838, 2002) to evaluate lake water quality, the particular water quality assessment index is converted into 5 levels, 1 to 5, which correspond respectively to excellent, good, medium, poor and very poor water quality. In traditional Chinese water resource management, there are two methods of water quality index assessment: the comprehensive evaluation approach (abbr. CNWQI-C) and the single-factor evaluation method (abbr. CNWQI-S). In the CNWQI-S method, the individual maximum index is directly taken and used as the water quality assessment index for small and low-requirement case (Zhu et al., 2010). However, the CNWQI-C approach requires computing steps to obtain the water quality index results for big or high-requirement projects, which are described as follows (Li et al., 2012):

The calculation of the individual index (I):

$$I = [(C - C_o) / (C_{o+1} + C_o)] + I_o \quad (3\text{-}18)$$

where C is the measured concentration for evaluation items I, C_o is the O-grade standard concentration for the assessed parameter, which is lower than C, and C_{o+1} is the (O + 1)-grade standard concentration of the factor, which is higher than C.

The calculation of the comprehensive index (WQI):

$$CNWQI - C = (1/n)(I_1 + I_2 + ... + I_n) \quad (3\text{-}19)$$

where n is the number of the evaluated index parameters involved in the project.

3. 3 Modeling on Contaminant Distribution and Pollution Control Planning for the Lake System

3.3.1 Lake water quality modeling

For modeling lake water quality, the near-shore mixing model was selected as the simulating method in this thesis. For the pollutant dispersion modeling, the horizontal currents were neglected and the water status was assumed to be steady. The formula of the advection distribution with first order decay is thus presented as (David, 2000):

$$D(\partial^2 c/\partial^2 x^2 + \partial^2 c/\partial^2 y^2) - kc = 0 \tag{3-20}$$

where *D* denotes the distribution coefficient, *c* is the pollutant concentration, and *k* is the constant of the first order decay within the XY coordinate system. Based on polar (r, θ) coordinates, Equation (3-20) can be provided as

$$\partial^2 c/\partial^2 r^2 + (1/r)\partial c/\partial r + (1/r^2)\partial^2 c/\partial\theta^2 - (k/D)c = 0 \tag{3-21}$$

As the concentration dispersion is radially homogeneous ($\partial^2 c/\partial\theta^2 = 0$) we then have

$$\partial^2 c/\partial^2 r^2 + (1/r)\partial c/\partial r - (k/D)c = 0 \tag{3-22}$$

From Equation (3-22), the following general solution is shown as

$$c(r) = AI_0(\sqrt{kr^2/D}) + BK_0(\sqrt{kr^2/D}) \tag{3-23}$$

Where A and B are constants, I_0 is revised as a Bessel function of the first kind, and K_0 is a modified Bessel function of the second kind.

Since $$C(r_0) = C_0 \tag{3-24}$$

$$C(\infty) = 0 \tag{3-25}$$

The concentration dispersion in the lake can be expressed as (O'Connor, 1962)

$$C = [K_0(\sqrt{(kr^2 / D)}) / K_0(\sqrt{(kr_0^2 / D)})]c_0 \tag{3-26}$$

3.3.2 Optimization for lake water quality management

3.3.2.1 Model formulation

An optimization programming model can be formulated as follows:

$$\min f_k = C_k X, k = 1, 2, ..., p \tag{3-27}$$

$$\max f_l = C_l X, l = p+1, p+2, ..., q \tag{3-28}$$

$$s.t. A_i X \le b_i, i = 1, 2, ..., m \tag{3-29}$$

$$X \ge 0 \tag{3-30}$$

where $X \in R^{t\times 1}$, $C_k \in R^{1\times t}$ ^{t}, $C_l \in R^{1\times t}$, $A_i \in R^{1\times t}$, R, t, k, l and i all express a series of numbers. Each of the variables is regarded as a deterministic number in the above formulae. When some variables on the right-hand side of the constraints are uncertain, the uncertainties can be denoted by probabilities by employing a chance-constrained programming model. Such a model includes setting a level of probability $pi \in [0, 1]$ for each constraint i and fixing the condition of the restriction i which is met with one or more chances of 1 - pi. The feasible solution set is then satisfied by the following constraints:

$$\Pr[A_i X \leq b_i] \geq 1 - p_i, i = 1, 2, ..., n \tag{3-31}$$

In formula (3-31), since the constraints are usually nonlinear, the set of possible constraints is convex for situations where (a) Ai are deterministic, but bi are random, (b) both Ai and bi are discontinuous parameters, and (c) Ai and bi have Gaussian distributions. Thus, when Ai are deterministic and bi are random, the necessary information about uncertainty is p_i for the unconditional distribution of b_i, and the constraint (3-31) becomes linear:

$$AiX \leq bi^{(p_i)}, \forall i, i = 1, 2, ..., n \tag{3-32}$$

where $b_i^{(pi)} = F_i^{-1}(p_i)$, given the cumulative distribution function of b_i (i.e.,$F_i(b_i)$), and the probability of violating constraint (p_i).

3.3.2.2 Model parameters

Economic development and environmental protection are always the two most important factors in optimization projects. Accordingly, the total net benefits and water pollution control are considered the key parameters of lake system planning. The issues of water supply and demand, agricultural development, raising of livestock and aquaculture and the residential population are also taken account as parameters in the lake system. Meanwhile, this study details distribution information for available water sources and water quality requirements (including the discharge of TP, NH_3-N and BOD_5) for different periods and various significant levels. The reasoning behind why the three factors are only considered in the optimization models is described in Section 3.3.2.4.

3.3.2.3 Single-objective programming (SOP) model

Economic development is usually taken for granted to be the first target. Thus, a maximum total net benefit is selected as the objective in the single-objective programming (SOP) model (Zhang et al., 2013). The selection of constraints in planning the model is essential for obtaining feasible and efficient trade-offs. In this study, a series of economic, social and ecological factors related to environmental concerns are taken into account in the system. These factors are water resources, land area for agriculture, livestock population, water area for aquaculture, the discharge limitation of TP, NH_3-N and BOD_5, population and other technical constraints.

Objective: total net benefit, which is derived from three parts, namely agriculture, the raising of livestock and aquaculture.

The constraints are as follows:

a. Water resource availability constraints

b. Land area for agriculture availability constraint

c. Livestock population availability constraint

d. Water area for aquaculture availability constraint

e. TP discharge limitation constraint

f. NH_3-N discharge limitation constraint

g. BOD_5 discharge limitation constraint

h. population constraint

i. non-negativity and technical constraint

3.3.2.4 Multi-objective programming (MOP) model

In the multi-objective programming model, total net benefit and water quality were selected as the two objectives in this research. Although maximum total net benefit was the principal objective due to concerns about local economic development, it was also imperative to attain the highest possible water quality. Water quality thus became the other primary objective in the MOP model.

There were three major polluting sources in HJH Lake as seen in Chapter 4. They were Total Phosphorus (TP), Ammonia Nitrogen (NH_3-N) and Five-Day Biological Oxygen demand (BOD_5). Thus, if the values of the three pollutants were well-controlled, the lake water quality could also be managed effectively. Therefore, the lake water quality results were derived from the full calculation of TP, NH_3-N, and BOD_5 through the employment of the proper approach. Based on the integral analysis, the Chinese Water Quality Index Comprehensive (CNWQI-C) method was selected for use in the study as the case was located in China and the Chinese relative method was acceptable to all stockholders in the local area.

Multiple objectives:

a. Total net benefit objective, which consisted of three parts: agriculture, the raising of livestock, and aquaculture.

b. Water quality objective, which was obtained through calculation by using Equation 3-18 and 3-19.

The constraints were the same as the constraints in SOP model.

3.4 Integration of Simulation and Optimization

A simulation-optimization approach is developed in this thesis by integrating lake water quality simulation and lake pollution control optimization. A contaminant dispersion simulation is conducted to provide input for the optimization study. Two models including SOP model and MOP model are developed, applied, and compared to support effective lake water contamination control planning under single-objective and multi-objective lake management scenarios.

According to the methodology described in Section 3.3.1, original simulation is the first step of the lake pollution control planning optimization to assess the feasibility of contamination control planning. For the given emission source locations and emission rates, a simulation of lake water quality is established and validated using the monitoring data. More importantly, the established simulation tool is used to identify the lake water quality based on different emission scenarios with consideration of water quality standards. Therefore, the reduction targets of source emissions can be determined for the next phrase lake pollution control planning. On the other hand, the pollution control planning with optimized emission reduction results can be examined by the established simulation tool and the GIS to present and visualize the pollution control planning results, which incorporates water quality index methods.

The distribution of the relevant pollutants, the margin of error between the modeling results of contaminant concentration and the real sampling data at each monitoring site would meet the related simulation requirements, then, this verification method is thus usable to simulate the pollutant concentration dispersion in real cases. The following flowchart shows the presented procedure:

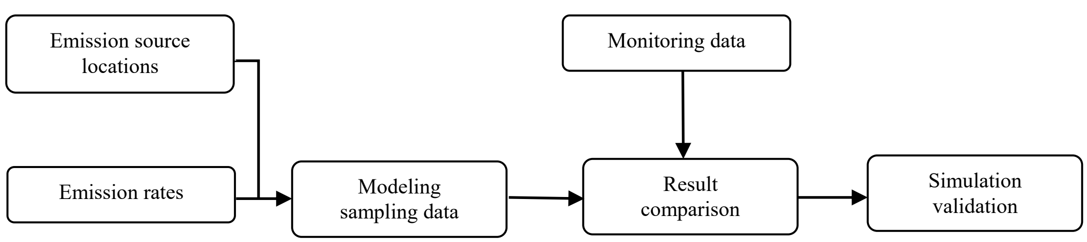


Figure 3-2 Flowchart of the simulation process

Both single- (SOP) and multiple- (MOP) objective programming methods are examined and developed for the study lake. Results from SOP and MOP models will be compared and discussed in this study. The optimization method with better lake pollution control planning will be integrated further with OWQI and CNWQI-C index methods to evaluate the planning results based on local standards for different pollution control scenarios.

3.5 GIS-Based Lake Water Management

With their capacity for capturing, storing, analyzing and displaying geographically referenced information, Geographic information systems (GIS) are extremely useful with regards to water quality control. GIS tools for spatial data management and analysis are currently experiencing rapid development, and the application of these tools tends to improve evaluations and analyses (Lynn, 2007). This study integrated GIS analysis functions, applicable water quality index methods and lake pollution control planning models, providing an extensive capacity for examining different water quality assessment methods and lake optimization models. It was intended to process a broad range of lake information and geo-referenced datasets, which in turn supplied the required input data for the water quality evaluation approaches and system planning. The relevant results were then displayed on the GIS maps for the lake case study. By using the ArcGIS engine 9.3 in this study, GIS was able to play a significant role in extending the traditional numerical results for the water quality assessment and lake pollution control optimization by delivering results with spatial references. By integrating GIS as the communication tool, this study enabled researchers and lake managers to better understand the spatial distribution of water quality statuses and relevant lake information as well as provide recommendations to decision-makers with supporting information.

3.6 Summary

This chapter presented the major components and working procedure of the integrated lake management approach referred to as WQAPCP in this thesis. The methods for water quality assessment addressed here include four index models: OWQI, CWQI, CNWQI-S and CNWQI-C. The following optimization models depicted an acceptable approach to lake pollution control planning which would protect the whole lake system. In the two above parts of this study, GIS technology acted as an integrator for the display of the relative results and provided reasonable suggestions to decision-makers through clear comparison.

CHAPTER 4 GIS-BASED WATER QUALITY ASSESSMENT

—A Case Study of HJH Lake

4.1 Study Area

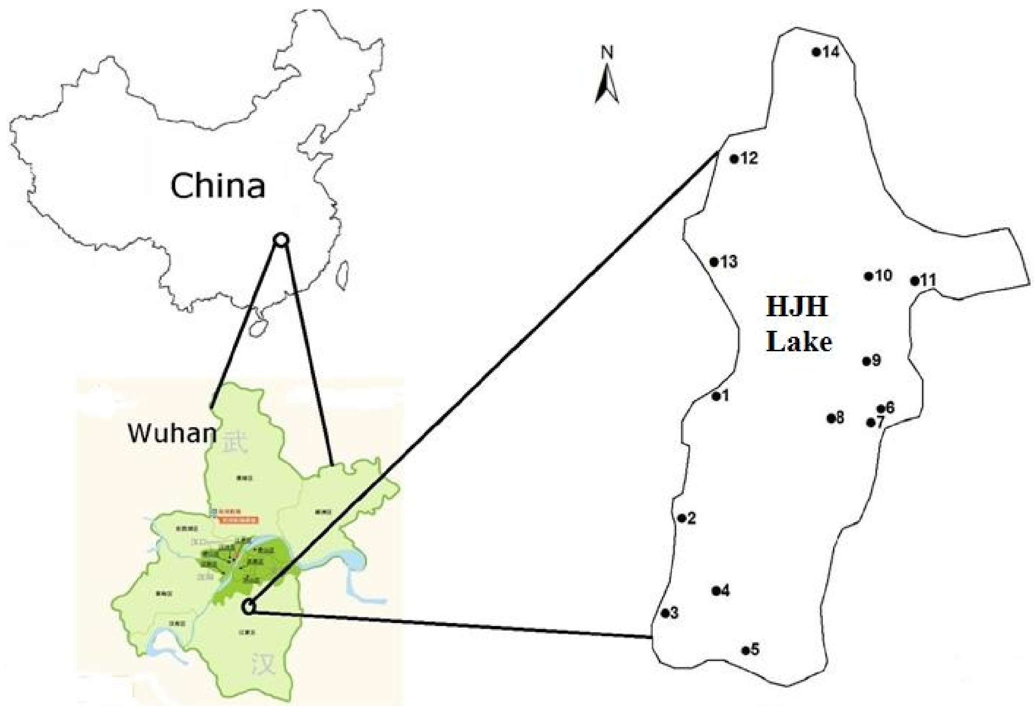


Figure 4-1 Study area and the sampling stations

This study focuses on HJH Lake, which is located in the Wuhan City of China as shown in Figure 4-1. It is important as a supply of fresh drinking water for the Wuhan metropolitan area. However, there has been an increase in adverse impacts on its water quality due to the generation of a significant amount of waste solids and liquids (Wang, 2004). The lake has a water area of 8.18 square kilometers, a depth ranging from 1.2 to 3.1 m, and a lakeshore line of more than 24 kilometers. Although the lake's water quality was classified as Level 3 (GB3838, 2002), it has been continuously observed at Level 5 since the end of the last century. The criteria for surface water quality are shown in Table 4-1 as follows:

Table 4-1 Environmental quality standards for surface water in China (GB3838, 2002)

Factors	Criteria of Surface water quality grades				
	1	2	3	4	5
Temperature	$\Delta T \leq 3$℃ per week				
pH	6-9				
Dissolved Oxygen (mg/l)	7	6	5	3	2
Five-Day Biochemical Oxygen Demand (mg/l)	3	3	4	6	10
Ammonium Nitrogen (mg/l)	0.15	0.50	1.00	1.50	2.00
Total Phosphorus (mg/l))	0.01	0.03	0.05	0.10	0.20

4.2 Data Collection

In this study, all monitored data regarding the water quality assessment were reported by the Huazhong University of Science and Technology (HUST). Nine water quality parameters were considered in this thesis as follows: Total Phosphorus (TP), Ammonium Nitrogen (NH_3-N), Nitrate Nitrogen (NO_3-N), Five-Day Biochemical Oxygen Demand (BOD_5), Dissolved Oxygen (DO), Total Suspended Solids (TSS), pH, Turbidity and Temperature.

A field monitoring study was conducted in 2013 by HUST with many trips for sampling and analysis. Representative sampling locations were selected across the lake water area as shown in Figure 4-1, and a large set of data, including parameters, was listed in Table 4-2, 3 and 4. The monitoring data for heavy metals such as Cr (+6), Pb (II) and Zn (II) were lower than the maximum permitted by local water quality standards and thus were not considered in this thesis. Three sets of valid monitoring data were obtained from multiple field sampling and analysis trips between August and October 2013. Data concerning TP, NH_3-N, NO_3-N, BOD_5, DO, and pH were sampled once per month. However, the values of TSS, Tur and T were the average amounts based on samples taken twice per week, totaling 8 samples per month. For each week, the difference in value met the following requirements: ΔTSS ≤ 25mg/L, ΔTur ≤8 NTU, ΔT ≤3 ℃ (Lumb et al., 2001). The monitoring data details are shown in Table 4-2, 4-3 and 4-4.

Table 4-2 Water quality monitoring data in August 2013 (HUST, 2013)

Sampling sites	TP (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	BOD_5 (mg/L)	DO (mg/L)	TSS (mg/L)	pH	Turbidity (NTU)	T (°C)
1	0.79	1.11	0.27	35.20	6.83	176.50	7.00	26.92	25.10
2	0.36	1.59	0.39	10.88	4.28	16.00	8.80	22.50	25.50
3	0.31	0.94	0.14	25.60	6.53	39.50	8.00	29.42	25.40
4	0.22	0.96	0.11	25.60	3.80	33.50	7.50	27.31	26.10
5	0.45	0.52	0.29	22.40	6.59	60.50	8.50	28.27	25.80
6	0.48	0.72	0.08	16.00	6.10	91.00	6.80	32.88	25.40
7	0.16	0.33	0.10	12.80	3.36	78.00	7.20	32.88	24.90
8	0.28	0.96	0.04	28.80	5.53	38.50	7.50	25.58	25.20
9	0.22	0.69	0.09	18.40	5.73	29.50	7.20	19.81	25.50
10	0.33	0.90	0.13	41.60	6.84	95.50	7.50	54.42	25.40
11	0.65	1.03	0.17	44.80	3.35	37.00	7.50	30.00	25.10
12	0.95	1.42	0.29	38.40	8.49	208.00	7.20	43.45	24.90
13	0.97	1.46	0.55	38.80	5.15	306.50	7.50	61.92	24.80
14	0.58	0.50	1.42	41.60	7.15	127.00	7.20	23.46	25.00

Table 4-3 Water quality monitoring data in September 2013 (HUST, 2013)

Sampling sites	TP (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	BOD_5 (mg/L)	DO (mg/L)	TSS (mg/L)	pH	Turbidity (NTU)	T (°C)
1	0.36	1.11	0.97	29.25	4.34	60.00	6.80	5.98	21.00
2	0.34	1.40	0.35	19.10	6.10	119.00	7.00	55.37	20.70
3	0.35	1.30	0.81	19.10	6.80	94.00	7.50	26.72	20.50
4	0.35	0.71	0.40	27.46	5.30	111.00	6.80	39.00	21.10
5	0.34	0.79	0.59	28.06	6.22	140.00	6.80	15.86	22.90
6	0.31	0.81	0.42	13.13	4.58	58.00	7.20	20.00	21.00
7	0.38	0.92	0.64	18.51	6.52	80.00	7.20	8.94	20.90
8	0.37	1.91	0.54	25.07	7.32	123.00	7.00	43.00	21.10
9	0.34	1.29	0.19	19.10	6.89	118.00	6.80	25.00	21.50
10	0.30	0.98	0.14	22.09	7.23	66.00	7.20	1.04	21.20
11	0.56	1.19	0.10	18.51	7.83	73.00	7.00	28.00	21.10
12	0.49	4.01	1.11	17.31	5.34	73.00	7.20	18.00	21.90
13	0.28	1.26	1.47	12.54	6.58	77.00	7.80	27.00	21.90
14	0.58	5.79	1.65	2.39	5.82	63.00	7.50	13.00	21.00

Table 4-4 Water quality monitoring data in October 2013 (HUST, 2013)

Sampling sites	TP (mg/L)	NH_3-N (mg/L)	NO_3-N (mg/L)	BOD_5 (mg/L)	DO (mg/L)	TSS (mg/L)	pH	Turbidity (NTU)	T (°C)
1	0.30	1.17	0.15	19.41	6.74	112.00	6.80	12.84	18.80
2	0.30	0.64	0.10	11.51	5.92	87.00	7.20	9.15	18.90
3	0.32	1.22	0.21	11.00	6.88	105.00	7.30	9.54	18.50
4	0.36	0.38	0.08	10.56	6.93	78.00	6.50	9.15	19.30
5	0.33	1.01	0.44	8.35	6.36	95.00	6.80	6.43	19.40
6	0.30	0.80	0.37	11.00	6.88	88.00	6.70	7.98	19.10
7	0.28	0.75	0.10	12.39	7.61	63.00	7.20	7.60	18.20
8	0.30	0.14	0.54	19.60	6.50	103.00	7.20	5.85	18.30
9	0.31	0.54	0.20	21.63	7.85	80.00	7.50	5.26	17.90
10	0.32	0.48	0.49	19.73	6.85	98.00	6.80	7.98	18.00
11	0.36	0.38	0.30	13.72	6.74	83.00	6.30	9.15	17.70
12	0.38	1.38	0.23	6.44	4.86	97.00	7.00	12.64	18.50
13	0.51	1.69	0.16	11.44	4.95	85.00	6.80	4.10	19.60
14	0.30	0.90	0.24	6.26	5.94	35.00	6.80	7.21	19.10

4.3 Method Implementation

According to the data collected during each survey and the formulae (3-1 to 3-19) presented in Section 3.2, OWQI, CWQI, CNWQI-S and CNWQI-C were able to be used to obtain the lake water quality evaluation results.

