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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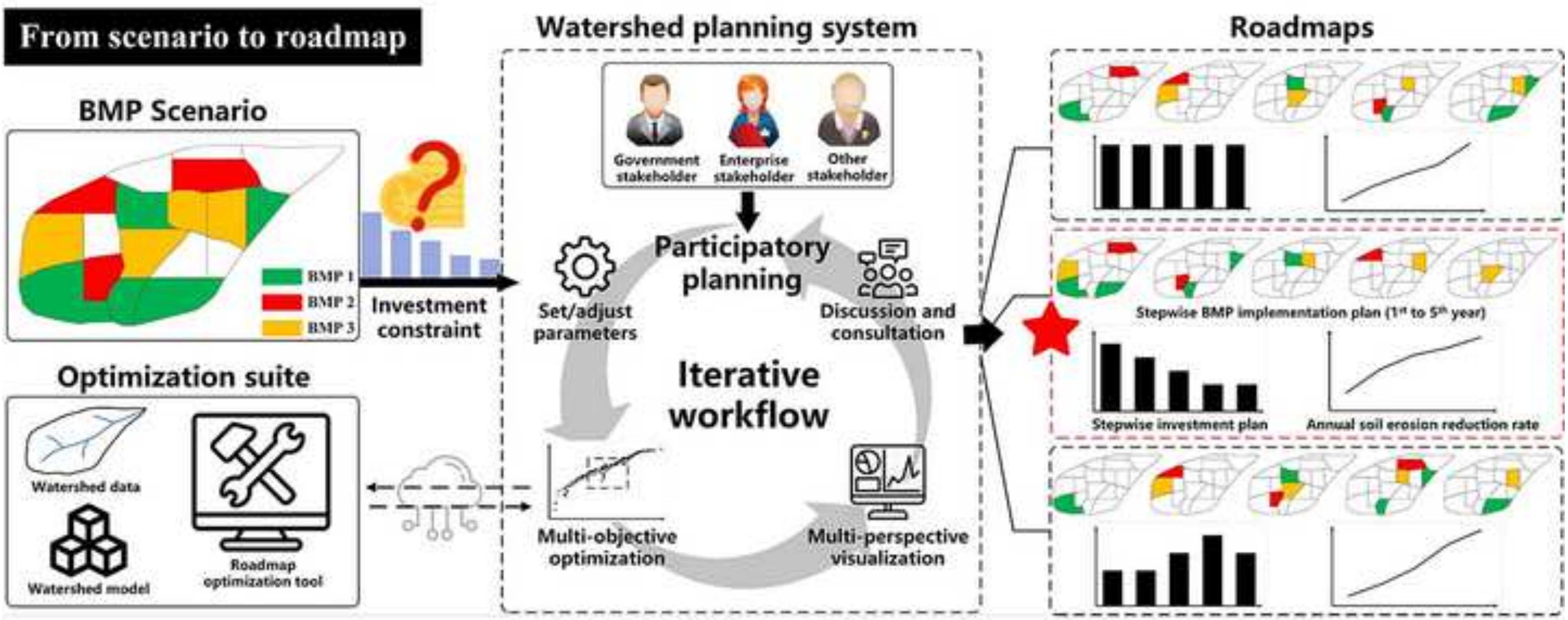
Graphical Abstracts



Highlights:

- Participatory system for multistage BMP implementation plans is still lacking.
- Design and developed a planning system for optimizing roadmaps from a BMP scenario.
- Allowed multiple stakeholders to participate in reaching a consensus.
- A user-friendly design to run optimization, analyze results, and select roadmaps.

Manuscript

Abstract:

Planning multistage implementation plans (i.e., roadmaps) from a best management practice (BMP) scenario is essential for accomplishing watershed management goals under realistic conditions such as stepwise investment. However, current watershed planning systems do not consider optimizing roadmaps under stepwise investment constraints that involve multiple stakeholders. This study proposed designing a user-friendly web-based watershed planning system to assist diverse stakeholders in the iterative optimization of roadmaps, analysis of spatiotemporal results, and reaching a consensus. The system server side integrated an optimization method for BMP implementation plans. The client side constructed a user-friendly interface 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. Based on the overall design, the Youwuzhen watershed planning system was implemented and demonstrated to optimize BMPs for soil erosion reduction in this agricultural watershed in Southeastern China to validate its 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. Watershed planning often requires a compromise between multiple potentially conflicting objectives, such as maximizing eco-environmental effectiveness and minimizing socioeconomic investment (Engel et al., 2003; Ruiz-Ortiz et al., 2019; Lai et al., 2007; Booth et al., 2011; Reichert et al., 2015; Sun, 2013). 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.

Existing watershed planning systems generally take two approaches for considering stakeholder participation in the investment constraints. 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 does not further arrange the optimized BMP scenario into multistage implementation plans. 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.

