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基于控制单元的湖北省小南海湖流域生态修复措施体系及布局分析

CONTROL-UNIT-BASED ANALYSIS OF THE ECOLOGICAL RESTORATION MEASURE SYSTEM AND ARRANGEMENT OF THE XIAONANHAI LAKE WATERSHED IN HUBEI PROVINCE, CHINA

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摘要

针对湖北省松滋市小南海湖流域水环境恶化、水生态系统破坏等现状，为了有效改善湖泊水质与生态环境，本研究首先依据行政区划和汇水分区对流域进行控制单元划分，再通过由土壤和水体评价模型和MIKE 21模型耦合而成的流域水环境系统模型统计并计算出了流域的污染源与污染负荷，并核算了其水环境容量。为了有效应对各类污染并落实责任主体，研究提出了基于控制单元的水生态修复体系，包括三级人工湿地工程、自然型湿地工程、清水廊道工程、湖岸缓冲带工程与浅水水生植物带工程。最后使用由污染物浓度控制与总量控制体系构成的“双控”体系对水生态修复效果进行评估。评估结果表明，以上5项生态修复措施可有效削减化学需氧量、总氮、总磷和氨氮等水质指标的总量，使小南海湖水质达到地表水Ⅲ类水质标准。

关键词

流域治理；控制单元；生态修复措施；水环境系统模型；小南海湖流域；“双控”体系

ABSTRACT

To deal with the water environmental degradation and ecological damage of the Xiaonanhai Lake watershed in Songzi City of Hubei Province, China, this study first divided the watershed into 32 control units according to the administrative division and catchment zones, then analyzed the pollution source and load and calculated the water environmental capacity of the watershed with the water environment system model coupled by the Soil and Water Assessment Tool model and the MIKE 21 model. To better deal with different pollutants and divide the responsibility more efficiently, the study proposed a control-unit-based system of five ecological restoration measures including the three-stage constructed wetland, the natural wetland, the clean water corridor, the lakeshore buffer zone, and the emerged and floating plant belt. Finally, the performance evaluation of these measures was conducted under the "Dual Control" system of concentration control and total load control of pollutants. The result proved that the five measures could effectively reduce the total amount of COD, TN, TP, and NH_3-N to improve the water quality, meeting the Surface Water Class Ⅲ Standard.

KEYWORDS

Watershed Management; Control Unit; Ecological Restoration Measures; Water Environment System Model; Xiaonanhai Lake Watershed; Concentration Control and Total Load Control of Pollutants

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翻译 张健 王颖
TRANSLATED BY Angus ZHANG WANG Ying

1 引言

目前世界各地的河湖生态系统普遍出现了水污染、河湖生态功能退化等问题，严重影响社会经济的可持续发展[1]。自20世纪80年代以来，中国流域的水资源短缺、水环境污染和水生态破坏等问题越发严重。随着水生态修复工作得到越来越多的重视，划分控制单元已成为有效落实相关政策和措施，进而改善水环境质量的重要方法[2]。控制单元是综合考虑水体、汇水范围和控制断面三个要素而划定的水环境空间管控单元，这一概念最早来源于美国《清洁水法案》提出的“最大日负荷总量”计划，主要用于辅助水质目标管理研究[3]。其目前也已被广泛应用于中国流域的研究中，例如方玉杰等针对江西省赣江流域进行了基于控制单元的水环境容量的计算、控制单元总量的分配与管理[4]，陈世勇等基于控制单元分析了广东省深圳市茅洲河流域的水环境现状，进而对流域的水质进行了预测[5]。

近年来，部分欧美国家提出了基于自然的解决方案（Nature-Based Solutions），使用生态工程措施来治理流域污染，不仅取得了较好的环境与生态效益，同时也提升了经济效益。这些措施主要包括湿地工程、植被缓冲区和植草水道等[6]。但这类实践中对于生态修复措施的布局常受限于对污染负荷量的考量，即仅布局在污染严重的地区[7]~[9]。若该地区涉及两个或以上行政区，这些措施的责任主体将难以落实。

湖北省松滋市小南海湖流域是洞庭湖上游重要的生态涵养区。但城市污水、湖泊水产养殖污染、农业面源污染等导致其水质长年处于地表水Ⅴ类或劣Ⅴ类水平。本研究首先建立基于控制单元的水环境系统模型，以改善小南海湖流域的水环境和水生态为核心目标，兼顾生态修复措施责任主体的落实，进而提出基于控制单元的水生态修复体系及布局，并从污染物浓度和总量控制两方面对水生态修复措施的实施效果进行评估。

2 研究区概况

小南海湖流域面积约390.72km^2，涉及松滋市新江口镇、王家桥镇、南海镇、街河市镇和斯家场镇。流域属亚热带过渡性季风气

1 Introduction

Worldwide rivers and lakes are facing problems such as water pollution and ecosystem degradation, which heavily impede the sustainable development of the social-economic system[1]. In China, water shortage, pollution, and ecological damage on the watershed scale have become severer since the 1980s. With a shift from focusing only on pollution control to substantial water ecological restoration, control-unit-based approaches are getting widely accepted in implementing policies and strategies to improve water environment[2]. Control units are spatial cells in water environmental management, determined by the waterbody, the catchment area, and the control section. This idea was first proposed in the Total Maximum Daily Load program in the U.S. Clean Water Act to support research on water quality management[3]. It has also been widely employed in Chinese watershed research. For instance, Fang Yujie et al. divided control units in Ganjiang River Basin in Jiangxi Province to calculate, allocate, and manage its total water environmental capacity[4]. Chen Shiyong et al. analyzed the water environment conditions in Maozhou River watershed in Shenzhen City, Guangdong Province based on control units to support prediction of its water quality [5].

In recent years, Nature-Based Solutions have been proposed in western countries to control watershed pollution with ecological engineering measures, including restoring wetlands, vegetation buffers, and grassed waterways[6]. Although these measures do promote the environmental and ecological performance along with good economic benefits, they only consider the pollution loads and are generally arranged within heavily polluted areas[7]~[9]. If such an area covers two or more administrative subjects, it would become challenging to decide the responsible subjects.

The study area, the Xiaonanhai Lake watershed in Songzi City, Hubei Province is an important ecological conservation area in the upper reaches of Dongting Lake. However, it has suffered heavily from urban sewage, aquacultural wastes, and agricultural non-point source pollution. This study firstly established a control-unit-based water environment management system, which focuses on water quality improvement and ecological restoration of Xiaonanhai Lake while determining the responsible subjects of the restoration measures, then proposed the water ecological restoration measure system and arrangement based on control units and evaluated the restoration effects from perspectives of concentration control and total load control of pollutants.

2 Overview of the Study Area

The Xiaonanhai Lake watershed with an area of 390.72 km^2

候，四季分明，年均气温16.0℃，年均无霜期为265天，年均日照时数为1 600 ~ 1 900小时，年均降水量为1 206mm。

小南海湖水面面积为8.03km^2，平均水位为38.2m，平均水深1.9m。由流域水系图（图1）可见，小南海湖的入湖通道主要有三条：一是北部用以排放城区洪水及污水处理厂尾水的红旗渠倒虹管；二是从南部丘岗入湖的蒿子港；三是从西部汇水区入湖的中槽沟。湖水通过东北部的南海闸沟流入松西河中[10]。流域数字高程模型（DEM）结果（图2）显示其处于山地丘陵地区与平原河湖地区的交界地段，水系结构和产流汇流过程较为复杂。

3 研究方法

本研究依据图3所示技术路线，首先划分流域控制单元，通过调查与数据收集，识别流域水环境问题，分析流域污染源，再建立水环境系统模型，计算流域污染负荷；其次针对现状水环境问题与污染负荷，落实责任主体，提出基于控制单元的生态修复措施，分别通过水环境系统模型与水环境容量计算得出不同措施下污染物的削减量；最后通过由污染物浓度和总量控制构成的“双控”体系评估削减效果。

3.1 控制单元划分

划分控制单元的目的是基于河流控制断面分布和行政区划等特征，评估流域的汇水特征和水环境功能的空间差异。在充分尊重水陆统筹原则的基础上，将流域内不同水功能区所在的水域向陆域延伸，

covers the Xinjiangkou Town, Wangjiaqiao Town, Nanhai Town, Jieheshi Town, and Sijiachang Town of Songzi City. The watershed features subtropical transitional monsoon climate with distinct seasonal changes. The mean annual temperature is 16.0 °C. The forest-free period lasts for 265 days per year in average, while the mean annual sunshine duration is 1,600 ~ 1,900 hours and the mean annual precipitation is 1,206 mm.