During the employment of the OWQI method, the first step was to select the proper equations based on the various contaminant concentrations at each monitoring site. Secondly, the sub-index value S_i for each parameter was obtained via calculation. The final results for the OQWI method were then determined. The assessment gradation of water quality based on OWQI regulations is as follows: Excellent: 90–100; Good: 85–89; Fair: 80–84; Poor: 60–79; Very poor: 10–59 (Cude, 2001).

For the CWQI approach, the basic procedure was the computation of the role factors Scope (F1), Frequency (F2) and Amplitude (F3). By using these data and the index equation, the CWQI results were obtained. The CWQI values for water quality fall into five different grades: Excellent (95–100), Good (80–95), Fair (65–79), Marginal (45–64) and Poor (0–44). In the present thesis, the objectives used for the CWQI method were as follows: TP = 0.05mg/L, NH_3-N = 2.20mg/L, NO_3-N = 2.93mg/L, BOD_5 = 20mg/L, DO = 5.00mg/L, $\triangle$TSS ≤ 25mg/L, pH = 6.5-9, $\triangle$Tur ≤ 8NTU, $\triangle$T ≤ 3 ℃ (Lumb et al., 2001).

The CNWQI approach features two methods, CNWQI-C and CNWQI-S, each with different calculation procedures. The single maximum index was used as the project assessment index of the water quality for the CNWQI-S method. However, the CNWQI-C method required the computation of the sub-index for each parameter at each sampling location by employing the relevant formulae (Zhu, 2010). Moreover, it necessitated the application of the following regulations to determine the classes of water quality assessment:

When $0 < \text{WQI results} \leq 1$, the water quality level is 1; when $1 < \text{WQI results} \leq 2$, the water quality level is 2; when $2 < \text{WQI results} \leq 3$, the water quality level is 3; $3 < \text{WQI results} \leq 4$, the water quality level is 4; and when $4 < \text{WQI results} \leq 5$, the water quality level is 5.

The dissolved oxygen index differs from the other indices in that the lower it is, the better the resulting water quality becomes. When $C_i > C_{io5}$, the water is the inferior gradation, and the single index should be counted as $I_i = 5$ (identically suitable for the single factor assessment method) (Li et al., 2012).

4.4 Results

The assessment results were exported from the database to an Excel file. The index results, including OWQI, CWQI, CNWQI-C, and CNWQI-S at the 14 sampling stations across three months, are presented in Table 4-5. Using GIS, Figure 4-2 displays the distribution of water quality during the research period according to these evaluation measures.

4.4.1 Results for water quality index

Table 4-5 Water quality index results for OWQI, CWQI, CNWQI-C and CNWQI-S in August, September, and October 2013

Sampling sites	OWQI results			CWQI results			CNWQI-C results			CNWQI -S results
	Aug	Sep	Oct	Aug	Sep	Oct	Aug	Sep	Oct	
1	21.49	25.30	29.12	43.34	50.75	58.39	4.82	4.58	3.79	5
2	21.84	25.69	29.53	48.97	57.38	65.79	4.63	4.42	3.71	5
3	25.21	29.31	33.90	53.33	62.50	71.68	4.36	4.25	3.57	5
4	26.49	28.79	34.52	45.35	52.13	59.91	4.22	4.00	3.42	5
5	26.15	31.03	34.95	55.15	65.00	74.76	3.95	3.87	3.34	5
6	22.26	26.17	30.12	49.45	58.23	66.76	3.89	3.72	3.23	5
7	23.61	27.81	31.93	55.36	65.12	74.82	3.74	3.58	3.06	5
8	22.11	26.05	29.95	50.12	59.04	67.94	4.02	3.95	3.47	5
9	25.09	31.85	32.65	50.49	59.64	68.52	4.47	4.25	3.43	5
10	22.28	26.09	30.13	49.91	58.77	67.54	4.33	4.17	3.54	5
11	22.19	26.07	29.88	48.75	57.35	65.75	4.56	4.33	3.68	5
12	19.85	23.33	26.73	37.04	45.54	50.17	4.37	4.33	3.52	5
13	18.39	21.64	24.81	41.17	48.67	55.87	4.71	4.50	3.81	5
14	20.72	24.35	28.24	39.68	46.50	54.13	4.45	4.19	3.55	5

Firstly, the values for OWQI in Table 4-5 were small and varied across a small range from 18.39 to 34.95. In August, the hottest month studied, the WQI results ranged between 18.39 and 26.49. In September, the values were a bit larger, ranging from 21.64 to 31.85. Finally, the results for the amounts at each of the 14 sampling stations were at their largest in October. Out of all the monitoring sites, Station 13 produced the smallest figures for each month. However, the largest amounts were not always measured at the same location. In August, the OWQI result at Station 4 was 26.49, which was the greatest value measured at any of the 14 sites that month. During the other two months Station 5 showed the best water quality results, with 31.85 in September and 34.95 in October. The three groups of values became larger and larger from August to October.

Secondly, the total figures for CWQI were much greater than those for OWQI in Table 4-5, and they showed a larger range of variation (from 37.04 to 74.82). In August, the WQI results ranged between 37.04 and 55.36. The values in September were larger (from 45.54 to 65.12). In October, the results for CWQI were similar to those for OWQI since the amounts at each of the 14 sampling stations were the largest seen within the entire period of study. Out of all the monitoring sites, Site 12 had the smallest values during each month. The highest values were located at Site 7, where the OWQI results for August, September, and October were 55.36, 65.12 and 74.82 respectively. Consequently, the three groups of values for CWQI displayed the same trend as in OWQI across the three months. The values for CWQI grew larger and larger during the studied period.

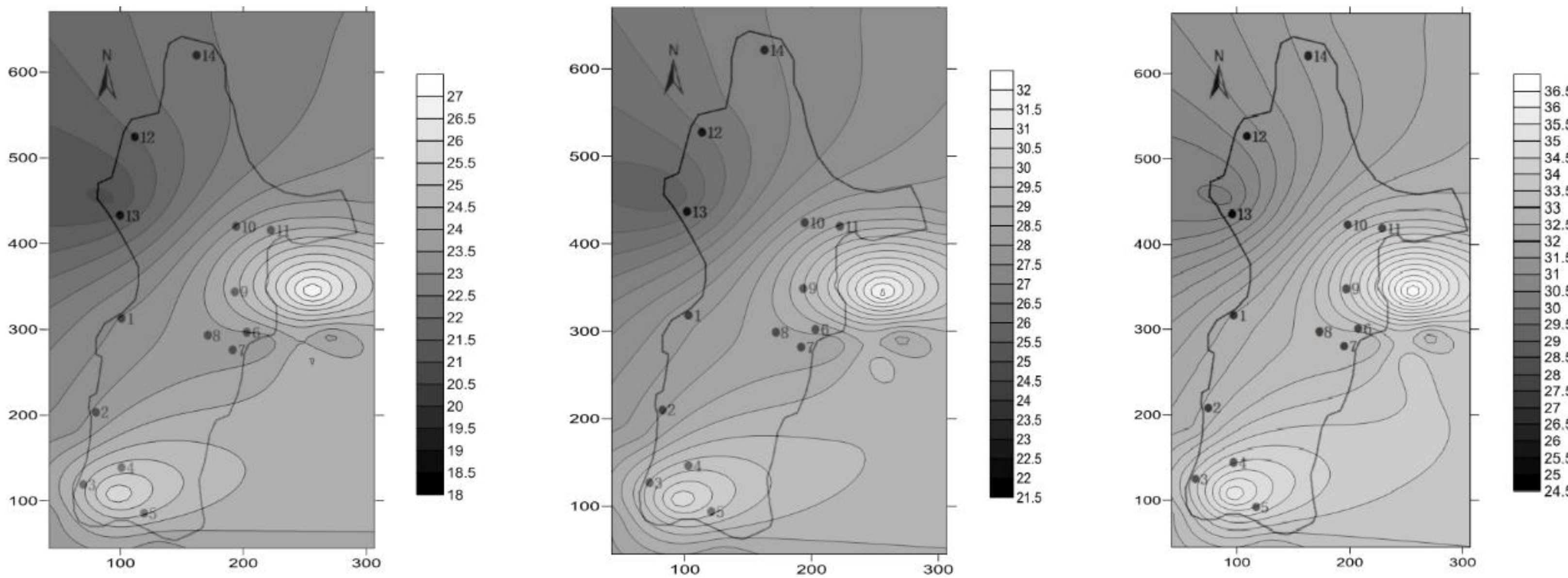
As for the Chinese methods, it was easily observed when using the CNWQI-S method that the water quality class was 5 at every time across every monitoring station (seen in Table 4-5). However, the CNWQI-C method had more complex water quality results than CNWQI-S due to the existence of abundant variations. Based on the difference between the water quality result standards of the OWQI and CWQI methods, the smaller values of CNWQI-C represented better water quality. During the three months of study, the results for CNWQI-C varied across the small range of 3.06 to 4.82. In the first month, the WQI figures ranged between 3.74 and 4.82. Afterwards, in

September, the amounts changed from 3.58 to 4.58. The results were the best in October as the quantities at each of the 14 sampling stations were the smallest recorded within the entire monitoring period. Out of all the monitoring stations, Site 7 displayed the lowest values in each month (3.74 in August, 3.58 in September, and 3.06 in October). However, the largest figures were not consistently observed at the same station, with the CNWQI-C result at Site 1 being 4.82 in August and 4.58 in September. In October, the largest recorded amount was 3.81 at Site 13. It can thus be seen that the results for CNWQI-C became smaller and smaller from August to September and from September to October.

4.4.2 Index result visualization based on GIS

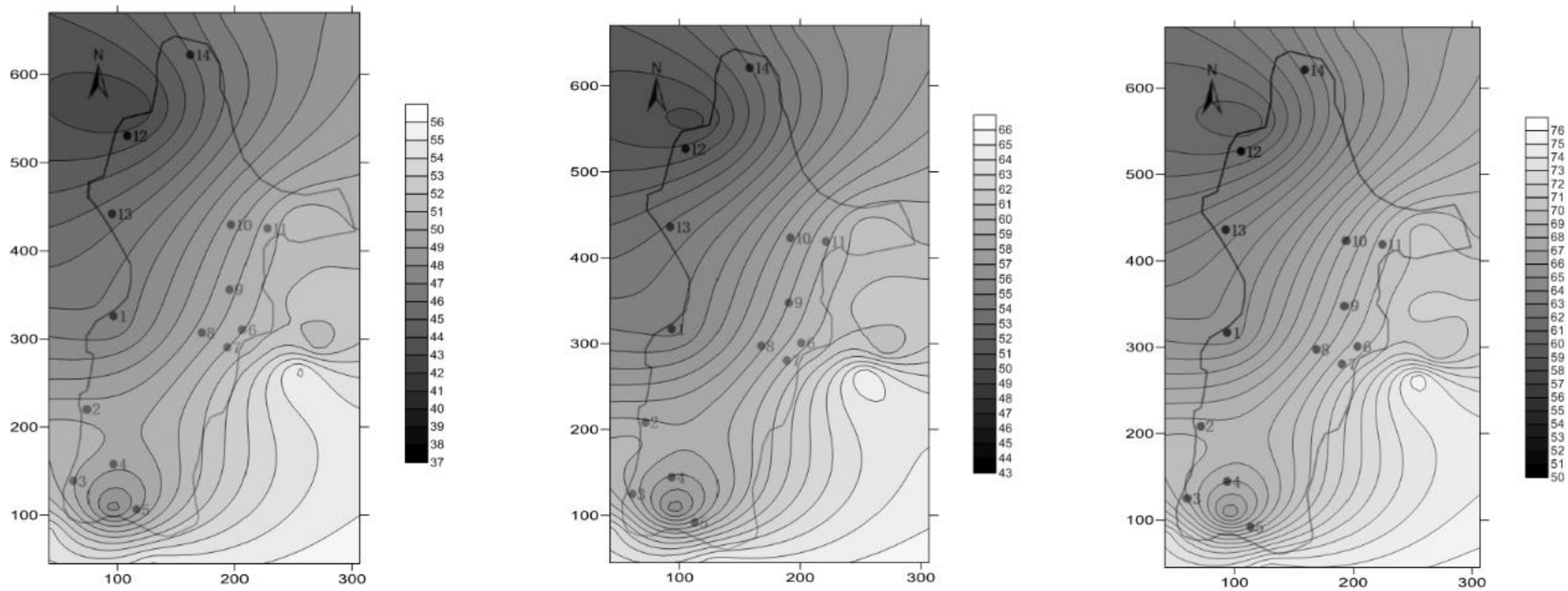
Figure 4-2 describes the distribution of and the changes in the water quality of HJH Lake in August, September and October 2013. In the map for the OWQI method, the water area including Sites 3, 4 and 5 showed the best water quality during the entire monitoring period. However, the water quality around Site 12, 13 and 14 reached the worst level during the three months. The CWQI method displayed a similar level of water quality in the water area of Sites 12, 13 and 14 during the same period, but the best water quality was seen in Sites 6, 7 and 11. In using different standards of computation processes and classification levels, the CNWQI-C method reached distinctly different results from the OWQI and CWQI methods. The area of lowest-grade water quality moved southwards, from the region including Sites 1, 12 and 13 to the area of Sites 2, 10 and 14. However, the best water quality level appeared at the southeast of HJH Lake around Sites 5, 6 and 7, where it occupied a part of the best water quality seen with the

OWQI method at Site 5 and some of the area of the highest water quality level seen with CWQI approach (Sites 6 and 7). Although the four water quality index methods obtained differing results, a common phenomenon was observed, namely that the water quality improved from August to September and from September to October due to the cooler weather.



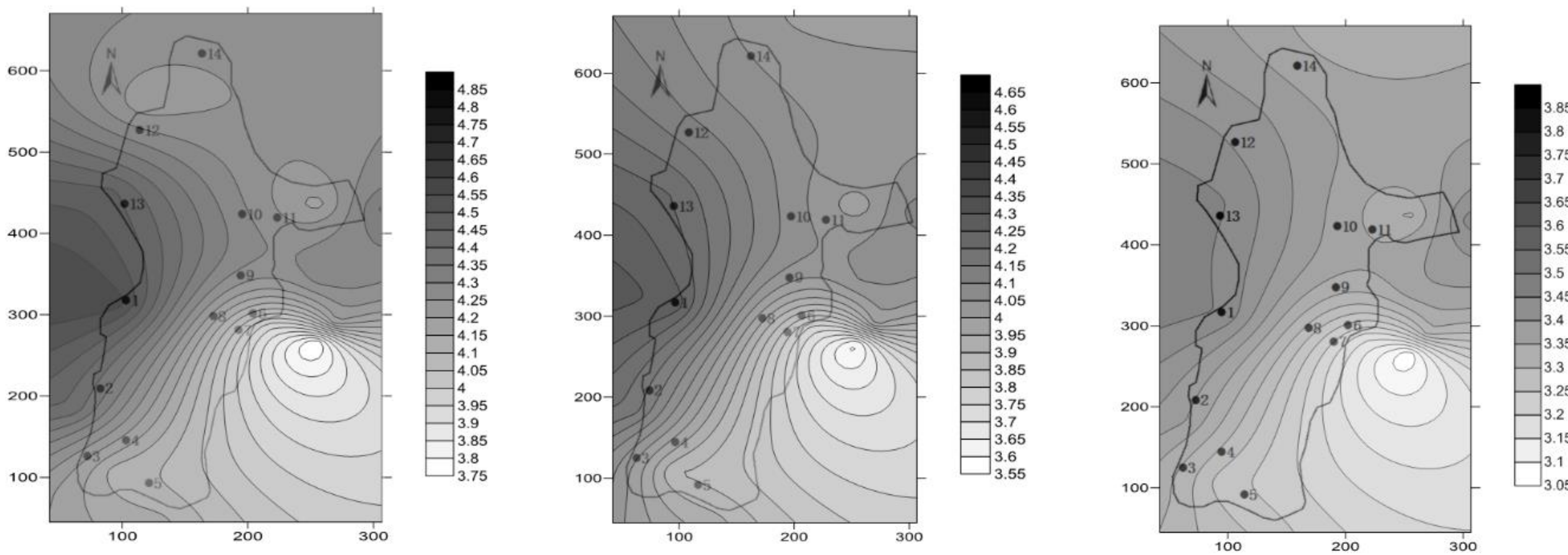
OWQI (Aug) OWQI (Sep) OWQI(Oct)

Figure 4-2 OWQI-based water quality assessment for August, September, and October 2013



CWQI (Aug) CWQI (Sep) CWQI(Oct)

Figure 4-3 CWQI-based water quality assessment for August, September, and October 2013



CNWQI-C (Aug) CNWQI-C (Sep) CNWQI-C (Oct)

Figure 4-4 CNWQI-C-based water quality assessment for August, September, and October 2013

4.5 Discussion

4.5.1 Water quality classes for OWQI, CWQI, and CNWQI

Table 4-6 Water quality categories based on OWQI, CWQI, and CNWQI (Cude, 2001; CCME, 2001; GB3838, 2002)

Classification	OWQI		CWQI		CNWQI	
	Grades	Results	Grades	Results	Grades	Results
A	Excellent	90-100	Excellent	95-100	Excellent	1
B	Good	85-89	Good	80-95	Good	2
C	Fair	80-84	Fair	65-79	Medium	3
D	Poor	60-79	Marginal	45-64	Poor	4
E	Very Poor	0-59	Poor	0-44	Very Poor	5

To explicitly compare the OWQI, CWQI and CNWQI methods, it was necessary to begin with the same water quality levels. Since each of the methods used five water quality classes, their grades could be unified from best to worst as A, B, C, D and E, with the relevant details being provided in Table 4-6 (Cude, 2001; CCME, 2001; GB3838, 2002). Based on the relevant water quality standards in the US, Canada, and China, the water quality classification levels for OWQI, CWQI and CNWQI were presented in Table 4-6.

4.5.2 Comparison of the final assessment results based on classification levels

Drawn from Table 4-5, 4-6, and Figure 4-2, the final results for the water quality evaluation were shown in Table 4-7 as grades and in Figure 4-5 as maps.

