From scenario to roadmap: A web-based participatory watershed planning system for optimizing multistage implementation plans of management practice scenario under stepwise investment

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Graphical Abstracts

How to facilitate non-expert stakeholders proposing stepwise investment plan for reaching agreed-upon roadmaps?

Practical watershed management needs

- Compromising among multi-objectives
- Discussing various alternative roadmaps
- Encouraging multi-stakeholders to participate

System design

- Easy-to-use interface for non-expert stakeholders
- Ensured credibility by validated specialized models
- Proposing investment plans and electing optimized roadmaps

Role-play experiment on example system

- Participatory process improves roadmaps
- User-friendly interactions facilitate participation

Highlights:

- ~~Participatory s~~System design meets practical watershed management needs for agreed-upon roadmaps ~~for multistage BMP implementation plans is still lacking.~~
- S~~Design and developed a planning s~~ystem separates easy-to-use interface for non-expert users from specialized models~~ for optimizing roadmaps from a BMP scenario.~~
- Browser/Server system facilitates participatory processes of ~~Allowed~~ multiple stakeholders~~ to participate in reaching a consensus.~~
- ~~A user~~Users participate in proposing investment plans~~-friendly design to run optimization, analyze results,~~ and electing optimized roadmaps
- Multi-stakeholder role-play experiment verifies system’s validity and practicality

Revised manuscript (with track changes) Click here to view linked References

Abstract:

Planning multistage implementation plans (i.e., roadmaps) from the spatial distribution of a best management practice (BMP) scenario is essential for achieving~~accomplishing~~ watershed management goals under realistic conditions such as stepwise investment plans that involve multiple stakeholders, including investors, economic and environmental beneficiaries. The state-of-art BMP scenario optimization method can address this optimization need but is over-specialized and complex to non-expert stakeholders. ~~However, current watershed planning systems do not consider the overall optimizationing of roadmaps during the implementation period under stepwise investment constraints that involve multiple stakeholders such as investors, economic beneficiaries, and environmental beneficiaries.~~ This study ~~proposed a~~ designed a user-friendly web-based participatory watershed planning system to assist diverse stakeholders in reaching a consensus on optimized roadmaps. The participatory process of stakeholders includes iteratively proposing stepwise investment constraints, submitting roadmap optimization tasks ~~of roadmaps~~, ~~analysis~~ analyzing ~~of~~ spatiotemporal results from multiple perspectives, and selecting preferred roadmap(s)~~reaching a consensus~~. The proposed system design separates the participatory process of non-expert stakeholders from the specialized modeling process of constructing simulation-optimization tools for BMP roadmaps, which is done in advance by professional modelers and encapsulated as webservices on the ~~system~~ server side ~~integrated an optimization method for BMP implementation plans~~. The webservices expose few but essential parameters to lower barriers to use. The interactively participatory process is presented to stakeholders through web browsers with~~The client side constructed a~~ easy-to-use~~r-friendly~~ interfaces ~~and an iterative workflow for participatory analysis, including setting investment constraints and optimization parameters, visualizing and analyzing spatiotemporal results from multiple perspectives, and ultimately reaching a consensus~~. The system~~Based on the overall~~ design~~,~~ ~~the Youwuzhen watershed planning system~~ was implemented and demonstrated in an agricultural watershed planning case study~~ to optimize BMPs~~ for soil erosion reduction~~ in this agricultural watershed in Southeastern China~~. A role-play experiment was designed to simulate multiple stakeholders with different positions proposing investment constraints during the participatory process and reaching a consensus. The experimental results show that the participatory process of multi-stakeholders can effectively improve the comprehensive effectiveness of ~~candidate roadmaps. The~~ agreed-upon roadmap(s) ~~can meet the positions of all stakeholders~~. The idea of system design and example implementation can provide a reference for the ease~~-of~~-to-use design for~~of~~ related environmental decision support systems. ~~s iterative optimization process and the rationality and diversity of optimized roadmaps.~~

Keywords:

watershed planning; multistage implementation plan; participatory modeling; best management practice; scenario optimization

1. Introduction

Watershed planning is a scientific and practical approach to provide effective decision support for solving environmental issues, including soil erosion and non-point source pollution and so on. Watershed planning often requires a compromise between multiple potentially conflicting objectives, such as maximizing eco-environmental effectiveness and minimizing socioeconomic investment, to reach agreed-upon best management practices (BMP) scenario(s) that satisfy positions of multiple stakeholders (e.g., investors, farmers, citizens, and authorities) with different positions (~~Engel et al., 2003;~~ Ruiz-Ortiz et al., 2019; ~~Lai et al., 2007;~~ Booth et al., 2011; Reichert et al., 2015; Sun, 2013). In existing studies, a selected BMP scenario often refers to a BMP spatial configuration in the watershed. However, such a BMP scenario usually cannot be implemented at one time due to the constraints of practical situations, including budgets (or investments), local policies, willingness of landowners, and human resources (Abebe et al., 2019; Okumah et al., 2020; Ryan et al., 2003). Among these constraints, overall or stepwise investment by stakeholders may be the most common and comprehensive representation (Hou et al., 2020; Shen et al., under review). Therefore, how to consider investment constraints that involve multiple stakeholders in watershed planning becomes an urgent requirement for effective solution.

~~This process comprises several critical stages, including defining management goals, designing and evaluating diverse spatial configurations of best management practices (BMP), and performing discussions to reach a consensus~~

~~(Reichert et al., 2015; Voinov et al., 2016). It is an iterative optimization process initiated by decision makers or managers determining management goals, powered by professional modelers utilizing scientific models and tools, and implemented by stakeholders in multiple roles with their experience, needs, and capabilities (Babbar-Sebens et al., 2015; Purkey et al., 2018; Wicki et al., 2021). To facilitate this process, watershed planning systems are designed to integrate diverse models and tools corresponding to different watershed planning stages, including watershed models, scenario analysis tools, and optimization tools (Martin et al., 2016; Sugumaran et al., 2004; Walling and Vaneeckhaute, 2020). They are expected to generate one or several comprehensive optimal BMP scenarios through effective communication between stakeholders in diverse roles (e.g., investors, farmers, citizens, and authorities) and professional modelers.~~

~~In existing studies, an optimized BMP scenario often refers to a selected BMP spatial configuration. Such a BMP scenario usually cannot be implemented at one time due to the constraints of practical situations, including budgets (or investments), local policies, willingness of landowners, and human resources (Abebe et al., 2019; Okumah et al., 2020; Ryan et al., 2003). Among these constraints, overall or stepwise (or staged) investment by stakeholders may be the most common and comprehensive representation (Hou et al., 2020; Shen et al., under review). When such practical constraints proposed by stakeholders are considered to reach a consensus, the optimized BMP scenario can be further converted to a practical roadmap, that is, an elaborate multistage implementation~~

~~plan. Each implementation stage includes a BMP spatial configuration, which is part of the optimized BMP scenario, and the corresponding investment. Therefore, the development of a watershed planning system that considers the participation of multiple stakeholders in investments to develop practical BMP scenarios has become an urgent requirement.~~

A lot of BMP scenario optimization methods have been proposed to support watershed planning and~~Existing watershed planning systems~~ generally take two approaches for considering stakeholder participation in the investment. The first regards all stakeholders as one role in proposing an overall investment constraint. They predominantly focused on BMP spatial optimization based on the assumption that a BMP scenario can be implemented simultaneously under the overall investment. Most research on BMP spatial optimization aimed at cost-effective scenarios (Gaddis et al., 2014; ~~Geng and Sharpley, 2019; Naseri et al., 2021;~~ Qin et al., 2018) or return on investment (Jones et al., 2017; Kroeger et al., 2019~~; Pattison-Williams et al., 2017~~) falls into this category. However, this approach cannot further arrange the optimized BMP scenario into multistage implementation plans, with~~such practical constraints proposed by stakeholders are considered to reach a consensus, the optimized BMP scenario can be further converted to a practical roadmap, that is, an elaborate multistage implementation plan.~~ each implementation stage including a BMP spatial configuration~~, which is part of the optimized BMP scenario,~~ and the corresponding investment (the so-called practical BMP roadmap in this study) to~~. Therefore, it cannot answer the~~

~~concerns of decision-makers further when (e.g., a specific year) to implement the BMP of one scenario. Thus, the corresponding watershed planning systems cannot~~ meet the requirements of making actual decisions effectively.

The second approach to consider stakeholder participation ~~in the investment constraint~~ is ~~by allowing stakeholders to~~ setting stepwise investments for multiple implementation periods and conducting optimization in two different ways (Hou et al., 2020; Shen et al., under review). The first way conduct~~Existing systems often utilize~~s separate optimization by stage (Hou et al., 2020; Podolak et al., 2017; Vogl et al., 2017). Simply put, BMP spatial configuration in each stage is treated as a separate optimization problem and optimized under independent geographic decision variables, environmental objectives, and the investment constraint (Hou et al., 2020). ~~derived the optimized BMP configuration of the first stage for several spatial units (corresponding to geographic decision variables, L.J. Zhu et al., 2021). Subsequently, they initiated the optimization of the remaining spatial units.~~ The staged optimization results were combined as a final ~~multistage implementation plan~~roadmap. However, this method only loosely combines independent optimization results and does not optimize the ~~multistage implementation plan~~roadmap in an overall optimization problem that considers multistage investments. ~~This method will lose part of the diversity of multi-objective optimization results, which may manifest in the decision support process due to the lack of adequate diverse candidate solutions to satisfy inherently conflicting stakeholder requirements.~~

To address this weakness, a new BMP roadmap optimization method ~~for multistage BMP implementation plans~~ considering the stepwise investment and time-varying effectiveness of BMPs was recently proposed by Shen et al. (under review). This method introduces the concept of net present value (NPV) to evaluate the economic effectiveness of the entire roadmap and time-varying effectiveness of BMPs to evaluate environmental effectiveness of the roadmap. This way can effectively generate more feasible roadmaps from a specific spatial distribution of BMP scenario with less investment burden at the cost of a slight loss of environmental effectiveness and thus can provide various choices with different stepwise investment constraints for watershed planning (Shen et al., under review).

However, the implementation of the state-of-art method involve highly specialized modeling processes, including collecting modeling data (e.g., watershed modeling and BMP knowledge data), improving and building the watershed model, and improving and executing the roadmap optimization tool (Shen et al., under review). In addition, the application of this method ~~comprises several critical stages, including defining management goals, designing and evaluating diverse spatial configurations of best management practices (BMP), and performing discussions to reach a consensus (Reichert et al., 2015; Voinov et al., 2016). It~~ is an iterative optimization process initiated by decision makers or managers determining management goals, powered by professional modelers utilizing scientific models and tools, and implemented by stakeholders in multiple roles with their experience, needs, and capabilities (Babbar-Sebens et al., 2015; ~~Purkey et al., 2018; ~~Wicki et al., 2021; Reichert et al., 2015; Voinov et al., 2016). This process is especially difficult for non-expert stakeholders. To facilitate this process, watershed planning system that utilizes user-friendly interfaces for ease of use for stakeholders without intensive specialized knowledge of BMP scenario analysis becomes the uncontested choice~~ designed to integrate diverse models and tools corresponding to different watershed planning stages, including watershed models, scenario analysis tools, and optimization tools~~ (Martin et al., 2016; Sugumaran et al., 2004; Walling and Vaneeckhaute, 2020).~~ They are expected to generate one or several comprehensive optimal BMP scenarios through effective communication between stakeholders in diverse roles~~

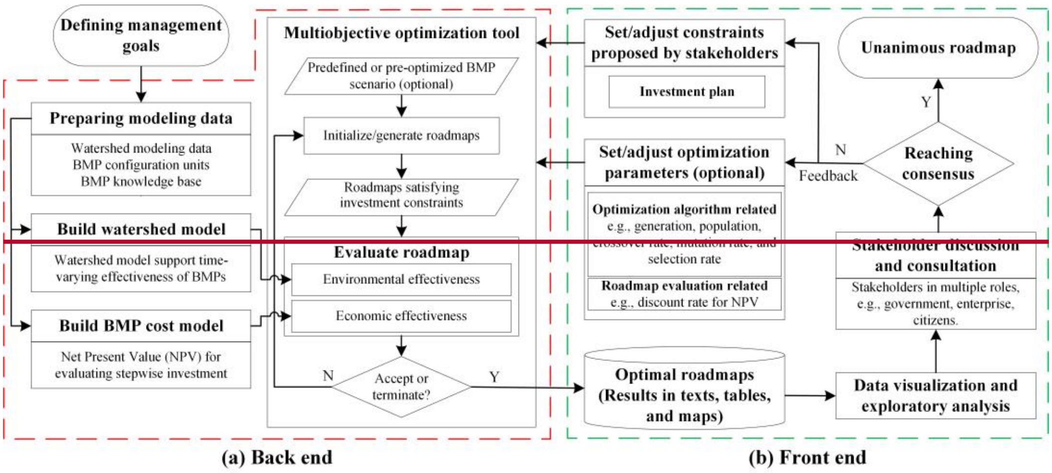
To the best of our knowledge, no watershed planning system~~s or software tools~~ supports the overall optimization of BMP roadmap~~ multistage implementation plan~~s under stepwise investment constraints that involve multiple stakeholders. Therefore, ~~to resolve this issue, t~~his study aims to design~~ed and developed~~ a web-based participatory system to iteratively assist various stakeholders in ~~setting ~~proposing investment constraints, optimizing roadmaps, analyzing results, and ~~developing ~~reaching unanimous plans. The basic idea and overall design of the system are introduced in Section 2. The case study ~~system implementation with a case study ~~of an agricultural watershed planning system for mitigating soil erosion is implemented as an example~~ presented~~ in Section 3. The multi-stakeholders role-play experimental design, results, and discussion are presented in Section 4 to verify the validity and practicality of this system design. Conclusions and future work are presented in Section 5.