Covering a water surface area of 8.03 km^2, Xiaonanhai Lake is currently recorded with an average water level of 38.2 m and average water depth of 1.9 m. As is shown in the map of the watershed (Fig. 1), there are three main watercourses into the lake. One is the inverted siphon installed in the Hongqi Canal in the north to discharge urban flood and tail water from sewage treatment plants; the second is the Haozigang River in the southern hilly area; and the Zhongcaogou River in the west. Through the Nanhai sluiceway in the northeast of the watershed, water flows from the lake into the Songxi River[10]. The digital elevation model (DEM) data (Fig. 2) indicates that the watershed enjoys a hilly terrain in the upper reaches and plain areas in lower reaches, which makes the water system and runoff yield and concentration processes rather complex.

3 Research Methods

This study followed the technical roadmap shown in Figure 3 to firstly divide the watershed into control units. Basing on the control units, the water environmental problems were identified with pollution sources analyzed according to investigation and data collection, and pollution load calculated by the water environment system model. Secondly, on identifying the responsible subjects

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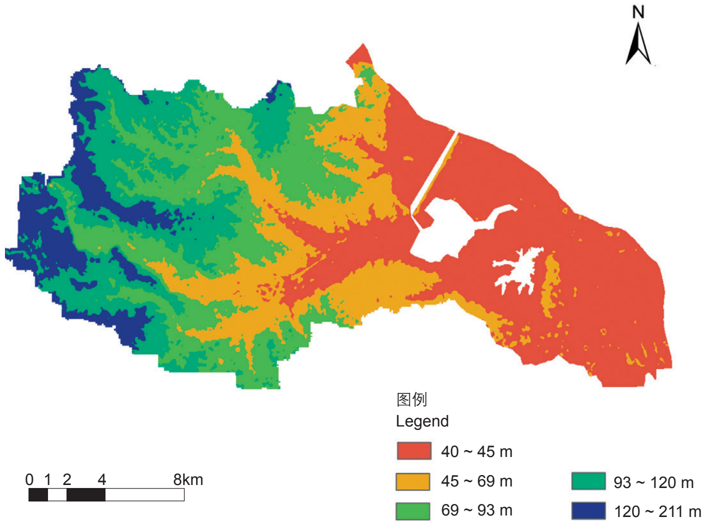

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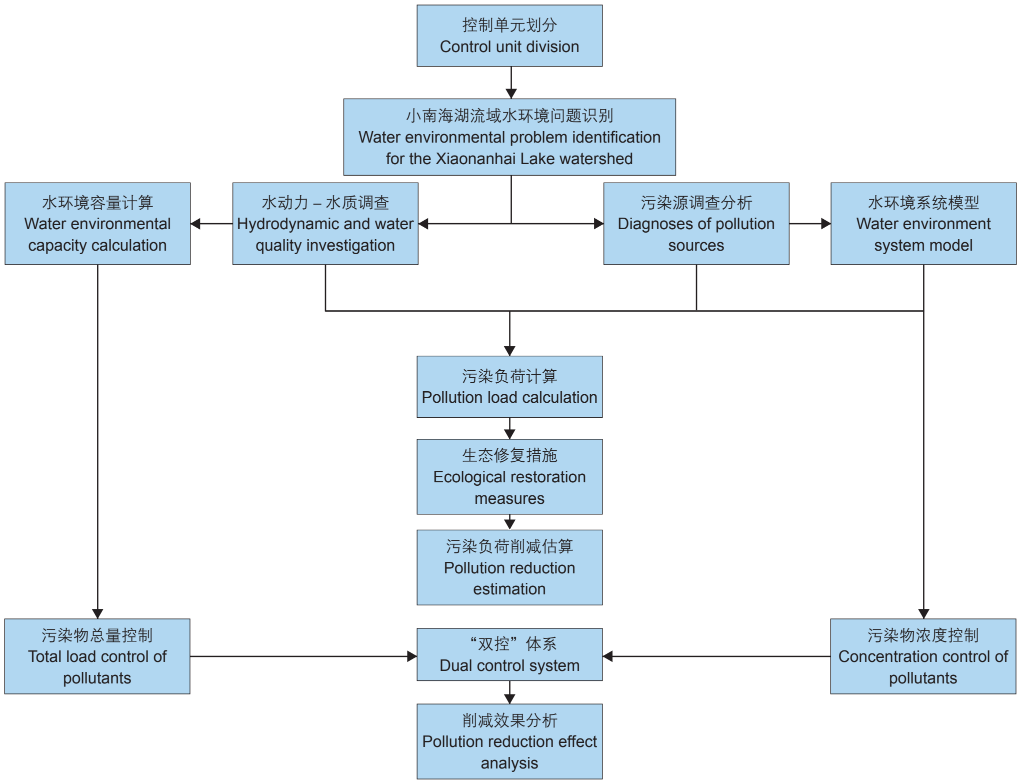

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1. 小南海湖流域示意图
2. 小南海湖流域DEM数据
3. 技术路线图

1. Map of the Xiaonanhai Lake watershed
2. DEM of the Xiaonanhai Lake watershed
3. Technological Roadmap

细化为若干个控制单元，以便实施针对性治理措施。为了逐级落实流域内的治理责任，要考虑所划分控制单元与现有行政区边界的交叉关系，以实现空间上的责任分担[11]。

在本研究中，划分控制单元的具体步骤为：

1）综合考虑小南海湖流域行政区划、土地利用规划、水体治理措施等空间布局规划，结合流域水系分布和地形地势特点，以及重要支流入河口等关键控制节点，在ArcGIS软件中建立空间基础数据库；

2）根据数据库生成的DEM数据对流域汇水区进行划分；

3）叠加相关区划成果，在涉及待评估水体的区域，识别每条河流的汇水范围，形成控制单元边界；

4）结合土地利用现状，分析每个汇水区土地利用和人类活动强度的空间异质性特征，对控制单元边界进行细化和微调；

5）在无待评估水体区域，主要根据现有水系规划和行政区边界明确控制单元边界。

3.2 小南海湖流域水环境系统模型构建

本研究将土壤和水体评价模型（SWAT模型）与MIKE 21模型进行耦合，构建小南海湖流域水环境系统模型。将SWAT模型计算得出的各入湖河流的流量与污染负荷作为边界条件输入MIKE 21模型中，再利用

of each control unit, this study proposed ecological restoration measures to deal with the water environmental problems and figured out the pollutant reduction of each measure through water environment system simulation and water environment capacity calculation. Finally, the restoration performance was evaluated regarding the effect of pollutant concentration control and total pollution load control.

3.1 Division of the Watershed into Control Units

Control units could help evaluate catchment features and spatial differences of the water environmental functions on account of the river control sections and administrative division. Following the principle of integrating the water and the land as a whole, the watershed is divided into control units with water areas of different functions combined with corresponding lands to better implement pertinent ecological restoration measures. Moreover, to assign the watershed management responsibility level by level in the spatial dimension, the potential conflicts between the control unit division and the existing administrative boundaries should be addressed[11].

The control units of this study were divided by steps as follows.

1) To establish a basic spatial database in ArcGIS according to the administrative division, land use planning, and pollution control measures applied in the Xiaonanhai Lake watershed, as well as the characteristics of its water system distribution, terrain, and key control nodes such as estuaries of the important tributaries;

2) To divide the watershed into catchments according to the DEM data generated from the database;

3) To identify the catchment boundary of each river located in the area with water bodies to be evaluated by superimposing the existing administrative division and plannings to form the boundary for each control unit;

4) To refine and adjust the control unit boundaries based on the spatial heterogeneity caused by diverse land use types and human activity intensities in different catchments;

5) For the areas with no water body to be evaluated, to decide the control unit boundaries mainly according to existing water system planning and administrative divisions.

3.2 Water Environment System Model Built for the Xiaonanhai Lake Watershed

In this study, the water environment system model of the Xiaonanhai Lake watershed was built by coupling the Soil and Water Assessment Tool (SWAT) model and the MIKE 21 model. The flow and pollution load of each river into the lake calculated

MIKE 21模型分析水质并定量评估各类生态修复措施对污染物的削减效果。

3.2.1 SWAT模型

SWAT模型是长周期分布式流域水文模型，可预测不同土壤类型、土地利用类型和管理措施下流域内不同分区的产流、产污情况，已逐渐成为水资源与水环境保护管理规划中不可或缺的工具。SWAT模型基于水量平衡方程对流域产流进行模拟，方程如下：

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad , \qquad (1)$$

式中，SW_t为时段t土壤的含水量（mm）；SW_0为时段初土壤的含水量（mm）；t为计算时段（d）；R_{day}为第i天的降雨量（mm）；Q_{surf}为第i天的地表径流（mm）；E_a为第i天的蒸发量（mm）；W_{seep}为第i天的渗漏量和测流量（mm）；Q_{gw}为第i天的基流量（mm）。

in the SWAT model were input into the MIKE 21 model as boundary conditions, then the MIKE 21 model was used to analyze the water quality and quantitatively assess the pollution reduction effect of the ecological restoration measures.