Table 4-7 Final assessment results

(Defined in Table 4-6)

Sampling Sites	OWQI Levels			CWQI Levels			CNWQI-C Levels			CNWQI -S Levels
	Aug	Sep	Oct	Aug	Sep	Oct	Aug	Sep	Oct	
1	E	E	E	E	D	D	E	E	D	E
2	E	E	E	E	D	C	E	E	D	E
3	E	E	E	D	D	C	E	E	D	E
4	E	E	E	D	D	D	E	D	D	E
5	E	E	E	D	C	C	D	D	D	E
6	E	E	E	D	D	C	D	D	D	E
7	E	E	E	D	C	C	D	D	D	E
8	E	E	E	D	D	C	E	D	D	E
9	E	E	E	D	D	C	E	E	D	E
10	E	E	E	D	D	C	E	E	D	E
11	E	E	E	D	D	C	E	E	D	E
12	E	E	E	E	E	D	E	E	D	E
13	E	E	E	E	D	D	E	E	D	E
14	E	E	E	E	D	D	E	E	D	E

As seen in Table 4-7, there were two situations describing the status of the water quality in HJH Lake. Firstly, the classes of water quality seen in OWQI were quite similar to the results from CNWQI-S. The worst water quality during the sampling period was Level E. With the other two methods, CWQI and CNWQI-C, these grades ranged from C to E. In the CWQI method, Levels D and E were observed in August. The classes changed to Level C, D and E in the second month, as well as in October, with the appearance of Levels C and D showing that the overall water quality had changed for the better. In the results from the CNWQI-C method, the grades of water quality in the first two months were similar to the results from CWQI. However, the water quality in October was observed at Level D with the CNWQI-C method, which was was an obvious improvement over the previous two months.

Figure 4-5 described the comparison among the four methods. The lake was observed at E, the lowest level of water quality, when using the OWQI and CNWQI-S assessment approaches. Nevertheless, the evaluation results improved with the CWQI and CNWQI-C methods, with the lake quality being observed across a range of three classes, Levels C, D and E. In the CWQI results, the water quality changed for the better from northwest to southeast during the three- month period. Two grades were observed during August, Levels D and E, which both took up nearly half the water area. In September, three classes of water quality, Levels C, D and E, were observed with the lake area mainly recorded at Level D. The water quality was observed at its best in October as approximately half the total lake area was seen to be at Level C. In the results for the CNWQI-C method, the water quality in August was the worst out of the entire three-month period, with the majority of the water area being recorded at Level E and only a small part at the southeast belonging to Level D. In September, the water quality improved as seen in the increasing area of Level D. The water quality, at Level D, was the best across the entire lake in the final month.

After comparison, the similarities and differences of the various evaluation approaches were found to be as follows:

(a) Due to its detailed sub-index, stringent computation process, exact values and related classification system, the OQWI model tended to be the most comprehensive model of the four for lake water quality assessment.

(b) Because of its lack of data, CWQI was not the most useful model in this study although the values and the categories for water quality seemed exciting.

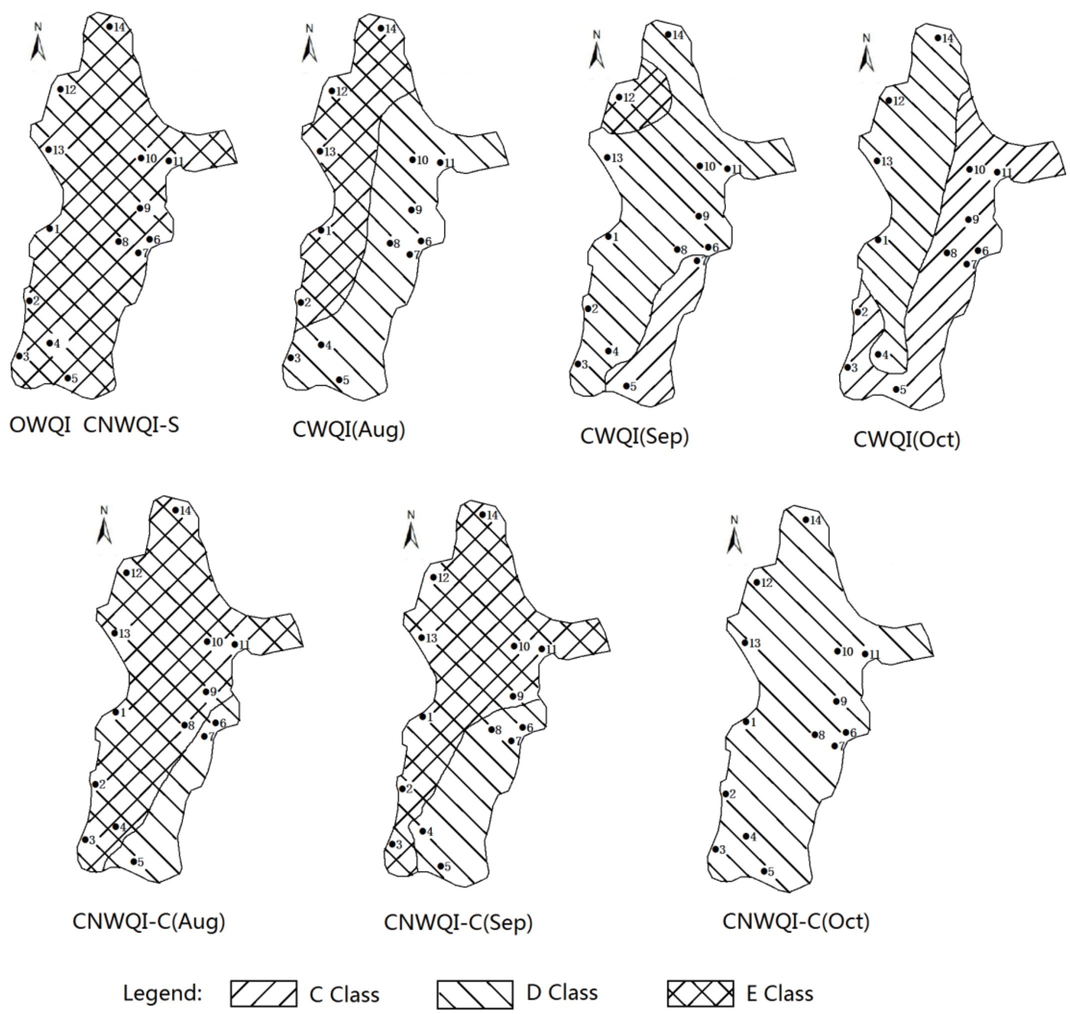


Figure 4-5 Lake water quality assessment results based on four index methods

(c) The CNWQI models are flexible for use in different projects. However, the CNWQI-S method is too arbitrary due to its negation of all the better data. Although the amounts observed with the CNWQI-C model are not conclusive due to its use of only a few directional ranges for the primary parameters, it is a much better method than CNWQI-S based on its overall consideration of water quality parameters. It is thus of greater use to Chinese researchers and decision-makers in local water pollution control and water body management.

4.5.3 Sensitivity analysis

This thesis aimed to discover an integrated approach to controlling lake contamination and managing the lake system. Therefore, sensitivity analysis was made to try to find suitable methods. OWQI was employed in this study to explore the various scenarios by which lake water quality might be improved.

As seen in Tables 4-5 and 4-7, the OWQI results showed the worst levels of water quality: “very poor” (E) with values between 18.39 and 34.52 from August to October. However, if the concentrations of TP, NH_3-N and BOD_5 were reduced by controlling runoff discharge into the lake, the water quality index would improve greatly. There was an obvious example in Sampling Site 3 which was very close to the main discharge point from a residential area. If the concentrations of TP, NH_3-N and BOD_5 in August remained constant, the original amount of OWQI was calculated as follows:

$$OWQI = SQRT(9/((1/\ S_{TP}{}^{2})+(1/\ S_{NH3-N}{}^{2})+\ldots+(1/\ S_{T}{}^{2})\ )\ ) = 25.21$$

Thus, the water quality level based on OWQI at Site 3 in August is "Very Poor" (0-59, E).

If the concentrations of TP and NH_3-N were reduced greatly, S_{TP} and $S_{NH3\text{-}N}$ would not need to be considered in the computation of theOWQ result. Thus:

$$OWQI = SQRT(7/((1/\ S_{NO3-N}{}^{2})+(1/\ S_{pH}{}^{2})+\ldots+(1/S_{T}{}^{2})\ )) = 58.06$$

Therefore, the water quality level observed at Site 3 using the OWQI method was "Very poor" (0-59, E), but the value approached 60 (D).

If the concentrations of TP, NH_3-N and BOD_5 were controlled and greatly reduced, S_{TP}, $S_{NH3\text{-}N}$ and S_{BOD5} would not need to be considered in the calculation process. Thus:

$$OWQI = SQRT(6/((1/\ S_{NO3-N}{}^{2})+(1/\ S_{pH}{}^{2})+\ldots+(1/\ S_{T}{}^{2})\ )\ ) = 69.27$$

The level of water quality observed at this station using the OWQI method was "Poor" (60-79, D).

The aforementioned sensitivity analysis showed that TP, NH_3-N and BOD_5 exerted a huge influence on the lake water quality. They were the most significant parameters in controlling the water contamination of HJH Lake.

4.6 Summary

These OQWI, CWQI, CNWQI-C and CNWQI-S water quality indexing methods were applied to assess the water quality of HJH Lake. The assessment results were displayed in the form of GIS maps which described the spatial distribution of the evaluation results including the water quality assessment results and the levels of water quality. Through sensitivity analysis and the comparison of the four models, the most suitable method of water quality assessment for lake management was identified in this chapter. The results showed that TP, NH_3-N and BOD_5 played significant roles in the influence on the water quality of HJH Lake as the most important parameters.

CHAPTER 5 LAKE POLLUTION CONTROL PLANNING FOR HJH LAKE

5.1 Study Site and Data

As seen in Section 4.1, HJH Lake is surrounded by agricultural land, a residential area, a hoggery and a fishery. The relevant information is presented in the following sections.

All the data used in this chapter were obtained from HUST. After a detailed analysis of the researched system, several major factors were considered when modeling this system to achieve the expected results. These parameters included total net benefits, the supply and demand of water resources, pollutant discharge limitations, agricultural development, aquaculture and the rearing of livestock. The distribution information regarding available water resources and water quality requirements is expressed in Table 5-1. In addition, system parameters including net benefits, water demand and the discharge of pollutants (TP, NH_3-N, and BOD_5) are given in Tables 5-2 and 5-3. As seen in the discussion of Chapter 4, these three types of contaminant paramters (TP, NH_3-N and BOD_5) play the most significant roles in the lake management of HJH Lake. TP, NH_3-N, and BOD_5 are thus taken into account in this study's lake pollution control planning.

Table 5-1 Water resources and water quality requirements with distribution information (HUST, 2013)

Parameters	Period k=1	k=2	k=3
	Maximum available water resource ($10^6 m^3$)		
p_i =0.01	1.83	1.92	2.07
pi =0.05	2.07	2.15	2.26
pi =0.10	2.14	2.31	2.48
	Maximum available TP discharge (10^3kg)		
p_i =0.01	4.63	2.28	1.17
pi =0.05	4.75	2.52	1.26
pi =0.10	5.08	2.78	1.35
	Maximum available NH_3-N discharge (10^4kg)		
p_i =0.01	3.10	2.10	1.05
p_i =0.05	3.15	2.15	1.10
p_i =0.10	3.20	2.30	1.20
	Maximum available BOD5 discharge (10^5kg)		
p_i =0.01	1.25	0.83	0.63
pi =0.05	1.30	0.90	0.67
pi =0.10	1.35	0.95	0.70

Table 5-2 Optimization model parameters of net benefit, water demand and contaminant discharge (TP, NH_3-N, and BOD_5) (HUST, 2013)

Parameters	Net benefit		Water demand		TP discharge		NH_3-N discharge		BOD_5 discharge	
	unit	value	unit	value	unit	value	unit	value	unit	value
Agriculture activities	10^6 \$/km^2	3.52	10^5 m^3/km^2	7.5	kg/km^2	60	kg/km^2	150	10^3 kg/km^2	4.9
Livestock rearing	\$/head	520	m^3/head	3.6	kg/head	3.15	kg/head	4	kg/head	8
Fishing farming	10^6 \$/km^2	2.85	m^3/km^2	50	kg/km^2	95	kg/km^2	160	10^3 kg/km^2	6
Residential population			m^3/people	102	kg/people	0.02	kg/people	0.14	kg/people	0.35

In Table 5-1, the factor k represents one of three periods, 1, 2 or 3, which respectively represent 2016-2020, 2021-2025 and 2026-2030. The other parameter i describes a set of significant levels, 0.01, 0.05 or 0.10, which were selected for use in this study according to the risk tolerance level of decision makers. The p_i levels mean that the constraints would be satisfied with a probability of at least 99, 95 or 90 %.

Table 5-3 Other optimization model parameters (HUST, 2013)

Parameters	Periods		
	k=1	k=2	k=3
α_{kl} (%)	75	85	95
α_{kp} (%)	70	80	90
β_{kl} (%)	85	90	95
β_{kp} (%)	70	75	85
θ_{kl} (%)	70	75	85
θ_{kp} (%)	70	75	85
EWD_k ($10^5 m^3$)	4.00	4.50	5.00
ILA_k (km^2)	2.00	2.00	2.00
ALA_k (km^2)	1.80	1.80	1.80
ILS_k (head)	80	80	80
ALS_k (head)	1500	1500	1500
IWF_k (km^2)	0.80	0.80	0.80
AWF_k (km^2)	1.50	1.50	1.50
IP_k (10^4people)	0.70	0.50	0.40
AP_k (10^4people)	1.00	0.85	0.70

The percentage parameters α_{lk}, α_{pk}, β_{lk}, β_{pl}, θ_{lk} and θ_{pk} present the average treatment efficiency for diverse pollutants in different periods. ALA_k and ALA_k respectively represent the maximum and minimum allowable areas of land for agriculture during the period k. The other factors are similar.

5.2 Coupled Simulation-Optimization Process

There are four steps in this chapter which comprise the entire planning system. They are as follows:

(1) Modeling the real monitoring data to support the possibility of optimization implementation;

(2) Model application including comparison of the SOP model and the MOP model to recommend the better method of the two to decision-makers;

(3) Water quality result comparison with the OWQI method and the CNWQI-C method based on the MOP optimization results;

(4) Modeling comparison between OWQI and CNWQI-C based on the MOP model results under two probabilities and two periods.

5.3 Water Quality Simulation

In order to give evidence for the possibility of optimization implementation, it is preferable that the first step in the planning system study be the selection of the monitoring value simulation method. The modeling approach used in this study was chosen based on the contaminant distribution theory described in Section 3.3.1 with the aim of imitating the real pollutant concentration diffusion situation in HJH Lake as accurately as possible. It was then used to validate the feasibility of the planning scheme and predict the future status of the water quality to support suggestions to decision-makers.

5.3.1 Emission sources and distribution

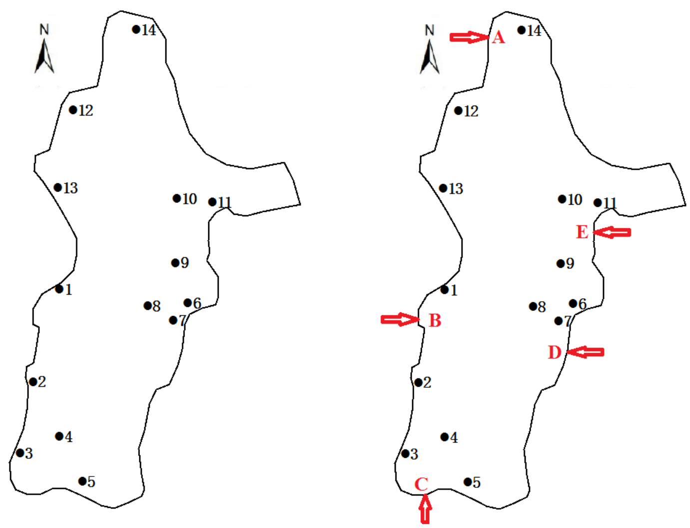


Figure 5-1 Locations of monitoring stations and emission sources

There were five contaminant discharging sources around the lake which were designated A, B, C, D and E as shown in Figure 5-1. It was assumed that the total quantity of each emission at each point remained unchanged during the entire simulation period. The discharge of TP, NH_3-N and BOD_5 per year was 7.45×10^3kg, 3.10×10^4kg and 3.73×10^5kg respectively (HUST, 2013). Table 5-4 provides the coordinates and the pollutant values of the discharge sources for TP, NH_3-N and BOD_5.

Table 5-4 Emission sources and locations for TP, NH_3-N, and BOD_5

Discharge sources	X (longitude)	Y (latitude)	TP (10^3kg)	NH_3-N (10^4kg)	BOD_5 (10^5kg)
A	114.286941	30.467259	3.14	1.57	1.76
B	114.278459	30.440375	1.21	0.58	0.97
C	114.278143	30.423206	1.05	0.34	0.37
D	114.293392	30.441937	0.94	0.25	0.31
E	114.294861	30.450748	1.11	0.36	0.32

5.3.2 Results and analysis

Based on Table 5-4 and the key equation for the pollutant concentration distribution (3-26) shown in Section 3.3.1 (O'Connor, 1962), the concentrations of the contaminants TP, NH_3-N and BOD_5 at the 14 sites in HJH Lake were computed using Excel. This is shown in Tables 5-5, 6 and 7. Comparisons were done between the monitoring data (expressed as -0) and modeling data (shown as -1) for these contaminants in order to validate their errors of difference and determine whether they meet the requirements of the simulation method.

Table 5-5 Comparison between the monitoring and modeling data for TP at 14 sampling stations

Sampling stations	X (longitude)	Y (latitude)	TP-0 (mg/l)	TP-1 (mg/l)	Error (%)
1	114.280196	30.444079	0.36	0.29	19.44
2	114.277618	30.435002	0.34	0.26	23.53
3	114.276324	30.427965	0.35	0.28	20.00
4	114.280205	30.429647	0.35	0.25	28.57
5	114.282433	30.425225	0.34	0.25	26.47
6	114.293545	30.442211	0.31	0.24	22.58
7	114.293257	30.442148	0.38	0.30	21.05
8	114.288874	30.442461	0.37	0.28	24.32
9	114.291604	30.446694	0.34	0.24	29.41
10	114.291748	30.452983	0.3	0.24	20.00
11	114.295773	30.452236	0.56	0.42	25.00
12	114.283358	30.461699	0.49	0.37	24.49
13	114.281364	30.453792	0.28	0.20	28.57
14	114.289718	30.469917	0.58	0.43	25.86

According to US standards, the margin of error between the sampling data and the simulation values should be less than 30 percent (USEPA, 2011). Although some errors can be seen in Tables 5-5 to 5-7, they are all smaller than 30 percent. They meet the requirements of the simulation. This verification method is thus usable to model the pollutant concentration dispersion in HJH Lake.