The second approach to consider stakeholder participation in the investment constraint is by allowing stakeholders to set stepwise investments for multiple implementation periods. Existing systems often utilize a method of 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. For example, 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. However, this method only loosely combines independent optimization results and does not optimize the multistage implementation plan 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 the best of our knowledge, no watershed planning systems or software tools support the overall optimization of multistage implementation plans under stepwise investment constraints that involve multiple stakeholders. To resolve this issue, this study designed and developed a web-based participatory system to iteratively assist various stakeholders in setting investment constraints, optimizing roadmaps, analyzing results, and developing unanimous plans. The basic idea and overall design of the system are introduced in Section 2. The system implementation with a case study is presented in Section 3. The experimental design, results, and discussion are presented in Section 4. Conclusions and future work are presented in Section 5.

2. Basic idea and overall design

2.1 Basic idea

To build a watershed planning system that allows multiple stakeholders to participate in setting investment constraints and reaching a consensus on optimizing multistage BMP implementation plans (i.e., roadmaps of a specific BMP scenario), two key issues need to be addressed. The system should integrate a method for optimizing roadmaps under stepwise investments for a given BMP scenario while simplifying the use of non-expert stakeholders by inputting investment constraints and outputting roadmaps. Next, the system must have an easy-to-use interface to help stakeholders with diverse roles to participate in the process of optimizing and analyzing roadmaps and reaching a consensus.

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).

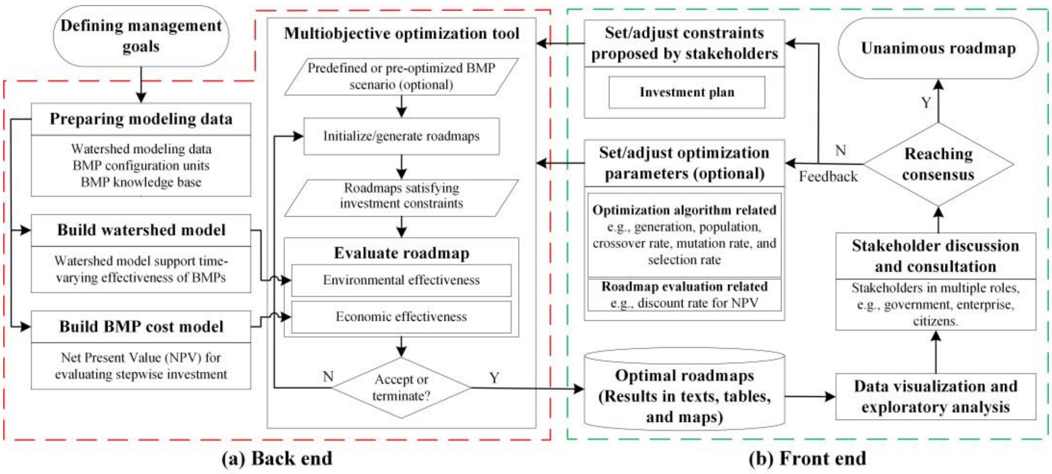


Figure 1 Framework of participatory optimization method for multistage implementation plans of best management practice (BMP) scenario under stepwise investment: (a) Back-end optimization method; (b) Front-end design of the participatory watershed planning system.

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. Iterative workflow is suitable for implementation by web-based application architecture, which allows stakeholders in diverse groups can access 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 modeling applications (Chen et al., 2020; Jiang et al., 2016; McDonald et al., 2019; Zhang et al., 2019; A.X. Zhu et al., 2021). User interaction in the iterative workflow can be handled by designing user-friendly front-end graphical interfaces. Simultaneously, computation-intensive optimization tasks can be executed in the back-end hardware infrastructure, including a single server or a high-performance computing (HPC) cluster, depending on the computation of actual tasks.

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). The presentation layer comprises a graphical interface for user interaction, data visualization, and front-end business logic for requesting and receiving data via the hyper-text transport protocol (HTTP) and adapting the data structure for presentation on graphical interfaces. The client side 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.

