Title page

From scenario to roadmap: Design and evaluation of a web-based participatory watershed planning system for optimizing multistage implementation plans of management practices under stepwise investment

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Graphical Abstract larger version

Highlights:

- System design meets practical watershed management needs for agreed-upon roadmaps
- System separates easy-to-use interface for non-expert users from specialized models
- Browser/Server system facilitates participatory processes of multiple stakeholders
- Users participate in proposing investment plans and electing optimized roadmaps
- Multi-stakeholder role-play experiment verifies system’s validity and practicality

Abstract:

Planning multistage implementation plans, or roadmaps, based on the spatial distribution of a best management practice (BMP) scenario is essential for achieving watershed management goals under realistic conditions, such as stepwise investment plans that involve multiple stakeholders, including investors, economic and environmental beneficiaries. The state-of-the-art BMP roadmap optimization method can address this need for optimization but is over-specialized and complex to non-expert stakeholders. This study designed a user-friendly web-based participatory watershed planning system to assist a diverse group of stakeholders in reaching a consensus on optimal roadmaps. The participatory process of stakeholders includes iteratively proposing stepwise investment constraints, submitting roadmap optimization tasks, analyzing spatiotemporal results from multiple perspectives, and selecting preferred roadmaps. 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 server side. The webservices expose a small set of essential parameters to lower barriers to use. The interactive participatory process is presented to stakeholders through web browsers with an easy-to-use interface. The system design was evaluated by implementing an agricultural watershed planning system for soil erosion reduction and conducting a role-playing experiment involving three groups of stakeholders with different standpoints in proposing investment constraints. The experimental results show that the optimal roadmap sets exhibit progressive improvements across three-round optimizations started by different stakeholders, effectively capturing the varying perspectives of stakeholders and facilitating consensus-building among them. The idea of system design and example implementation can serve as a valuable reference for developing related user-friendly environmental decision support systems.

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, such as 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, to reach agreed-upon best management practice (BMP) scenarios that satisfy standpoints of multiple stakeholders (e.g., investors, farmers, citizens, and authorities) (Ruiz-Ortiz et al., 2019; Booth et al., 2011; Reichert et al., 2015; Sun, 2013). In existing studies, a selected BMP scenario often refers to a spatial distribution of BMPs 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., 2023). Therefore, how to consider investment constraints that involve multiple stakeholders in watershed planning becomes an urgent requirement for effective solutions.

A lot of BMP scenario optimization methods have been proposed to support watershed planning and generally take two types of 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 studies on BMP spatial optimization aimed at cost-effective scenarios (Gaddis et al., 2014; Qin et al., 2018) or return on investment (Jones et al., 2017; Kroeger et al., 2019) fall into this category. However, this type of approach cannot further arrange the optimal BMP scenario into multistage implementation plans (the so-called practical BMP roadmap in this study), with each implementation stage including a BMP spatial distribution and the corresponding investment to meet the requirements of making actual decisions effectively.

The second type of approach to consider stakeholder participation is setting stepwise investments for multiple implementation periods and conducting optimization in two different ways (Hou et al., 2020; Shen et al., 2023). The first way conducts 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). The staged optimization results were combined as a final roadmap. However, this type of approach only loosely combines independent optimization results and does not optimize the roadmap in an overall optimization problem that considers multistage investments. To address this weakness, a new BMP roadmap optimization method considering the stepwise investment and time-varying effectiveness of BMPs was recently proposed by Shen et al. (2023). 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 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., 2023).

However, the implementation and application of the state-of-the-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., 2023). This is an iterative optimization process initiated by decision makers or managers determining management goals, powered by professional modelers utilizing scientific models and tools, and participated by stakeholders in multiple roles with their experience, needs, and capabilities (Babbar-Sebens et al., 2015; Wicki et al., 2021; Reichert et al., 2015; Voinov et al., 2016). To facilitate the participation of non-expert stakeholders in this process, based on pre-prepared specialized models by professional modelers on the backend, a watershed planning system that utilizes a user-friendly interface that does not require intensive specialized knowledge of BMP scenario analysis becomes the uncontested choice (Martin et al., 2016; Sugumaran et al., 2004; Walling and Vaneeckhaute, 2020).