Table 5-6 Comparison between the monitoring and modeling data for NH_3-N at 14 sampling stations

Sampling stations	X (longitude)	Y (latitude)	NH3-N-0 (mg/l)	NH_3-N-1 (mg/l)	Error (%)
1	114.A280196	30.444079	1.40	1.12	20.00
2	114.277618	30.435002	1.11	0.94	15.32
3	114.276324	30.427965	1.30	1.03	20.77
4	114.280205	30.429647	0.71	0.67	5.63
5	114.282433	30.425225	0.79	0.83	-5.06
6	114.293545	30.442211	1.31	1.35	-3.05
7	114.293257	30.442148	1.82	1.70	6.59
8	114.288874	30.442461	1.52	1.43	5.92
9	114.291604	30.446694	1.29	0.94	27.13
10	114.291748	30.452983	0.98	1.06	-8.16
11	114.295773	30.452236	1.19	1.14	4.20
12	114.283358	30.461699	4.01	2.97	25.94
13	114.281364	30.453792	1.26	1.61	-27.78
14	114.289718	30.469917	5.79	4.23	26.94

Table 5-7 Comparison between the monitoring and modeling data for BOD_5 at 14 sampling stations

Sampling stations	X (longitude)	Y (latitude)	BOD_5-0 (mg/l)	BOD_5-1 (mg/l)	Error (%)
1	114.280196	30.444079	25.25	19.74	21.82
2	114.277618	30.435002	19.10	14.33	24.97
3	114.276324	30.427965	19.10	18.52	3.04
4	114.280205	30.429647	17.46	17.32	0.80
5	114.282433	30.425225	18.06	18.05	0.06
6	114.293545	30.442211	17.13	16.54	3.44
7	114.293257	30.442148	23.51	19.25	18.12
8	114.288874	30.442461	21.07	17.05	19.08
9	114.291604	30.446694	19.10	16.90	11.52
10	114.291748	30.452983	18.09	18.35	-1.44
11	114.295773	30.452236	22.51	20.07	10.84
12	114.283358	30.461699	17.31	16.46	4.91
13	114.281364	30.453792	12.54	8.91	28.95
14	114.289718	30.469917	22.39	23.57	-5.27

5.4 Optimization Models for HJH Lake

All optimization projects must first attain a few objectives, such as maximal benefit, minimal risks, minimal negative influence, minimal cost, etc. Researchers must often thus face a choice between single-objective and multi-objective. Single-objective is usually considered to be comparatively simple. Its primary goal is to find the "best" solution, which sometimes simply corresponds to the most important objective and other times corresponds to the minimum or maximum value of a single objective function that integrates each different goal into a single one. This type of optimization is useful as a tool with which to provide decision makers with insights into the nature of the problem faced. However, it usually cannot provide a set of alternative solutions that weigh different objectives against each other. On the other hand, in multi-objective optimization with conflicting objectives, there is no single optimization approach and the interaction among the various objectives results in a suite of compromised methods (Dragon, 2008). The present study therefore focuses on finding a method, based on a comparison between the SOP model and the MOP model, which is more suitable for lake water contamination control in order to provide sound recommendations to decision-makers for optimal lake water pollution management.

“What's Best! 14.0” was employed in the following modeling approach. It is a piece of Excel add-in software which can build large-scale planning models within a spreadsheet. “What's Best! 14.0” has the capacity to integrate Linear, Nonlinear, Stochastic and other types of optimization with Microsoft Excel. “What's Best! 14.0” is the newest version which comprises several stronger functions with a much wider range of utilization. (http://www.hearne.software/Software/What-s-Best!/Editions).

5.4.1 SOP model

Economic development is usually taken for granted to be the the first target. Maximum total net benefit is thus selected as the objective for the SOP model (shown as Equation 5-1). The selection of constraints in planning the model is essential for obtaining feasible and efficient trade-offs. In this study, a series of economic, social and ecological factors related to environmental concerns are considered in the system, such as water resources, agricultural land area, livestock number, water area used for aquaculture, the discharge limitations of TP, NH_3-N and BOD_5, the local residential population and other technical constraints (Equation 5-1 to 5-10).

Total benefit objective

$$\max f = \sum_{i=1}^{I}\sum_{k=1}^{K} AX_{ik} * ANB_k + \sum_{i=1}^{I}\sum_{k=1}^{K} LX_{ik} * LNB_k + \sum_{i=1}^{I}\sum_{k=1}^{K} FX_{ik} * FNB_k \tag{5-1}$$

where AX_{ik} is the area of agricultural land planted with a probability level of p_i during the period k (km^2/year), ANB_k is the net benefit from the agricultural plantation in period k (\$/km^2), LX_{ik} is the number of livestock farmed in the system with a probability level of p_i during period k (head/year), LNB_k is the net benefit from farmed animals during period

k (\$/head), FX_{ik} is the aquaculture area in the system with a probability level of p_i in period k (km^2/year) and FNB_k is the net benefit from the aquaculture in period k (\$/km^2).

Constraints:

a. Water resource availability constraints

$$\sum_{i=1}^{I}\sum_{k=1}^{K} AX_{ik} * AWD_k + \sum_{i=1}^{I}\sum_{k=1}^{K} LX_{ik} * LWD_k + \sum_{i=1}^{I}\sum_{k=1}^{K} FX_{ik} * FWD_k + \sum_{i=1}^{I}\sum_{k=1}^{K} PX_{ik} * PWD_k + EWD_k \le TW_{ik}, \forall i, k \tag{5-2}$$

where AWD_k, LWD_k, FWD_k and PWD_k are the water demand during period k for agricultural land, the raising of livestock, aquaculture and people, respectively (m^3/km^2). EWD_k is the water demand for ecological protection in the system during period k (m^3), and TW_{ik} is the maximum allowable amount of water resources available with a probability level of p_i in period k (m^3).

b. Agricultural land area availability constraint

$$ILA_k \le \sum_{i=1}^{I}\sum_{k=1}^{K} AX_{ik} \le ALA_k, \forall i, k \tag{5-3}$$

where ILA_k and ALA_k are the minimum and maximum allowable areas of land for agriculture during period k (km^2), respectively.

c. Livestock rearing availability constraint

$$ILS_k \le \sum_{i=1}^{I}\sum_{k=1}^{K} LX_{ik} \le ALS_k, \forall i, k \tag{5-4}$$

where ILS_k and ALS_k are the minimum and maximum allowable number of livestock in period k (head), respectively.

d. Water area for aquaculture availability constraint

$$IWF_k \le \sum_{i=1}^{I}\sum_{k=1}^{K} FX_{ik} \le AWF_k, \forall i, k \tag{5-5}$$

where IWF_k and AWF_k are the minimum and maximum allowable areas of water for aquaculture during period k (km^2), respectively.

e. TP discharge limitation constraint

$$\sum_{i=1}^{I}\sum_{k=1}^{K} AX_{ik} * AP_k + \sum_{i=1}^{I}\sum_{k=1}^{K} LX_{ik} * LP_k * (1-\alpha_{lk}) + \sum_{i=1}^{I}\sum_{k=1}^{K} FX_{ik} * FP_k + \sum_{i=1}^{I}\sum_{k=1}^{K} PX_{ik} * PP_k * (1-\alpha_{pk})$$

$$\leq TP_k, \forall i, k \qquad (5\text{-}6)$$

where AP_k is the amount of phosphorus generated by agricultural activities in period k (kg/ km^2), LP_k is the amount of phosphorus generated by livestock in period k (kg/head), FP_k is the amount of phosphorus generated by fish in period k (kg/ km^2), PP_k is the amount of phosphorus generated by human activities in period k (kg/people), TP_k is the maximum allowable amount of phosphorus in the system during period k (kg) and αl_k and αp_k are the average treatment efficiencies for phosphorus discharged respectively by livestock and residents in period k (%).

f. NH_3-N discharge limitation constraint

$$\sum_{i=1}^{I}\sum_{k=1}^{K} AX_{ik} * (ANH3 - N_k) + \sum_{i=1}^{I}\sum_{k=1}^{K} LX_{ik} * (LNH3 - N_k) * (1 - \beta_{lk}) + \sum_{i=1}^{I}\sum_{k=1}^{K} FX_{ik} * (FNH3 - N_k) +$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K} PX_{ik} * (PNH3 - N_k) * (1 - \beta_{pk}) \leq NH3 - N_k, \forall i, k \qquad (5\text{-}7)$$

where $ANH3\text{-}N_k$ is the value of ammonia nitrogen generated by agricultural activities in period k (kg/ km^2), $LNH_3\text{-}N_k$ is the value of ammonia nitrogen generated by livestock in period k (kg/head), $FNH_3\text{-}N_k$ is the amount of ammonia nitrogen generated by fish in period k (kg/ km^2), $PNH_3\text{-}N_k$ is the value of ammonia nitrogen generated by human activities in period k (kg/people), $NH_3\text{-}N_k$ is the maximum allowable value of ammonia nitrogen in the system during period k (kg) and β_{lk} and β_{pk} are the average treatment efficiencies for ammonia nitrogen discharged respectively by livestock and residents in period k (%).

g. BOD_5 discharge limitation constraint

$$\sum_{i=1}^{I}\sum_{k=1}^{K} AX_{ik} * ABOD_k + \sum_{i=1}^{I}\sum_{k=1}^{K} LX_{ik} * LBOD_k * (1-\theta_{lk}) + \sum_{i=1}^{I}\sum_{k=1}^{K} FX_{ik} * FBOD_k + \sum_{i=1}^{I}\sum_{k=1}^{K} PX_{ik} * PBOD_k$$

$$* (1-\theta_{pk}) \le BOD_k, \forall i, k \qquad (5\text{-}8)$$

where $ABOD_k$ is the amount of BOD_5 generated by agricultural activities in period k (kg/ km^2), $LBOD_k$ is the amount of BOD_5 generated by livestock in period k (kg/head), $FBOD_k$ is the amount of BOD_5 generated by fish in period k (kg/ km^2), $PBOD_k$ is the amount of BOD_5 generated from human activities in period k (kg/people), BOD_k is the maximum allowable amount of BOD_5 in the system during period k (kg) and θ_{lk} and θ_{pk} are the average treatment efficiencies for BOD_5 discharged respectively from livestock and residents in period k (%).

h. Population constraint

$$IP_k \le \sum_{k=1}^{K} PX_k \le AP_k, \forall i, k \qquad (5\text{-}9)$$

where IP_k and AP_k are respectively the initial and maximum allowable number of residents in the system during period k (people).

i. Non-negativity and technical constraint

$$AX_{ik}, LX_{ik}, FX_{ik}, PX_k \geq 0, \forall i, k \quad (5\text{-}10)$$

5.4.2 MOP model

In the multi-objective programming model, the two objectives for this study were chosen to be total net benefit and water quality. Although the key aim was for the principal objective to be maximum total net profit due to concerns for local economic development, it was also imperative to have the best possible water quality. As shown in chapter 4, the three primary polluting paramters in HJH Lake were TP, NH_3-N and BOD_5. If the values of these three pollutants were controlled, the lake water quality could thus also be managed quite effectively. Therefore, the lake water quality results are obtained from the full calculation of TP, NH_3-N, and BOD_5 through the employment of the proper approach. Based on the integral analysis, the CNWQI-C method is considered to apply to the study as the case is located in China and the Chinese relative method is acceptable to all stockholders in the local area. The second objective of the MOP model is shown in Equations 5-11, while Equations 5-12 to 5-14 are for the computation of water quality index.

Multiple objectives

a. Total benefit objective

the equation is the same as Equation 5-1.

b.Water quality objective (based on Equations 3-18 and 19) (Zhu, 2010)

$$\min CNWQI - C = (1/3)\sum_{i=1}^{I}\sum_{k=1}^{K}(I_{TP-ik} + I_{NH3-N-ik} + I_{BOD5-ik}) \quad (5\text{-}11)$$

where CNWQI-C is the Chinese comprehensive water quality index and I_{TP-ik}, $I_{NH3-N-ik}$ and $I_{BOD5-ik}$ are the indices of TP, NH_3-N and BOD_5 respectively with a probability level of p_i during period k.

$$C_{TP} = [\sum_{i=1}^{I}\sum_{k=1}^{K} AX_{ik} * AP_k + \sum_{i=1}^{I}\sum_{k=1}^{K} LX_{ik} * LP_k * (1-\alpha_{lk}) + \sum_{i=1}^{I}\sum_{k=1}^{K} FX_{ik} * FP_k + \sum_{i=1}^{I}\sum_{k=1}^{K} PX_{ik} * PP_k * (1-\alpha_{pk})]$$

$$/V, \forall i, k \quad (5\text{-}12)$$

$$C_{NH3-N} = [\sum_{i=1}^{I}\sum_{k=1}^{K} AX_{ik} * (ANH3 - N_k) + \sum_{i=1}^{I}\sum_{k=1}^{K} LX_{ik} * (LNH3 - N_k) * (1-\beta_{lk}) + \sum_{i=1}^{I}\sum_{k=1}^{K} FX_{ik} * (FNH3 -$$

$$N_k) + \sum_{i=1}^{I}\sum_{k=1}^{K} PX_{ik} * (PNH_3 - N_k) * (1 - \beta_{pk})] / V, \forall i, k \qquad (5\text{-}13)$$

$$C_{BOD_5} = [\sum_{i=1}^{I}\sum_{k=1}^{K} AX_{ik} * ABOD_{5k} + \sum_{i=1}^{I}\sum_{k=1}^{K} LX_{ik} * LBOD_{5k} * (1 - \theta_{kl}) + \sum_{i=1}^{I}\sum_{k=1}^{K} FX_{ik} * FBOD_{5k} + \sum_{i=1}^{I}\sum_{k=1}^{K} PX_{ik} *$$

$$PBOD_{5k} * (1 - \theta_{kp})] / V, \forall i, k \qquad (5\text{-}14)$$

where C_{TP}, $C_{NH3\text{-}N}$ and C_{BOD5} are the concentrations of TP, NH_3-N and BOD_5 in HJH Lake and V is the volume of HJH Lake (m^3).

Constraints: they are the same as the constraints from Equations 5-2 to 5-10 in Section 5.4.1.

5.4.3 Results

Based on the "Chinese Surface Water Environment Quality Standard" (GB3838, 2002) with the use of the “What's Best! 14.0” software, the results for the SOP and MOP models were obtained.

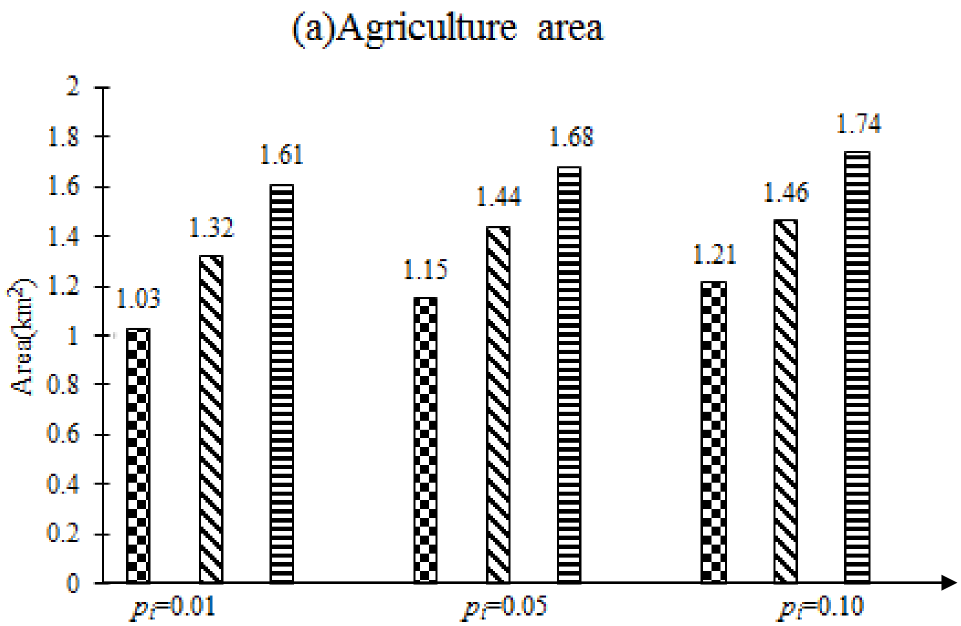
5.4.3.1 SOP model results

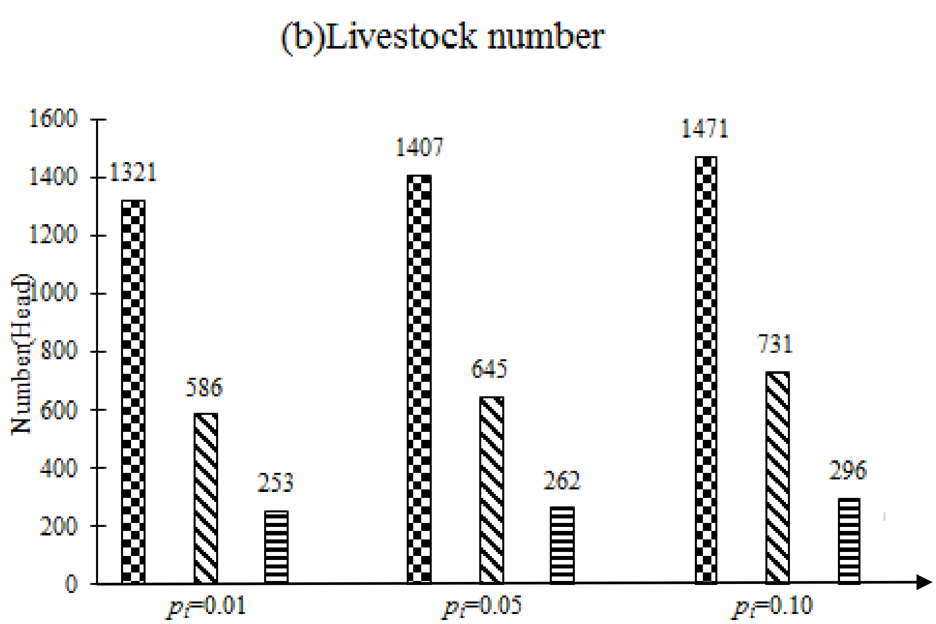
Figure 5-2(a) shows the optimization results for the agricultural planning area under three different *pi* levels during the different three periods. In period 1, the area was 1.03, 1.15 and 1.21 km^2 where p_i equaled 0.01, 0.05 and 0.10, respectively. In period 2, the agricultural area increased to 1.32, 1.44 and 1.46 km^2 under the three p_i levels. In period 3, the area changed to 1.61, 1.68 and 1.74 km^2 under the three p_i respectively. Similarly, under p_i = 0.01, the area was 1.03, 1.32 and 1.61 km^2 when k equaled 1, 2 and 3 respectively. Under p_i = 0.05 it increased to 1.15, 1.44 and 1.68 km^2 over the three periods. When *pi* equaled 0.10, it changed to 1.21, 1.46 and 1.74 km^2 in the three periods respectively. In Figure 5-3 (a), two growths show the change of the agricultural area, one being that every value of the agricultural area grew larger and larger from $k = 1$ to $k = 2$ and to $k = 3$ when p_i equaled 0.01, 0.05 and 0.10, respectively, and the other being that the planning result for each period increased under the three different p_i levels.

Figure 5-2(b) provides the results for livestock development under the three p_i levels over the three periods. In period 1, the number of livestock was 1321, 1407 and 1471 where p_i equaled 0.01, 0.05 and 0.10 respectively. In period 2, the livestock number increased from 586, 645 and 731 under the three p_i levels. In the last period, it changed to 253, 262 and 296 under the three p_i respectively. Similarly, under p_i = 0.01, it was 1321, 586 and 253 when k equaled 1, 2 and 3, respectively. Under p_i = 0.05, it increased from 1407, 645 and 262 over the three periods. Finally, where p_i equaled 0.10, it changed to 1471, 731 and 296 in the three periods respectively. For the raising of livestock, two different changes were observed. Firstly, every result for the cattle number greatly decreased from $k = 1$ to $k = 2$ and $k = 3$ under each level among p_i = 0.01, p_i = 0.05, and

p_i = 0.10. However, every optimized result increased in the same period from p_i =0.01 to p_i = 0.05 and p_i = 0.10, although the growths were small.

Figure 5-2(c) presents the optimization solutions for the aquaculture area in the entire optimization period under the three p_i levels. When p_i equaled 0.01, the aquaculture area grew from 1.26 to 1.38 and then to 1.43 k m^2 where k equaled 1, 2 and 3 respectively. When p_i equaled 0.05, the area increased from 1.15 to 1.23 and then to 1.27 km^2 in the three periods. When p_i equaled 0.10, the optimization area became 0.96, 1.02 and 1.11 km^2 when k equaled 1, 2 and 3 respectively. Conversely, in period 1, the area decreased from 1.26 to 1.15 and then to 0.96 where p_i equaled 0.01, 0.05 and 0.10 respectively. In period 2, the aquaculture area also diminished, going from 1.38 to 1.23 and then 1.02 under the three p_i levels. In the last period, it changed to 1.43, 1.27 and 1.11 under the three p_i respectively. This group of data shows that the aquaculture area decreased within the optimization period under the same p_i level. Meanwhile, the results indicated that fishery has provided more profitless devotion into lake water contamination. Nevertheless, it's readily acceptable that the aquaculture area increased when p_i equaled 0.01, 0.05 and 0.10, since the three p_i levels indicate the three various satisfactory degrees for the constraints with a possibility of at least 99, 95 and 90%.