2. Basic idea and overall design

2.1 Basic idea

To design~~build~~ a watershed planning system that allows multiple stakeholders to participate in ~~setting~~ proposing investment constraints and reaching a consensus on optimized~~ing multistage BMP implementation plans (i.e.,~~ roadmaps of a specific BMP scenario, two key issues need to be addressed. The system should integrate the BMP roadmap ~~a method for~~ optimizing method~~roadmaps~~ under stepwise investments~~This method was proposed as a universal framework that can be implemented based on the existing spatial optimization systems/tools of BMP scenarios~~ (see the simplified workflow depicted in the red dashed part in Figure 1; adapted from Shen et al., under review)~~.~~ ~~for a given BMP scenario~~ while streamlining~~simplifying~~ the use ~~of non-expert stakeholders~~ by inputting investment constraints and outputting roadmaps (Figure 1). Next, the system must have an easy-to-use interface to facilitate~~help~~ stakeholders with different ~~educational~~ knowledge backgrounds and diverse roles to participate~~ in the process of optimizing and analyzing roadmaps and reaching a consensus~~.~~Based on the simplified usage of the roadmap optimization method of a specific BMP scenario,~~ The participation process ~~of non-expert stakeholders in determining roadmaps~~ can be summarized as an iterative workflow: setting/adjusting investment constraints and optional optimization algorithm-based parameters, submitting the roadmap optimization task, evaluating the optimized roadmaps and comparing them with existing ones if any, discussing and consulting among multiple stakeholders, and feeding back by adjusting investment plans~~parameter settings~~ or attaining unanimous roadmaps (Figure 1b).

~~A new optimization method for multistage BMP implementation plans considering the stepwise investment and time-varying effectiveness of BMPs was recently proposed by Shen et al. (under review). This method introduces the concept of net present value (NPV) to evaluate the economic effectiveness of roadmaps and time-varying effectiveness of BMP to evaluate environmental effectiveness. This method was proposed as a universal framework that can be implemented based on the existing spatial optimization systems/tools of BMP scenarios (see the simplified workflow depicted in the red dashed part in Figure 1; adapted from Shen et al., under review). The implementation and application of this method involves highly specialized modeling processes, including collecting modeling data (e.g., watershed modeling and BMP knowledge data), improving and building the watershed model, and improving and executing the optimization tool (Figure 1a). Once professional modelers prepare these specialized processes according to the management goals, the system can only expose simple input parameters (i.e., investment constraints and optional optimization parameters) to non-expert stakeholders to execute the optimization and derive the corresponding roadmaps (Figure 1b).~~



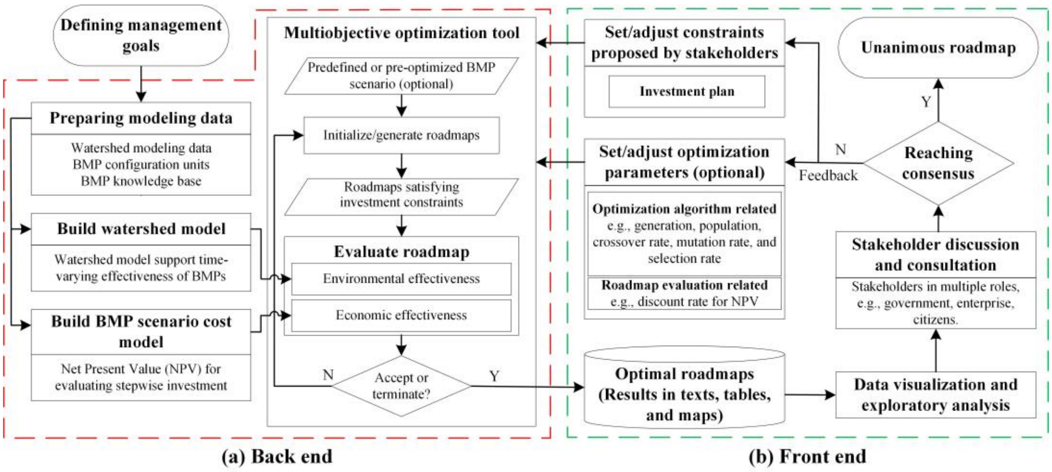


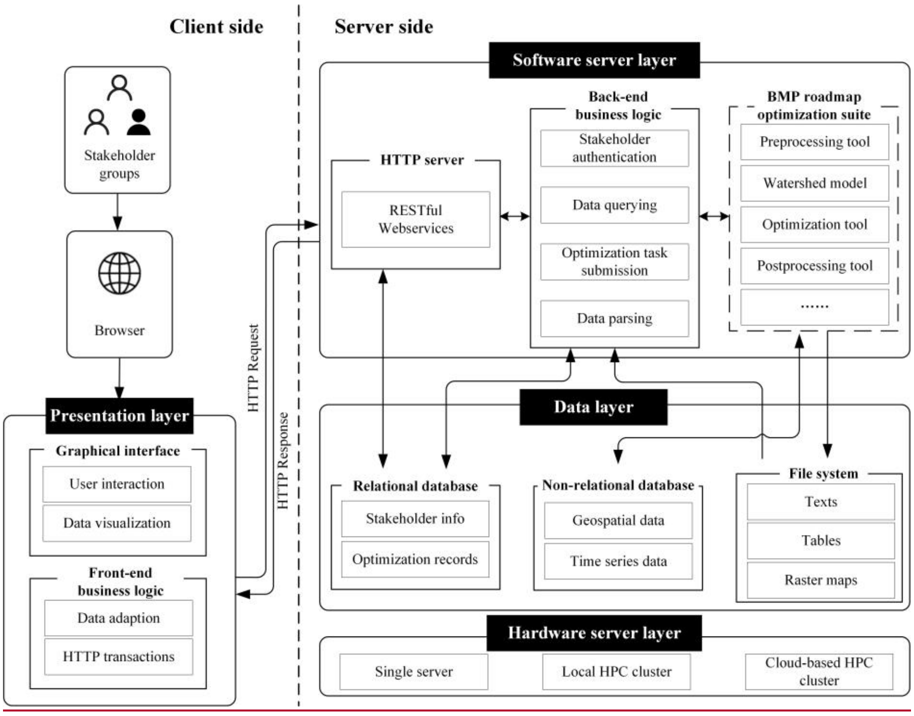
Figure 1 ~~Framework of p~~Participatory optimization framework for multistage implementation plans of best management practice (BMP) scenario under stepwise investment: (a) BMP roadmap optimization method encapsulated in the back end; (b) iterative participatory workflow designed for easy-to-use front end~~gn of the participatory watershed planning system~~.

~~Based on the simplified usage of the roadmap optimization method of a specific BMP scenario, the participation of non-expert stakeholders in determining roadmaps can be summarized as an iterative workflow: setting/adjusting investment constraints and optional optimization algorithm-based parameters, submitting the roadmap optimization task, evaluating the optimized roadmaps and comparing them with existing ones if any, discussing and consulting among multiple stakeholders, and feeding back by adjusting parameter settings or~~

~~attaining unanimous roadmaps (Figure 1b). Among these, the intuitive roadmap visualization is essential for stakeholders to judge the merits of diverse roadmaps and guide the adjustment of investment constraints.~~ Such an iterative workflow is suitable for implementation by web-based application architecture, which ~~allows stakeholders in diverse groups~~ can be accessed ~~the application~~ through a browser without installing software or configuring the environment and has become mainstream in promoting the development of easy-to-use geographic and environmental modeling applications (Chen et al., 2020; ~~Jiang et al., 2016;~~ McDonald et al., 2019; ~~Zhang et al., 2019;~~ A.X. Zhu et al., 2021). Section 2.2 presents the overall architectural design of the web-based participatory watershed planning system~~ for multistage BMP implementation plans~~. Sections 2.3–2.5 highlight three key functional designs of this system, including roadmap optimization method integration, visualization of roadmaps from spatial and temporal perspectives, and defining multiple stakeholder roles with diverse watershed management standpoints.

2.2 Overall architecture design

To achieve the above basic idea, we adopted the design of a layered browser/server (B/S) architecture, including the presentation layer on the client side and the software server, data, and hardware server layers on the server side (Figure 2). T~~In the workflow, t~~he client side is ~~majorly~~ responsible for user interaction in setting parameters ~~setting~~ before submitting the optimization task and exploring data~~ analysis~~ of the optimization ~~results~~BMP roadmaps with the support of the ~~presentation layer comprises a graphical interface for user interaction, data visualization, and~~ front-end business logic. The business logic ~~of the presentation layer for~~ requests and receives ~~data~~optimized ~~BMP~~ roadmaps data via the hyper-text transport protocol (HTTP) and adapts the data structure for presentation on graphical interfaces. The ~~client side~~system takes the stakeholder group as the user unit and establishes a shared space within the group, wherein stakeholders can explore the historical optimization results of all members from ~~various~~spatial and temporal perspectives (See Section 2.4).~~The result of each optimization task usually comprises a set of optimal solutions under multiple objectives, which can be plotted as points (i.e., Pareto front). Stakeholders can explore Pareto fronts optimized by all group members~~ and mark their preferred roadmaps as candidates for further discussion. The unanimous roadmap(s) can be found if a consensus can be reached, and the iterate workflow ends. Otherwise, stakeholders will propose new investment plan~~parameters~~ based on current results~~the parameters are adjusted by stakeholders~~ in the next iteration.



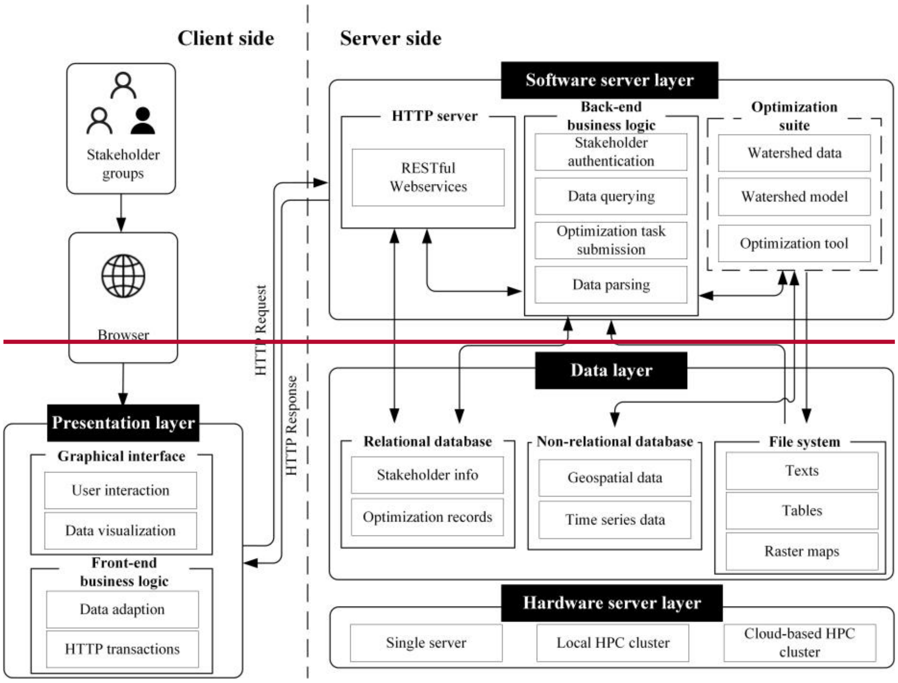


Figure 2 Overall architecture design of the watershed planning system

~~Server side~~The server side is ~~majorly~~ responsible for receiving and executing the submitted optimization task from the front end, and parsing, formatting, and sending back the optimization results. ~~refers to all programs and data that run on~~

~~the hardware server.~~ The ~~The software server layer comprises three components.~~ ~~B~~back-end business logic is the key component that handles all user-, data-, and optimization-related matters by interacting with other components or layers, including data querying, optimization task submission, and data parsing. The BMP roadmap optimization suite ~~is the core component that~~ encapsulates models and tools of the roadmap optimization method~~, including watershed data processing tools, watershed models, and optimization tools, into~~as several interfaces to be loosely coupled ~~connect~~ with the business logic component (Section 2.3). HTTP server is the communication component responsible for communication between the server and client sides and within the server side. For the data layer, except for the simple file system, the system designs~~utilizes~~ relational and non-relational databases to manage structured business data (e.g., stakeholder information and optimization records) and spatiotemporal data (e.g., geospatial and time series data), respectively.~~ Additionally, some optimization result files are written directly to the file system.~~ For the hardware server layer, the system can ~~either~~ deploy~~run~~ on a single server or ~~completely~~ use the parallel computing capabilities of a local high-performance computing (HPC) or a cloud-based HPC cluster with elastic scaling capabilities to accelerate optimization tool execution.