3.2.1 SWAT Model

The SWAT model is a long-periodic distributed watershed hydrological model to predict the yield of runoff and pollution in different zones with varied soil types, land-use types, and management measures. It has been widely applied in the protection and management planning of water resources and water environment. The water balance formula for the SWAT model to simulate the runoff yield of a watershed is:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad , \qquad (1)$$

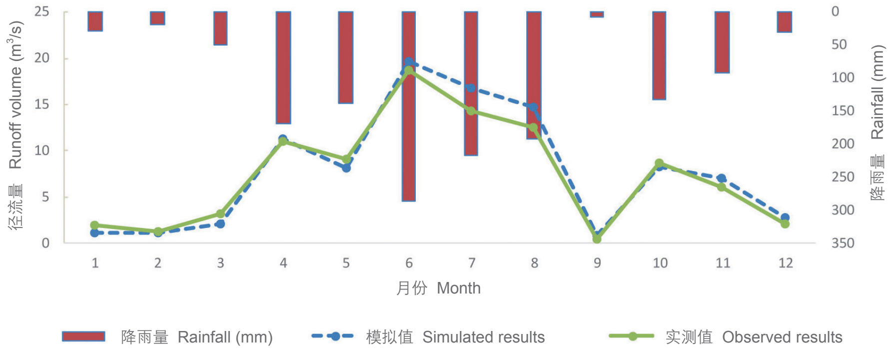
where SW_t is the soil moisture content (mm) in a certain time frame t; SW_0 is the initial soil moisture content (mm); t is the time frame (d) for calculation; R_{day} represents the rainfall (mm) in the i-th day; Q_{surf} is the surface runoff (mm) in the i-th day; E_a is the evaporation quantity of water (mm) in the i-th day; W_{seep}

表1：模型水文参数敏感性分析
Table 1: Sensitivity analysis of hydrological parameters in the SWAT model

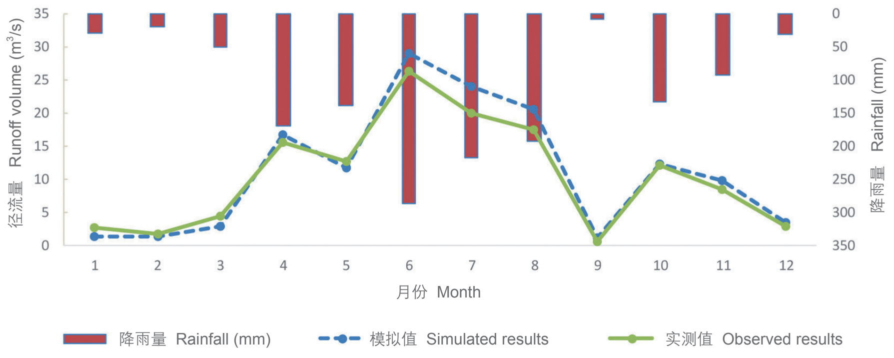
水文参数 Hydrological parameters	参数定义 Parameter definition	最终取值 Final value	文件格式 File format
CN2	湿润条件下SCS径流曲线数 SCS runoff curve number in wet conditions	70	.mgt
SOL_AWC	土壤有效水含量 Available soil water content	1.7	.sol
ESCO	土壤蒸发补偿系数 Soil evaporation compensation factor	0.2	.hru
ALPHA_BF	基流消退系数 Baseflow recession constant	0.02	.gw
REVAPMN	浅层地下水再蒸发的深度阈值 Threshold depth of shallow groundwater for re-evaporation	305	.gw
GW_REVAP	地下水再蒸发系数 Groundwater re-evaporation coefficient	0.05	.gw
RECHR_DP	深部含水层渗透系数 Deep aquifer permeability coefficient	0.3	.gw

表2：SWAT模型率定和验证结果
Table 2: Calibration and verification results of the SWAT model

	率定期（2015年）Calibration period (2015)	验证期（2016年）Validation period (2016)
R^2	0.89	0.86
Ens	0.92	0.88



中槽沟 Zhongcaogou River



蒿子港 Haozigang River

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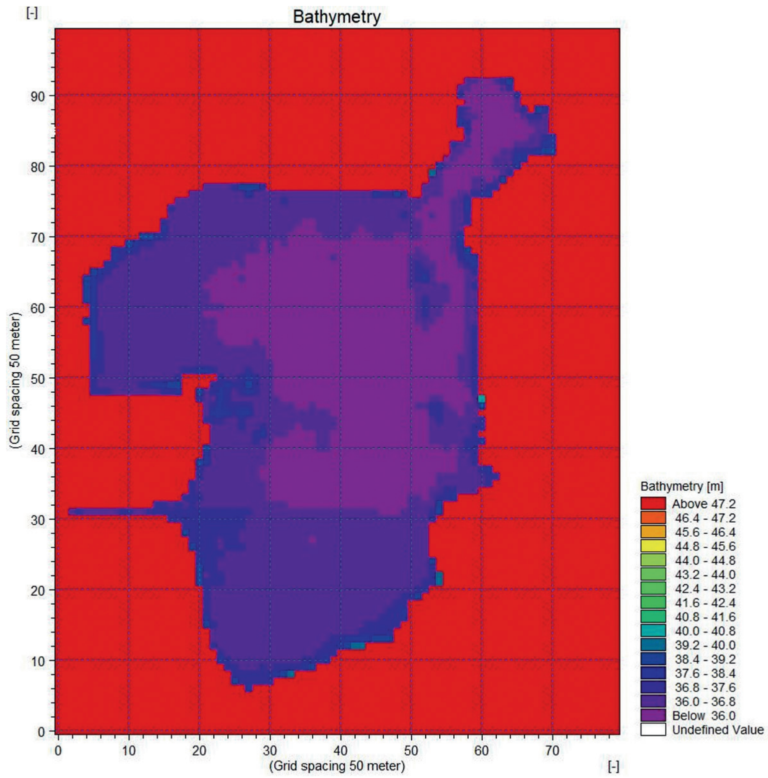
4. 2016年小南海湖流域中槽沟、蒿子港降雨－径流变化情况
5. MIKE 21模型中小南海湖流域的计算网格（2016年）

4. The rainfall and runoff changes in the Zhongcaogou River and Haozigang River of the Xiaonanhai Lake watershed in 2016
5. The computational grid of the Xiaonanhai Lake watershed (2016) in MIKE 21 model



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构建SWAT模型需要DEM数据、土地利用类型、土壤类型、气象数据及当地农作物管理措施等资料。在备齐所有基础资料后，可对SWAT模型进行率定和验证。在模型运行后，当决定系数$R^2>0.6$、效率系数$Ens>0.5$时，模型结果适用性较好[12]。本研究选取7个水文参数，使用SWAT–CUP软件对参数进行敏感性分析，结果如表1所示。研究采用中槽沟与篙子港的流量数据对SWAT模型进行率定和验证，模型运行结果如表2所示，模拟结果如图4所示。结果表明：SWAT模型的决定系数R^2和效率系数Ens均满足模型所需的精度要求。

因缺少入湖河流的水质监测数据，而基于参数移植法①的SWAT模型在缺少资料地区具有一定的适用性[13]，故本研究的水质参数主要参考了《滇中引水工程洱海水环境影响专题研究报告》。

3.2.2 MIKE 21模型

MIKE 21模型可以对二维自由水面的流动进行模拟，适用于湖泊、河口、海湾和海岸地区的水动力与水质研究。小南海湖有多条入湖支流，水流受力复杂，水面宽广。采用MIKE 21模型中的水动力模块可演算小南海湖的水位，采用其水质模块则可模拟湖中污染物在对流和扩散作用下的传输过程。

小南海湖流域的MIKE 21模型应用涵盖整个湖区，采用矩形网格进行计算，模型计算网格距为50m，计算单元数为2 974个。模型采用干湿单元自动判别的方法识别陆域及水域面积，默认水深0.2m以上的网格为水域，参与水动力部分的计算，计算网格如图5所示。在设置模型边

is the seepage quantity (mm) of water in the i-th day; and Q_{gw} represents the basic flow quantity in the i-th day (mm).