(a)Agriculture area
Area(km²)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.03
1.32
1.61
1.15
1.44
1.68
1.21
1.46
1.74
pf=0.01
pf=0.05
pf=0.10


(b)Livestock number
Number(Head)
1600
1400
1200
1000
800
600
400
200
0
1321
586
253
1407
645
262
1471
731
296
pf=0.01
pf=0.05
pf=0.10

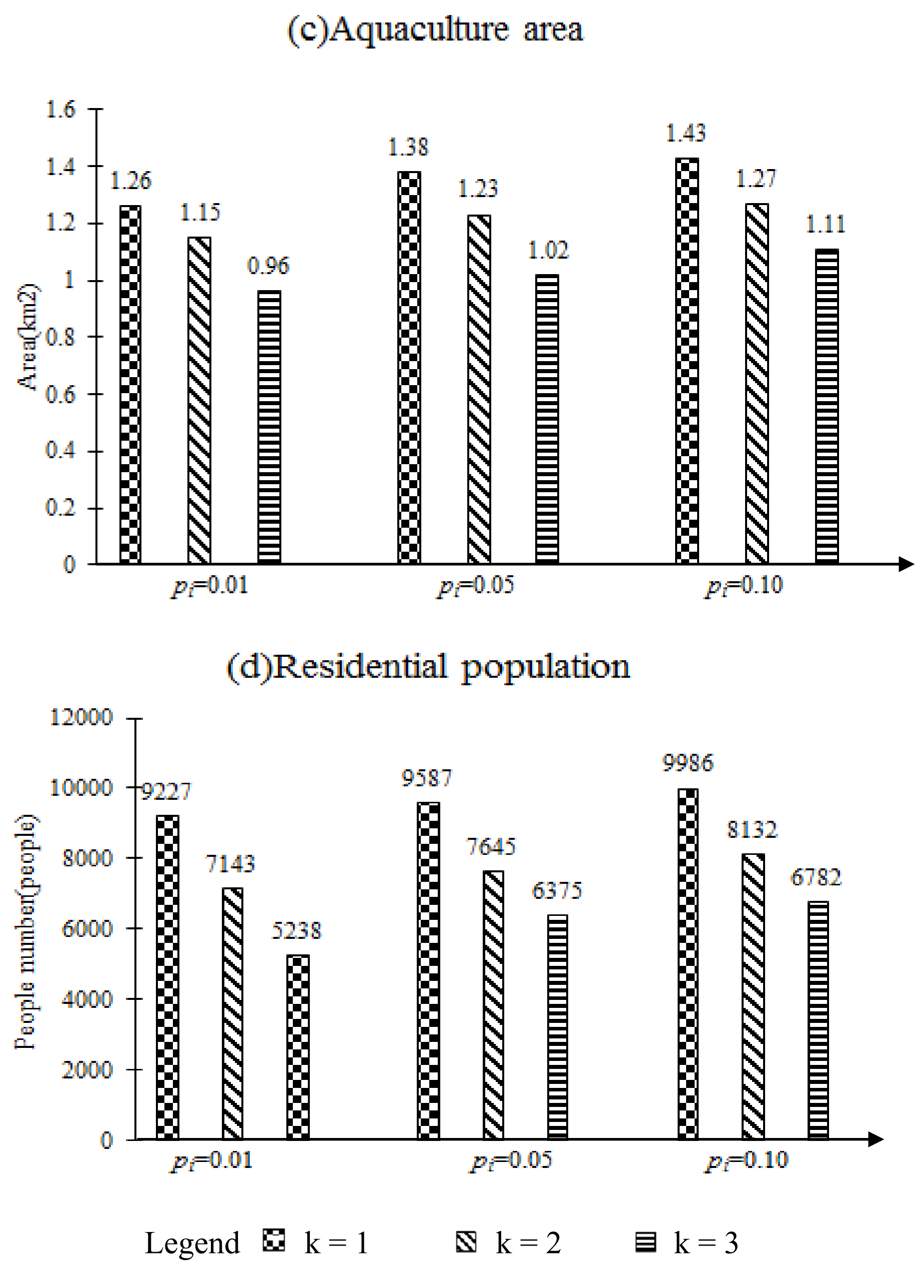


Figure 5-2 Results for SOP model for (a) agricultural area, (b) livestock number, (c) aquaculture area and (d) residential population under three p_i levels and three periods

Figure 5-2(d) shows the planning results for the residential population under the three p_i levels over the three periods. When p_i equaled 0.01, the number of inhabitants was 9227, 7143 and 5238 when k equaled 1, 2 and 3 respectively. Where p_i equaled 0.05, it decreased from 9587 to 7645 and 6375 over the three periods. Finally, where p_i equaled 0.10, it changed to 9986, 8132 and 6782 in the three periods respectively. In period 1, the residential population was 9227, 9587 and 9986 where p_i equaled 0.01, 0.05 and 0.10 respectively. In period 2, it changed to 7143, 7645 and 8132 under the three p_i levels. In the last period, it changed to 5238, 6375 and 6782 under the three p_i respectively. For the inhabitants, there are two approximate directions, as with livestock rearing and fish farming, from $k = 1$ to $k = 2$ and $k = 3$ under each level among $p_i = 0.01$, $p_i = 0.05$ and $p_i = 0.10$.

Tables 5-8 to 5-10 show the optimization results for the total net benefit and water demand pollutant discharge over the three p_{i} levels in the three periods. It can be observed that the total net benefit as the single objective varied under the different p_{i} levels. In detail, when p_{i} equaled 0.01, the total net benefits were 7.90×10^6, 8.23×10^6 and 8.53×10^6 \$ in the three periods. Where $p_{\mathrm{i}} = 0.05$, they changed to 8.20×10^6, 8.63×10^6, and 8.96×10^6 \$ when k equaled 1, 2 and 3 respectively. Under the last p_{i} level, the total net benefits became 9.10×10^6, 9.14×10^6 and 9.44×10^6 \$ over the three periods. To clearly compare the water quality results between the SOP and MOP models, this section provides water quality details including the discharge, the concentration of TP, NH_3-N and BOD_5, the WQI results, CNWQI-C and the gradation of water quality. When p_{i} equaled 0.01, the TP release values were 4.53×10^3, 2.18×10^3, and 1.09×10^3 kg in the three periods. Where $p_{\mathrm{i}} = 0.05$, they turned to 4.67×10^3, 2.38×10^3 and1.15×10^3 kg when k equaled 1, 2 and 3 respectively. Under the last p_{i} level, the TP discharge values corresponded to 5.04×10^3, 2.67×10^3 and 1.26×10^3 kg over the three periods. The TP values, including concentration and sub-index, were respectively computed according to Equations 5-12 and 3-18 and presented in Tables 5-8 and 9. The related data about NH_3-N and BOD_5 is also provided in Tables 5-8 and 9. WQI results were calculated based on Equation 3-19 and shown in Table 5-10. Finally, each lake water quality gradation for CNWQI was indicated in Table 5-10 under different p_i levels in each period. Altogether, this last set of results shows that a high p_i level led to less satisfactory lake water quality but a higher total net benefit. Conversely, these final values reflect that a lower p_i level produced more satisfactory lake water quality but resulted in a lower total net benefit.

Table 5-8 SOP model optimization results for total net benefit, water demand and pollutant discharge under three p_i levels and three periods

Optimized results	Different p_i levels								
	p_i = 0.01			p_i = 0.05			p_i = 0.10		
	k=1	k=2	k=3	k=1	k=2	k=3	k=1	k=2	k=3
Total net benefit (10^6\$)	7.90	8.23	8.53	8.20	8.63	8.96	9.10	9.14	9.44
Water demand ($10^6 m^3$)	1.71	1.72	1.74	1.79	1.80	1.91	1.93	1.94	2.00
TP discharge (10^3kg)	4.53	2.18	1.09	4.67	2.38	1.15	5.04	2.67	1.26
NH_3-N discharge (10^3kg)	5.81	3.77	2.14	7.16	4.05	2.36	7.69	4.48	2.55
BOD_5 discharge (10^4kg)	2.36	2.02	1.75	2.74	2.19	1.87	2.98	2.35	1.99

Table 5-9 SOP model optimization results for concentration of TP, NH_3-N, and BOD_5 under three p_i levels and three periods

Concentration	Different p_i levels								
	p_i = 0.01			p_i = 0.05			p_i = 0.10		
	k=1	k=2	k=3	k=1	k=2	k=3	k=1	k=2	k=3
TP (mg/l)	0.219	0.105	0.053	0.226	0.115	0.056	0.243	0.129	0.061
NH_3-N (mg/l)	0.281	0.182	0.103	0.346	0.196	0.114	0.371	0.216	0.123
BOD_5(mg/l)	1.140	0.976	0.845	1.324	1.058	0.903	1.440	1.135	0.961

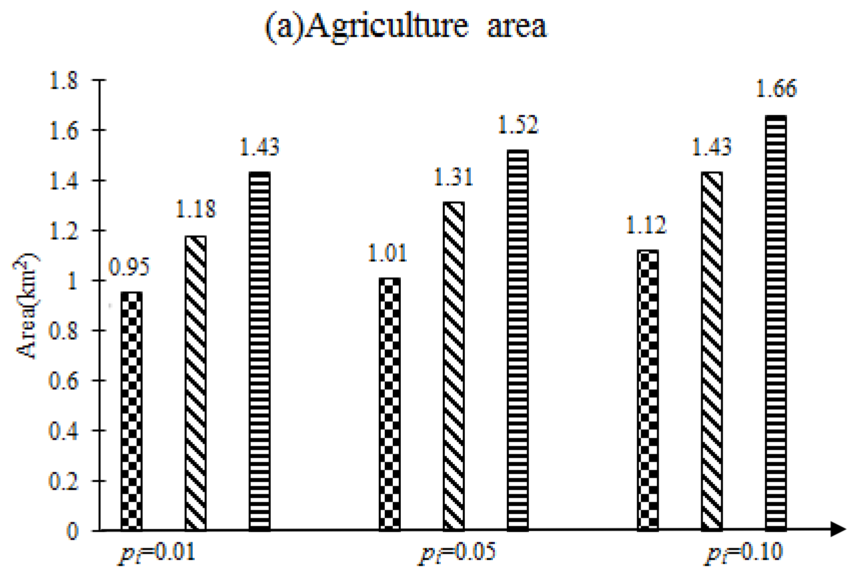
Table 5-10 SOP model optimization results for water quality details under three p_i levels and three periods

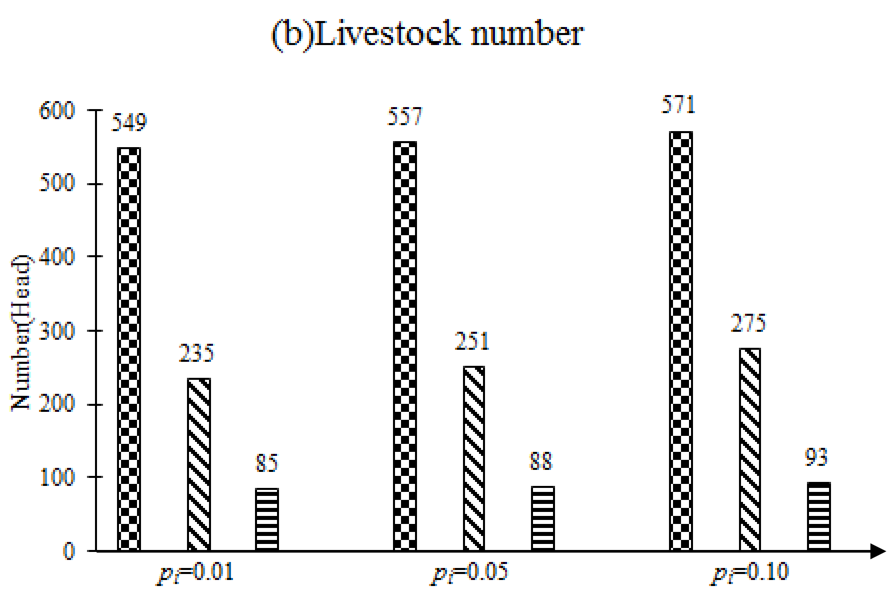
Water quality	Different p_i levels								
	$p_i = 0.01$			$p_i = 0.05$			$p_i = 0.10$		
	k=1	k=2	k=3	k=1	k=2	k=3	k=1	k=2	k=3
WQI results	3.33	3.00	2.33	3.33	3.00	2.33	3.33	3.00	2.33
CNWQI-C	4	3	3	4	3	3	4	3	3
Gradation of CNWQI-C	Poor	Fair	Fair	Poor	Fair	Fair	Poor	Fair	Fair

5.4.3.2 MOP model results

Figure 5-3(a) presents the planning solutions for the optimized agricultural area in the three different periods under the three different *pi* levels. In Figure 5-3(a), there are two growth tendencies for the farming area. The first is that each result for the agricultural area increased from k = 1 to k = 2 and k = 3 under each level when p_i = 0.01, p_i = 0.05, and p_i = 0.10. Secondly, each optimized result increased from p_i = 0.01 to p_i = 0.05 and p_i = 0.10 in each period. In period 1, the result was 0.95, 1.01 and 1.12 km^2 where *pi* equaled 0.01, 0.05 and 0.10 respectively. Subsequently, in period 2, the agricultural area increased from 1.18 to 1.31 and 1.43 km^2 under the three *pi* levels. Finally, in period 3, it changed to 1.43, 1.52 and 1.66 km^2 under the three *pi* respectively. Similarly, under p_i = 0.01, the result was 0.95, 1.18 and 1.43 km^2 when k equaled 1, 2 and 3 respectively. Under p_i = 0.05, it increased from 1.01, 1.31 and 1.52 km^2 over the three periods. Eventually, where *pi* equaed 0.1, the result changed to 1.12, 1.43 and 1.66 km^2 in the three periods respectively. Although agricultural activities unavoidably create contaminants, the demands of population growth and economic development need as as much land area as possible devoted to agriculture to plant more crops. Meanwhile, on the basis of a proper planning method, it is possible to obtain both more agricultural land area and higher net benefits under the satisfaction of many kinds of constraints.

Figure 5-3(b) provides the optimization solutions for the development of livestock rearing over the three periods under the three *pi* levels. For the case of livestock rearing, one decreasing tendency and one increasing tendency were observed. Firstly, every result for the number of livestock decreased from $k = 1$ to $k= 2$, and $k = 3$ under each level among $p_i = 0.01$, $p_i = 0.05$ and $p_i = 0.10$, while every optimized result grew from $p_i = 0.01$ to $p_i = 0.05$ and $p_i = 0.10$ over the three periods. In period 1, the result was 549, 557 and 571 where *pi* equaled 0.01, 0.05 and 0.10 respectively. In period 2, the livestock number increased from 235 to 251 and 275 under the three *pi* levels. In the last period, it changed to 85, 88 and 93 under the three *pi* respectively. Under $p_i = 0.01$, the result was 549, 235 and 85 when k equaled 1, 2 and 3 respectively. Under $p_i = 0.05$, it changed to 557, 251 and 88 over the three periods. Finally, where *pi* equaled 0.10, the number changed to 571, 275 and 93 in the three periods respectively. These results make it clear that the number of livestock would decrease steadily during the entire planning period under each level with the aim of producing greater water quality as a contribution to lake management.


(a)Agriculture area
Area(km²)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.95
1.18
1.43
1.01
1.31
1.52
1.12
1.43
1.66
pi=0.01
pi=0.05
pi=0.10


(b)Livestock number
Number(Head)
600
500
400
300
200
100
0
549
235
85
557
251
88
571
275
93
pi=0.01
pi=0.05
pi=0.10

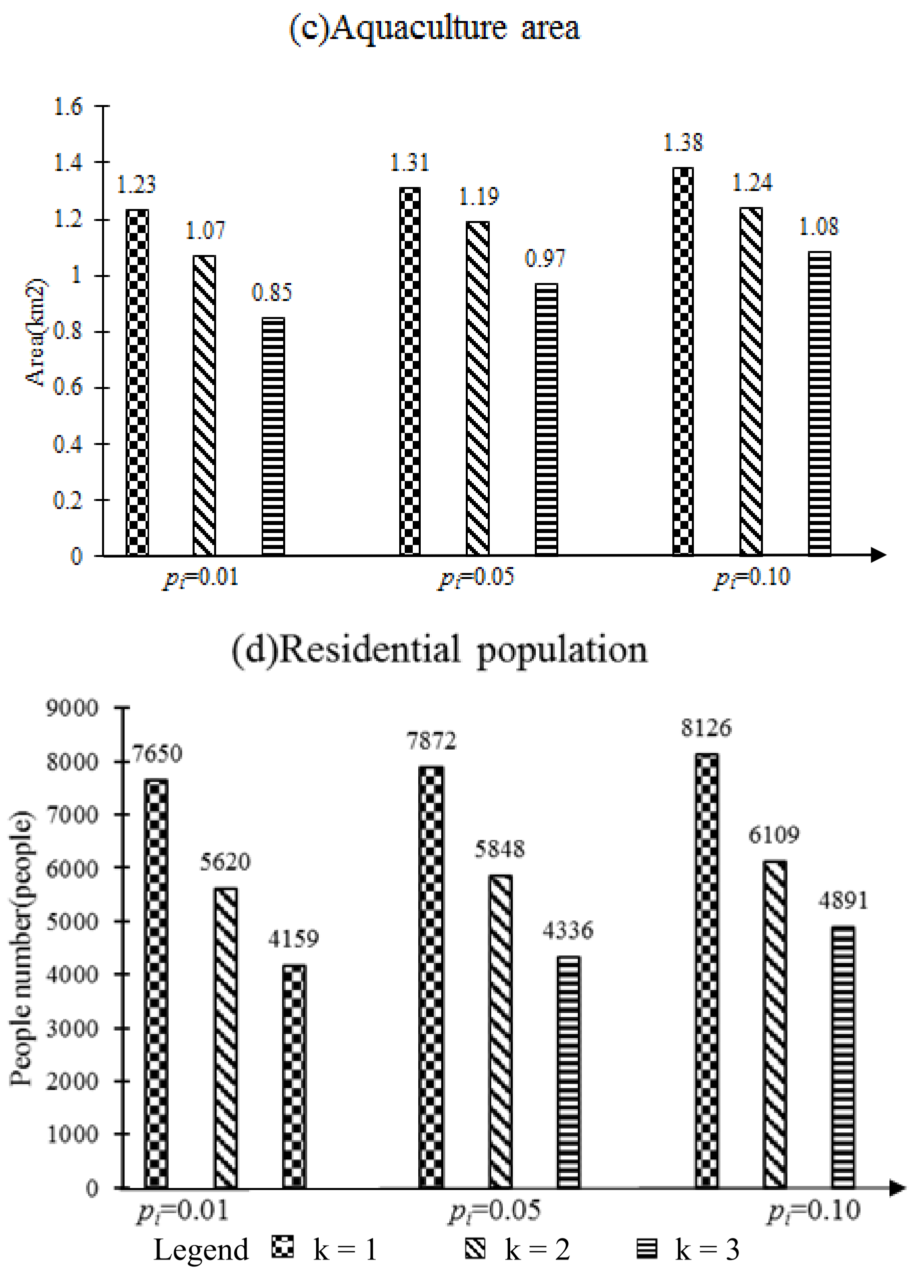


Figure 5-3 Results of MOP model for (a) agriculture area, (b) livestock number, (c) aquaculture area and (d)residential population under three p_i levels and three periods

Figure 5-3(c) describes the optimization results for the aquaculture area under the three p_i levels across the entire optimization period. The aquaculture area showed the same situation as the livestock number, with two opposite tendencies as follows: the aquaculture area decreased in the three periods under the same p_i level. However, it increased under the three p_i degrees in the same period. When p_i equaled 0.01, the aquaculture area declined from 1.23 to 1.07 and then to 0.85 km^2 where k equaled 1, 2 and 3 respectively. When p_i equaled 0.05, the area changed from 1.31 to 1.19 and then to 0.97 km^2 in the three periods, and when p_i equaled 0.10, the optimization area became 1.38, 1.24 and 1.08 km^2 when k equaled 1, 2 and 3 respectively. Conversely, in period 1, the area was 1.23, 1.31 and 1.38 km^2 when p_i equaled 0.01, 0.05 and 0.10 respectively. In period 2, the aquaculture area increased from 1.07 to 1.19 and 1.24 km^2 under the three p_i levels. In the last period, it changed to 0.85, 0.97 and 1.08 km^2 under the three p_i respectively. This group of data shows that the aquaculture area would decrease within the optimization period under a constant p_i level. Meanwhile, the results indicate that fishery has provided more profitless devotion into lake water contamination. Nevertheless, it is readily acceptable that the aquaculture area increased when p_i equaled 0.01, 0.05 and 0.10, since the three *pi* levels indicate the three various satisfactory degrees for the constraints with a possibility of at least 99, 95 and 90%.