~~The iterative participatory workflow of non-expert stakeholders in determining roadmaps requires cooperation between the client and the server (Figure 2). In the workflow, the client side is majorly responsible for user interaction in the parameter setting before optimization and exploratory data~~

~~analysis of the optimization results. The server side is majorly responsible for receiving and executing the submitted optimization task from the front end and parsing and formatting the optimization results. The result of each optimization task usually comprises a set of optimal solutions under multiple objectives, which can be plotted as points (i.e., Pareto front). Stakeholders can explore Pareto fronts optimized by all group members and mark their preferred roadmaps as candidates for further discussion. A unanimous roadmap(s) is found if a consensus can be reached, and the workflow ends. Otherwise, the parameters are adjusted by stakeholders in the next iteration.~~

~~In Section 3, the above design is implemented as a basic web-based participatory watershed planning system and a complete and operational system with a selected study area with relevant data and models built to enrich the client- and server-side functions of the system. Sections 2.3–2.5 highlight three key functional designs of this system.~~

2.3 Integrating BMP roadmap optimization method

The BMP roadmap optimization method proposed by Shen et al. (under review) is a universal modeling framework that ~~suite for multistage BMP implementation plans adopts a component-based design that~~ includes several independent and sequenced functional components, ~~including~~ such as data preprocessing ~~scripts~~tools, watershed model and BMP scenario cost model, optimization algorithm ~~scripts~~ tools, and postprocessing tools (Figure 1 and Figure 2)~~(Zhu et al., 2019; Shen et al., under review)~~. ~~The optimization algorithm tool~~

~~implements a multi-objective intelligent optimization algorithm. The algorithm first generates a population consisting of roadmaps as individuals. Then it uses stepwise investment constraints to filter the roadmaps that meet the requirements. Next, a complete watershed process simulation is performed for each roadmap whose economic and environmental effectiveness are evaluated. The algorithm follows this process iteratively until the end. This design provides flexibility in parallel execution of roadmap simulations executing diverse subtasks with rich configurable parameters.~~ Each component ~~The optimization suite~~ can be invoked in the API (Application Programming Interface) from other programs or command lines, which is unfriendly to the use of non-expert~~ stakeholders ~~s but convenient for system integration.

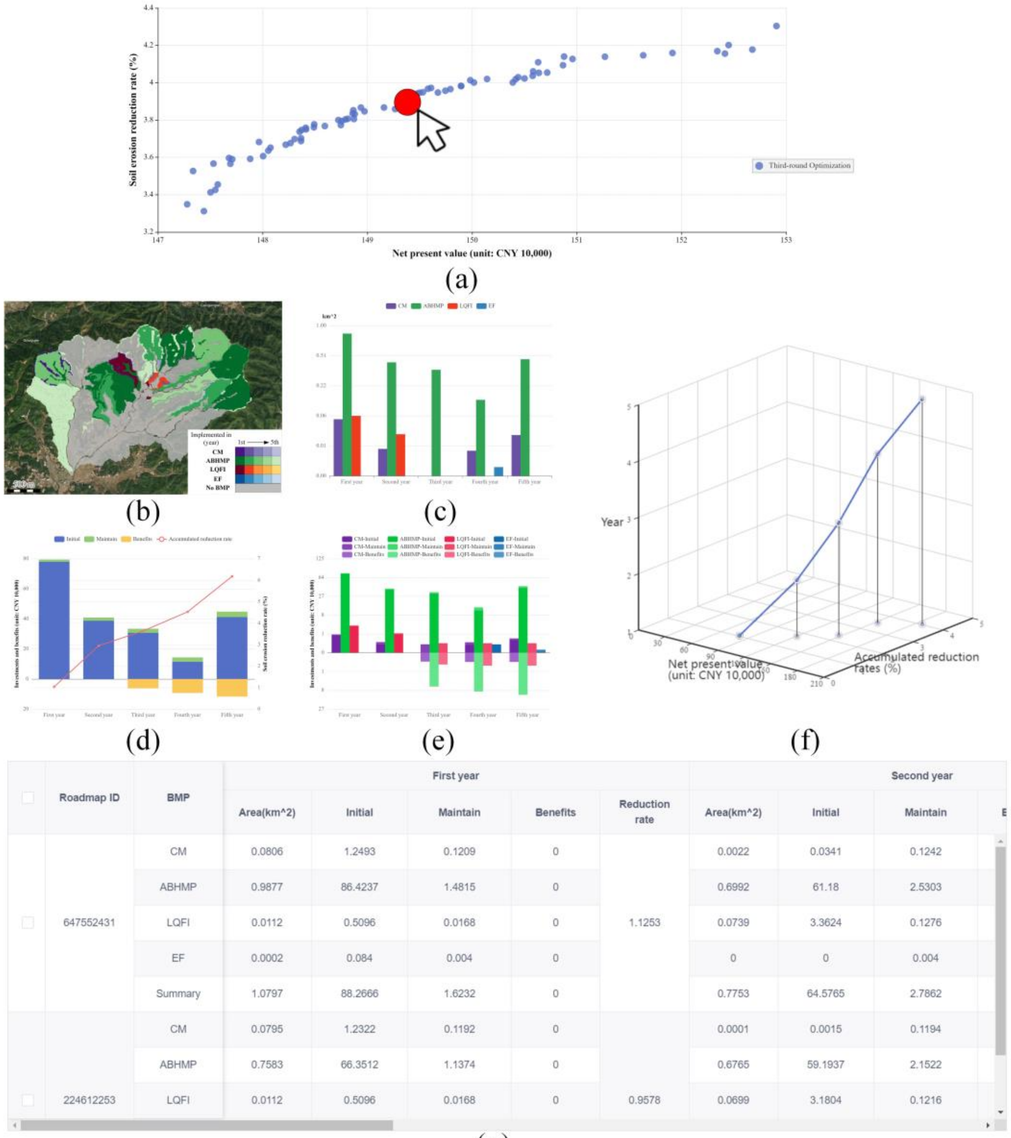
The proposed watershed planning system focuses on the participation of multi-stakeholders in proposing various investment plans to derive agreed-upon BMP roadmaps, not the specialized modeling processes according to the management goals, including preparing modeling data, building watershed model and BMP scenario cost model, and customizing multi-objective optimization tool (Figure 1). Therefore, the system is designed to integrate the specific implementation and application of the BMP roadmap optimization method, including the calibrated watershed model, the BMP knowledge base, and the BMP roadmap optimization tool under multi-objective (e.g., maximizing environmental effectiveness and minimizing investment) with a pre-optimized or pre-defined BMP spatial distribution scenario (Shen et al., under review). Hence, a new roadmap optimization task can be started by accepting only investment constraints proposed by stakeholders and optional optimization parameters (e.g., population size and maximum generation number of genetic algorithms) (Figure 1). More details about the BMP roadmap optimization method can be found in Shen et al. (under review).

~~In this study, the optimization suite was integrated as a critical component of the server side and loosely coupled with the back-end business logic program (Figure 2). The optimization task execution workflow is designed as follows:1) the required settings of the investment constraints and optimization parameters are transferred from the client side; 2) these parameters are packaged and submitted to the optimization suite by the business logic program through the exposed web service API, which ensures independent execution of the optimization task; and 3) post optimization task completion, the business logic program reads the optimization results and sends the parsed and formatted data back to the client side via HTTP for analysis and visualization.~~

2.4 Multi-perspective visualization of roadmaps

The ~~multistage~~BMP ~~implementation plan~~roadmap ~~for BMPs~~ in this study is essentially a type of spatiotemporal data (Shen et al., under review). All staged BMP spatial configurations ~~of the BMPs~~ constitute the ~~roadmap~~ spatiotemporal dimensions. Besides, the stepwise investment plans and environmental evaluation results are time-series data. Therefore, spatiotemporal data visualization and the expression of its internal connections are key for assisting stakeholders in understanding, analyzing the roadmap, and making decisions.

A linked visualization method is designed to ensure the consistency of the data displayed when stakeholders explore roadmaps, as shown in Figure 3. Each time the stakeholder selects a point in the Pareto front (Figure 3a), the multi-perspective data of this roadmap are displayed including map, bar and line charts, and table ~~in their respective views~~. A mapping method that considers the temporal information of BMP implementation is designed to visualize the roadmap, wherein different color tunes represent different BMP types, and color saturations from dark to light represent the implementation time, for example, from the first to the fifth year as shown in Figure 3b. Bar charts were utilized to express the statistical staged information: the annual construction area for each BMP type (Figure 3c), a summary of annual economic data (Figure 3d), and detailed annual economic data for each BMP (Figure 3e). A three-dimensional line chart was designed to clearly express the effect that an implementation plan can achieve at each stage (e.g., environmental and economic effectiveness), expanding the time axis based on traditional two-dimensional visualization (Figure 3f). Any roadmap can be added to the well-designed data table for an elaborate comparsion (Figure 3g).



(a)

(b) (c)

(d) (e) (f)

☐	Roadmap ID	BMP	First year					Second year		
			Area(km^2)	Initial	Maintain	Benefits	Reduction rate	Area(km^2)	Initial	Maintain
☐	647552431	CM	0.0806	1.2493	0.1209	0	1.1253	0.0022	0.0341	0.1242
		ABHMP	0.9877	86.4237	1.4815	0		0.6992	61.18	2.5303
		LQFI	0.0112	0.5096	0.0168	0		0.0739	3.3624	0.1276
		EF	0.0002	0.084	0.004	0		0	0	0.004
		Summary	1.0797	88.2666	1.6232	0		0.7753	64.5765	2.7862
☐	224612253	CM	0.0795	1.2322	0.1192	0	0.9578	0.0001	0.0015	0.1194
		ABHMP	0.7583	66.3512	1.1374	0		0.6765	59.1937	2.1522
		LQFI	0.0112	0.5096	0.0168	0		0.0699	3.1804	0.1216

(g)

Figure 3 Spatiotemporal data visualization for selected roadmap(s): (a) visualization and interactive mode of Pareto front; (b) a map of multistage BMP spatial ~~configuration plan~~distributions, wherein different color tunes represent different BMP types, and the saturations from dark to light represent the implementation time (e.g., from the first year to the fifth year); (c) the annual construction area for each BMP type; (d) the total initial construction cost, maintenance cost, and income by year; (e) subdivides these data by BMP types; (f) the stepwise economic and environmental effectiveness that a roadmap can reached at each stage; (g) the well-designed table containing detailed roadmap data for comparative analysis.

2.5 Stakeholder roles designed in participatory planning

Public–private partnership between a government agency and a private sector company or individual business is one of the most ~~commonly~~ used management modes of special funds for watershed management projects, ~~including~~ such as soil and water conservation (Qian et al., 2020). The government provides funds to social groups (e.g., enterprises) or individuals (e.g., governance professionals) through subsidies or incentives to conduct projects. Enterprises or governance professionals (hereinafter referred to as enterprises) invest additional funds on their own to implement management practices within the scope of policies and regulations and enjoy the economic benefits of these practices.

Therefore, this ~~study~~ system design considers three stakeholder roles: investors, economic beneficiaries, and environmental beneficiaries. Accordingly, we designed a stakeholder group with the three stakeholders: 1) the government stakeholder is the primary investor and environmental beneficiary; 2) the enterprise stakeholder is both a co-investor and an economic beneficiary, focusing on the balance between cost and benefit; and 3) the other stakeholders from ordinary farmers and citizens living in the watershed can be primarily considered as environmental beneficiaries.

3. Case ~~Implementation with the~~ study of an agricultural watershed planning system for mitigating soil erosion~~area~~

Based on the above overall design, we chose a small agricultural watershed planning case study for soil erosion reduction ~~the Youwuzhen watershed in Southeastern China,~~ as an example ~~the study area~~ to develop the ~~operational watershed~~ planning system which can be accessed via http://easygeoc.net:9091/.