To the best of our knowledge, no watershed planning system supports the overall optimization of BMP roadmaps under stepwise investment constraints involving multiple stakeholders. Therefore, this study aims to design a web-based participatory watershed planning system and evaluate its ability to iteratively assist various stakeholders in proposing investment constraints, optimizing roadmaps, analyzing results, and reaching agreed-upon plans through a case study. The basic idea and overall design of the system are introduced in Section 2. The case study of an agricultural watershed planning system for mitigating soil erosion is implemented in Section 3. The multistakeholder role-playing 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 a watershed planning system that allows multiple stakeholders to participate in proposing the investment constraints and reaching a consensus on optimized roadmaps of a specific BMP scenario, two key issues need to be addressed. The system should integrate the BMP roadmap optimizing method under stepwise investments while streamlining the use through inputting investment constraints and outputting roadmaps (Figure 1a; adapted from Shen et al., 2023). The workflow is an iterative optimization process of initializing, generating, and evaluating BMP roadmaps under the framework of an intelligent optimization algorithm. The evaluations of each BMP roadmap are conducted by the customized watershed model and BMP scenario cost model according to the watershed management goals. Newly generated BMP roadmaps are screened to satisfy investment constraints before being evaluated. After the maximum iteration is reached or other conditions are satisfied, the optimization finishes and outputs optimal roadmaps (Figure 1a).

Next, the system must have an easy-to-use interface to facilitate the participation of stakeholders with different knowledge backgrounds and diverse roles. The participation process 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 or attaining agreed-upon roadmaps unanimously (Figure 1b).

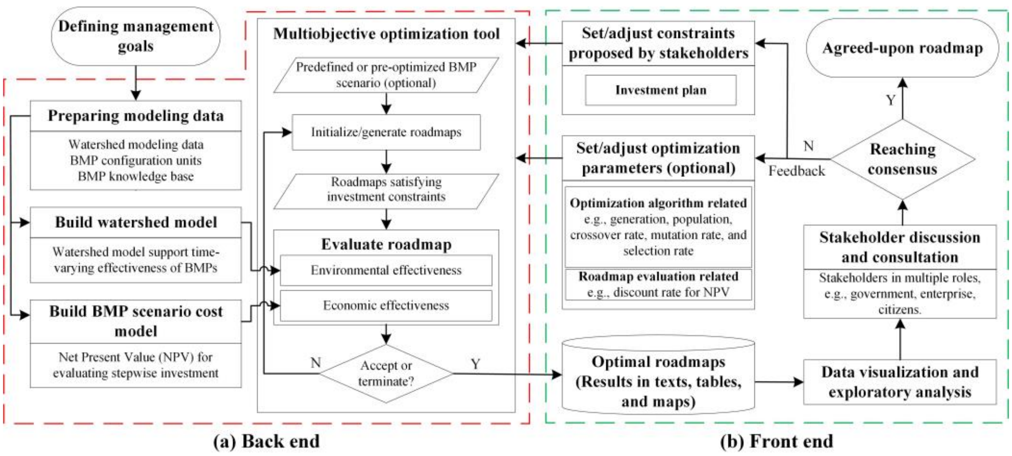


Figure 1 Participatory optimization framework for multistage implementation plans of best management practices (BMPs) under stepwise investment: (a) BMP roadmap optimization method encapsulated in the back end (adapted from Shen et al., 2023); (b) iterative participatory workflow designed for easy-to-use front end.