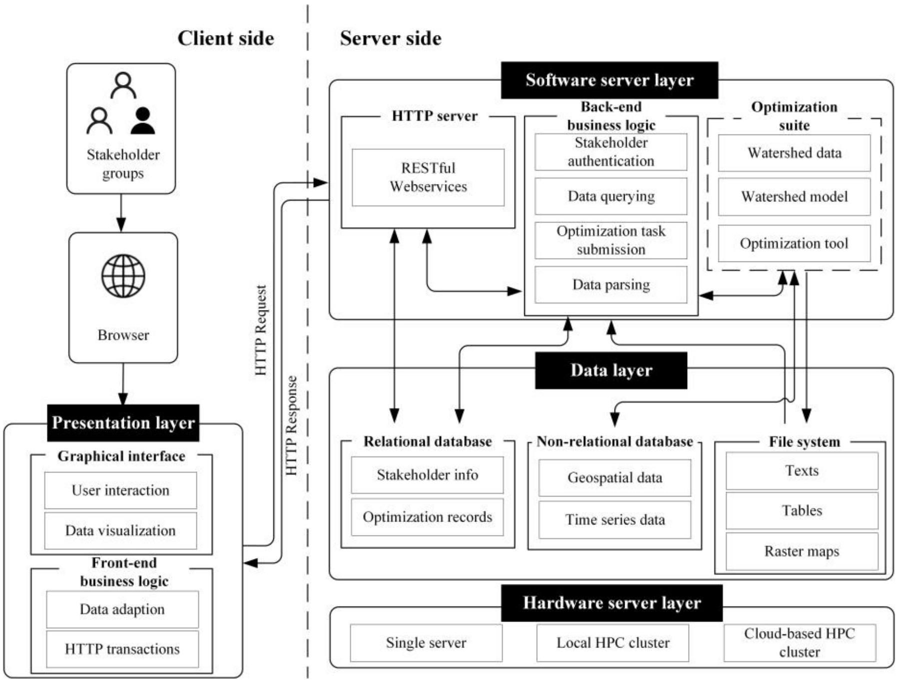


Figure 2 Overall architecture of the watershed planning system

Server side refers to all programs and data that run on the hardware server. The software server layer comprises three components. 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 optimization suite is the core component that encapsulates the roadmap optimization method, including watershed data processing tools, watershed models, and optimization tools, into several interfaces to connect with the business logic component. HTTP server is the communication component responsible for communication between the server and client sides and within the server side. For the data layer, the system utilizes relational and non-relational databases to manage structured business (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 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 roadmap optimization method

The optimization suite for multistage BMP implementation plans adopts a component-based design that includes several independent and sequenced functional components, including data preprocessing scripts, watershed models, and optimization algorithm scripts (Zhu et al., 2019; Shen et al., under review). This design provides flexibility in executing diverse subtasks with rich configurable parameters. The optimization suite can be invoked in the API (Application Programming Interface) from other programs or command lines, which is unfriendly to non-expert stakeholders but convenient for integration.

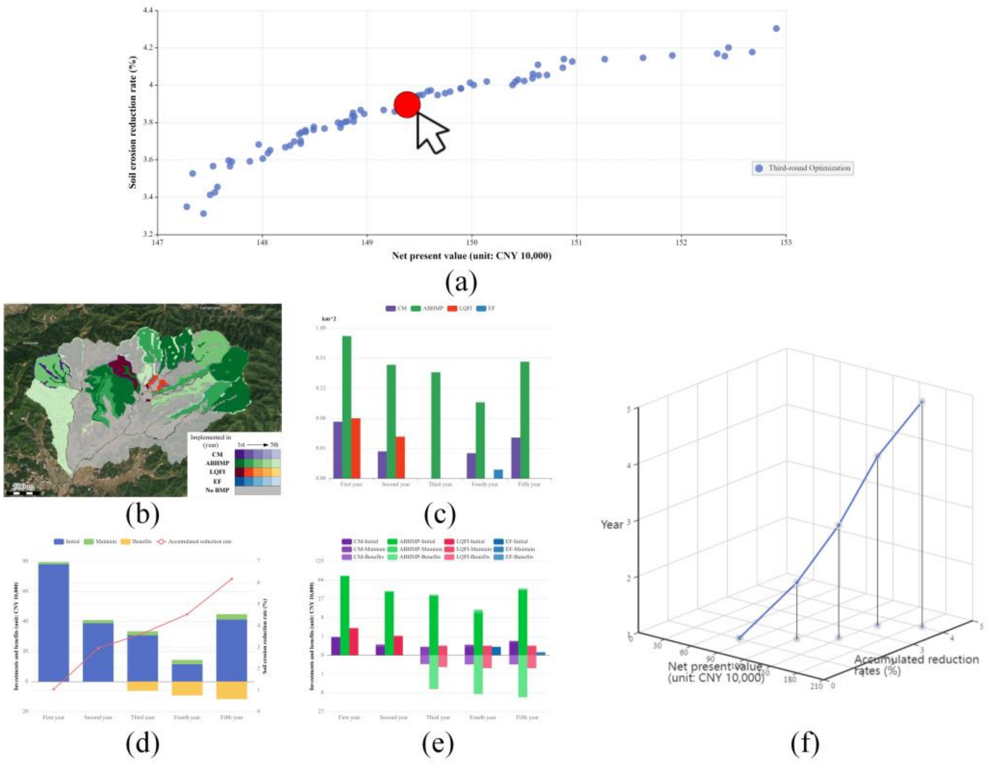
In this study, the optimization suite was integrated as a critical component of the server side and loosely coupled with the back-end business logic program (Figure 2). The optimization task execution workflow is designed as follows:1) the required settings of the investment constraints and optimization 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 implementation plan for BMPs in this study is essentially a type of spatiotemporal data (Shen et al., under review). All staged spatial configurations of the BMPs constitute the roadmap spatiotemporal dimensions. The stepwise investment plans and environmental evaluation results were 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. Each time the stakeholder selects a point in the Pareto front (Figure 3a), the multi-perspective data of this roadmap are displayed 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).