T~~he source of t~~his system is open-sourced via Github[1]. ~~In addition to the basic participatory watershed planning system, watershed data, models, and tools relevant to the study area must be prepared in advance, along with the selected BMP scenario for roadmap optimization.~~ The~~An overall~~ technical selections are prevailing frameworks (e.g., Spring Boot and Vue.js), software (e.g., MongoDB database), programming languages (e.g., Java, JavaScript, Python, and C++), and self-developed BMP roadmap optimization suite by Shen et al. (under review), as shown detailed ~~schematic is depicted~~ in Figure 4. ~~Section 3.1 presents the technical details of the overall implementation, Section 3.2 introduces the overview of the study area, and Section 3.3 illustrates the data, model, and tool required to customize the study area in the system.~~

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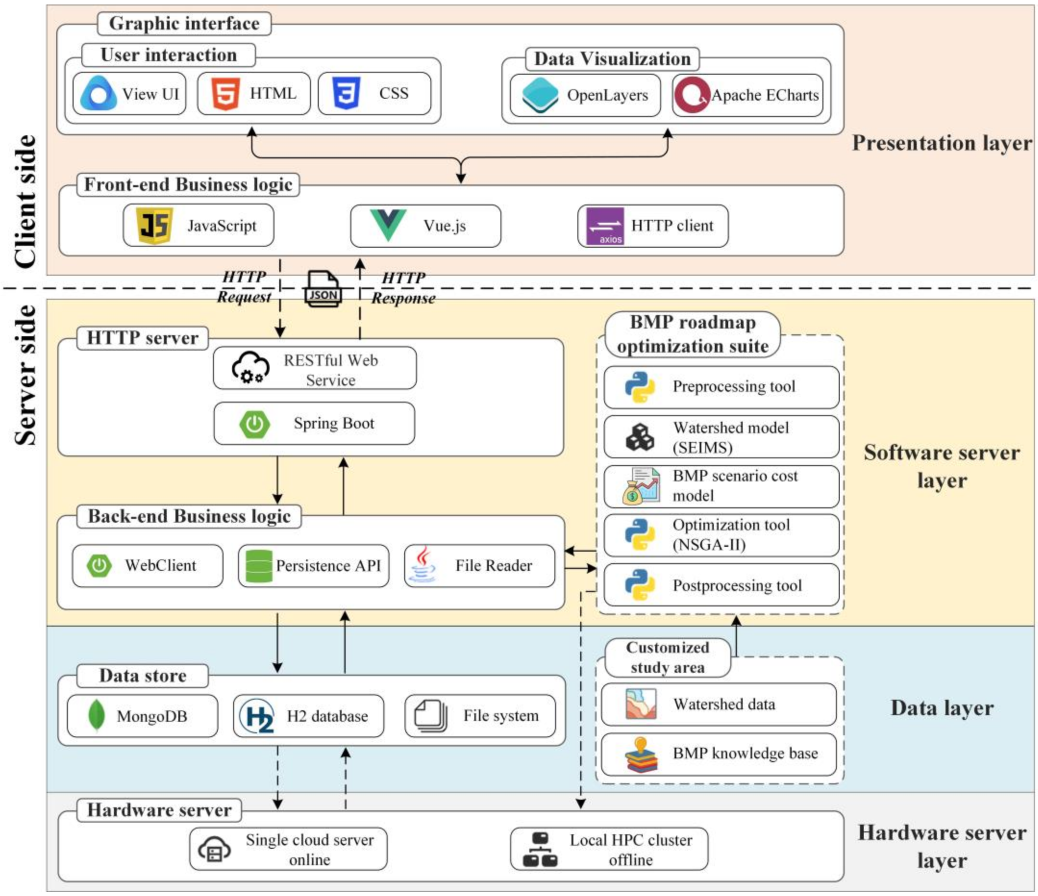
[1] https://github.com/lreis2415/WatershedPlanningSystem


Client side
Graphic interface
User interaction
View UI
HTML
CSS
Data Visualization
OpenLayers
Apache ECharts
Presentation layer
Front-end Business logic
JavaScript
Vue.js
HTTP client
axios
HTTP Request
JSON
HTTP Response
Server side
HTTP server
RESTful Web Service
Spring Boot
BMP roadmap optimization suite
Preprocessing tool
Watershed model (SEIMS)
BMP scenario cost model
Optimization tool (NSGA-II)
Postprocessing tool
Software server layer
Back-end Business logic
WebClient
Persistence API
File Reader
Data store
MongoDB
H2 database
File system
Customized study area
Watershed data
BMP knowledge base
Data layer
Hardware server
Single cloud server online
Local HPC cluster offline
Hardware server layer

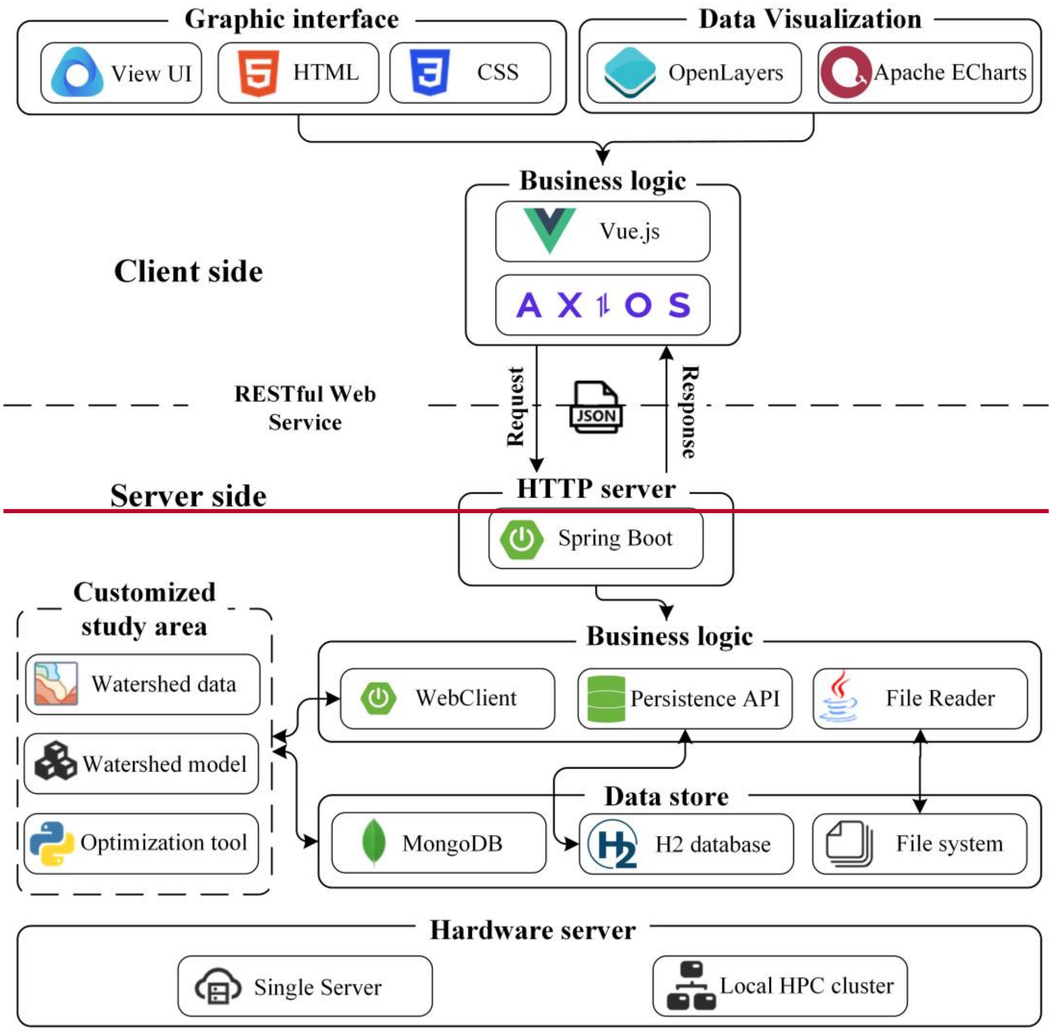


Figure 4 Overall technical schematic diagram of the watershed planning system implemented in the Youwuzhen watershed case study

3.1 Overall implementation

On the server side, the implementation of the BMP roadmap optimization suite by Shen et al. (under review) was integrated, including the calibrated watershed model and roadmap optimization tool based on the latest version of SEIMS (spatially explicit integrated modeling system) that supports evaluating the environmental effectiveness of the multistage BMP implementation plan using time-varying effectiveness of BMPs (Zhu et al., 2019a; Shen et al., under review).

The simulation time was from 2011 to 2017, and the division of simulation stages, simulation process, and BMP update mechanism were consistent with the case study settings in the previous study (Shen et al., under review). ~~3.1.1 Server side~~

~~The HTTP server program was developed on the server-side software server layer based on the prevailing Spring Boot framework. The back-end business logic program comprises the built-in features of Java (i.e., Java File Reader), the WebClient from Spring Web and the Java Persistence API from the Spring Data project. The WebClient initiates requests to the web services provided by the optimization suite to start the optimization task and receives response data. The File Reader reads, analyzes, and formats the optimization results. The Java Persistence API generates an object-relational mapping and manages relational databases.~~

The process of invoking the optimization suite through its Python interface is as follows: The stepwise investment constraints and optimization parameters are organized into a JSON (JavaScript Object Notation) string and sent to the HTTP server by post request. Next, the HTTP server received the JSON object and converted it into a Java object. Then, the WebClient is instanced and configured to send the optimization request and its parameters to the optimization suite through web services API. Subsequently, when the optimization suite completed the optimization task, the running status is returned to the WebClient and the results are written into the data store server in the files and database records. The FileReader reads files and constructs a new Java object, which is converted to a

JSON string and returned to the client side via the HTTP response.

We implemented the optimization task execution in online and offline modes using two hardware architectures to deal with different application scenarios. When the optimization task of a user can be completed quickly (e.g., a case study in a small area with coarse-resolution data), the online mode is activated, where the optimization suite runs on a single cloud server. For performance reasons, we currently restrict the total number of model executions to 20 and use 30m resolution data in online mode to ensure that optimization tasks can be completed in less than 10 minutes. That is, only optimization tasks with the product of evolutionary generations and population size less than or equal to 20 can be executed online (e.g., optimization of five generations with four individuals in the initial generation). Alternatively, to improve the computing efficiency of a compute-intensive case study, the offline mode is adopted, where the administrator manually submits the optimization task in the local HPC cluster. The system will email the user once the optimization task is finished.

~~3.1.2 Client side~~

On the client side, t~~Vue.js[2] was selected as the major framework to process basic business logic, and the Axios library[3] was adopted to send HTTP requests and receive responses. T~~he entire graphical interface was implemented based on HTML5 and CSS 3, and the View UI, a component library based on Vue.js, was utilized for rapid prototyping. The ~~JavaScript mapping library~~ OpenLayers and

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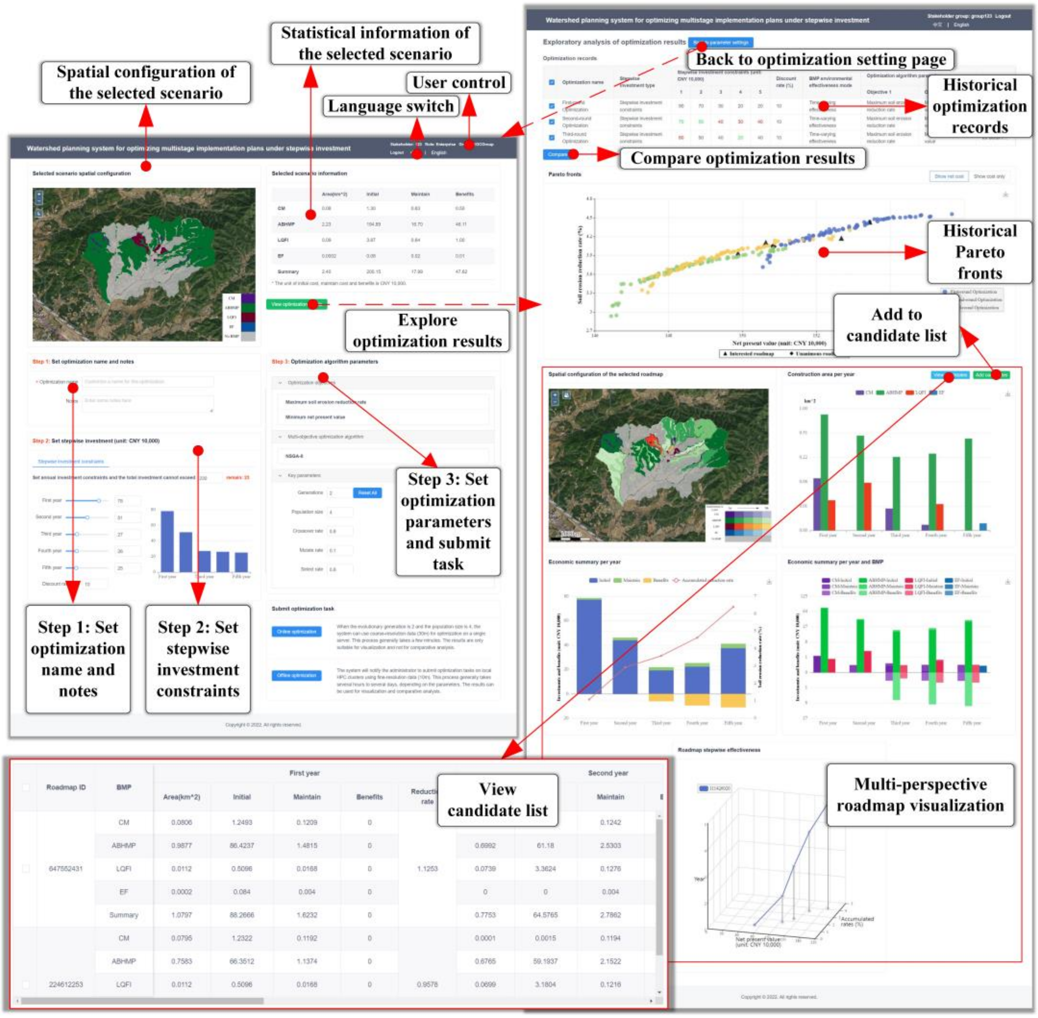
~~[2] https://vuejs.org/~~

~~[3] https://axios-http.com/~~

Apache Echarts[4] were used to visualize the roadmap spatial dimensions and bar and three-dimensional line charts, respectively ~~were rendered based on the open-source JavaScript visualization library Apache Echarts[4]~~. The client-side graphical user interface is depicted in Figure 5.