The applicability of the SWAT model should be tested through calibration and verification with the DEM Data, land-use types, soil types, meteorological data, local crop management measures, etc., which can be proved good with a coefficient of determination $R^2 > 0.6$ and an efficiency coefficient $Ens > 0.5$[12]. In this study, seven runoff parameters were selected and the sensitivity analysis of them was conducted using the SWAT-CUP software, with the results shown in Table 1. The flow data of Zhongcaogou River and Haozigang River were chosen to calibrate and verify the SWAT model used in this study. According to the result shown in Table 2 and the simulated result shown in Figure 4, both R^2 and Ens of the model met the accuracy requirements.

Considering that the SWAT model based on the parameter transfer method① is applicable in areas with insufficient materials[13], this study referred to the water quality parameters from the Monographic Study Report on the Impact of the Water Diversion Project in Central Yunnan on the Water Environment of Erhai Lake for the lack of water quality monitoring data for rivers flowing into the lake.

3.2.2 MIKE 21 Model

The MIKE 21 model is applicable to the hydrodynamic research and water quality research of lakes, estuaries, gulfs, and coasts by simulating the flow of the two-dimensional free water surface. For the broad Xiaonanhai Lake that has several tributaries into it with complex water flow forces, the hydrodynamic module of MIKE 21 model was used to simulate its water levels and the water quality module to simulate the pollutant transport process under the forces of convection and diffusion.

The MIKE 21 model was built covering the whole area of the Xiaonanhai Lake watershed, using rectangular grids of 50-meter spacing for computing. Finally, there were 2,974 units divided, of which the land area and water area were identified automatically. Grids with a water depth of 0.2 meter or more were defaulted as the water area for hydrodynamic calculation (Fig. 5). After setting the boundary and initial conditions for the MIKE 21 model, the hydrodynamic module and water quality module for Xiaonanhai Lake were calibrated and validated. According to the pollutant degradation coefficients set for lake models in the Monographic Study Report on the Impact of the Water Diversion Project in Central Yunnan on the Water Environment of Erhai Lake and the Comprehensive Planning for Water Pollution Control in the Qilu Lake Watershed, Yunnan Province, the

① 参数移植法即选择与研究流域相似的有资料流域作为参证流域，将其相关参数移用到缺乏资料的流域，作为其模型参数。

① The parameter use method is to use parameters of a referenced watershed that has similar characteristics with the studied watershed with insufficient materials.

界与初始条件后，对小南海湖水动力模块和水质模块进行率定和验证。参考《滇中引水工程洱海水环境影响专题研究报告》和《云南杞麓湖流域水污染防治综合规划》中湖泊模型污染物的降解系数对参数进行反复调整，最终确定模型中化学需氧量（COD）、总氮（TN）、总磷（TP）和氨氮（NH_3-N）的综合降解系数分别为0.0005/d、0.002/d、0.004/d、0.0015/d。由表3可知，水质模块中COD、TN、TP和NH_3-N浓度模拟数值与小南海湖实测数值的平均相对误差分别为0.11、0.05、0.04和0.14。整体而言，MIKE 21模型在小南海湖流域的水质模拟中具有较好的适用性。

3.3 污染源分析与污染负荷计算方法

根据现场调研，小南海湖流域面源污染主要来源为农村生活污水、农业种植与分散式畜禽养殖，本研究采用SWAT模型计算面源污染负荷；点源污染主要来源于城镇生活污水、规模化畜禽养殖与水产养殖，分别根据《城镇污水处理厂污染物排放标准》（GB18918-2002）与《畜禽养殖业污染物排放标准》（GB18596-2001）来计算不同来源的污染负荷。

4 结果分析

4.1 控制单元划分结果

研究共在小南海湖流域划分控制单元32个（图6），控制单元命名与编码采取“序号—河流—行政区域”的规则，具体划分结果如表4所示。其中，直接影响小南海湖水质的控制单元有6个，分别为5号、18号、19号、21号、28号和31号控制单元。

4.2 污染负荷计算结果

依据3.3部分所示污染源分析及负荷计算方法，最终得出小南海湖流域不同来源的污染负荷（表5）。由结果可知，流域中面源污染负荷

module parameters were decided after repeated adjustment. The composite degradation coefficients for COD, TN, TP and NH_3-N in the model were 0.0005/d, 0.002/d, 0.004/d, and 0.0015/d, respectively. Considering that the average relative errors between the simulated results and the observed results of COD, TN, TP, and NH_3-N concentration in Xiaonanhai Lake were 0.11, 0.05, 0.04, and 0.14 respectively (Table 3), the MIKE 21 model was proved applicable for water quality simulation of the Xiaonanhai Lake watershed.

3.3 Pollution Source Analysis and Pollution Load Calculation Methods

After the field investigation to the Xiaonanhai Lake watershed, the study team concluded that the non-point source pollution was mainly from rural domestic sewage, agriculture, and scattered livestock and poultry breeding; the point source pollution mainly came from urban sewage, industrialized livestock and poultry breeding, and aquaculture. Based on this result, the SWAT model was used for non-point source pollution load calculation and parameters from the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB18918-2002) and the Discharge Standard of Pollutants for Livestock and Poultry Breeding (GB18596-2001) were applied for point source pollution load calculation.

4 Result Analyses

4.1 Control Unit Division

32 control units were divided for the Xiaonanhai Lake watershed (Fig. 6), each named in the form of “number-the river involved-the administrative region involved.” The detailed

6. 小南海湖流域控制单元划分图

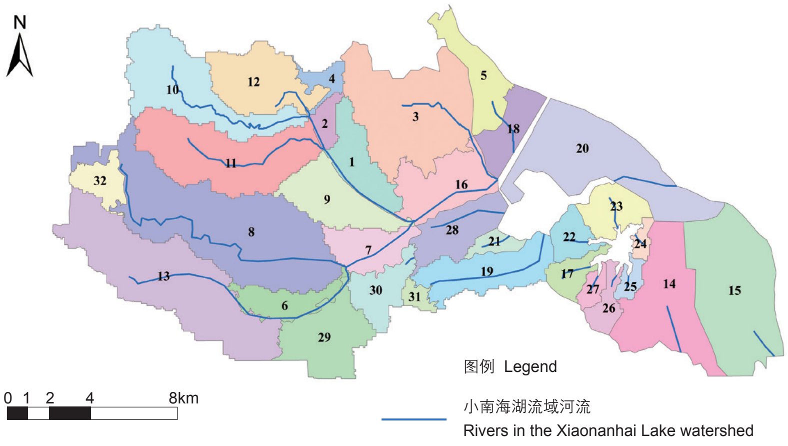
6. Control unit division result of the Xiaonanhai Lake watershed

表3：小南海湖各点位水质指标模拟值与实测值对比
Table 3: Comparison between the simulated and observed levels of water quality at observation points in Xiaonanhai Lake

测点 Observation point	COD			TN			TP			NH_3-N		
	模拟值 Simulated result (mg/L)	实测值 Observed result (mg/L)	相对误差 Relative error	模拟值 Simulated result (mg/L)	实测值 Observed result (mg/L)	相对误差 Relative error	模拟值 Simulated result (mg/L)	实测值 Observed result (mg/L)	相对误差 Relative error	模拟值 Simulated result (mg/L)	实测值 Observed result (mg/L)	相对误差 Relative error
小南海湖心 Center of Xiaonanhai Lake	31.66	32.4	-0.02	2.25	2.15	0.05	0.31	0.28	0.12	1.37	1.44	-0.05
横坝 Dam	33.58	45.4	-0.26	—	—	—	0.34	0.47	-0.26	1.43	1.88	-0.24
小南海东侧湖心 East center of Xiaonanhai Lake	35.39	37.2	-0.05	—	—	—	0.36	0.35	0.02	—	—	—

表4：小南海湖流域各控制单元基本信息
Table 4: Basic information of the control units in the Xiaonanhai Lake watershed