	Roadmap ID	BMP	First year					Second year			
			Area(km^2)	Initial	Maintain	Benefits	Reduction rate	Area(km^2)	Initial	Maintain	B
	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 multistage spatial configuration plan, 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 partnerships 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 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 considers three stakeholder roles: investors, economic beneficiaries, and environmental beneficiaries. Accordingly, we designed a stakeholder group with 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. Implementation with the study area

Based on the above overall design, we chose a small agricultural watershed, the Youwuzhen watershed in Southeastern China, as the study area to develop an operational planning system which can be accessed via http://easygeoc.net:9091/. The source of this system is open-sourced via Github (https://github.com/lreis2415/WatershedPlanningSystem). 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. An overall technical 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.

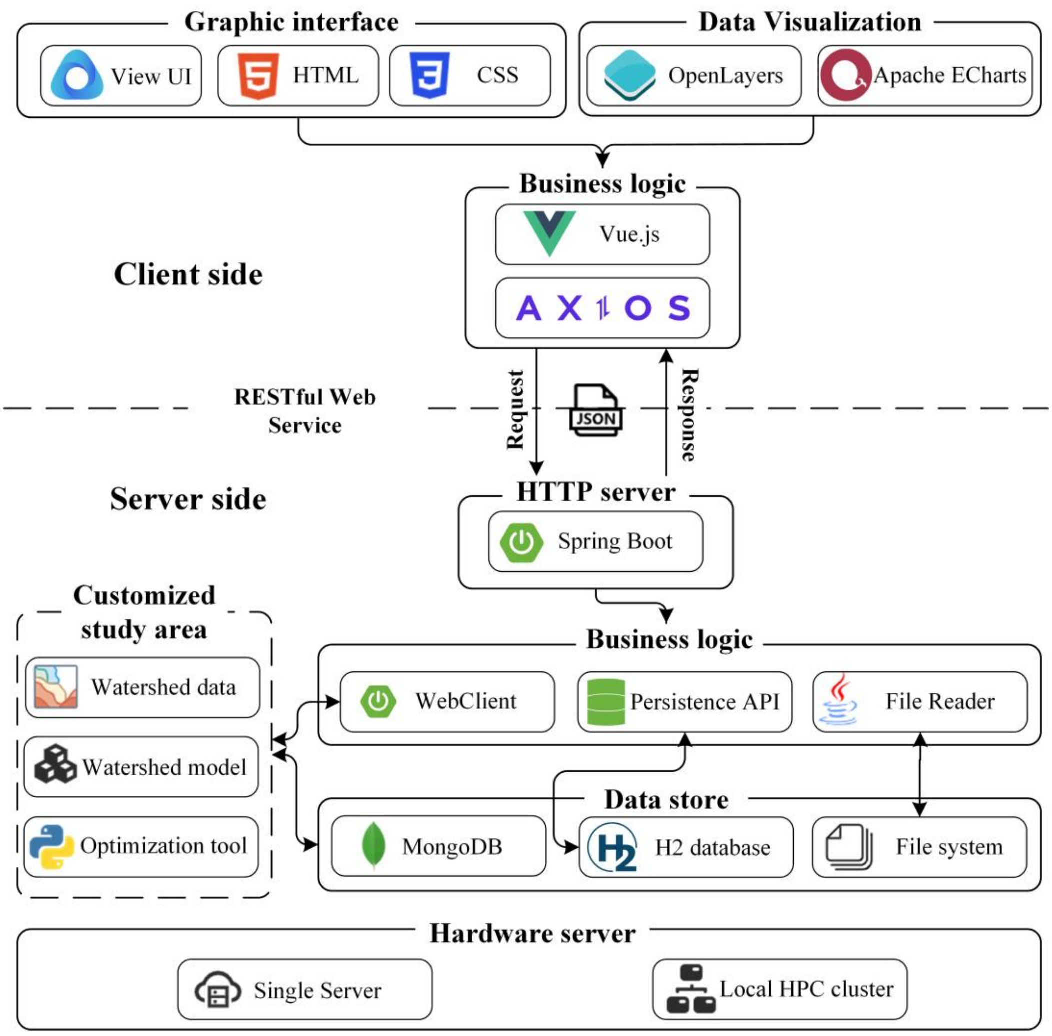


Figure 4 Overall technical schematic diagram of the watershed planning system implemented in this study