Figure 5-3(d) shows the optimization solutions for the residential population over the three periods under the three p_i levels. For the inhabitants, as with livestock rearing and fish farming, there were two approximate directions of growth from $k = 1$ to $k = 2$ and $k = 3$ under $p_i = 0.01$, $p_i = 0.05$, and $p_i = 0.10$. In period 1, the residential population was 7650, 7872 and 8126 where p_i equaled 0.01, 0.05 and 0.10, respectively. In period 2, it decreased from 5620, 5848 and 6109 under the three p_i levels. In the last period, it changed to 4159, 4336 and 4891 under the three p_i respectively. Similarly, under p_i =

0.01, the population was 7650, 5620 and 4159 when k equaled 1, 2 and 3 respectively. Under p_i = 0.05, it decreased from 7872 to 5848 and 4336 over the three periods. Finally, where p_i equaled 0.10, the population changed to 8126, 6109 and 4891 in the three periods respectively. The above data shows that the number of residents was maintained or reduced within the optimization process regardless of any levels due to its negative influence on water quality.

Table 5-11 MOP model optimization results for total net benefit, water demand and Water quality under three p_i levels and three periods

Optimized results	Different p_i levels								
	p_i = 0.01			p_i = 0.05			p_i = 0.10		
	k=1	k=2	k=3	k=1	k=2	k=3	k=1	k=2	k=3
Total net benefit (10^6\$)	7.13	7.33	7.50	7.58	8.13	8.16	8.17	8.71	8.97
Water demand ($10^6 m^3$)	1.49	1.46	1.50	1.56	1.57	1.58	1.67	1.70	1.74
WQI results	2.33	1.67	1.33	2.67	2.00	1.67	2.67	2.00	1.67
CNWQI-C	3	2	2	3	2	2	3	2	2
Gradation of CNWQI-C	Fair	Good	Good	Fair	Good	Good	Fair	Good	Good

Table 5-11 shows the optimization results for total net benefit, water demand and water quality under the three p_i levels across the three periods. It can be observed that the two objectives of total net benefit and CNWQI-c results changed under the different p_i levels. Firstly, when p_i equaled 0.01, the total net benefits were 7.13×10^6, 7.33×10^6 and 7.50×10^6 \$ in the three periods. Where p_i = 0.05, they changed to 7.58×10^6, 8.13×10^6 and 8.16×10^6 \$ when k equaled 1, 2 and 3 respectively. Under the last p_i level, the total net benefits became 8.17×10^6, 8.71×10^6 and 8.97×10^6 \$ over the three periods. Secondly, when p_i equaled 0.01, the WQI results were 2.33, 1.67 and 1.33 in the three periods.

Where p_i = 0.05, they changed to 2.67, 2.00 and 1.67 when k equaled 1, 2 and 3 respectively. Finally, under the last p_i level, the WQI results became 2.67, 2.00 and 1.67 over the three periods. Based on the same reason for comparing the results for water quality between the SOP and MOP models, Tables 5-12 and 5-13 similarly present detailed water quality information from the discharge, the concentration and the sub-index of TP, NH_3-N, and BOD_5. When p_i equaled 0.01, the TP release values were 2.06×10^3, 1.03×10^3 and 0.52×10^3 kg in the three periods. Where p_i = 0.05, they changed to 2.09×10^3, 1.09×10^3 and 0.54×10^3 kg when k equaled 1, 2 and 3 respectively. Under the last p_i level, the values of TP discharge correspond to 2.15×10^3, 1.19×10^3 and 0.59×10^3 kg over the three periods. The related data concerning NH_3-N and BOD_5 is also provided in Table 5-12 and 5-13. Similarly, the last set of values implies that a high p_i level produced less satisfactory lake water quality but a higher total net benefit, while on the other hand a lower p_i level would result in more satisfactory lake water quality but a lower total net benefit.

To compare the results for the SOP and MOP models in detail, Tables 5-12 and 5-13 show the discharge and average concentration of TP, NH_3-N and BOD_5 under the conditions of different levels and periods.

Table 5-12 MOP model optimization results for emissions of TP, NH_3-N and BOD_5 under three p_i levels and three periods

Discharge	Different p_i levels								
	$p_i = 0.01$			$p_i = 0.05$			$p_i = 0.10$		
	k=1	k=2	k=3	k=1	k=2	k=3	k=1	k=2	k=3
TP discharge (10^3kg)	2.06	1.03	0.52	2.09	1.09	0.54	2.15	1.19	0.59
NH_3-N discharge (10^3kg)	3.61	2.08	1.27	3.69	2.21	1.34	3.81	2.37	1.48
BOD_5 discharge (10^4kg)	1.91	1.60	1.42	2.00	1.76	1.55	2.12	1.88	1.71

Table 5-13 MOP model optimization results for concentration of TP, NH_3-N, and BOD_5 emissions under three p_i levels and three periods

Concentration	Different p_i levels								
	$p_i = 0.01$			$p_i = 0.05$			$p_i = 0.10$		
	k=1	k=2	k=3	k=1	k=2	k=3	k=1	k=2	k=3
TP (mg/l)	0.099	0.049	0.025	0.101	0.053	0.026	0.104	0.057	0.029
NH_3-N (mg/l)	0.174	0.100	0.061	0.178	0.107	0.065	0.184	0.114	0.071
BOD_5 (mg/l)	0.923	0.773	0.686	0.966	0.850	0.749	1.024	0.908	0.826

5.4.4 Comparison and analysis

This section focuses on the comparison between the SOP model and the MOP model. It attempts to discover the similarities and differences between the two models and which is preferable for lake management and pollution control. The analysis of the relationship between the SOP and MOP models, based on Figures 5-1 to 5-5 and Tables 5-1 to 5-16, is presented as follows:

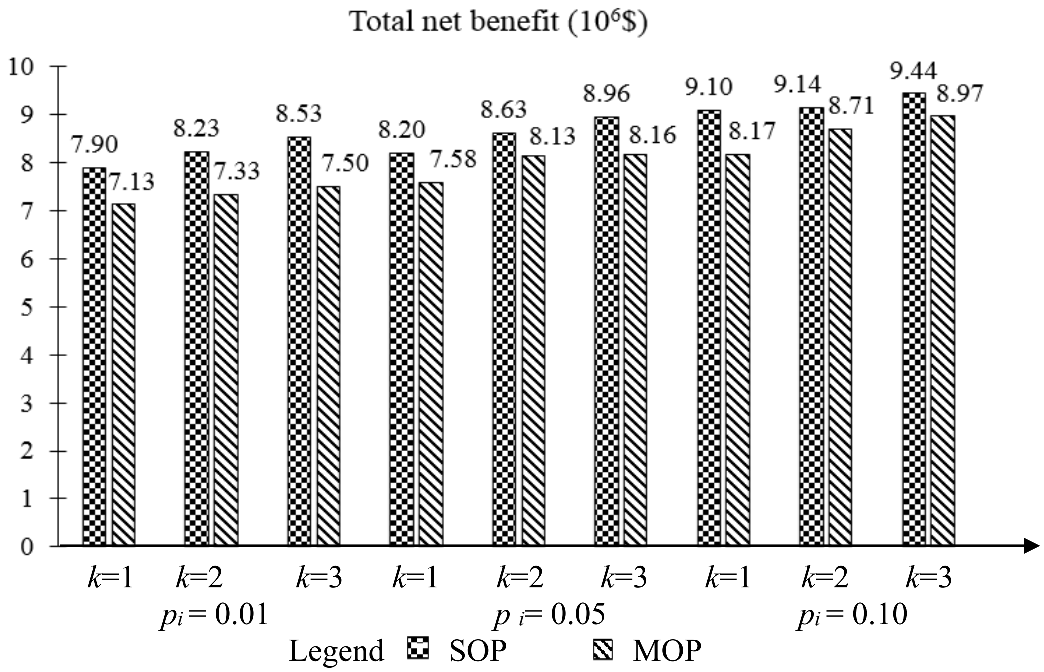


Figure 5-4 Comparison for total net benefit between SOP and MOP models

(each left one is for SOP model, and each right one is for MOP model)

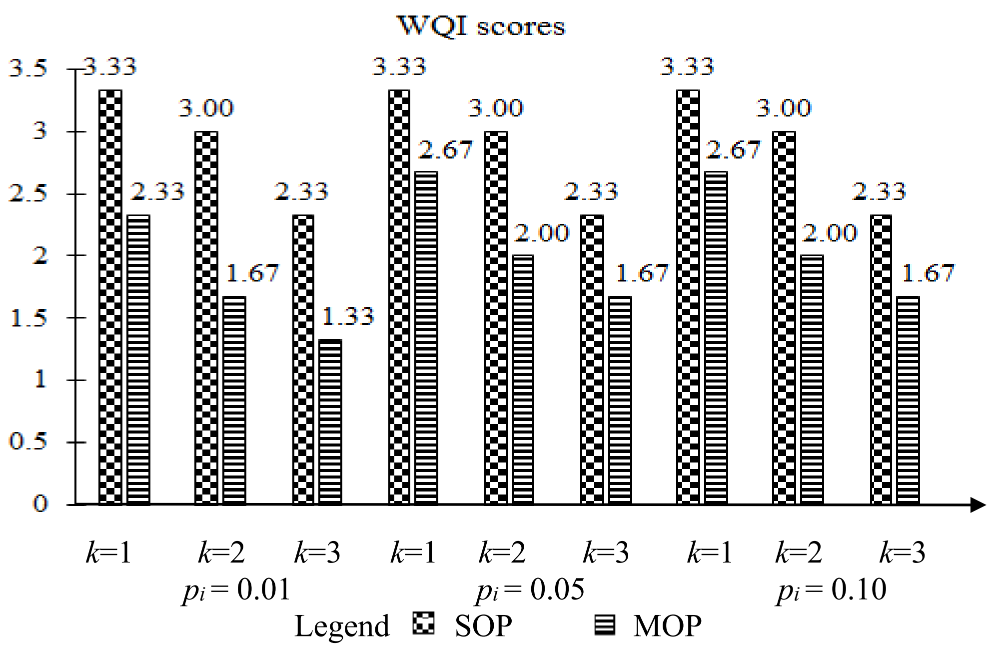


Figure 5-5 WQI results based on SOP and MOP optimization

(each left one is for SOP model, and each right one is for MOP model)

Table 5-14 Comparison of total net benefit resulted from SOP and MOP models under three p_i levels and three periods

Total net benefit (10^6\$)	Different p_i levels								
	$p_i = 0.01$			$p_i = 0.05$			$p_i = 0.10$		
	k=1	k=2	k=3	k=1	k=2	k=3	k=1	k=2	k=3
SOP model	7.90	8.23	8.53	8.20	8.63	8.96	9.10	9.14	9.44
MOP model	7.13	7.33	7.50	7.58	8.13	8.16	8.17	8.71	8.97

Table 5-15 Comparison of water demand resulted from SOP and MOP models under three p_i levels and three periods

Water demand ($10^6 m^3$)	Different p_i levels								
	$p_i = 0.01$			$p_i = 0.05$			$p_i = 0.10$		
	k=1	k=2	k=3	k=1	k=2	k=3	k=1	k=2	k=3
SOP model	1.71	1.72	1.74	1.79	1.80	1.91	1.93	1.94	2.00
MOP model	1.49	1.46	1.50	1.56	1.57	1.58	1.67	1.70	1.74

Table 5-16 Comparison of water quality resulted from SOP and MOP models under three p_i levels and three periods

Water quality	Different p_i levels								
	$p_i = 0.01$			$p_i = 0.05$			p_i =0 .1		
	k=1	k=2	k=3	k=1	k=2	k=3	k=1	k=2	k=3
WQI results for SOP	3.33	3.00	2.33	3.33	3.00	2.33	3.33	3.00	2.33
WQI results for MOP	2.33	1.67	1.33	2.67	2.00	1.67	2.67	2.00	1.67
CNWQI-C of SOP	4	3	3	4	3	3	4	3	3
CNWQI-C of MOP	3	2	2	3	2	2	3	2	2
Gradation of SOP	Poor	Fair	Fair	Poor	Fair	Fair	Poor	Fair	Fair
Gradation of MOP	Fair	Good	Good	Fair	Good	Good	Fair	Good	Good

(1)The similar results:

a. In the two proposed models, optimization values of total net benefits and agricultural area became progressively larger under each p_i level across the three periods. Although the WQI results became smaller under the same conditions, their variations mean that every optimized lake water quality result became better and better from k = 1 to k = 2 and k = 3. The water demand results for the SOP and MOP models had a slightly larger variation from p_i = 0.01 to 0.10 and from k = 1 to 3 except where p_i = 0.01 in the period of 2.

b. The series of optimization data for the livestock number, aquaculture area and residential population vary similarly with each p_i level. Within both the SOP model and the MOP model, the values gradually became smaller over the three periods under each p_i and the amounts grew larger and larger under the three probabilities in each period.

c. Whether in the SOP model or the MOP model, this last set of results shows that at a higher p_i level, the lake water quality decreased, but the total net benefit was higher, while at a lower p_i level the lake water quality increased but the total net benefit was lower.

(2) The differences:

a. The values for the total net benefit, water demand, agriculture area, livestock number, aquaculture area and residential population were larger when using the SOP model than when using the MOP model under the three p_i levels and acoss the three periods;

b. All the results for the concentrations of TP, NH_3-N and BOD_5 based on the SOP model were also larger than the corresponding values obtained from the SOP model under the three p_i levels and three periods;

c. All the WQI results under different p_i levesl and periods based on the SOP model were smaller than the corresponding values from the MOP model. In addition, the relevant gradation of WQI was worse and became one class lower.

With the SOP model, so long as the constraints were met, particularly the limitations of TP, NH_3-N and BOD_5 discharge, the single objective of total net benefit saw a better result based on the loose restrictions for water quality. However, the MOP model had to meet more rigorous requirements for lake water quality as the second objective. On one hand, it not only needed to comply with all the constraints, but was also interrelated with the first objective (total net benefit). On the other hand, the residential population did not contribute to the total net benefit. Nevertheless, the people living in the residential area continued to generate contaminants including TP, NH_3-N and BOD_5 and discharge them into HJH Lake. Although each result for the total net benefit in the SOP model was larger than the corresponding value in the MOP model due to the addition of the figures for the agriculture, livestock rearing and aquaculture areas, the relevant gradation of WQI in the SOP model was worse and dropped one class lower than MOP under the corresponding p_i levels and periods due to the greater discharge of TP, NH_3-N and BOD_5.

5.5 Discussion

5.5.1 OWQI and CNWQI-C water quality results based on MOP optimization

Since HJH Lake is located in China, the relevant Chinese regulations and methods are more acceptable for all interest groups. However, as discussed in the aforesaid section concerning the comparison of water quality assessment methods between US-OQWI, CWQI, CNWQI-S and CNWQI-C, this study aims to determine the best approach to lake system management. This section thus features a comparison of water quality between the OWQI and CNWQI-C methods based on the MOP optimization results and average concentration.

Using the MOP model pollutant concentration results in Table 5-13 and the relevant equation shown in Section 3.2.1, the water quality indices were calculated employing the OWQI method and shown in Table 5-17 under each level and each period:

Table 5-17 OWQI analysis based on MOP optimization
under three p_i levels and three periods

Index	Different p_i levels								
	$p_i = 0.01$			$p_i = 0.05$			$p_i = 0.10$		
	k=1	k=2	k=3	k=1	k=2	k=3	k=1	k=2	k=3
S_{TP}	70.35	85.08	92.51	69.75	84.13	92.21	68.85	82.93	91.31
S_{NH3-N}	58.91	71.11	79.13	58.34	69.80	78.24	57.51	68.53	76.95
S_{B0B5}	83.20	85.72	87.22	82.49	84.42	86.13	81.54	83.45	84.82

Table 5-18 provides the OWQI results and levels of water quality according to the values in Tables 5-11 and 5-17 and Equation 3-1. Meanwhile, the following table presents a comparison between the CNWQI-C and OWQI methods.

Table 5-18 Water quality assessment results based on MOP optimization

Water quality	Different p_i levels								
	$p_i = 0.01$			$p_i = 0.05$			$p_i = 0.10$		
	k=1	k=2	k=3	k=1	k=2	k=3	k=1	k=2	k=3
WQI results for CNWQI-C	2.33	1.67	1.33	2.67	2.00	1.67	2.67	2.00	1.67
Gradation of CNWQI-C	Fair	Good	Good	Fair	Good	Good	Fair	Good	Good
WQI results for OQWI	68.75	79.73	85.75	68.13	78.50	84.95	67.23	77.31	83.74
Gradation of OQWI	Poor	Poor	Good	Poor	Poor	Fair	Poor	Poor	Fair

Table 5-18 shows the comparison of the water quality results between the OWQI and CNWQI-C methods based on the results for the MOP model under the three p_i levels and three periods. Firstly, when p_i equaled 0.01, the OWQI results were 68.75, 79.73 and 85.75 in the three periods. Where $p_i = 0.05$, they changed to 68.13, 78.50 and 84.95 when k equaled 1, 2 and 3 respectively. Under the last p_i level, they became 67.23, 77.31 and 83.74 over the three periods. Secondly, when p_i equaled 0.01, the gradations of OWQI were Poor, Poor and Good across the three periods, and where $p_i = 0.05$, they changed to Poor, Poor and Fair when k equaled 1, 2 and 3 respectively. Under the last p_i level, the gradations of OWQI were also Poor, Poor and Fair over the three periods. It can be observed that the two WQI methods displayed a similar change wherein the water quality results for both became better and better as the value of k increased from 1 to 2 and 3 and p_i changed from 0.01 to 0.05 and 0.10. However, the OQWI method showed worse water quality, implying the results were more believable.

5.5.2 OWQI and CNWQI-C based MOP model results under two probabilities and two periods

As the comparisons in Section 5.5.1 are all based on the average concentration of TP, NH_3-N and BOD_5, the related results are so theoretical that either big or small deviation exist unavoidably. Thus, the following study focuses on simulating the optimization data to testify the reality of the planning measure under the comparison of OWQI method and CNWQI-C method.