序号 Number	控制单元名称 Name of the control unit	所属河流/湖泊 The river / lake the unit sits in / around	所属行政区域 Administrative area	面积（km^2） Area (km^2)	序号 Number	控制单元名称 Name of the control unit	所属河流/湖泊 The river / lake the unit sits in / around	所属行政区域 Administrative area	面积（km^2） Area (km^2)
1	1-碾盘-新江口镇 1-Nianpan-Xinjiangkou Town	碾盘河 Nianpan River	新江口镇 Xinjiangkou Town	8.17	17	17-庆寿寺-南海镇 17-Qingshou Temple-Nanhai Town	庆寿寺湖 Qingshou Temple Lake	南海镇 Nanhai Town	3.57
2	2-碾盘-新江口镇 2-Nianpan-Xinjiangkou Town	碾盘河 Nianpan River	新江口镇 Xinjiangkou Town	2.38	18	18-红旗渠-南海镇 18-Hongqi Canal-Nanhai Town	红旗渠 Hongqi Canal	南海镇 Nanhai Town	6.3
3	3-幸福-新江口镇 3-Xingfu-Xinjiangkou Town	幸福渠 Xingfu Canal	新江口镇 Xinjiangkou Town	26.35	19	19-蒿子港-南海镇 19-Haozigang River-Nanhai Town	蒿子港 Haozigang River	南海镇 Nanhai Town	11.48
4	4-碾盘-新江口镇 4-Nianpan-Xinjiangkou Town	碾盘河 Nianpan River	新江口镇 Xinjiangkou Town	2.42	20	20-新河-南海镇 20-Xin River-Nanhai Town	新河 Xin River	南海镇 Nanhai Town	24.83
5	5-红旗渠-新江口镇 5-Hongqi Canal-Xinjiangkou Town	红旗渠 Hongqi Canal	新江口镇 Xinjiangkou Town	8.12	21	21-散流片-南海镇 21-Scattered Flow Area-Nanhai Town	散流片 Scattered Flow Area	南海镇 Nanhai Town	2.11
6	6-南河-王家桥镇 6-South River-Wangjiaqiao Town	南河 South River	王家桥镇 Wangjiaqiao Town	5.92	22	22-庆寿寺-南海镇 22-Qingshou Temple-Nanhai Town	庆寿寺湖 Qingshou Temple Lake	南海镇 Nanhai Town	3.88
7	7-新河-王家桥镇 7-Xin River-Wangjiaqiao Town	新河 Xin River	王家桥镇 Wangjiaqiao Town	7.2	23	23-庆寿寺-南海镇 23-Qingshou Temple-Nanhai Town	庆寿寺湖 Qingshou Temple Lake	南海镇 Nanhai Town	5.94
8	8-北河-王家桥镇 8-North River-Wangjiaqiao Town	北河 North River	王家桥镇 Wangjiaqiao Town	39.66	24	24-庆寿寺-南海镇 24-Qingshou Temple-Nanhai Town	庆寿寺湖 Qingshou Temple Lake	南海镇 Nanhai Town	1.33
9	9-碾盘-王家桥镇 9-Nianpan-Wangjiaqiao Town	碾盘河 Nianpan River	王家桥镇 Wangjiaqiao Town	10.74	25	25-庆寿寺-南海镇 25-Qingshou Temple-Nanhai Town	庆寿寺湖 Qingshou Temple Lake	南海镇 Nanhai Town	1.75
10	10-碾盘-王家桥镇 10-Nianpan-Wangjiaqiao Town	碾盘河 Nianpan River	王家桥镇 Wangjiaqiao Town	18.95	26	26-庆寿寺-南海镇 26-Qingshou Temple-Nanhai Town	庆寿寺湖 Qingshou Temple Lake	南海镇 Nanhai Town	3.17
11	11-碾盘-王家桥镇 11-Nianpan-Wangjiaqiao Town	碾盘河 Nianpan River	王家桥镇 Wangjiaqiao Town	22.42	27	27-庆寿寺-南海镇 27-Qingshou Temple-Nanhai Town	庆寿寺湖 Qingshou Temple Lake	南海镇 Nanhai Town	1.78
12	12-碾盘-王家桥镇 12-Nianpan-Wangjiaqiao Town	碾盘河 Nianpan River	王家桥镇 Wangjiaqiao Town	12.7	28	28-中槽沟-南海镇 28-Zhongcaogou River-Nanhai Town	中槽沟 Zhongcaogou River	南海镇 Nanhai Town	8.75
13	13-南河-斯家场镇 13-South River-Sijiachang Town	南河 South River	斯家场镇 Sijiachang Town	32.08	29	29-南河-街河市镇 29-South River-Jieheshi Town	南河 South River	街河市镇 Jieheshi Town	12.12
14	14-松西-南海镇 14-Songxi-Nanhai Town	松西河 Songxi River	南海镇 Nanhai Town	18.49	30	30-新河-街河市镇 30-Xin River- Jieheshi Town	新河 Xin River	街河市镇 Jieheshi Town	6.46
15	15-松西-南海镇 15-Songxi-Nanhai Town	松西河 Songxi River	南海镇 Nanhai Town	26.18	31	31-蒿子港-街河市镇 31-Haozigang River- Jieheshi Town	蒿子港 Haozigang River	街河市镇 Jieheshi Town	1.58
16	16-新河-南海镇 16-Xin River-Nanhai Town	新河 Xin River	南海镇 Nanhai Town	11.16	32	32-北河-斯家场镇 32-North River-Sijiachang Town	北河 North River	斯家场镇 Sijiachang Town	4.31



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division result is shown in Table 4. Control Unit 5, 18, 19, 21, 28, and 31 impact the water quality of Xialnanhai Lake the most.

4.2 Pollution Load Calculation Results

According to the pollution source analysis and pollution load calculation method presented in Section 3.3, the loads of different pollutants into the Xiaonanhai Lake watershed were figured out and shown in Table 5. It indicates that the non-point

所占比重大于点源污染，其中面源污染主要由农业种植造成，城镇生活污水与水产养殖污染是点源污染负荷的主要来源。

5 生态修复措施体系布局及效果评估

5.1 生态修复措施体系布局

基于小南海湖流域污染负荷分析结果，研究针对各类污染源提出不同的生态修复措施，以期达到最佳的水环境治理与水生态修复效果。具体措施包括三级人工湿地工程、自然型湿地工程、清水廊道工程、湖岸缓冲带工程和浅水水生植物带工程（表6）。

5.1.1 三级人工湿地工程

污水处理厂尾水经红旗渠倒虹管直排入小南海湖，严重破坏了湖泊水环境。此外，若初期雨水冲刷地面所携带的污染物直接排入河道，也将加剧水体污染，不利于河道水质与生态的保持。三级人工湿地处理工程可将污水引入湿地进行净化，削减水体中的污染物含量。一级湿地采用表面流-水平潜流复合型人工湿地，在湿地前端增设可调节截留初期雨水径流的稳定塘。二级湿地类型与一级湿地一致，由现有鱼塘改建而成，用于处理一级湿地尾水。三级湿地为表流型人工湿地，用于处理二级湿地尾水，进一步提高出水水质。湿地空间布局如图7所示，拟建设在18、20、23号控制单元上。

5.1.2 自然型湿地工程

中槽沟来水水质较好，基本达到地表水Ⅲ类水质标准；蒿子港来水水质较差，采用重铬酸钾测定的化学需氧量（CODcr）浓度为地表水Ⅴ类水质标准、五日生化需氧量（BOD5）和TP等浓度为地表水Ⅳ类水质标准，污染严重。蒿子港为山溪性河流，河道流量受降雨影响较大，汛期流量较高，污染来源主要为降雨冲刷造成的面源污染。通过构建蒿子港自然型湿地，有助于形成湿地生态系统，营造健康稳定的水生动植物群落，达到净化水质、美化环境和保护水资源的效果。自然型湿地的空间布局如图8所示，拟建设在19号控制单元上。

5.1.3 清水廊道工程

清水廊道即具有过滤污染物、防治水土流失、防风固沙、调蓄洪水等功能的廊道。根据现场调研，中槽沟、蒿子港河岸多为农田和鱼塘，在此建设清水廊道可有效拦截降雨径流给河湖带来的污染物，恢复小南海湖排洪通道正常功能，改善河道水质，提升区域水环境质量。清水廊道空间布局如图9所示，拟建设在19号、28号和31号控制单元上。

表5：小南海湖流域不同来源的污染负荷（t/a）
Table 5: Different types of pollution load of the Xiaonanhai Lake watershed (t/a)

污染源类型 Types of pollution source		COD	TN	NH_3-N	TP
面源污染 Non-point source pollution	农村生活污水 Rural domestic sewage	46	5.1	4.9	0.8
	农业种植 Agriculture	655.1	54.6	17.5	4.1
	分散式畜禽养殖 Scattered livestock and poultry breeding	70.4	7.1	5.2	2.7
点源污染 Point source pollution	城镇生活污水 Urban domestic sewage	192.3	40	20.8	3.8
	规模化畜禽养殖 Industrialized livestock and poultry breeding	0.6	0.2	0.1	0
	水产养殖 Aquaculture	200	16	8.2	6.9
污染负荷总量 Total amount of pollution load		**1,164.4**	**123**	**56.7**	**18.3**