~~[4] https://echarts.apache.org/~~

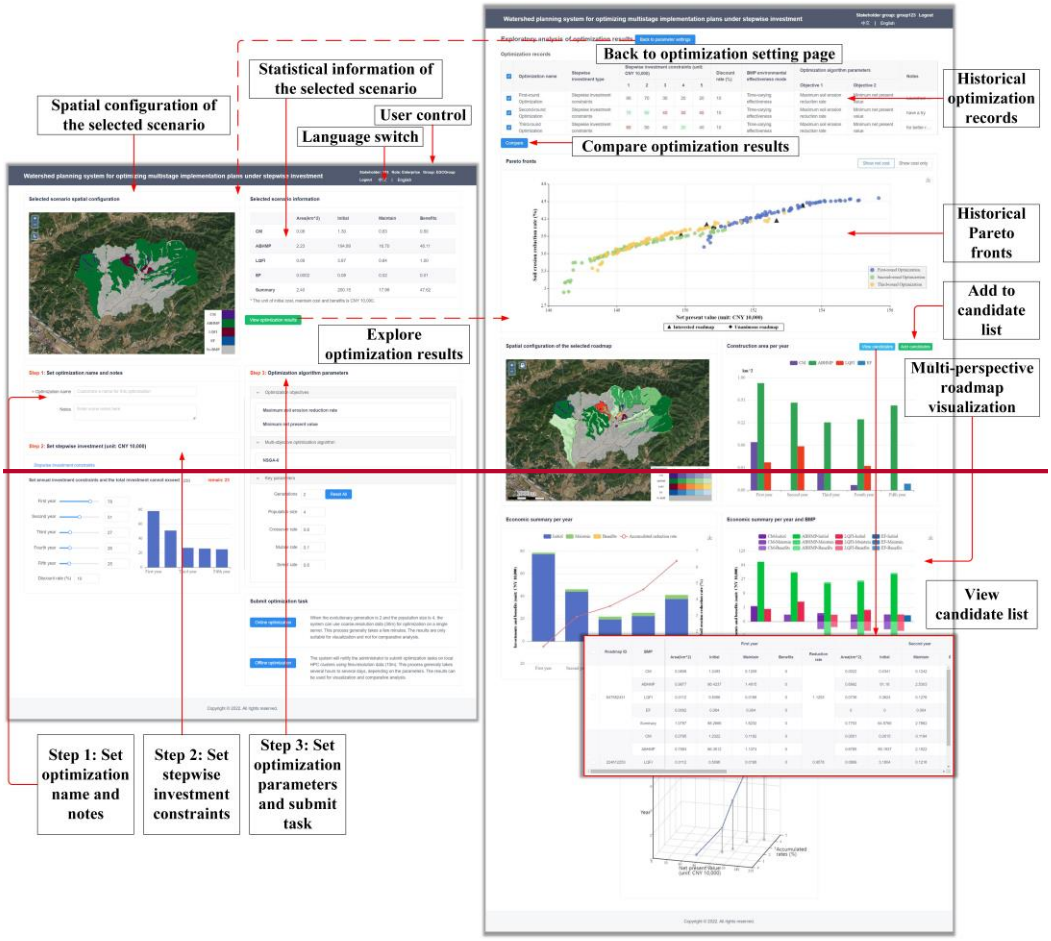


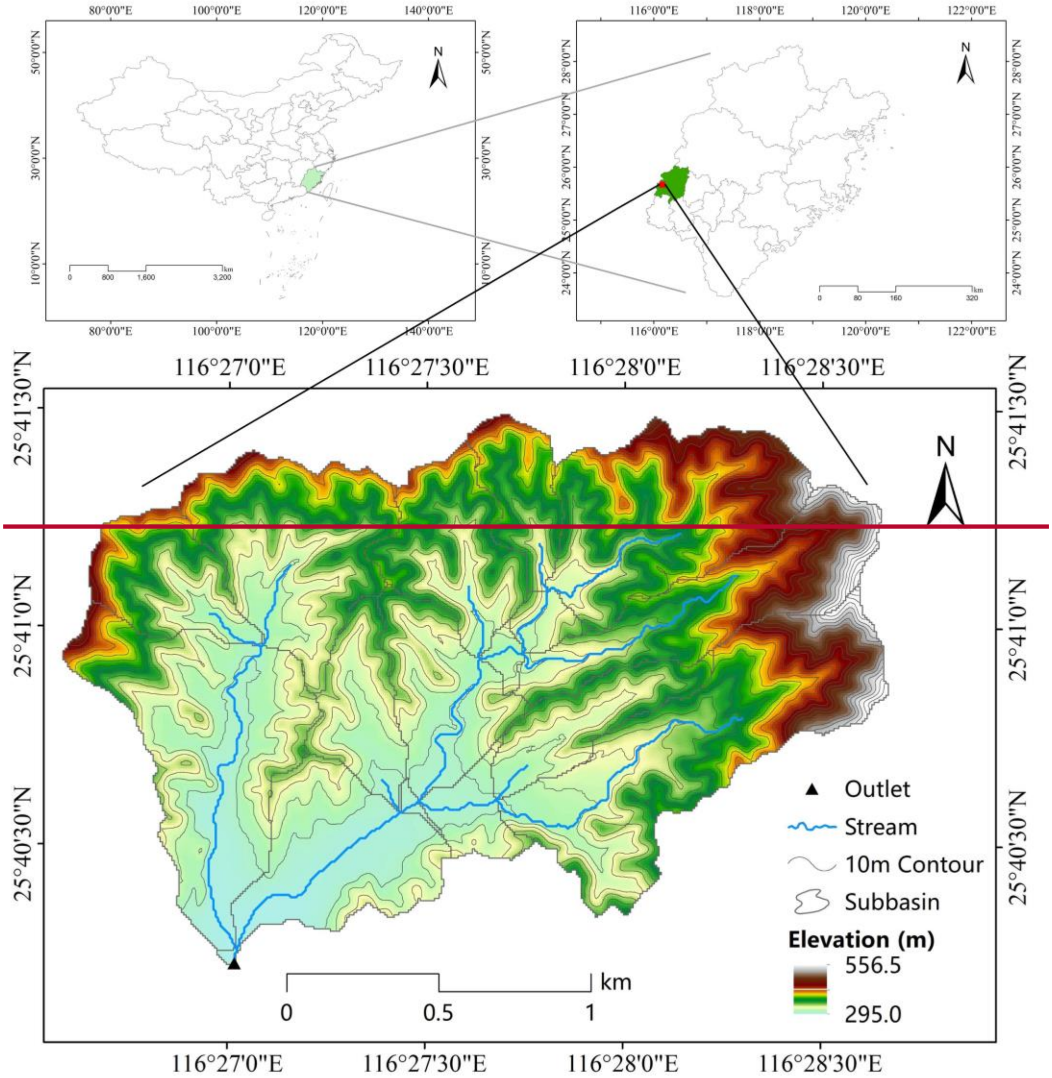
Figure 5 The client-side graphical user interface of the Youwuzhen watershed planning system

3.2 Study area and watershed management goal

The Youwuzhen watershed (approximately 5.39 km^2), which is part of the Zhuxi watershed within Changting County, Fujian Province, China, was chosen as the study area (Figure 6). ~~This study area is one of the counties with the most severe soil erosion in the granite red soil region of Southern China (L.J. Zhu et al., 2021). The soil erosion type is majorly severe and moderate water erosion according to the national professional standards SL190-2007 *for classification and gradation of soil erosion* (Ministry of Water Resources of China (MWRC), 2008).~~ The primary geomorphological characteristics of the small watershed are the low mountains and hills. ~~The elevation ranges from 295.0 to 556.5 m with an average~~

~~slope of 16.8°. The topographic trend inclines from Northeast to Southwest and the riverbanks are relatively flat and wide.~~ The study area has a mid-subtropical monsoon moist climate, with an annual average temperature of 18.3 °C and precipitation of 1697 mm~~ (Chen et al., 2013)~~. Precipitation is characterized by concentrated and intense thunderstorm events, contributing about three-quarters of the annual precipitation from March to August~~ (Chen et al., 2013)~~. The mainland-use types were forests, paddy fields, and orchards, with area ratios of 59.8, 20.6, and 12.8%, respectively. Additionally, the forests in the study area are dominated by secondary or human-made forests with scattered Masson's pine (*Pinus massoniana*)~~ (Chen et al., 2013, 2017)~~. The soil types in the study area were red soil (78.4%), majorly distributed in hilly regions, and paddy soil (21.6%), primarily distributed in broad alluvial valleys (Chen et al., 2013, 2017)~~, which can be classified as *Ultisols* and *Inceptisols* in the US Soil Taxonomy, respectively (Shi et al., 2010)~~.

This study area is in one of the counties with the most severe soil erosion in the granite red soil region of Southern China (L.J. Zhu et al., 2021). The watershed management goal in the Youwuzhen watershed in this case study is maximizing the soil erosion reduction rate and minimizing the investment. The modeling process of this watershed planning optimization application adopts the work of Shen et al. (under review) and is briefly introduced in the following subsection.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27°0'0"N
26°0'0"N
25°0'0"N
24°0'0"N
0 80 160 320 km
116°27'0"E
116°27'30"E
116°28'0"E
116°28'30"E
25°41'30"N
25°41'0"N
25°40'30"N
Outlet
Stream
10m Contour
Subbasin
Elevation (m)
556.5
295.0
0 0.5 1 km

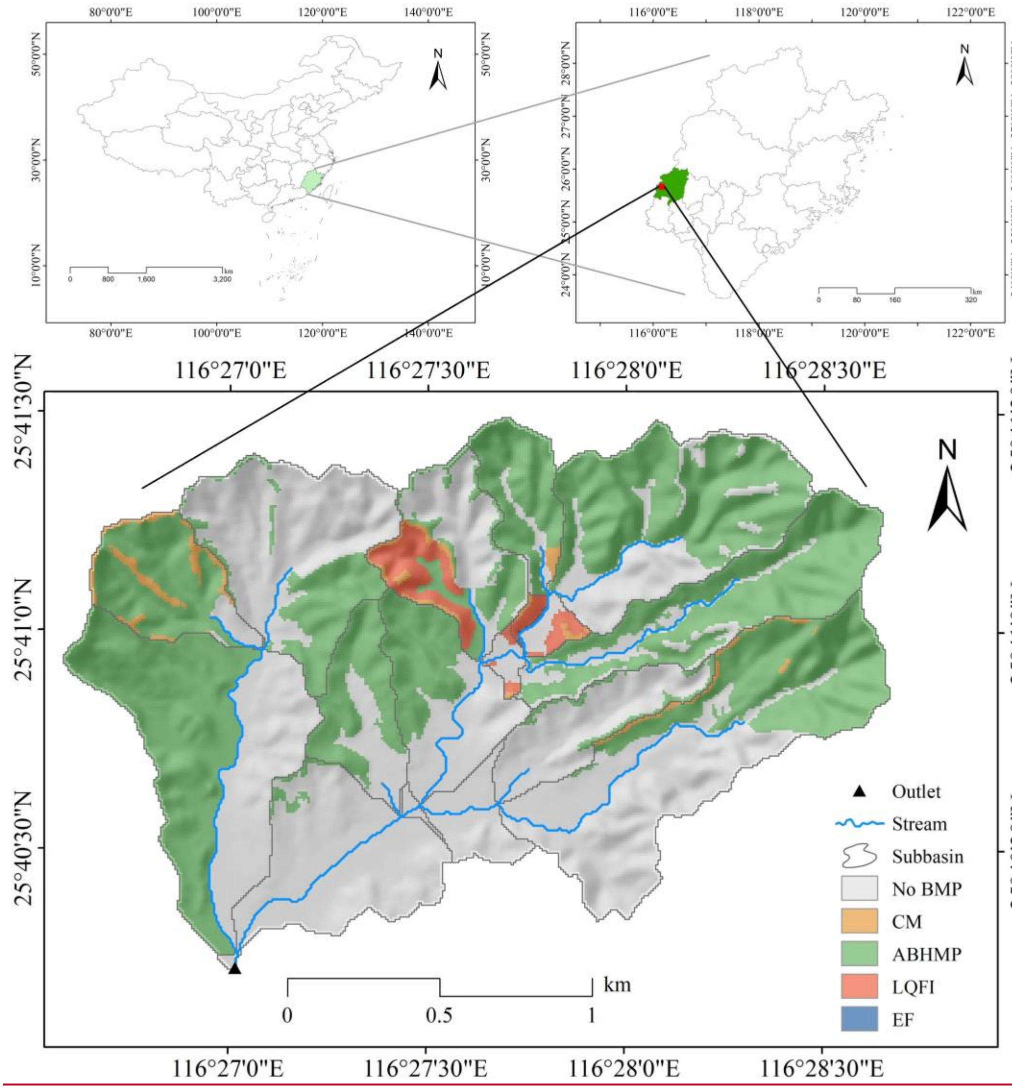


Figure 6 Map of Youwuzhen watershed in Changting County, Fujian Province, China, and spatial distribution of the fundamental spatial distribution scenario of best management practices (BMPs) based on slope position units derived from Zhu et al. (2019b). Four BMPs are included: closing measures (CM), arbor–bush–herb mixed plantation (ABHMP), low-quality forest improvement (LQFI), and economic fruit (EF).