5.5.2.1 Integration of Simulation and optimization

Based on the simulation approach to contaminant distribution presented in Section 5.3 and the results from Table 5-12, two situations were chosen for this study, namely where p_i equals 0.10 in the period of 1 and p_i equals 0.01 in the third period of 3. The first group of discharge values for TP, NH_3-N and BOD_5 into the lake is 2.15 $\times 10^3$kg, 3.81 $\times 10^3$kg and 2.12 $\times 10^4$ kg per year respectively. The second group of discharge results for TP, NH_3-N and BOD_5 into the lake is 0.52 $\times 10^3$kg, 1.27 $\times 10^3$kg and 1.42 $\times 10^4$ kg per year respectively. The corresponding data would be received as in the above part as showed in Tables 5-19 to 5-22:

Table 5-19 Emission sources and locations for TP, NH_3-N and BOD_5 under p_i =0.10 and k= 1

Discharge sources	X(longitude)	Y (latitude)	TP (10^3kg)	NH_3-N (10^3kg)	BOD_5 (10^3kg)
A	114.286941	30.467259	0.92	1.98	9.99
B	114.278459	30.440375	0.37	0.72	5.53
C	114.278143	30.423206	0.30	0.39	2.12
D	114.293392	30.441937	0.25	0.30	1.74
E	114.296439	30.451748	0.31	0.42	1.82

Table 5-20 Emission sources and locations for TP, NH_3-N and BOD_5 under p_i =0.01 and k= 3

Discharge sources	X(longitude)	Y (latitude)	TP (10^3kg)	NH_3-N (10^3kg)	BOD_5 (10^3kg)
A	114.286941	30.467259	0.22	0.66	6.71
B	114.278459	30.440375	0.09	0.24	3.69
C	114.278143	30.423206	0.07	0.13	1.41
D	114.293392	30.441937	0.06	0.10	1.17
E	114.296439	30.451748	0.08	0.14	1.22

Table 5-21 Coupled simulation-optimization results for TP, NH_3-N and BOD_5 at 14 sampling stations under p_i =0.10 and k= 1

Sampling stations	TP (mg/l)	NH_3-N (mg/l)	BOD_5 (mg/l)
1	0.087	0.138	1.080
2	0.075	0.116	0.780
3	0.087	0.127	1.012
4	0.075	0.086	0.944
5	0.075	0.101	0.985
6	0.069	0.168	0.903
7	0.087	0.213	1.053
8	0.075	0.179	0.930
9	0.069	0.116	0.930
10	0.069	0.134	0.998
11	0.126	0.142	1.094
12	0.121	0.370	0.903
13	0.057	0.202	0.492
14	0.133	0.527	1.286

Table 5-22 Coupled simulation-optimization results for TP, NH_3-N and BOD_5 14 sampling stations under $p_i = 0.01$ and $k = 3$

Sampling stations	TP (mg/l)	NH_3-N (mg/l)	BOD_5 (mg/l)
1	0.021	0.046	0.724
2	0.018	0.039	0.522
3	0.021	0.042	0.678
4	0.018	0.029	0.632
5	0.018	0.034	0.660
6	0.017	0.056	0.605
7	0.021	0.071	0.705
8	0.018	0.060	0.623
9	0.017	0.039	0.623
10	0.017	0.045	0.669
11	0.030	0.047	0.733
12	0.029	0.123	0.605
13	0.014	0.067	0.330
14	0.032	0.176	0.861

5.5.2.2 Water quality assessment based on OWQI and CNWQI-C

Using the relevant equations and the data from Tables 5-19 to 5-22, the water quality sub-index, results and graduations using the OWQI method and the CNWQI-C method are shown in Table 5-23, 24, 25 and 26 under the two described levels and periods.

Table 5-23 OWQI-based water quality assessment results at 14 sampling stations under p_i = 0.10 and k = 1

Sampling stations	S_{TP}	$S_{NH3\text{-}N}$	S_{BOD5}	OWQI results	Water quality classes
1	73.97	64.39	80.63	72.06	Poor
2	77.40	68.21	85.61	76.08	Poor
3	73.97	66.26	81.73	73.18	Poor
4	77.40	73.86	82.85	77.78	Poor
5	77.40	70.95	82.18	76.42	Poor
6	79.45	59.77	83.53	71.82	Poor
7	73.97	53.72	81.07	66.35	Poor
8	77.40	58.16	83.08	70.28	Poor
9	79.45	68.21	83.08	76.09	Poor
10	79.45	65.00	81.96	74.26	Poor
11	62.33	63.78	80.41	67.53	Poor
12	63.70	38.46	83.53	53.06	Very Poor
13	82.88	55.14	90.65	70.94	Poor
14	60.27	29.45	77.40	43.36	Very Poor

For OWQI, Tables 5-23 and 5-24 describe diverse changes at 14 sampling stations under three periods and three probabilities. When p_i = 0.10 and k = 1, the sub-indices of TP were from 60.27 to 82.88 at these sampling stations. For $I_{NH3\text{-}N}$ in Table 23, the group of data ranged between 29.45 and 73.86. The set amounts of I_{BOD5} changed to around 80 at 14 sampling stations. In Table 24, which shows the details of water quality where p_i = 0.01 and k = 3, all the figures, including I_{TP}, $I_{NH3\text{-}N}$, and I_{BOD5} apparently become larger than the relevant digits above from each monitoring site presented in Table 5-23. In both conditions, two main water quality graduations were observed at 14 sampling stations, with all of them being Poor class except for two stations with Very Poor class when p_i =0.10 and k = 1, and all of them being graded as Good except two for sites with an Excellent grade and two sites with a Fair grade under p_i = 0.01 and k = 3. At both Stations

12 and 14, the water quality levels were one to two classes lower than at the other monitoring points under both conditions.

Through the result analysis of Tables 5-18, 5-23 and 5-24, this study shows the very similar water quality results between the MOP model with average pollutant concentration and the simulation method with the modeled contaminant concentration under the two probabilities and periods. When p_i = 0.10 and k = 1, the OQWI results described in Table 5-23 ranged from 43.36 to 77.78 and the relevant amount using the MOP model was 67.23, which is within the range of the simulated data. Where p_i equaled 0.01 in the period of 3, the OWQI results provided in Table 5-24 changed between 73.61 and 91.72, while the relative score based on the MOP model under the same concentration was 85.75, which is also in the range of 73.61-91.72.

Table 5-24 OWQI-based water quality assessment results at 14 sampling stations under p_i = 0.01 and k = 3

Sampling stations	S_{TP}	$S_{NH3\text{-}N}$	S_{BOD5}	OWQI results	Water quality classes
1	93.71	86.97	86.57	88.91	Good
2	94.53	90.70	90.12	91.72	Excellent
3	93.71	88.84	87.36	89.85	Good
4	94.53	95.68	88.16	92.61	Good
5	94.53	93.19	87.68	91.66	Good
6	95.03	81.99	88.65	88.07	Good
7	93.71	76.95	86.89	85.00	Good
8	94.53	80.12	88.33	87.05	Good
9	95.03	90.70	88.33	91.23	Excellent
10	95.03	87.59	87.52	89.85	Good
11	90.89	86.35	86.41	87.81	Good
12	91.22	66.90	88.65	79.82	Fair
13	95.86	77.76	93.64	87.90	Good
14	90.39	58.69	84.23	73.61	Fair

Table 5-25 and 5-26 respectively presents Sub-index, WQI results and water quality class under two periods and two probabilities by CNWQI-C measure. Under p_i = 0.10 and k = 1, Table 25 shows a group of noticeably big values among the values of I_{TP} with a range of 3.05 to 4.11 at the sampling stations. To I_{NH3-N}, a series of data become quite stable, and most of them are 1.00 except several values changing from 1.03 to 2.04; as the last index, I_{BOD5} has the same amount such as 2.00 at each sampling station. Table 26 provide the details of water quality where p_i = 0.01 and k = 3, and the figures of I_{TP} vary in a small range from 1.11 to 2.00 at 14 sampling stations. Similarly, I_{NH3-N} data turns more coincident as 1.00 except Station 14 with the amount of 1.04; as the last index, the set of I_{BOD5} values are entirely unchanged as 2.0 and the same as the above provided index of BOD_5 in Table 5-25 at each monitoring site. In the two situations, there are just two kinds of water quality graduations at 14 sampling stations, such as Fair class when p_i = 0.10 and k = 1, and as Good level under p_i = 0.01 and k = 3.

Through the analysis of the results in Tables 5-18, 5-25 and 5-26, this study also shows the exact same consequences on observed water quality between the MOP model with average pollutant concentration and the simulation method with the modeled contaminant concentration under the two probabilities and periods. When p_i = 0.10 and k = 1, the CNWQI-C results described in Table 5-25 ranged from 2.04 to 2.72 and the corresponding amount using the MOP model was 2.67, which is within the range of the simulated data. Where p_i equaled 0.01 in period 3, the CNWQI-C results provided in Table 5-26 changed between 1.40 and 1.68, while the relative score based on the MOP

Table 5-25 CNWQI-C-based water quality assessment results at 14 sampling stations under p_i = 0.10 and k = 1

Sampling stations	I_{TP}	I_{NH3-N}	I_{BOD5}	CNWQI-C scores	Water quality classes
1	3.25	1.00	2.00	2.08	Fair
2	3.17	1.00	2.00	2.06	Fair
3	3.25	1.00	2.00	2.08	Fair
4	3.17	1.00	2.00	2.06	Fair
5	3.17	1.00	2.00	2.06	Fair
6	3.12	1.03	2.00	2.05	Fair
7	3.25	1.10	2.00	2.11	Fair
8	3.17	1.00	2.00	2.06	Fair
9	3.12	1.00	2.00	2.04	Fair
10	3.12	1.00	2.00	2.04	Fair
11	4.09	1.00	2.00	2.36	Fair
12	3.47	1.34	2.00	2.27	Fair
13	3.05	1.08	2.00	2.04	Fair
14	4.11	2.04	2.00	2.72	Fair

Table 5-26 CNWQI-C-based water quality assessment results at 14 sampling stations under p_i = 0.01 and k = 3

Sampling stations	I_{TP}	I_{NH3-N}	I_{BOD5}	CNWQI-C results	Water quality classes
1	1.31	1.00	2.00	1.44	Good
2	1.24	1.00	2.00	1.41	Good
3	1.31	1.00	2.00	1.44	Good
4	1.24	1.00	2.00	1.41	Good
5	1.24	1.00	2.00	1.41	Good
6	1.19	1.00	2.00	1.40	Good
7	1.31	1.00	2.00	1.44	Good
8	1.24	1.00	2.00	1.41	Good
9	1.19	1.00	2.00	1.40	Good
10	1.19	1.00	2.00	1.40	Good
11	2.00	1.00	2.00	1.67	Good
12	2.00	1.00	2.00	1.67	Good
13	1.11	1.00	2.00	1.37	Good
14	2.00	1.04	2.00	1.68	Good

model under the same concentration was 1.33, which is closer to the simulated range (1.40-1.68).

Within the GIS platform, the data from Tables 5-23 to 5-26 are used in the following Figure 5-6 to show the water quality in the entire lake based on the US-WQI and CNWQI-C methods under $p_i = 0.10$, $k = 1$ and $p_i = 0.01$, $k = 3$.

5.5.2.3 Comparison of water quality assessment based on OWQI and CNWQI-C

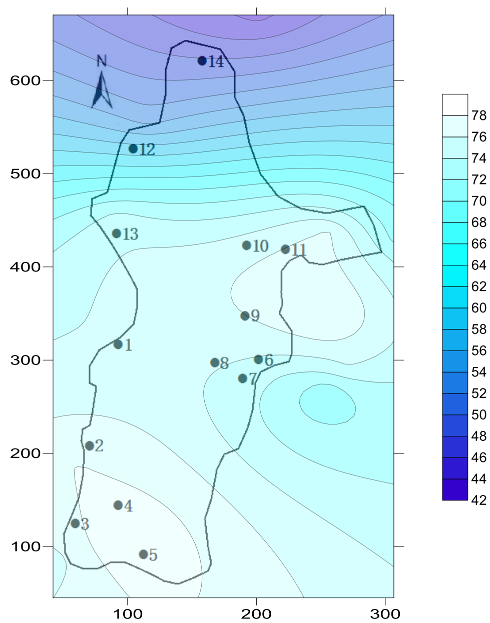
Within the comparison of the water quality results from the CNWQI-C and OWQI methods, there are several notable similarities and differences:

(1) The similar points:

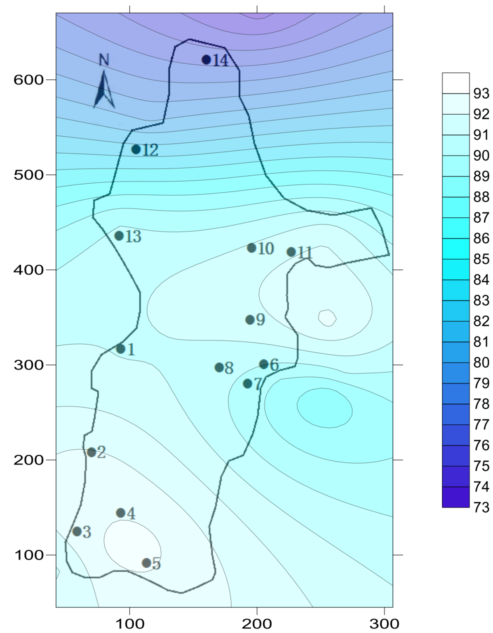
a. The two proposed methods both show that the water quality changed for the better from $k = 1$ to $k = 3$ and from $p_i = 0.01$ to $p_i = 0.10$;
b. In the north of the lake, especially around modeling stations 12 and 14, the water quality was the worst in the lake in both presented approaches. Towards the south, the water quality became better and better whether using the CNWQI-C method or the OWQI method.

(2) The differences:

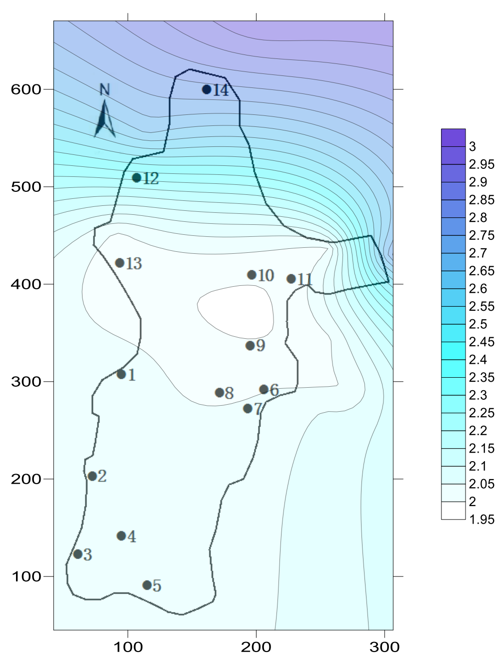
c. The water quality at each sampling site employing the CNWQI-C method under $k = 1$ and $p_i = 0.10$ was better than the corresponding results using OWQI. The level at



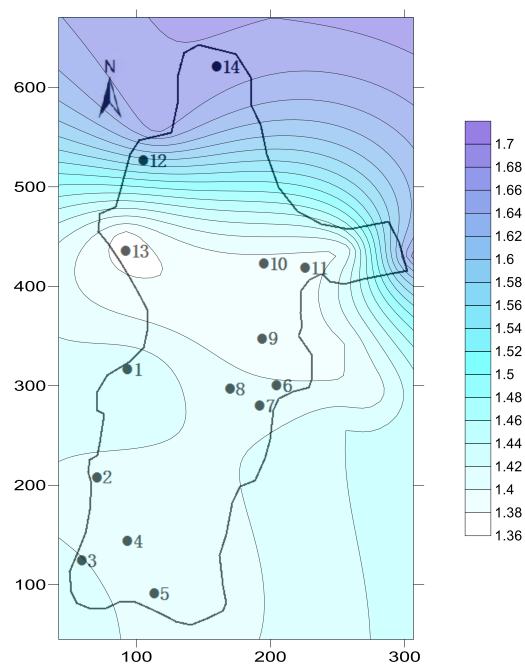
(a) OWQI (p_i =0.10 and k= 1)



(b) OWQI (p_i =0.01 and k=3)



(c)CNWQI-C (p_i =0.10 and k= 1)



(d) CNWQI-C (p_i =0.01 and k= 3)

Figure 5-6 Water quality visualization based on OWQI and CNWQI-C most of them was one class higher, including at Sites 12 and 14 where the water quality grades obtained with OWQI were two levels lower than those obtained with CNWQI-C;

d. Each group of WQI results under a certain p_i level and period based on CNWQI-C was quite stable around 1 or 2. However, the relative values of OWQI varied within a large digital range, such as between 43 and 78 or 73 and 92.

5.6 Summary

A real case study was conducted by employing lake pollution control planning in the optimization of HJH Lake. A comparison and analysis between the SOP and MOP models showed that the MOP model is undoubtedly the better planning approach due its greater consideration, especially towards total net benefit and water quality. After a discussion and comparison of CNWQI-C and OWQI based on the MOP optimization results, it was clear that the more detailed procedure and acceptable results for the OWQI method support more useful suggestions to lake managers.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This thesis was presented to develop an approach, named WQAPCP, which includes water quality assessment, pollution control planning and GIS technology integrating water quality evaluation and lake optimization.

A series of study tasks were conducted in this thesis:

GIS-based water quality assessment methods were developed though the use of GIS and a database made up of four groups of evaluated data including the OWQI, CWQI, CNWQI-S and CNWQI-C methods. These approaches to the water quality index were applied to assess the water quality of a real case named HJH Lake. The assessment results were displayed in the form of maps which described the spatial distribution of the evaluation results including the water quality evaluation results and the levels of water quality. Through scenario analysis, it was clearly determined that TP, NH_3-N and BOD_5 exerted a huge influence on the lake water quality. They were the most significant parameters for controlling lake water contamination. The four evaluation methods have a few similar points, but a greater number of differences which are due to their detailed sub-indices, stringent computation processes, exact values and related classification systems. Of the four aforementioned models, the OQWI model appeared to be the most comprehensive model for lake water quality assessment. Because there were not enough data in the study, CWQI was not the most usable model even though the values and the water quality categories it generated seemed exciting. The CNWQI models are flexible for use in different projects, but CNWQI-S method seemed too arbitrary because of its negation of the better data. The values obtained by the CNWQI-C model, including the processing values and the assessed results, were not convictive due to the use of only a few directional ranges for the primary parameters, but it is a much better method than CNWQI-S based on its overall consideration of water quality parameters. Based on the comparison of these methods, the most suitable method of water quality assessment for lake management was determined to be the OWQI method.

This thesis presented several approaches to lake pollution control planning through the simulation of contaminant dispersion and the optimization of lake management. In order to provide evidence for the possibility of optimization implementation, the simulation method of the monitoring values was employed as the first step of the entire planning system study. Using the relevant contaminant distribution theory, the modeling approach was determined to be suitable for use in this study to imitate the real pollutant concentration diffusion situation in HJH Lake. A comparison between the SOP model and the MOP model was then addressed in the research to support water contamination control planning in a continual lake management system. Through the selection and confirmation of objectives and constraints, this study utilized both different methods in order to discover the strengths and deficiencies of the SOP and MOP models. By performing a comparison of the two kinds of programming models, this thesis showed some shortcomings of the use of the SOP model for lake water management and pollution control. It determined that the MOP model produced more efficient results for the relevant stakeholders. Three periods and a set of significant levels were considered in this study to determine the development and the probability of realization of the lake management system. Another comparison of the OWQI and CNWQI-C methods was conducted according to the MOP optimization results in order to discover a more acceptable approach to lake optimization. It comprised the above water quality evaluation methods. It was found that the OWQI method produced a more detailed procedure and more acceptable results which would support stronger decision-making.

GIS technology was employed in this study to integrate the water quality assessment methods and the optimization methods for pollution control and lake management. Due to its ability to compound the relevant data and create visual maps of the study results, GIS played a significant role in extending the traditional numerical results for the assessment methods and lake planning by producing results with spatial references. By integrating GIS as a communication tool, this study enables researchers and lake managers to better understand the spatial distribution of water quality risks and supports better recommendations for local administration.