表6：各生态修复措施信息
Table 6: Information on Ecological Restoration Measures

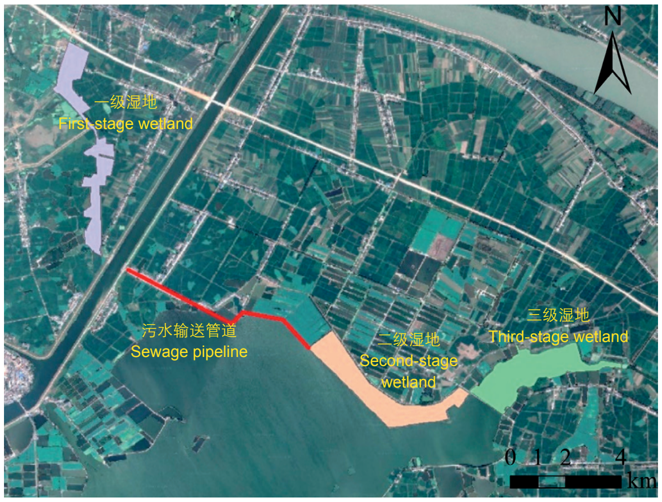
生态修复措施 Ecological restoration measures	所在控制单元序号 Control unit(s) to treat	针对污染源 Target pollution
三级人工湿地工程 Three-stage constructed wetland project	18、20、23	点源污染 Point source pollution
自然型湿地工程 Natural wetland project	19	面源污染 Non-point source pollution
清水廊道工程 Clean water corridor project	19、28、31	面源污染 Non-point source pollution
湖岸缓冲带工程 Lakeshore buffer zone project	21	面源污染 Nonpoint source pollution
浅水水生植物带工程 Emerged and floating plant belt project	—	湖体中的营养盐 Nutrients in the lake

source pollution caused mainly by agriculture accounts for a larger proportion than the point source pollution caused mainly by urban domestic sewage and aquaculture.

5 Arrangement of the Ecological Restoration Measure System and Its Performance Evaluation

5.1 Arrangement of the Ecological Restoration Measure System

Based on the pollution load calculation of the Xiaonanhai Lake watershed, the study proposed 5 different ecological restoration measures, namely the three-stage constructed wetland,



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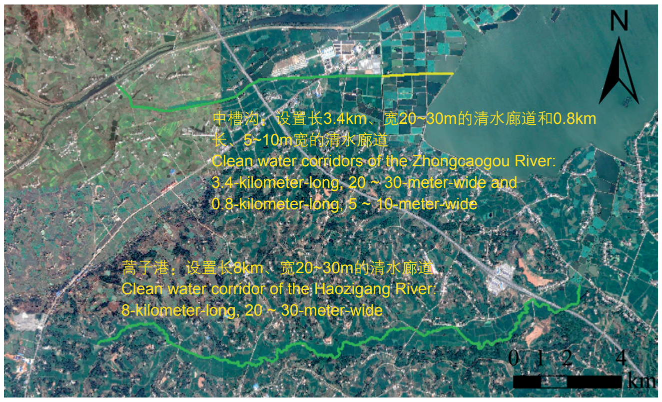

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7. 三级人工湿地工程空间布局
8. 蒿子港自然型湿地工程空间布局
9. 清水廊道工程空间布局
10. 湖岸缓冲带工程空间布局

7. Spatial arrangement of the three-stage constructed wetland project
8. Spatial arrangement of the natural wetland project around the Haozigang River
9. Spatial arrangement of the clean water corridor project
10. Spatial arrangement of the lakeshore buffer zone project

the natural wetland, the clean water corridor, the lakeshore buffer zone, and the emerged and floating plant belt, to deal with specific pollutant for better water environment treatment and water ecological restoration.

5.1.1 The Three-Stage Constructed Wetland Project

Both of the tail water from the sewage treatment plant via the inverted siphons installed in the Hongqi Canal and the initial rainwater runoff with pollutants aggravate the water pollution and ecological damage to Xiaonanhai Lake. To deal with this problem, the study proposed the three-stage constructed wetland project to purify the wastewater and reduce the pollutants discharged. The first-stage wetland of this project is a compound of the surface flow wetland and horizontal subsurface flow wetland with a stabilization pond to regulate and intercept initial rainwater runoff; the second-stage wetland which has the same structure as the first-stage wetland is transformed from existing fishponds to treat tail water from the first; and the third-stage wetland is a surface flow wetland to treat the tail water from the second. The spatial arrangement of the three-stage constructed wetland planned on Control Unit 18, 20, and 23 is shown in Figure 7.

5.1.2 The Natural Wetland Project

Water from the Haozigang River into Xiaonanhai Lake is heavily polluted with the CODcr concentration of the Surface Water Class V and BOD5 and TP concentration of the Surface Water Class IV. As a mountain river, the Haozigang River suffers mainly from non-point source pollution caused by heavy rainfall erosion in the flood season. It is suggested to introduce a natural wetland project along the river to establish a wetland ecosystem with healthy and stable aquatic flora and fauna to purify the water and protect water resources with beautiful landscape. The arrangement of this type of wetland on Control Unit 19 is shown in Figure 8.

5.1.3 The Clean Water Corridor Project

The clean water corridors could play several roles such as pollutant filtration, water and soil erosion reduction, and flood control exactly applicable to the farmlands and fishponds located along the banks of the Zhongcaogou River and Haozigang River to effectively intercept pollutants brought by rainfall runoff into rivers and lakes, so that the water quality of Xiaonanhai Lake could be improved and the flood drainage channels can work better. The arrangement of the clean water corridor planned on Control Unit 19, 28, and 31 is shown in Figure 9.

5.1.4 湖岸缓冲带工程

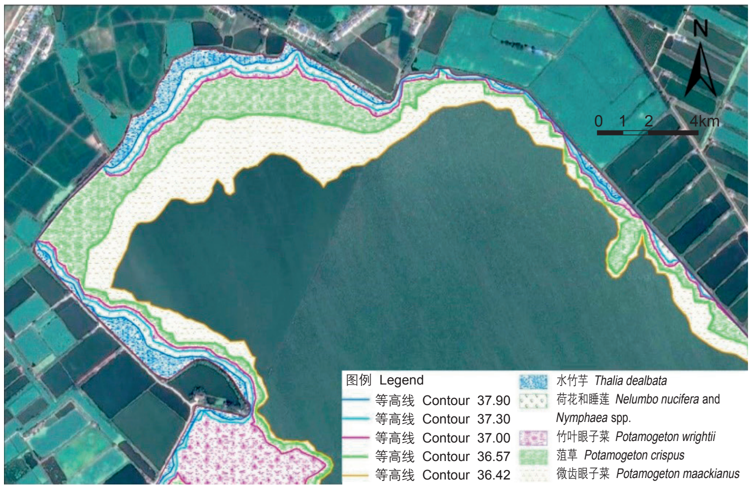
小南海湖流域西南部的部分村落处在散流片区，该区域无入湖河道，由此处汇入小南海湖的主要为降雨散流，易将污染物冲刷带入湖中。该地区缺乏污水收集与处理设施，农村生活污水及农业种植污染直排入湖，严重影响水质。因此，可建设湖岸缓冲带控制面源污染，其空间布局如图10所示，拟建设在21号控制单元上。

5.1.5 浅水水生植物带工程

小南海湖现状主要污染因子包括氮、磷、NH_3–N等，同时在枯水期处于中度或重度富营养化状态。种植水生植物可削减湖体中污染物的含量，净化水质，丰富湖泊水生植物群落，逐步修复水生态环境。根据污染现状、水深要求、水生植物的适宜水深及其可处理的污染物（表7），研究建议配置由水竹芋（*Thalia dealbata*）、荷花（*Nelumbo nucifera*）、睡莲（*Nymphaea* spp.）、竹叶眼子菜（*Potamogeton wrightii*）、菹草（*Potamogeton crispus*）、微齿眼子菜（*Potamogeton maackianus*）等组成的水生植物带，其空间布局如图11所示。

表7：常见水生植物适宜水深及可处理污染物
Table 7: Suitable planting depths and target pollutants for common aquatic plants

植物类型 Plant type	种名 Scientific name	适宜水深 Suitable planting depth	可处理污染物 Target pollutant
挺水植物 Emergent plant	水竹芋 *Thalia dealbata*	0 ~ 60 cm	氮、磷污水 Sewage with N and P
浮叶植物 Floating-leaved plant	荷花 *Nelumbo nucifera*	40 ~ 120 cm	氮、磷污水，TN去除率较高 Sewage with N and P (better removal effect for TN)
	睡莲 *Nymphaea* spp.	30 ~ 80 cm	氮、磷污水，铬、铜、锌等 Sewage with N and P, and Cr, Cu, and Zn
沉水植物 Submerged plant	竹叶眼子菜 *Potamogeton wrightii*	60 ~ 120 cm	氮、磷污水 Sewage with N and P
	菹草 *Potamogeton crispus*	120 ~ 150 cm	氮、磷污水，TP去除率较高 Sewage with N and P (better removal effect for TN)
	微齿眼子菜 *Potamogeton maackianus*	350 ~ 400 cm	氮、磷污水 Sewage with N and P