3.3 Preparation for the Youwuzhen watershed planning system

This section presents the data, models, and tools required for the watershed planning system customized for the Youwuzhen case study.

3.3.1 Basic geographic data collection

The basic spatial data collected for Youwuzhen watershed modeling included a gridded digital elevation model, land-use type map, and soil type map, all of which were unified to a 10 m resolution (Qin et al., 2018). Property lookup tables for land use/land cover and soil were prepared according to our previous studies (Qin et al., 2018; Zhu et al., 2019b). Daily climate data, including temperature, relative moisture, wind speed, and sunshine duration from 2011 to 2017, were derived from the National Meteorological Information Center of the China Meteorological Administration. Daily precipitation data were obtained from local monitoring stations. Streamflow and sediment discharge data from 2011 to 2017 at the watershed outlet periodic site were provided by the Soil and Water Conservation Bureau of Changting County.

3.3.2 BMP knowledge base

In this study area, four representative BMPs have been vastly implemented ~~in Changting County~~ for soil and water conservation: closing measures (CM), arbor–bush–herb mixed plantation (ABHMP), low-quality forest improvement (LQFI), and economic fruit (EF) (Figure 6). Their brief descriptions were adapted from Zhu et al. (2019b) and are enlisted in the Appendix (Table A.1).

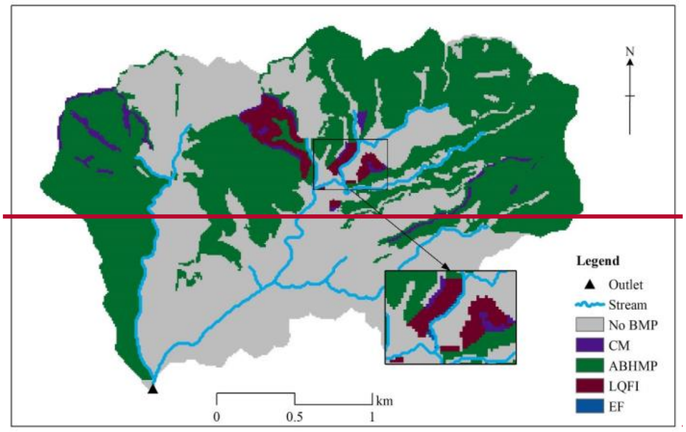
The BMP knowledge base comprises spatial configuration knowledge (e.g., suitable locations of each BMP and spatial relationships among BMPs), environmental effectiveness and economic effectiveness data (Qin et al., 2018). The first knowledge type is not used in this case study since the roadmap optimization is based a pre-optimized BMP spatial scenario. Detailed BMP environmental effectiveness and cost-benefit data adapted from Shen et al. (under review) can be found in Table A.2 of the Appendix.

~~The BMPs cost-benefit data were estimated by Wang (2008) according to the price standards adopted 15 years ago. Although this is no longer applicable to current price standards, it is still suitable for this study to discuss and evaluate the relative costs and benefits of BMP scenarios.~~ The cost-benefit data include initial construction cost (one-time cost only in the first year of implementation), maintenance cost (annual cost after implementation), and benefits (direct economic benefits (e.g., fruit production growth, forest stock volume) computed starting from the third (e.g., CM, ABHMP, and LQFI) or fifth year (e.g., EF) after implementation).

3.3.3 Calibrated watershed model and the selected ~~optimal~~ scenario for roadmap optimization

We constructed and calibrated a daily ~~spatially explicit integrated modeling system (~~SEIMS-based watershed model~~; Zhu et al., 2019a)~~ that utilizes gridded cells as the basic simulation unit to simulate daily soil erosion in the Youwuzhen watershed. The elaborated modeling process is not the core content of this study, which will not be repeated, and the details can be found in Zhu et al. (2019b). ~~The SEIMS-based watershed model was customized to evaluate the environmental effectiveness of the multistage implementation plan using the BMPs time-varying effectiveness (Shen et al., under review).~~

We selected an optimized BMP scenario from Zhu et al. (2019b) as the fundamental spatial scenario for optimizing the implementation plans (Figure 6). The scenario uses a simple system of three types of slope positions (ridge, backslope, and valley) as BMP configuration units, which have been proven to be effective in our previous studies (Qin et al., 2018; Zhu et al., 2019b; L.J. Zhu et al., 2021). In the fundamental scenario (Figure 6), ABHMP occupies most of the area, with large clumps distributed over the western, central, and northeastern areas. The CM and LQFI have approximately the same area but are distributed in different locations. The former is scattered on the west, central, and eastern ridges and backslope. The latter was concentrated on the middle region backslope. EF had the smallest area in the central valley.



~~Figure 7 Spatial distribution of the fundamental spatial scenario based on slope position units from Zhu et al. (2019b) with partially enlarged details of the configured economic fruit (EF) along the stream~~

3.3.4 Multi-objective optimization method for roadmaps

The multi-objective in this case study refers to maximizing the soil erosion reduction rate and minimizing the roadmap discounted net cost (i.e., net present value (NPV)). The NPV introduced into the BMP cost model can reasonably evaluate the investment process by integrating multistage investments into a numerical indicator (Shen et al., under review). A generalized roadmap spatial optimization problem can be formulated as：

$$min\{-f(R), g(R)\} \qquad (1),$$

$$f(R) = \sum_{t=1}^{q} f(R,t)/q = \sum_{t=1}^{q} \frac{V(0)-V(R,t)}{V(0)} \times 100\%/q \qquad (2),$$

$$g(R) = \sum_{t=1}^{q} \frac{O_t - F_t}{(1+r)^t} \qquad (3),$$

$$O_t = \sum_{k=1}^{n} O(S,k,t) = \sum_{k=1}^{n} \begin{cases} A(X(k),t) * \{C(X(k)) + M(X(k),t)\}, if\ t \geq T(k) \\ 0, if\ t < T(k) \end{cases} \qquad (4),$$

$$F_t = \sum_{k=1}^{n} F(S,k,t) = \sum_{k=1}^{n} \begin{cases} A(X(k),t) * B(X(k),t), if\ t > T(k) \\ 0, if\ t \leq T(k) \end{cases} \qquad (5),$$

where $f(R)$ is the average soil erosion reduction rate after implementing roadmap R during the implementation period (Equation 2), and $g(R)$ is the NPV in the first year of roadmap R (Equation 3). t is the implementation period, q is the total number of time periods, $f(R, t)$ represents the soil erosion reduction rate within period t, and $V(0)$ and $V(R, t)$ are the total amounts of sediment yields from the hillslope routed into the channel (kg) under the baseline scenario and scenario in roadmap R in period t, respectively. O_t and F_t are cash outflow and inflow during period t, which can be computed using the configured BMP area on the kth spatial unit $A(X(k), t)$, the initial construction cost $C(X(k))$, maintenance cost $M(X(k), t)$, and benefits of BMPs implemented in this period and before $B(X(k), t)$; and r is the discount rate set by the investor or project manager (e.g., 10%) (Khan and Jain, 1999; Žižlavský, 2014).

The vastly used non-dominated sorting genetic algorithm (NSGA-II) (Deb et al., 2002) was adopted as the intelligent optimization algorithm by the BMP implementation order optimization suite (Shen et al., under review).

4 Experimental design and evaluation

4.1 Experimental design

A multi-stakeholder role-play experiment was designed to verify that the watershed planning system constructed in this study can assist stakeholders to participate in proposing stepwise investment constraints to develop practical and reasonable roadmaps~~, we designed a decision-making experiment for watershed roadmap planning with stakeholder participation under stepwise investment constraints~~. ~~The participatory decision-making process initiates with setting optimization parameters and ends with reaching a consensus and obtaining unanimous roadmap(s). The entire process involved the participation of multiple stakeholders with diverse roles, and the system constructed in this study was utilized for multiple rounds of optimization and discussion.~~

~~The selected fundamental spatial scenario requires a total investment of 218.14 (with the unit of CNY 10,000; similarly hereinafter) and an income of 47.62 during the five-year implementation period. We slightly increased the overall investment constraint to 230.~~

~~The simulation time was from 2011 to 2017, and the division of simulation stages, simulation process, and BMP update mechanism were consistent with the case study settings in our previous study (Shen et al., under review).~~

The experiment assumed three stakeholder roles (see Section 2.5) and analyzed possible participatory behaviors from the perspective of their role characteristics and actual requirements. To reach a consensus faster between stakeholders, the experiment assumed that stakeholders participate in the decision-making process in a particular order, and each stakeholder can refer to the previous optimization results before initiation. A typical participation order ~~in the decision-making process~~ was designed as follows:1) government, 2) enterprise, and 3) other stakeholders (e.g., citizens living in the watershed). This order represents a prevalent cooperation mode in the local area and is adjustable. Diverse participation orders may affect the roadmaps in the optimization results, but this does not obstruct multiple stakeholders from reaching a consensus. The optimization results obtained by multiple stakeholders with diverse roles should reflect their actual requirements. The detailed ~~decision-making~~participatory process was designed as follows:

1) The government stakeholder is the primary investor who leads the first-round optimization and discussion with the position of striving for as much environmental effectiveness as possible with as little investment pressure as possible. Since the selected fundamental spatial scenario requires a total investment of 218.14 (with the unit of CNY 10,000; similarly hereinafter) and an income of 47.62 during the five-year implementation period, we slightly increased the overall investment constraint to 230. Based on this, a~~ setting up ~~ regular stepwise investment constraint is proposed as 90, 70, 30, 20, and 20 for the five-year implementation (the NPV without income is 188.29)~~s and suggesting candidate implementation plans or an acceptable range of multiple objectives~~.

2) The second~~- and third~~-round optimization is launched by the enterprise stakeholder based on the elected roadmap(s) by the government stakeholder. The enterprise stakeholder is both investor and economic beneficiary who expects initial investment pressure reduction in the implementation plan.

3) The third-round optimization is conducted by other stakeholders (e.g., citizens living in the watershed) who pay more attention to improving environmental improvement.~~ They may adjust the previous stepwise investment constraints to ensure that the optimization results reflect their requirements and wishes.~~

~~3) All stakeholders discuss, compare, and evaluate candidate roadmaps and ultimately reach a consensus.~~

After the above three rounds of optimizations and discussions with the cooperation of the three stakeholders, the optimized roadmaps should primarily meet all their requirements. ~~Roadmaps with better comprehensive effectiveness should be gradually explored in terms of economic and environmental effectiveness. If the above criteria are met, it can be demonstrated that the watershed planning system constructed in this study can assist stakeholders in developing a more reasonable and practical roadmap.~~

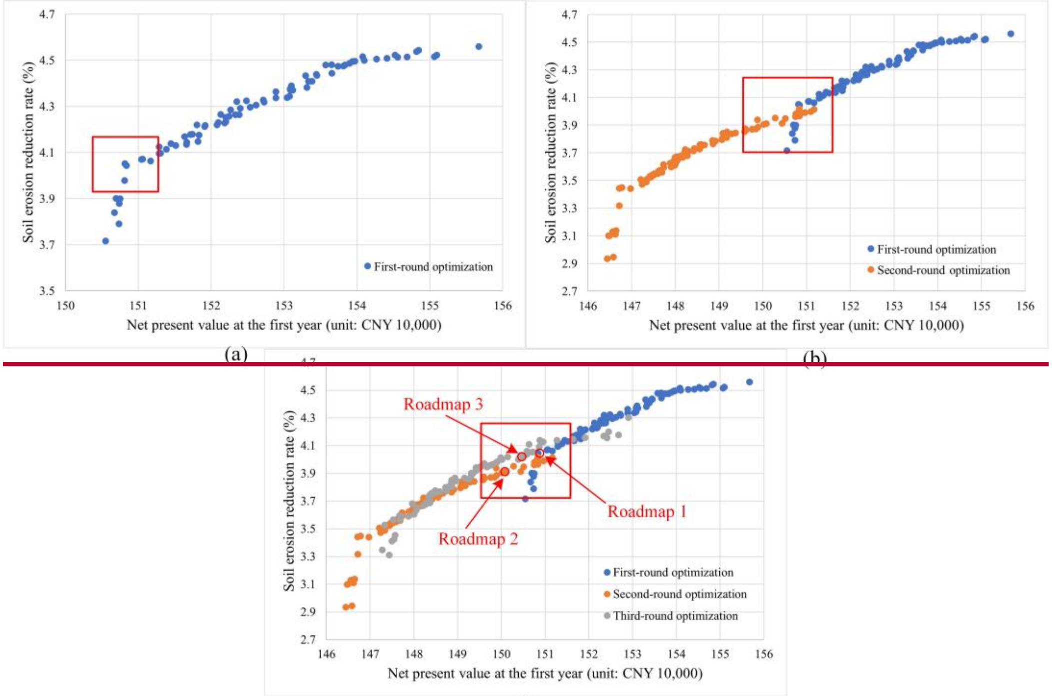
~~The selected fundamental spatial scenario requires a total investment of 218.14 (with the unit of CNY 10,000; similarly hereinafter) and an income of 47.62 during the five-year implementation period. We slightly increased the overall investment constraint to 230.~~

~~The simulation time was from 2011 to 2017, and the division of simulation stages, simulation process, and BMP update mechanism were consistent with the case study settings in our previous study (Shen et al., under review).~~

4.2 Experimental results and discussions

4.2.1 Effectiveness of iterative optimization process in the system

After the above optimizations and discussions among stakeholders, a candidate range of multi-objectives can be built by stakeholders, from which unanimous roadmap(s) can be determined. Figure7 depicts the Pareto fronts of the three optimization rounds. The detailed process of each optimization round is as follows.