3.1 Overall implementation

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[1]. The back-end business logic program comprises the built-in features of Java[2] (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[3] interface is as follows: The stepwise investment constraints and optimization parameters were organized into a JSON (JavaScript Object Notation)[4] 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 was 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 was returned to the WebClient and the results were written into the data store server in the files and database records. The

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[1] https://spring.io/projects/spring-boot
[2] https://www.java.com/
[3] https://www.python.org/
[4] https://www.json.org/

FileReader read files and constructed a new Java object, which was 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, Vue.js[5] was selected as the major framework to process basic business logic, and the Axios library[6] was adopted to send HTTP requests and receive responses. The entire graphical interface was implemented based on

[5] https://vuejs.org/
[6] https://axios-http.com/

HTML5[7] and CSS 3[8], and the View UI[9], a component library based on Vue.js, was utilized for rapid prototyping. The JavaScript mapping library OpenLayers[10] was used to visualize the roadmap spatial dimensions. Bar and three-dimensional line charts were rendered based on the open-source JavaScript visualization library Apache Echarts[11]. The client-side graphical user interface is depicted in Figure 5.

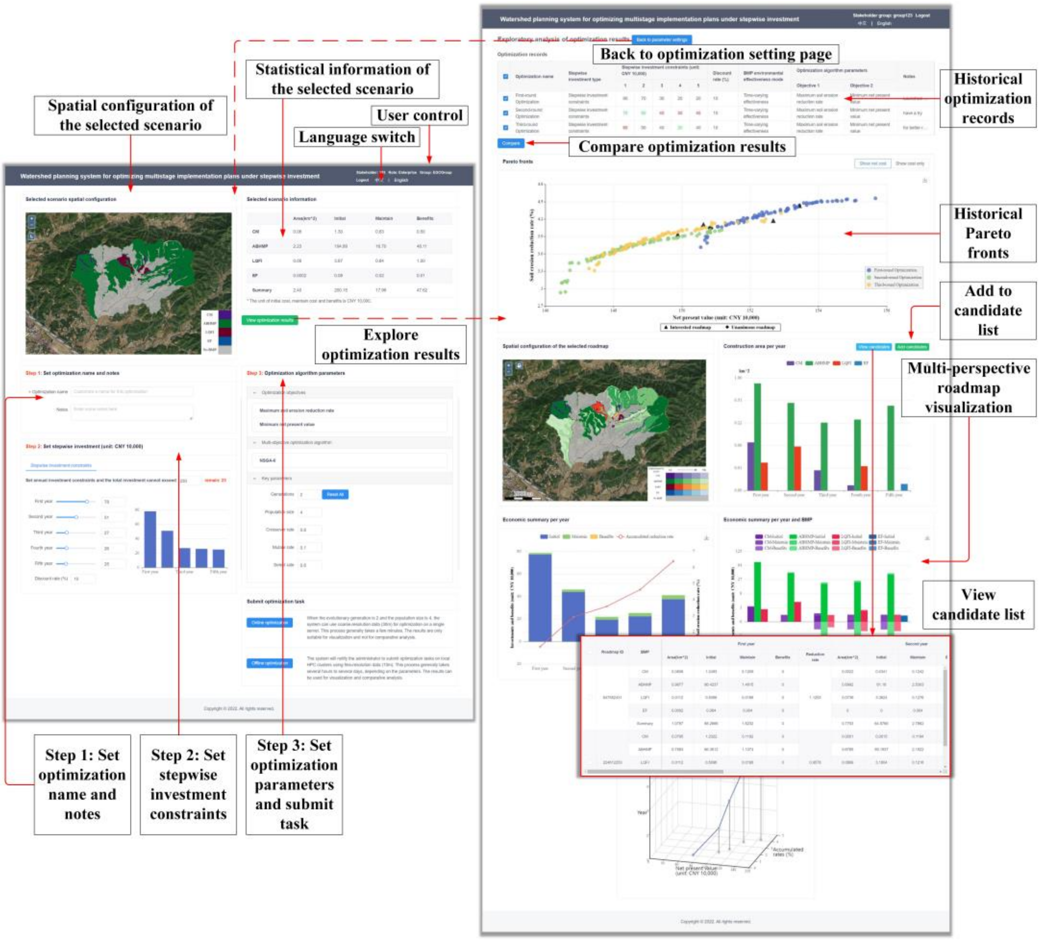

Figure 5 The client-side graphical user interface of the Youwuzhen watershed planning system

3.2 Study area

The Youwuzhen watershed (approximately 5.39 km^2), which is part of the

7 https://dev.w3.org/html5/spec-LC/
8 https://www.w3.org/Style/CSS/Overview.en.html
9 http://v4.iviewui.com/docs/introduce
10 https://openlayers.org/
11 https://echarts.apache.org/

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, which can be classified as *Ultisols* and *Inceptisols* in the US Soil Taxonomy, respectively (Shi et al., 2010).