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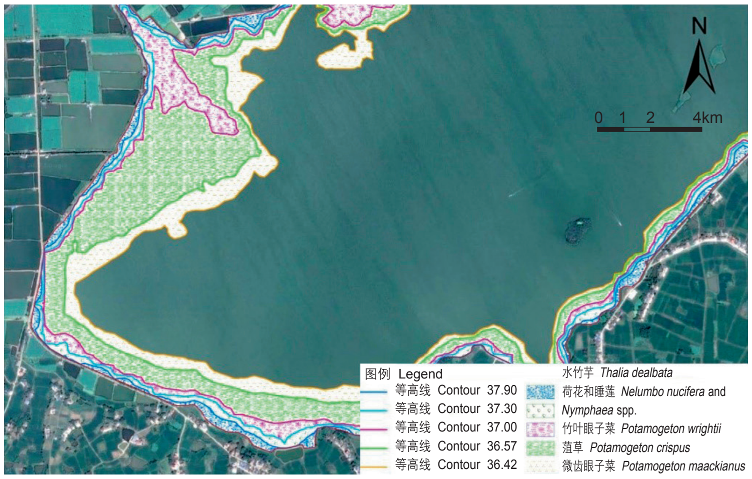

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5.1.4 The Lakeshore Buffer Zone Project

There are several villages located in the scattered flow area in the southwest of the Xiaonanhai Lake watershed with no river flowing into the lake. In this area, the pollutants are mainly brought into the lake by rainwater runoff. The lack of sewage collection and treatment facilities aggravates the problem caused by the rural domestic sewage and agriculture pollution discharging directly into the lake. This lakeshore buffer zone could be constructed on Control Unit 21 to control the non-point source pollution (Fig. 10).

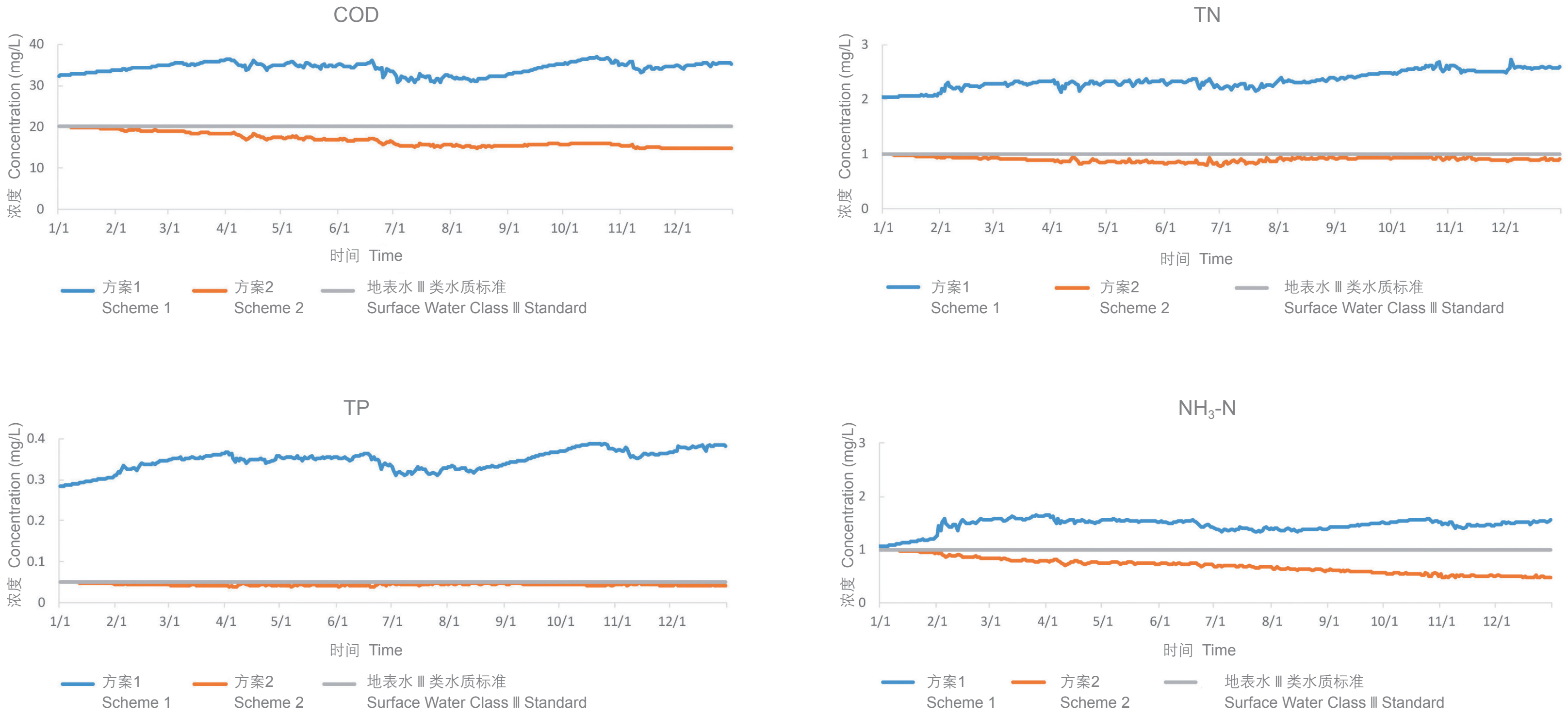
5.1.5 The Emerged and Floating Plant Belt Project

Currently, Xiaonanhai Lake is mainly polluted by N, P, and NH_3-N, and will be in moderate or severe eutrophication during the dry season. Planting aquatic plants could reduce these pollutants effectively and enrich the plant community to restore the ecological environment gradually. Considering the current pollution situation, water depth of the lake, suitable planting depth, and the pollutants they can treat (Table 7), this study proposed an aquatic plant belt consisting of *Thalia dealbata*, *Nelumbo nucifera*, *Nymphaea* spp., *Potamogeton wrightii*, *Potamogeton crispus*, and *Potamogeton maackianus* (Fig. 11).

5.2 Performance Evaluation of the Ecological Restoration Measures

5.2.1 Concentration Control of the Pollutants

Using the water environment system model, this study simulated the condition of the Xiaonanhai Lake watershed in 2016 and evaluated the performance of the five ecological



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11. 小南海湖流域北部（图11-1）、南部（图11-2）水生植物种植空间布局图
12. 方案1和方案2中小南海湖各污染物浓度对比

11. Spatial arrangement of the aquatic plants planted in the north (Fig. 11-1) and south (Fig. 11-2) of Xiaonanhai Lake
12. Pollutant concentration comparison between Scheme 1 and Scheme 2 in Xiaonanhai Lake

5.2 生态修复措施效果评估

5.2.1 污染物浓度控制

通过在水环境系统模型中对比小南海湖流域2016年现状水平下未采取任何措施（方案1）与2016年现状水平下采取5.1章节所述5种生态修复措施（方案2）后的污染物含量，评估修复措施效果。由图12所示结果可知，基于方案1的小南海湖流域的COD、TN、TP和NH_3–N所表征的污染物浓度全年高于地表水Ⅲ类水质标准值，污染严重；实施生态修复措施后，以上4种污染物浓度全年均符合或低于地表水Ⅲ类水质标准值。

5.2.2 污染物总量控制

（1）小南海湖水环境容量计算

COD的水环境容量计算模型如公式（2）所示，TN、TP和NH_3–N水环境容量采用狄龙（Dillon）模型计算，计算公式如（3）所示。

$$W=\left(\sum_{j=1}^{m}Q_jC_S-\sum_{i=1}^{n}Q_iC_{0i}\right)+kVC_S \qquad （2）$$

式中，Q_j为第j条出湖河流的流量（m^3/s）；C_S为COD控制目标浓度（g/m^3）；Q_i为第i条入湖河流的流量（m^3/s）；C_{0i}为第i条河流的污染物

restoration measures presented in Section 5.1 (Scheme 2) in pollutant reduction by comparing its result to the situation with no measures applied (Scheme 1). It can be seen from Figure 12 that these five measures can effectively reduce the concentration of COD, TN, TP, and NH_3-N all year round to meet the Surface Water Class III Standard.