(a) (b)

(c)

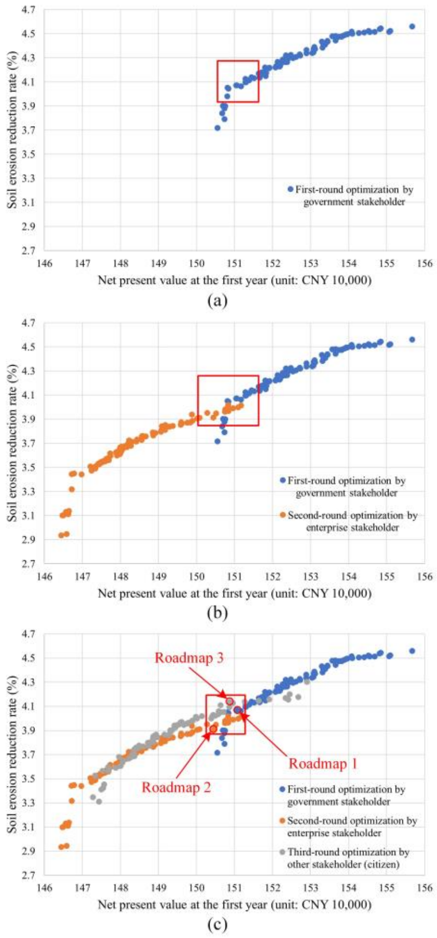


Figure 7 Pareto fronts of the three optimization rounds launched by three stakeholder groups

The first-round optimization by government stakeholders showed~~proposed a regular stepwise investment constraint (90, 70, 30, 20, and 20; the NPV without income was 188.29). The derived Pareto front (blue points) had~~ an obvious inflection point at an NPV of approximately 151 (Figure 7a). As the Pareto fronts NPV decreased, the soil erosion reduction rate gradually decreased, but declined rapidly post the inflection point. The annual investment of roadmaps (visualized in the form of Figure 3d) on the left of the infection point indicated this phenomenon is caused by the low investment in the first year than the second

(Shen et al., under review). Roadmaps near the inflection point (in the red box) are most likely given priority by the government stakeholders.

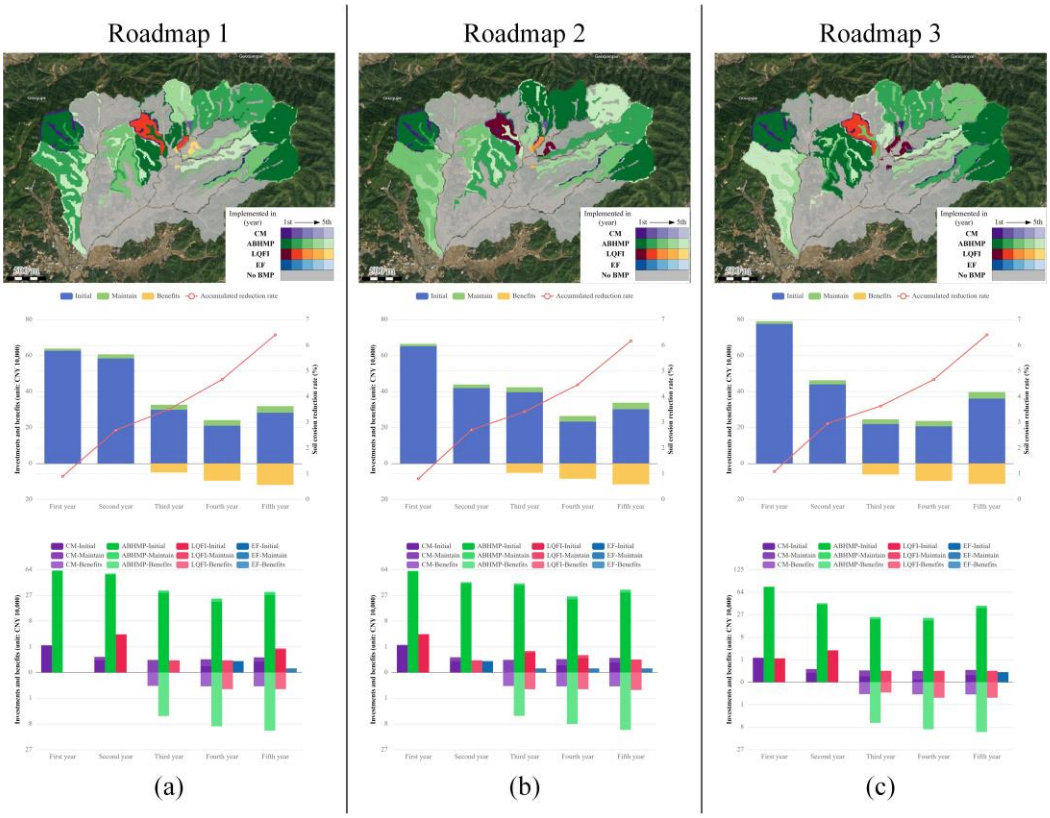
On the basis of reducing the first-year investment but still being greater than the second year, ~~The second-round optimization is led by~~ the enterprise stakeholder proposed a ~~, who is both investor and economic beneficiary, expecting further initial investment pressure reduction in the implementation plan, that is, lower NPV in the first year. A~~ modified investment plan to start the second-round optimization, i.e., 70, 50, 40, 30, and 40 and the NPV without income is 180.34~~)~~ ~~is proposed based on comprehensive consideration of previous investment constraints, optimization results, and stakeholder needs~~. As shown in ~~This investment plan moves part of the investment in the first two to the next three years, and its optimization result is the orange Pareto front (~~Figure 7b, compared to the first-round Pareto front, the new Pareto front moves to the lower left as a whole, which means that these ~~implementation plans~~roadmaps sacrifice some environmental effectiveness in exchange for lower investment pressures.

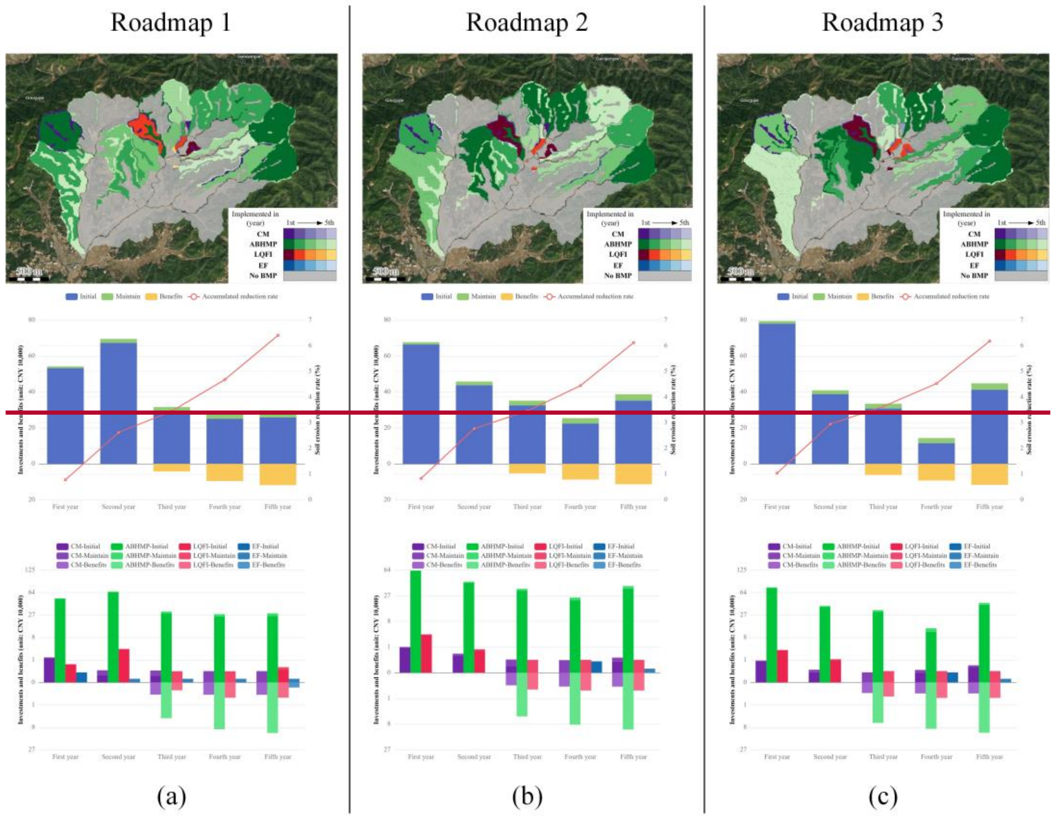
The exploratory analysis of the previous results showed that among roadmaps with similar investment plans in the first three years, a higher investment in the fifth year than the fourth year often results in a slightly higher soil erosion reduction rate. Therefore, to further achieve higher environmental effectiveness, the ~~third-round optimization is conducted by~~ other stakeholders ~~(e.g., citizens living in the watershed), who~~ proposed a revised investment constraint by reducing part of the fourth-year investment and increasing it in the first-year and keep the fifth-year unchanged, i.e., 80, 50, 40, 20, and 40 and the NPV without income is 182.60~~) as they paid more attention to improving environmental effectiveness. This investment plan reduces part of the investment in the fourth year and increases it in the first year~~. ~~The exploratory analysis of the roadmaps in the first two rounds demonstrates that roadmaps with higher investment in the first year usually have higher environmental effectiveness, which is consistent with a previous study (Shen et al., under review). The reason for reducing investment in the fourth instead of the fifth year is to that implementing the prominent BMP, ABHMP, in the fifth year, which will produce better comprehensive effectiveness (see further discussion in Section 4.2.2).~~ The optimization results~~ is the grey Pareto front, which~~ indeed validated the proposal that further improvements in the comprehensive effectiveness of roadmaps occurred within the candidate range of multi-objective (red box in Figure 7c).

Therefore, the final optimization results can well meet the positions and investment proposals~~ requirements~~ of all stakeholder groups. The progressive shifts in the three ~~Pareto fronts~~optimized roadmap sets can well reflect the differences in ~~requirements~~ positions among stakeholders and facilitate the reach of agreed-upon solutions, demonstrating the effectiveness of the iterative ~~optimization~~ participatory process in the system.

4.2.2 The rationality and diversity of the optimized roadmaps

The overlapping part among multiple Pareto fronts is often the focus of discussions among all stakeholder groups, and is also a potential area where agreed-upon~~compromise~~ solutions can be reached. In this experiment, the scope of this candidate area was focused step by step (the red box in Figure 7a–c) and the investment-environmental effectiveness ~~gap~~ differences between the roadmaps in the ~~candidate~~ area ~~(the red box in Figure 8c7c)~~ were no longer apparent, indicating that ~~there was no significant disagreement among stakeholders in~~ the agreed-upon roadmap(s) is most likely to be elected within this area. Meanwhile, there were still some differences among the roadmaps, reflecting the diversity of the Pareto solution sets. Three representative roadmaps were selected from the candidate area in Figure 7c, one for each Pareto front, and their spatiotemporal implementation configurations, stepwise investments, and economic benefits were compared to illustrate their rationality and diversity.





(a) (b) (c)

Figure 8 Three representative roadmaps selected from candidate area after three round optimizations, one for each Pareto front. The map in the first row demonstrates the BMP spatiotemporal configuration in the roadmap. The bar chart in the second row demonstrates the annual investment and income, and the line chart demonstrates the ~~annual~~ yearly soil erosion reduction rate. The bar chart in the third row demonstrates detailed investment and income annually of each BMP.