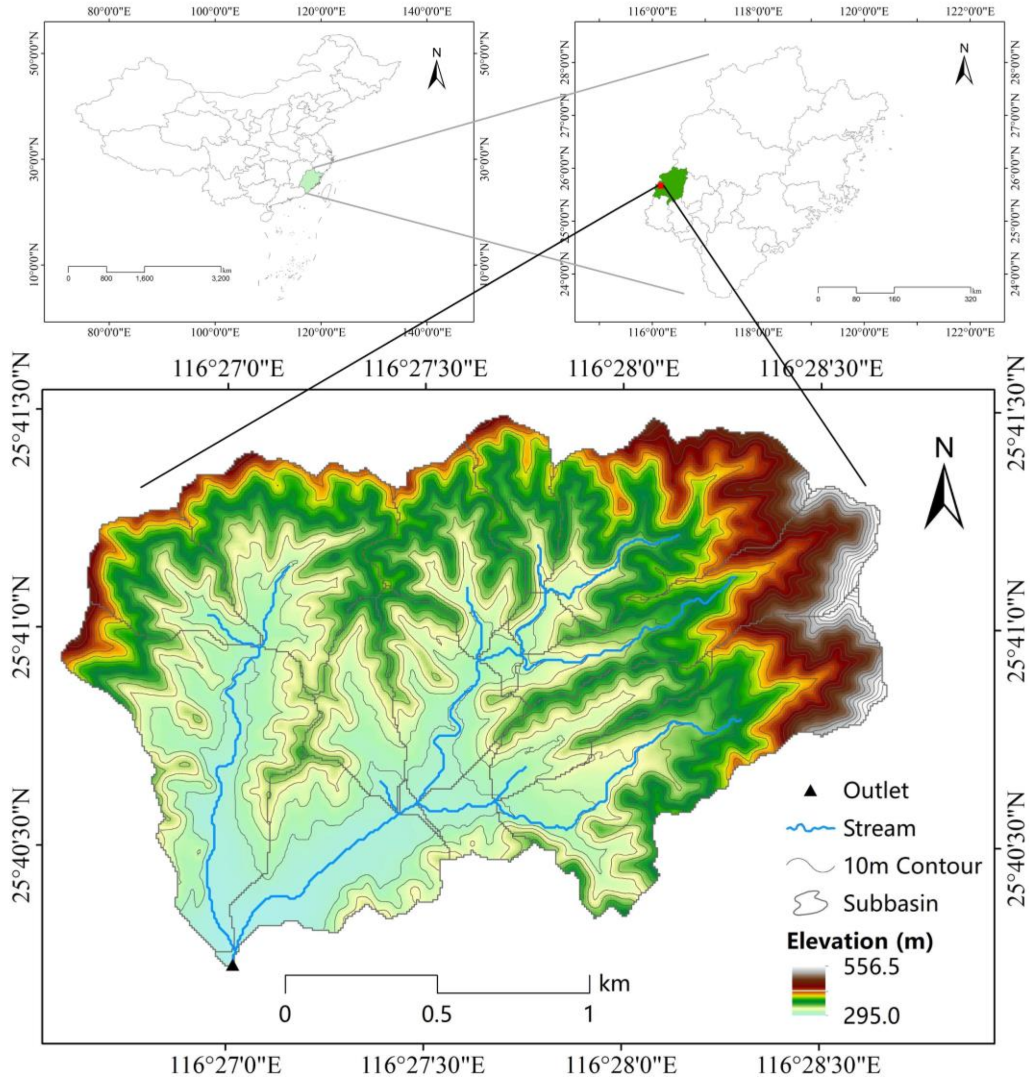

Figure 6 Map of Youwuzhen watershed in Changting County, Fujian Province, China

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 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, 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). Their brief descriptions were adapted from Zhu et al. (2019b) and are enlisted in the Appendix (Table A.1). 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 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 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 7). 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; L.J. Zhu et al., 2021; Zhu et al., 2019b). In the fundamental scenario (Figure 7), 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.

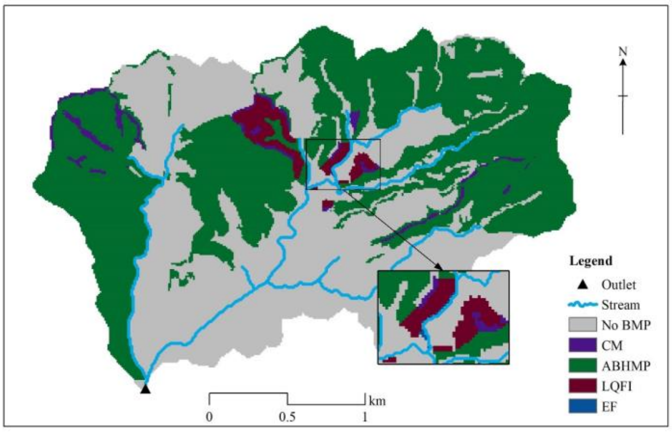

Figure 7 Spatial distribution of the fundamental spatial scenario based on slope position units from Zhu et al. (2019b) with partially enlarged details of the configured economic fruit (EF) along the stream

3.3.4 Multi-objective optimization method for roadmaps

The multiobjective 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).