In conclusion, the research work presented in this thesis demonstrated that it is useful to apply spatial information technology in effective water quality assessment and lake optimization. The research results indicated that the GIS-based integrated approach (WQAPCP) developed in this thesis provides practical support for water quality management and lake contamination control. The developed methods and modeling tools can also be applied in the management of other lakes in other areas.

6.2 Contributions

This thesis study contains the following contributions:

(1). Proposed a GIS-based lake water quality assessment method by based on the integrated application of surface water quality index assessment, the ArcGIS, and evaluation databases. Four water quality assessment index methods are examined and compared based on a real case study to provide reliable and intuitive results regarding the spatial distribution of water quality levels. This provides to basis of selecting the most suitable assessment method for lake water quality control.

(2). Developed a GIS-based lake pollution control planning approach (WQAPCP) that integrates lake water quality assessment, simulation, and pollution control optimization. GIS is coupled with the integrated approach to visualize the assessment, simulation, and pollution control planning results with location based GIS database. Both SOP and MOP optimization models are examined and developed for a real lake area. The developed approach helps to provide scientific basis and support to systematically control lake water pollution.

(3). Conducted a field scale case study based on the validated water quality simulation and integrated simulation-optimization. The study lake is first assessed based four quality index methods, the study lake is found being polluted by both point and nonpoint emissions of TP, NH_3-N and BOD_5. Therefore, the proposed simulation-optimization approach is formulated and applied to deliver the systematic and lake pollution control strategies for direct implementation of the control measures. The emission reductions are identified based on the developed WQAPCP and the expected lake water quality improvements are quantified based on different strategies of implementations.

6.3 Recommendations for Future Work

Future studies may focus on:

1. The further development of the data computation functions of water quality assessment and lake pollution control planning within GIS to make the use of the method more convenient.

2. In the current study, three major water quality parameters were included in the optimization of HJH Lake. More parameters could be considered in the future, if applicable, to produce more comprehensive lake control planning in HJH Lake.

3. The graphical user interface will need to be built and the application will be continuously improved for new case studies.

References

AEP (Albert Environment and Parks) (2016). http://aep.alberta.ca/water/reports-data/alberta-river-water-quality-index.aspx, access date: Apr, 2016.

Alberta Ministry of the Environment (2003). http://www.finance.gov.ab.ca/publications/measuring/annrept02/environment.pdf Annual Report: 2001-2002, access date: May, 2016.

Al-Sabhan W., Mulligan M. and Blackburn G. A. (2003). A real-time hydrological model for flood prediction using GIS and the WWW. Computers, Environment and Urban Systems 27 (1): 9-32.

Bandyopadhyay S. and Saha S. (2013). Some Single- and Multi-objective Optimization Techniques. Springer-Verlag, Berlin, Heidelberg, DOI 10.1007/978-3-642-32451-2_2.

B. C. Ministry of Environment, Land and Parks (1996). British Columbia Water Quality Status Report: 181.

B. C. Ministry of Environment, Lands and Parks (1996). Non-Point Source Pollution: Problem Definition. Vancouver, B. C.. http://wlapwww.gov.bc.ca/wat/wq/wqhome.html, access date: Sep, 2016.

Brandmeyer J. E. and Karimi H. A. (2000). Coupling methodologies for environmental models. Environmental Modelling & Software 15 (5): 479-488.

Brown R. M., Mclelland N. I. and Deininger R. (1973). Validating the WQI. Presented at national meeting of American Society of Civil Engineers on Water Resources Engineering, Washington, DC.

Carpenter S. R., Caraco N. F., Correll D. L., Howarth R. W., Sharpley A. N. and Smith V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications (8): 559–68.

CCME (2005). Canadian water quality guidelines for the protection of aquatic life. CCME water quality index 1.0, User's Manual. CCME, Winnipeg, Manitoba, Canada. http://www.ccme.ca/ assets/pdf/wqi_usermanualfctsht_e.pdf, access date: Jan, 2016.

Charnes A., Cooper W. W., Kirby P. (1972). Chance constrained programming: an extension of statistical method. Optimizing Methods in Statistics (2): 391–402.

Charnes A. and Cooper W. W. (1983). Response to decision problems under risk and chance constrained programming: dilemmas in the transitions. Management Science (29): 750–753.

Chen Z., Huang G. H., Chakma A. (2003). Hybrid fuzzy-stochastic modeling approach for assessing environmental risks at contaminated groundwater systems. Environmental Engineering 129(1): 79-88.

Cheng H. Q., Yang Z. F., Chan C. W. (2003). An expert system for decision support of municipal water pollution control. Engineering Application of Artificial Intelligence 16(2):159-166.

Cheng H. W., Chang N. B. (2010). Water pollution control in the river basin by fuzzy genetic algorithm-based multi-objective programming modeling. Water Science & Technology 37 (8) :55-63.

Chen Z., Huang G. H., Chakma A. (1998). Integrated environmental risk assessment for petroleum-contaminated sites - a North American case study. Water Science &Technology 38(4-5):131-138

Chin D. A. (2000). Water-Sources Engineering. Prentice Hall, Upper Saddle River, New Jersey (07458): 649-663,

City of Edmonton (2003). Office of the Environment Edmonton's Environment: A Snapshot 2002. http://www.gov.edmonton.ab.ca/am_pw/office_of_the_environment/stateofenv.pdf., access date: Jul, 2016.

Cohon, J. L. (1978). Multi-objective Programming and Planning. Academic Press, New York.

Connor D. J. O. (1962). The bacterial distribution in a lake in the vicinity of a sewage discharge. In Proceeding of the 2nd Purdue Industrial Waste Conference, West Lafayette, IN.

Cude, C. G. (1999). The McKenzie Watershed Water Quality Report— June 1999. Oregon Department of Environmental Quality, Portland, Oregon.

Cude C. G. (2001). Oregon water quality index: A tool for evaluating water quality management effectiveness. Water Resource Association 37(1):125–137.

Dinius S. H. (1987). Design of index quality. Water Resource Association 23(5):823–843.

Dojlido J.R., Best G.A. (1993). Chemistry of water and water pollution. Department of Water Chemistry and Biology, Institute of Meteorology and Water Management, Warsaw, Poland: 55-67.

Dragan S. (2008). Single-objective vs. Multi-objective Optimisation for Integrated Decision Support Centre for Water Systems. Department of Engineering School of Engineering and Computer Science, University of Exeter, United Kingdom. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.122.7951&rep=rep1&type=pdf, access date: Feb, 2016.

Dunnette D. A. (1979). A geographically variable water quality index used in Oregon. Water Pollution Control Federation 51(1):53–61.

Environment Canada (2003). CCME National Water Quality Index Workshop: A Path Forward for Consistent Implementation and Reporting. November 24 – 25. Halifax, Nova Scotia (2003). Workshop Proceedings: 81. http://www.ccme.ca/assets/pdf/wqi_wkshp_rpt_nov_2003_e.pdf, access date: Jan, 2016.

Environment Canada CESI (2008). http://publications.gc.ca/collections/collection_2009/ec/En81-5-1-2008-1E.pdf, access date: Aug, 2016.

Forester, D. L. (2000). Water Quality in the Credit River: 1964 to 1998, M.A. 2000, Deborah Lynn Forester. Department of Geography/Institute for Environmental Studies, University of Toronto. http://www.utoronto.ca/env/ies/debfor/, access date: Sep, 2016.

Gao L., Zhou J. M., Yang H. and Chen J. (2005). Phosphorus fractions in sediment profiles and their potential contributions to eutrophication in Dianchi Lake. Environmental Geology (48): 835–844.

GB3838 (2002). Environmental quality standards for surface water in China. http://www.doc88.com/p-015708746750.html, access date: Mar, 2016.

Geng L. K., Chen Z., Lu F., Lu X. Q. and Wang S. L. (2014). GIS-based water quality assessment for Huangjiahu Lake. Presented at CSCE 13th International Environmental Specialty Conference, Halifax, Nova Scotia, Canada.

Gharibi H. A. H., Mahvi R., Nabizadeh H., Arabalibeik M., Yunesian N -. and Sowlat M. H. (2012). A novel approach in water quality assessment based on fuzzy logic. Environmental Management (112): 87-95.

Halls J. N. (2003). River run: an interactive GIS and dynamic graphing website for decision support and exploratory data analysis of water quality parameters of the lower

Cape Fear river. Environmental Modelling & Software 18(6): 513-520.

Ham J., Yoon C. G., Kim H. J., Kim H. C. (2010). Modeling the effects of constructed wetland on nonpoint source pollution control and reservoir water quality improvement. Environmental Sciences 22(6):834-839.

Hèbert S. (2005). Comparison between the index of overall quality of water in Quebec (IQBP) and the water quality index CCME(WQI) for the protection of aquatic life. In: Monitoring the state of environment. Ministry of Sustainable Development, Environment and Parks Department, Quebec, ISBN: 2-550-45900-8.

Helmer R. and Hespanhol I. (2011). Water Pollution and Environmental Health Hazards. Encyclopedia of Occupational Health and Safety: 53.

Hobaek A., Eivind L. J., Rohrlack T. , Jannickemoe S. , Grung M. , Bennion H. , Claeke C. and Gayane T. P. (2012). Eutrophication, recovery and temperature in Lake Mjosa: detecting trends with monitoring data and sediment records. Freshwater Biology (57): 998-1014.

Horton R. K. (1965). An index number system for rating water quality. Water Pollution Control Federation 37(3): 300–306.

Huang B., and Jiang B. (2002). AVTOP: a full integration of TOPMODEL into GIS. Environmental Modelling & Software 17(3): 261-268.

Huang G. H., Batez B. W., Patry G. G. (1992). A grey linear programming approach for municipal solid waste management planning under uncertainty. Civil Engineering Environmental System 9(4):319–35.

Huang S., Titus S. J., and Wines D. P. (1992). Comparison of nonlinear high-diameter functions for major Albert tree species. Forest Research (22): 1297-1304.

Huang X. P., Huang L. M. and Yue W. Z. (2003). The characteristics of nutrients and eutrophication in the Pearl River estuary, South China. Marine Pollution Bulletin 47(1-6):30-6.

Hurley T., Sadiq R. and Mazumder A. (2012). Adaptation and evaluation of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) for use as an effective tool to characterize drinking source water quality. Water Research 46(11): 3544-3552.

Jiang J., Wang P., Lung W., Guo L. and Li M. (2012). A GIS-based generic real time risk assessment framework and decision tools for chemical spills in the river basin. Hazardous

Materials (2): 227–228, 280-291.

Jing H. W., Hua L., Sun C. H. and Guo J. (2008). Analysis on urban lakes eutrophication status in Beijing. Lake Sciences (20): 357–363.

Jing S. R., Lin Y. F., Shih K. C. and Lu H. W. (2008). Applications of constructed wetlands for water pollution control in Taiwan: review. Waste Management (12): 249–59.

Johnson R.K. (1995). The indicator concept in freshwater biomonitoring. Genes to Ecosystems (5): 11-27.

Kazi T. G., Arain M. B., Jamali M. K., Jalbani N., Afridi H. I., Sarfraz R. A., Baig J. A. and Shah A. Q. (2009). Assessment of water quality of polluted lake using Multi-variate statistical techniques: A case study. Ecotoxicology and Environmental Safety 72(2): 301-309.

Lee J. Y., Cheon J. Y., Lee K. K., Lee S. Y. and Lee M. H. (2001). Statistical evaluation of geochemical parameter distribution in a ground water system contaminated with petroleum hydrocarbons. Environmental Quality (30): 1548-1563.

Liao Y., Xu J. and Wang W. (2011). A method of water Quality assessment based on biomonitoring and multiclass support vector machine. Procedia Environmental Sciences 10(A): 451-457.

Li M., Zhang J., Laing N., Lin L., Li X. and Wen H. (2012). Analysis and comparison of Water environmental quality assessment. Progress Geography 31: 5-16.

Liua Y., Caib C. Y. P., Huanga G. H. and Donga C. (2012). The 18th Biennial Conference of International Society for Ecological Modelling Interval-parameter chance-constrained fuzzy multi-objective programming for water pollution control with sustainable wetland management. Procedia Environmental Sciences (13): 2316 – 2335.

Liu Y., Guo H. C., Zhou F., Qin X., Huang K. and Yu Y. (2008). Inexact Chance-Constrained Linear Programming Model for Optimal Water Pollution Management at the Watershed Scale. Water Resource Planning Management (134): 347-356.

Liu Y, Zou R. and Guo H. C. (2011). Risk Explicit Interval Linear Programming Model for Uncertainty-Based Nutrient-Reduction Optimization for the Lake Qionghai Watershed. Water resource Planning and Management (2): 83-91.

Liu W. C. and Chen W. B. (2012). Prediction of water temperature in a subtropical subalpine lake using an artificial neural network and three-dimensional circulation models. Computers & Geosciences (45): 13-25.

Liu Y., Cai Y. P., Huang G. H. and Dong C. (2012). Interval-parameter chance-constrained fuzzy multi-objective programming for water pollution control with sustainable wetland management. Procedia Environmental Sciences (13): 2316-2335.

Lumb A., Sharma T. C. and Bibeault J. F. (2011). A review of genesis and evolution of water quality index (WQI) and some future directions. Water Quality Exposure Health 3(1): 11–24.

McClelland N. I., Brown R. M. and Deininger R. A. (1976). WQI-enhancing appreciation of quality improvement. National Sanitation Foundation. Paper Presented at the American Chemical Society, New York, N.Y., Apr 8.

McKinney D. C. and Cai X. (2002). Linking GIS and water resources management models: an object-oriented method. Environmental Modelling & Software 17(5): 413-425.

Miller J. D., Kim H., Kjeldsen T. R., Packman J., Grebby S. and Dearden, R. (2014). Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. Hydrology: 515, 559–570.

Missaghi S., Hondzo M. and Melching C. (2013). Three dimensional lake water quality modeling: sensitivity and uncertainty analyses. Environmental Quality (42):1684–1698.

Newfoundland Department of Environment (2001). Water resources Management Division (Water Quality Index applied to the Exploits River Watershed): 24. http://www.gov.nf.ca/env/Env/waterres/Surfacewater/WQI/Exploits-WQI-study.pdf, access date: Feb, 2016.

Pejman A. H., Bidhendi G. R. N., Karbassi A. R., Mehrdadi N. and Bidhendi M. E. (2009). Evaluation of spatial and seasonal variations in surface water quality using Multi-variate statistical techniques. Environmental Science & Technology 6 (3): 467-476.

Qin H., Su Q., Khu S. T. and Tang N. (2014). Water Quality Changes during Rapid Urbanization in the Shenzhen River Catchment. An Integrated View of Socio-Economic and Infrastructure Development Sustainability (6):7433-7451.

Ran G., Xu L., Wang D., Li H. and Xu J. (2016). Water Quality Modeling for a Typical Urban Lake Based Environ Model Assess. EFDC Model (21):643–655.

Reghunath R., Murthy T. R. S. and Raghavan B. R. (2002). The utility of Multi-variate statistical techniques in hydrogeochemical studies: An example from Karnataka, India. Water Resource 36 (10):2437-2442.

Rehana S. and Mujumdar P. P. (2009). An imprecise fuzzy risk approach for water quality management of a river system. Environmental Management 90 (11): 3653-3664.

Resende P. C., Resende P., Pardal M., Almeida S. and Azeiteiro U. (2010). Use of biological indicators to assess water quality of the Ul River (Portugal). Environmental Monitoring Assessment 170(1-4):535-44.

Rickwood C. J., Carr J. M. (2009). Development and sensitivity analysis of a global drinking water quality index. Environmental Monitoring Assessment (156): 73–90.

Richard A. M. M. (1997). Development of an Esturaine water Quality Index (Ewqi) for New South Wakles, unpublished dissertation, the University of Sydney.

Rocchini R. and Swain L. G. (1995). The British Columbia water quality index. Water Quality Branch, Environmental Protection Department, British Columbia Ministry of Environment Land and Parks: 13-15.

Sánchez-Avila J., Bonet J., Velasco G. and Lacorte S. (2009). Determination and occurrence of phthalates, alkylphenols, bisphenol A, PBDEs, PCBs and PAHs in an industrial sewage grid discharging to a Municipal Wastewater Treatment Plant. Science of the Total Environment 407(13): 4157-4167.

Santini M., Caccamo G., Laurenti A., Noce S. and Valentini R. (2010). A multicomponent GIS framework for desertification risk assessment by an integrated index. Applied Geography 30(3): 394-415.

Schaffner M., Bader H. P., Scheidegger R. (2009). Modeling the contribution of point sources and non-point sources to Thachin River water pollution. Science Total Environ, 407(17):4902–4915.

Shrestha S. and Kazama F. (2007). Assessment of surface water quality using Multi-variate statistical techniques: A case study of the Fuji river basin, Japan. Environmental Modelling & Software 22(4): 464-475.

Silva T., Vinçon-Leite B., Lemaire B., Le Vu B., Quiblier C., Prévot F. C., Calzas M., Degres Y. and Tassin B. (2011). Water quality in urban lakes: from continuous monitoring to forecasting. Application to cyanobacteria dynamics in Lake Enghien (France). In European Geosciences Union General Assembly.

Sladecek V. (1973). System of water quality from biological point of view. Advances in Limnology (7): 218.

Slowinski R. and Teghem J. (1990). Stochastic vs. fuzzy approaches to multi-objective mathematical programming under uncertainty. Dordrecht Kluwer Academic Publishers.

Smith P.N. (1995). Environmental evaluation: fuzzy impact aggregation. Journal of Environmental and System 24(2): 191-204.

Snow J. (1854). On the mode of communication of cholera. John Churchill, London, UK. http://www.ph.ucla.edu/epi/snow.html, access date: Apr, 2016.

Spanou M. and Chen D. (2001). An object-oriented tool for the control of point-source pollution in river systems. Environmental Modelling Software 15(1): 35-54.

Steinhart C. E., Schierow L. J. and Sonzogni W. C. (1982). An environmental quality index for the Great Lakes. Water Resource Bulletin 18(6):1025–1031.

United Nations Department of Economic and Social Affair (2014). International Decade for Action---Water FOR LIFE 2005-2015. http://www.un.org/waterforlifedecade/quality.shtml, access date: Oct, 2016.

Vega M., Pardo R., Barrado E. and Deban L. (1998). Assessment of seasonal and polluting effects on the quality of river water by exploratory data analysis. Water Resource Bulletin 32 (12):3581-3592.

Wunderlin D. A., Diaz M. P., Ame M. V., Pesce S. F., Hued A. C. and Bistoni M. A. (2001). Pattern recognition techniques for the evaluation of spatial and temporal variations in water quality. A case study: Suquia river basin (Cordoba, Argentina). Water Resource Bulletin 35 (12):2881-2894.

Yang T., Liu Q., Chan L. and Liu Z. (2007). Magnetic signature of heavy metals pollution of sediments: a case study from the East Lake in Wuhan, China. Environmental Geology (52): 1639–1650.

Zedler J. B. and Suzanne K. (2005). Wetland sources: status, trends, ecosystem services, and restorability. Annual Review of Environment and Sources (30): 39-74.

Zhao N., Liu Y. and Chen J. N. (2009). Regional industrial production's spatial distribution and water pollution control: a plant-level aggregation method for the case of a small region in China. Science Total Environ 407(17): 4946–4953.

Zhang X., Huang K., Zou R., Liu Y. and Yu Y. (2013). A Risk Explicit Interval Linear Programming Model for Uncertainty-Based Environmental Economic Optimization in the Lake Fuxian Watershed. China Hindawi Publishing Corporation-The Scientific World Journal (824078):14.

Zheng L., Cui W. and Jia Y. (2007). Evaluation on seawater quality by fuzzy comprehensive evaluation method in Qingdao dumping area. Marine Environmental Science 26 (1): 38-41.