~~Roadmap 1 came from the first-round optimization, and its stepwise investment plan (54.21, 69.49, 27.31, 18.62, and 17.53; the NPV with income is 150.83) met the constraints set by the government stakeholder.~~ Compared with roadmap#1 derived by the government stakeholder, roadmap#2 by the enterprise stakeholder~~, one of the results of the second-round optimization, had a stepwise investment plan (67.65, 45.79, 29.81, 16.62, and 27.38; the NPV with income is~~

~~150.09),~~ reduced investment in the ~~first tw~~second year (also in the first two years) and thus led to a lower environmental effectiveness~~, and increased investment for the following three years. This is consistent with the pursuit of enterprise stakeholders to ease the pressure on the initial investment~~. Roadmap#3 from the third-round optimization obtained the ~~considers~~ highest environmental effectiveness with a maximum ~~based on the investment constraints of the first two optimization rounds. Its investment plan (79.43, 40.89, 27.21, 5.06, and 33.09; the NPV with income is 150.45) had more~~first-year investment, lowest fourth-year investment, ~~in the first~~ and highest fifth-year investment~~s and further reduced the investment in the fourth year~~. Thus, roadmap#3 or similar roadmaps are more likely to become the final agreed-upon roadmap(s).

The roadmap optimization results affected by stepwise investment plans can~~is phenomenon may~~ be explained by the particularity of the BMPs selected in this case study. In the selected fundamental spatial scenario (Figure 6), ABHMP occupied the most prominent area. This BMP can take effect quickly post implementation, and slightly decrease and then remain stable (see Appendix Table A.2). The environmental effectiveness of the ABHMP peaked in the first year. Therefore, roadmap#3 tended to deploy more ABHMP in the last year of the project implementation period, which not only ensures good environmental effectiveness, but also reduces the overall ~~economic benefits~~investment as the fifth-year investment after discounting is smaller than investments in other years. ~~Therefore, roadmap 3 is a more cost-effective implementation plan and is~~

~~reasonable from the comprehensive effectiveness perspective.~~

4.3 Evaluation of the designed and implemented watershed planning system

To facilitate the successful development of environmental decision support systems (EDSS), Walling and Vaneeckhaute (2020) identified 13 major challenges from stakeholder-, model-, and system-oriented perspectives and proposed evaluation criteria for EDSSs accordingly. For example, identifying stakeholders and prioritizing their influence and participation are primary challenges from the stakeholder-oriented perspective. Based on this, we briefly evaluated the watershed planning system designed and implemented in this study.~~focused can be used or~~

From the stakeholder-oriented perspective, ~~this system~~ with the ~~focuses on the~~ focus of assisting the participation of multi-stakeholders in proposing different investment plans to derive agreed-upon BMP roadmaps, this system identified three types of stakeholders, including investors, economic beneficiaries, and environmental beneficiaries and designed three stakeholder groups (government, enterprise, and other stakeholders) to simulate the role-play experiment~~three~~. The case study indicated that this system could provide effective comprehensibility of optimized roadmaps through ~~effective~~ spatiotemporal data visualization~~ and exploratory data analysis~~. The successful role-play experiment designed and conducted according to~~that meets~~ the practical needs provided confidence in participation for stakeholders.

From the model-oriented perspective, the premise of this system is the accurate definition and modeling of BMP roadmap optimization problems by professional modelers. Based on this, stakeholders only need to propose the investment constraint to trigger the execution of the specialized roadmap optimization task, which generates multiple near-optimal solutions for evaluation and discussion. After three rounds of optimization and discussion, roadmaps that met the requirements of the stakeholders continued to emerge, and the comprehensive effectiveness gradually improved. The Pareto fronts in the candidate area in Figure 7 reflect the improvement process of comprehensive effectiveness. Therefore, professional modelers guarantee the accuracy of the roadmap optimization suite, and the system provides convincing and simplified usage.

From the system-oriented perspective, the iterative workflow ~~designed in the system~~ provides sufficient technical support for the sequential participation of the three stakeholder groups in the case study~~ with diverse roles~~. ~~After multiple rounds of optimization and discussion, roadmaps that meet requirements of the stakeholders continued to emerge, and the comprehensive effectiveness gradually improved. The Pareto fronts in the candidate area in Figure 8~~ 7 ~~reflect the improvement process of comprehensive effectiveness. Stakeholders can also adjust the order of participation or the number of iterations according to actual requirements. Iterative workflows provide watershed planning systems with the ability to respond to changing requirements and facilitate consensus.~~

~~In the process of proposing investment constraints, analyzing and electing~~

~~roadmaps~~~~optimization and discussion, the system can assist stakeholders in making decisions through technical means, including spatiotemporal data visualization and exploratory data analysis.~~ Multi-perspective linked visualization effectively allows stakeholders to compare, evaluate, and comprehend multistage implementation plans, which also stimulates stakeholders to propose new ideas in decision-making. Simple interactions and rich spatiotemporal visualizations designed in the system satisfy stakeholder requirements to evaluate the roadmap. The parallel computing adopted by the roadmap optimization suite and the HPC hardware in the offline mode saves time in arriving at the results. Most importantly, the B/S structure of the system ensures that there is no barrier for stakeholders to access.

Overall, this study proposed the design of a watershed planning system to promote the application of the state-of-art BMP roadmap optimization method among multiple stakeholders with different positions. When applied to other case studies with different watershed management contexts, except for the basic structure of the system including the encapsulated roadmap optimization suite on the ~~back-end~~back end and the user-friendly interactive workflow and spatialtemporal data visualization~~ and interaction~~, many details of the system implementation can be adjusted by developers~~detailed ~~. For example, ~~, used for roadmap optimization, ~~watershed management goals and the accordingly customized multi-objective optimization tool (e.g., Kumeda et al., 2021) and the watershed model (e.g., SWAT model), and selected BMPs and their representation in the watershed model.

5. Conclusions and future works

To promote the application of the state-of-art optimization method of multistage implementation plans under stepwise investment constraints that involve multiple stakeholders to meet practical watershed management needs for agreed-upon roadmaps, ~~manamanet , no watershed planning system support the overall optimization of.~~ ~~T~~this study proposed the design of~~ed and implemented~~ a web-based participatory watershed planning system~~ that can allow multiple stakeholders to devise a multistage implementation plan and create a unanimous roadmap~~. The system design separates easy-to-use interfaces for non-expert stakeholders from specialized models preprepared by professional modelers and encapsulated on the back end.~~ed based on two essential ideas. One is integrating the optimization method of multistage BMP implementation plans under stepwise investments for a given BMP scenario and simplifying the usage for non-expert stakeholders. The other is to utilize an easy-to-use interface to help stakeholders in diverse roles participate in optimizing and evaluating roadmaps and attaining a consensus.~~ The ~~overall~~ system implementation ~~can be divided into~~comprises server and client sides with independent technical routes. The system design was implemented and demonstrated in an agricultural watershed planning case study for soil erosion reduction. The role-play experimental design of three stakeholder groups (i.e., government, enterprise, and other stakeholders such as citizens) verified the validity and practicality of the system.~~The system was applied to a~~

~~small agricultural watershed to control soil erosion and prove its validity.~~

The system design has high flexibility and is easy to implement. The watershed model and optimization tool in the optimization suite can be replaced with components with similar functionality. The loosely coupled frontend and backend design allows~~makes it possible to apply~~ interface-oriented programming to be applied regardless of specific programming languages and implementation details. The input and output data utilized in the system are in text format (e.g., text, comma-separated values), independent of the programming language. Network transmission data are based on standard data-exchange formats (e.g., JSON). Therefore, system implementation can be customized for applications in other study areas with only a few technical or engineering changes. Moreover, the system design and example implementation can also be used as a suitable platform for inspiring the simulation-and-optimization-based decision-making thinking of those students who take environmental management-related courses.

~~There is still much room for improvement in the operational system performance. The major bottleneck for the current performance is that watershed models need to be executed many times during the spatiotemporal optimization of BMPs, and watershed simulation tends to become extremely time-consuming with an increase in the study area and the amount of refined data. The parallel execution of the watershed model is a typical improvement concept. In this study, a local HPC cluster was employed to demonstrate the feasibility of this idea. The next step is to utilize the parallel capabilities of supercomputers to improve the~~

~~performance of parallel execution of watershed simulations.~~

~~The current online optimization mode can only be conducted on a single server. The major reason behind this is that for cybersecurity, computing clusters or supercomputers usually cannot be accessed directly from the internet; that is, they need to be connected through special networks, including springboard machines, fortress machines, and virtual private networks. This hinders us from building a completely automated workflow, which is the basis for constructing an online optimization mode. This issue can be resolved with the development of cybersecurity technology.~~

As intended to be a general watershed planning system providing roadmap planning for non-expert stakeholders, several issues still require further study. The most important ones may include: (1) developing an integrated modeling platform to enable watershed planning systems and preceding watershed modeling systems can not only work independently but also be seamlessly connected; (2) enriching parameter configuration during the optimization process for a specific application, including more options for optimization algorithms, multi-perspective constraints, and governance objectives, to meet diverse stakeholder needs with reasonable simplification; and (3) employing a cloud-native architecture to implement the design idea of this study to improve the system performance. ~~There are at least two advantages of cloud-native architecture. It can completely exploit the advantages of cloud computing, which is well known for flexible resource allocation; thus, optimization tasks can be conducted efficiently. Next, the latest elastic high-~~

~~performance computing service, a new cloud infrastructure-based service that can build parallel computing clusters and dynamically adjust computing and storage resources as required, could be a feasible solution to provide massive amounts of computing power and build completely automated workflows.~~

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Table A.1 Brief descriptions of the four BMPs considered in this study (adapted from Zhu et al. (2019b) and photos from Chen et al. (2013))

BMP	Photo	Brief description
Closing measures (CM)		Closing the ridge area and/or upslope positions from human disturbance (e.g., tree felling and forbidding grazing) to facilitate afforestation.
Arbor–bush–herb mixed plantation (ABHMP)		Planting trees (e.g., *Schima superba* and *Liquidambar formosana*), bushes (e.g., *Lespedeza bicolor*), and herbs (e.g., *Paspalum wettsteinii*) in level trenches on hillslopes.
Low-quality forest improvement (LQFI)		Improving infertile forest located in the upslope and steep backslope positions by applying compound fertilizer on fish-scale-pits.
Economic fruit (EF)		Building new orchards on the middle and down slope positions or improving them under superior water and fertilizer conditions by constructing level terraces, drainage ditches, storage ditches, irrigation facilities and roads, planting economic fruit (e.g., chestnut, waxberry), and interplanting grasses and Fabaceae (Leguminosae) plants.

Table A.2 Environmental effectiveness and cost–benefit knowledge of the four best management practices (BMPs) within 5 years after implementation (adapted from Shen et al. (under review))

BMP	**Year**	**Environmental effectiveness [1]**						**Cost–benefit (CNY 10,000/km^2)**		
		OM	**BD**	**PORO**	**SOL_K**	**USLE_K**	**USLE_P**	**Initial**	**Maintain**	**Benefits**
CM	1	1.50	0.98	1.02	2.21	0.78	0.90	15.50	1.50	0.00
	2	1.62	0.97	1.03	4.00	0.99	0.90	0.00	1.50	0.00
	3	1.69	0.95	1.05	3.35	0.70	0.90	0.00	1.50	2.00
	4	1.74	0.94	1.06	3.60	0.60	0.90	0.00	1.50	2.00
	5	1.77	0.92	1.08	5.24	0.26	0.90	0.00	1.50	2.00
ABHMP	1	1.30	0.99	1.01	1.39	0.71	0.50	87.50	1.50	0.00
	2	1.36	0.98	1.02	1.38	0.89	0.50	0.00	1.50	0.00
	3	1.40	0.97	1.03	1.26	0.76	0.50	0.00	1.50	6.90
	4	1.42	0.96	1.04	1.15	0.75	0.50	0.00	1.50	6.90
	5	1.42	0.95	1.05	1.07	0.80	0.50	0.00	1.50	6.90
LQFI	1	2.80	0.98	1.02	1.54	0.88	0.50	45.50	1.50	0.00
	2	3.22	0.96	1.04	2.00	0.80	0.50	0.00	1.50	0.00
	3	3.47	0.94	1.07	2.76	0.60	0.50	0.00	1.50	3.90
	4	3.66	0.92	1.09	2.53	0.69	0.50	0.00	1.50	3.90
	5	3.8	0.90	1.11	2.38	0.73	0.50	0.00	1.50	3.90
EF	1	1.20	0.99	1.01	0.90	1.10	0.75	420.00	20.00	0.00
	2	1.23	0.98	1.02	1.16	1.06	0.75	0.00	20.00	0.00
	3	1.25	0.96	1.04	0.95	0.70	0.75	0.00	20.00	0.00
	4	1.26	0.95	1.05	1.60	0.65	0.75	0.00	20.00	0.00
	5	1.30	0.94	1.06	1.81	0.76	0.75	0.00	20.00	60.30

Note. [1] environmental effectiveness of BMPs includes soil property parameters [organic matter (OM), bulk density (BD), total porosity (PORO), and soil hydraulic conductivity (SOL_K)] and universal soil loss equation (USLE) factors [soil erodibility factor (USLE_K) and conservation practice factor (USLE_P)]. Values in each column represent relative changes (multiplying) and, thus, have no units. For example, OM would increase in ratios of 1.50, 1.62, 1.69,1.74, and 1.77, respectively, after implementing CM within 5 years. The conservation practice factor USLE_P will not change within 5 years.

CM, closing measures; ABHMP, arbor–bush–herb mixed plantation; LQFI, low-quality forest improvement; EF, economic fruit.

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