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

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).

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

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

where 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 initial construction cost, maintenance cost, and benefits of BMPs implemented in this period and before; 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

To verify that the watershed planning system constructed in this study can assist stakeholders in participating in 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 process is as follows:

1) The government leads the first-round optimization and discussion by setting up stepwise investment constraints and suggesting candidate implementation plans or an acceptable range of multiple objectives.

2) The second- and third-round optimizations were launched by enterprises and other stakeholders, respectively. 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.

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 multiple objectives can be built by stakeholders, from which unanimous roadmap(s) can be determined. Figure 8 depicts the Pareto fronts of the three optimization rounds. The detailed process of each optimization round is as follows.

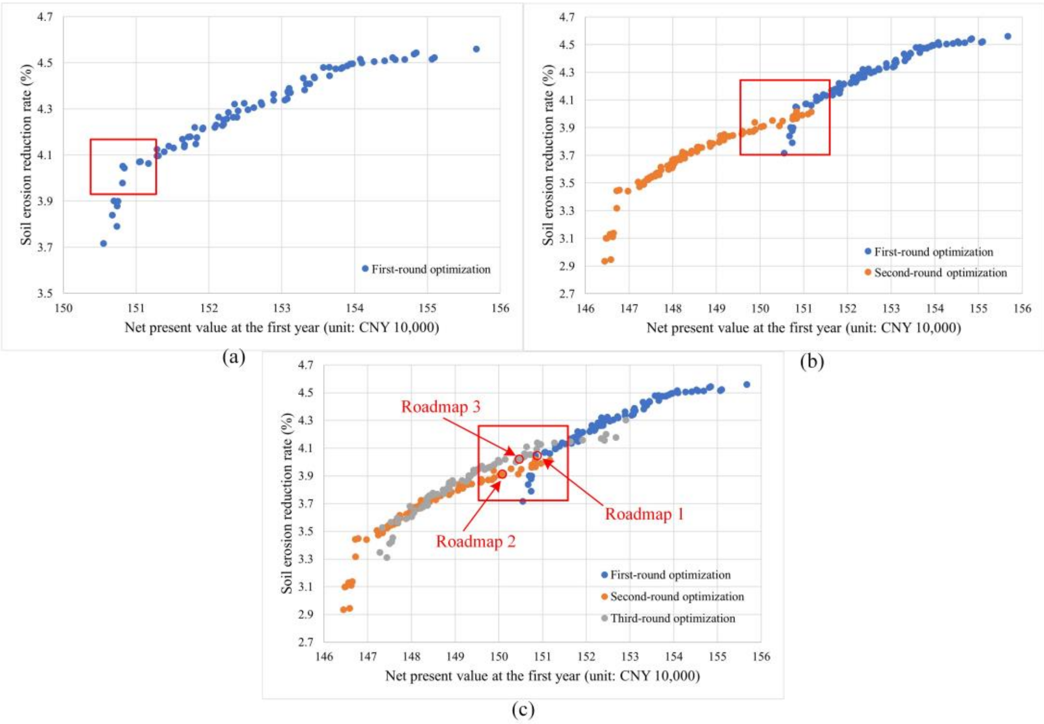

Figure 8 Pareto fronts of the three optimization rounds launched by three stakeholders

During the first-round optimization, government stakeholders 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 8a). As the Pareto fronts NPV decreased, the soil erosion reduction rate gradually decreased, and declined rapidly post the inflection point. Considering that government stakeholders are primary investors, they should strive for as much environmental effectiveness as possible with as little investment pressure as possible. Therefore, roadmaps near the inflection point (in the red box) are given priority.

The second-round optimization is led by the enterprise stakeholder, 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 (70, 50, 40, 30, and 40; the NPV without income is 180.34) is proposed based on a comprehensive consideration of previous investment constraints, optimization results, and stakeholder needs. 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 8b). Compared to the first-round Pareto front, the new Pareto front moves to the lower left as a whole (Figure 8b), which means that these implementation plans sacrifice some environmental effectiveness in exchange for a lower NPV.

The third-round optimization is conducted by other stakeholders (e.g., citizens living in the watershed), who proposed revised investment constraints (80, 50, 40, 20, and 40; 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 implement the prominent BMP, ABHMP, in the fifth year, which will produce better comprehensive effectiveness (see further discussion in Section 4.2.2). The optimization result is the grey Pareto front, which further improves the comprehensive effectiveness within the candidate range (red box in Figure 8c).