5.2.2 Total Load Control of the Pollutants

(1) Calculation of Water Environmental Capacity of Xiaonanhai Lake

This study calculated the water environmental capacity of COD according to Formula (2), and calculated the water environmental capacity of TN, TP, and NH_3-N by the Dillon model according to Formula (3).

$$W=\left(\sum_{j=1}^{m}Q_jC_S-\sum_{i=1}^{n}Q_iC_{0i}\right)+kVC_S \qquad (2)$$

In Formula (2), Q_j is the flow of the j-th river out of the lake, m^3/s; C_S is the target concentration of COD, g/m^3; Q_i is the flow of the *i*-th river into the lake, m^3/s; C_{0i} is the average

平均浓度（g/m^3）；V为设计条件下小南海湖的湖泊容积（m^3），k为COD综合降解系数。

$$\begin{aligned}&P=L_P\left(1-R_p\right)/\beta h\\&\beta=Q_a/V\\&R_p=1-W_{出}/W_{入}\end{aligned}\qquad(3)$$

式中，P为湖泊中TN、TP或NH_3–N的平均浓度（g/m^3）；L_P为年湖泊中TN、TP或NH_3–N的单位面积负荷（g/m^2・a）；R_P为TN、TP或NH_3–N在湖泊中的滞留系数（1/a）；β为水力冲刷系数（1/a）；h为湖泊平均水深（m）；Q_a为湖泊年出流水量（m^3/a）；V为设计条件下小南海湖的湖泊体积（m^3）；$W_{出}$为TN、TP或NH_3–N的年出湖量（t/a）；$W_{入}$为TN、TP或NH_3–N的年入湖量（t/a）。

根据计算条件和参数，得到小南海湖流域COD、TN、TP和NH_3–N在地表水Ⅲ类水质标准控制目标下的水环境容量（表8）。

（2）各措施削减效果评估

直接汇入小南海湖并影响其水质的6个控制单元及污水处理厂污染物总入河量如表9所示。根据各类生态修复措施的规模与一般实施效果，计算出了其削减总量，各措施的削减总量如表10所示。由表8、表9和表10可知，采取本文提出的生态修复措施后水质指标COD、TN、TP和NH_3–N的入湖总量分别为495.1t/a、21.0t/a、1.8t/a和20.4t/a，基本低于小南海湖的水环境容量，可保障水质达到地表水Ⅲ类水质标准。

6 结论

针对小南海湖流域的水环境与水生态问题，本研究主要依据行政区划和汇水分区将小南海湖流域划分为32个控制单元，分析了小南海湖流域污染源并计算了污染负荷，总结得出面源污染负荷高于点源污染负荷。进而提出包括三级人工湿地工程、自然型湿地工程、清水廊道工程、湖岸缓冲带工程与浅水水生植物带工程在内的生态修复措施体系，并针对不同污染源特征将各类生态修复措施布局在小南海湖流域不同的控制单元上。随后分别通过水环境系统模型与水环境容量计算，对生态修复措施效果进行评估。结果表明，在实施本研究所提出的生态修复措施后，小南海湖水质可达地表水Ⅲ类水质标准。

定量分析各类生态修复措施的污染物削减效果，对小南海湖流域污染负荷识别与调控提供定量化依据具有重要意义。而基于控制单元的水环境管理亦可有效明确责任主体，更好地落实水环境问题与治理措施。受资料所限，本研究仅计算了2016年的水环境容量。但由于水文条件直接影响河湖的水环境容量大小，不同水文年份河湖水环境容量大小差别较大，故而在今后的研究中可进一步收集水文资料，探究不同水文条件下各类生态修复措施对污染物的削减效果。LAF

concentration of COD of the i-th river, g/m^3; V is the designed volume of the Xiaonanhai Lake, m^3; and k is the composite degradation coefficient of COD.

$$\begin{aligned}&P=L_P\left(1-R_p\right)/\beta h\\&\beta=Q_a/V\\&R_p=1-W_{out}/W_{in}\end{aligned}\qquad(3)$$

In Formula (3), P is the average concentration of TN, TP, or NH_3-N in the lake, g/m^3; L_P is the annual load of TN, TP, or NH_3-N per unit area, g/m^2·a; R_P is the retention coefficient of TN, TP, and NH_3-N in the lake, 1/a; β is the hydraulic erosion coefficient, 1/a; h is the average water depth of the lake, m; Q_a is the annual outflow volume of the lake, m^3/a; V is the designed volume of the Xiaonanhai Lake, m^3; W_{out} is the annual amount of TN, TP, and NH_3-N out of the lake, t/a; W_{in} is the annual amount of TN, TP, and NH_3-N into the lake, t/a.

According to the calculation conditions and parameters, Xiaonanhai Lake's water environmental capacity of COD, TN, TP, and NH_3-N under the control target of Surface Water Class III Standard was calculated and shown in Table 8.

(2) Performance Evaluation of the Measures

Table 9 shows the amount of pollutants discharged into the lake by the six control units and the sewage treatment plant that heavily impacts the water quality. Table 10 presents the total pollutant reduction of each ecological restoration measure according to their application scales and general practical effect. With an analysis of Table 8, 9, and 10, it could be concluded that the total amount of COD, TN, TP, and NH_3-N into the lake were 495.1 t/a, 21.0 t/a, 1.8 t/a, and 20.4 t/a after implementing the ecological restoration measures proposed in this study, which can ensure the water quality to meet the Surface Water Class III Standard.

6 Conclusions

To deal with the water environmental and ecological problems of the Xiaonanhai Lake watershed, this study first divided the watershed into 32 control units according to the administrative division and catchment zones. Second, the pollution source and load of the watershed were analyzed and calculated by the water environment system model, indicating that the non-point source pollution was severer than the point source pollution. On this basis, the study proposed five ecological restoration measures including the three-stage constructed wetland, the natural wetland, the clean water corridor, the lakeshore buffer zone, and the emerged and floating plant belt onto specific control units in the watershed. The following performance evaluation of these measures, utilizing the water environment system model to calculate water environmental capacity, proved that they were effective to improve the water quality to meet the Surface Water Class III Standard.

This type of quantitative analysis of the pollutant reduction performance of different ecological restoration measures provides important support for the pollution load quantification and control in the Xiaonanhai Lake watershed. Moreover, the control-unit-based watershed management could assign responsibility more efficiently to identify water environmental problems and implement these measures. This study only calculated the water environmental capacity of 2016 due to the data limitation. However, the water environmental capacity changes significantly under different hydrological conditions. Thus, future studies could be conducted with more hydrological data to explore the pollution reduction effects of different ecological measures. **LAF**

表8：地表水Ⅲ类水质标准下小南海湖水环境容量（t/a）
Table 8: Water environmental capacity of the Xiaonanhai Lake (t/a) under the Surface Water Class Ⅲ Standard

水质指标 Water quality index	COD	TN	TP	NH_3-N
水环境容量 Water environmental capacity	511.76	52.27	1.56	25.49

表9：6个控制单元及污水处理厂污染物入河量（t/a）
Table 9: The amount of pollutants discharged by the six control units and the sewage treatment plant into river (t/a)

污染物来源 Pollutant sources	COD	TN	TP	NH_3-N
控制单元5 Control Unit 5	84.3	7.4	0.7	3.4
控制单元18 Control Unit 18	169.6	14.7	1.8	6.3
控制单元19 Control Unit 19	256.5	22.1	2.5	8.8
控制单元21 Control Unit 21	46	4	0.5	1.6
控制单元28 Control Unit 28	181.2	15.5	1.6	5.9
控制单元31 Control Unit 31	32.9	2.9	0.4	1.3
污水处理厂 Sewage treatment plant	192.3	40	3.8	20.8
总计 **Total**	**962.8**	**106.4**	**11.3**	**48.1**

表10：各类生态修复措施污染物削减总量（t/a）
Table 10: The total pollution reduction of each ecological restoration measure (t/a)

生态修复措施 Ecological restoration measures	COD	TN	TP	NH_3-N
三级人工湿地工程 Three-stage constructed wetland project	192.3	40	3.8	20.8
自然型湿地工程 Natural wetland project	275.4	22.4	2.4	6.4
湖岸缓冲带工程 Lake shore buffer zone project	/	1.2	0.2	0.5
浅水水生植物带工程 Emerged and floating plant belt project	/	21.8	3.5	/
措施削减量合计 **Total pollution reduction**	**467.7**	**85.4**	**9.5**	**27.7**

注释
由于模型无法对清水廊道工程的工况进行模拟，因此本研究未对其污染物削减能力进行评估。
NOTE
This study did not evaluate the pollution reduction effect of the clean water corridor project as the models cannot simulate its operating conditions.

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