Therefore, the optimization results can meet the requirements of all stakeholders. The shifts in the three Pareto fronts can well reflect the differences in requirements among stakeholders, demonstrating the effectiveness of the iterative optimization 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 stakeholders, and is also a potential area where compromise solutions can be reached. In this experiment, the investment-environmental effectiveness gap between the roadmaps in the candidate area (the red box in Figure 8c) was no longer apparent, indicating that there was no significant disagreement among stakeholders in the roadmaps within this area. However, there were still some differences among the roadmaps, reflecting the diversity of the Pareto solution sets. Three representative roadmaps were selected from the candidate areas, one for each Pareto front, and their spatiotemporal implementation configurations and stepwise investments were compared to illustrate their rationality and diversity.

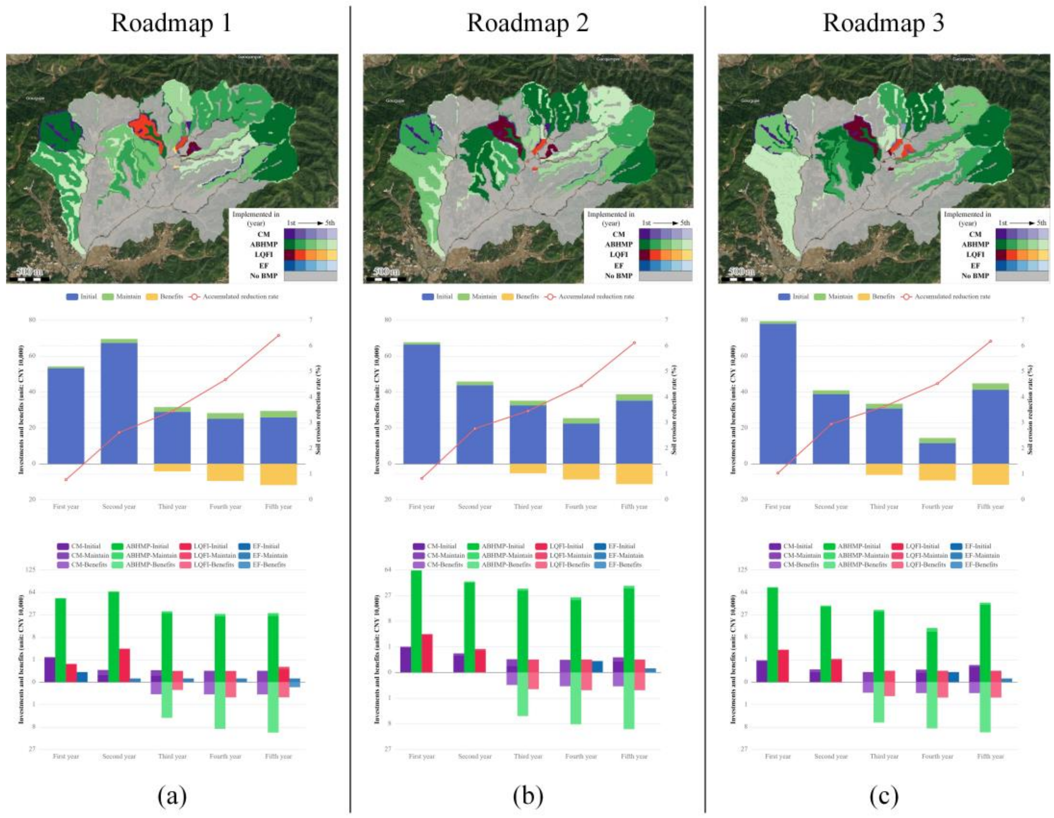

Figure 9 Three representative roadmaps selected from candidate area of three round optimizations, one for each Pareto front. The map in the first row demonstrates the BMP spatiotemporal configuration in the roadmap. The bar chart in the second row demonstrates the annual investment and income, and the line chart demonstrates the annual 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 roadmap1, roadmap 2, 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 two years, 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 considers higher environmental effectiveness 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 investment in the first and fifth years and further reduced the investment in the fourth year.

This phenomenon may be caused by the particularity of the BMPs selected in this case study. In the selected fundamental spatial scenario, ABHMP occupied the most prominent area. This BMP can take effect quickly post implementation, and slightly decrease and then remain stable. 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 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.

4.2.3 Effects of other essential designs

The iterative workflow designed in the system provides technical support for sequential participation of stakeholders 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 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 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.

5. Conclusions and future works

This study designed 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. This system was designed 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 implementation can be divided into server and client sides with independent technical routes. 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 makes it possible to apply interface-oriented programming 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.

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; and (3) employing a cloud-native architecture to implement the design idea of this study. 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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