Based on the basic idea and the relationship between the BMP roadmap optimization method and the iterative participatory workflow designed for stakeholders illustrated in Figure 1, Section 2.2 presents the overall architectural design of the participatory watershed planning system using the web application architecture, the mainstream architecture in promoting the development of easy-to-use geographic and environmental modeling applications (Chen et al., 2020; McDonald et al., 2019; A.X. Zhu et al., 2021). 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

The system adopted a layered browser/server (B/S) architecture, including the presentation layer on the client side (i.e., web browser) and the software server, data, and hardware server layers on the server side (Figure 2). The client side is responsible for user interaction in setting parameters before submitting the optimization task and exploring data of the optimized BMP roadmaps with the support of the front-end business logic. The business logic requests and receives optimized roadmaps data via the hyper-text transport protocol (HTTP) from the HTTP server and adapts the data structure for presentation on a graphical interface. The system takes the stakeholder group as the user unit and establishes a shared space within the group, wherein stakeholders can explore the historical optimized roadmaps of all members and mark their preferred roadmaps as candidates for further discussion. The agreed-upon roadmaps can be found if a consensus can be reached, and the iterate workflow ends. Otherwise, stakeholders will propose new investment plans based on current results in the next iteration (Figure 1b).

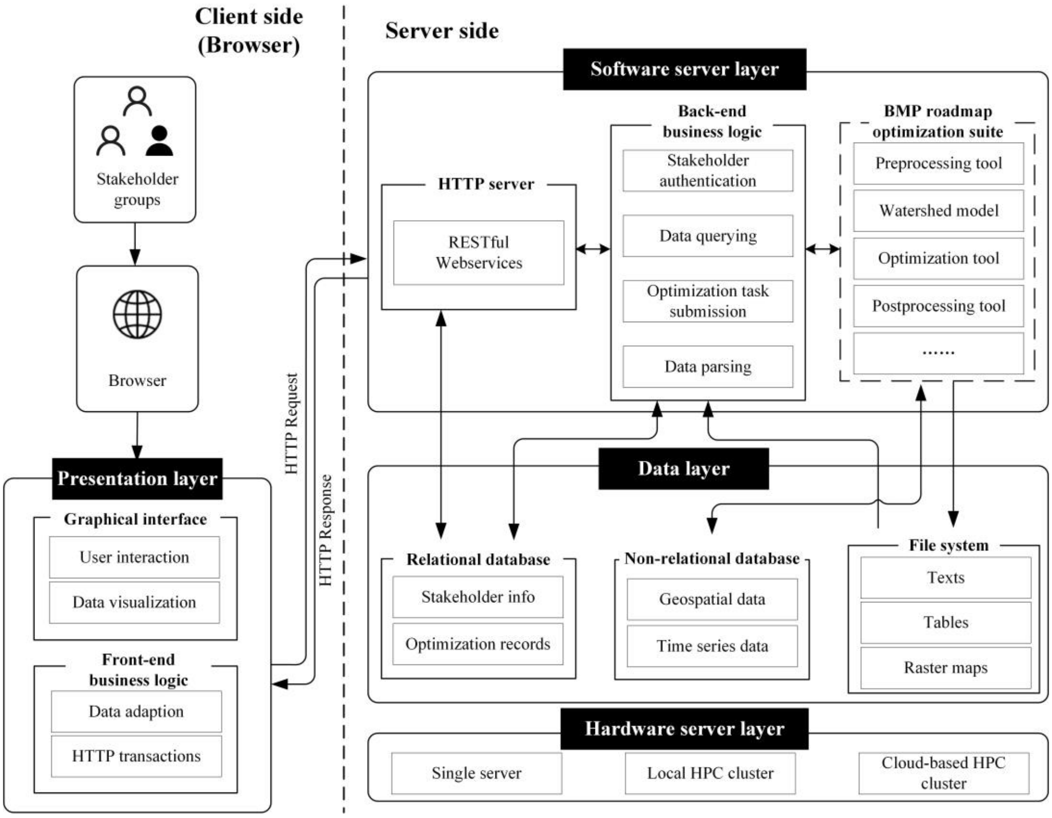


Figure 2 Overall layered browser/server (B/S) architecture design of the watershed planning system

The server side is responsible for receiving and executing the submitted optimization tasks from the web browser, and parsing, formatting, and sending back the optimized roadmaps. The 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 encapsulates models and tools of the specific implementation of the roadmap optimization method as several application programming interfaces (API) to be loosely coupled 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 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. For the hardware server layer, the system can deploy on a single server or use the parallel computing capabilities of a local high-performance computing (HPC) or a cloud-based HPC cluster with elastic scaling capabilities to accelerate the execution of optimization tools.

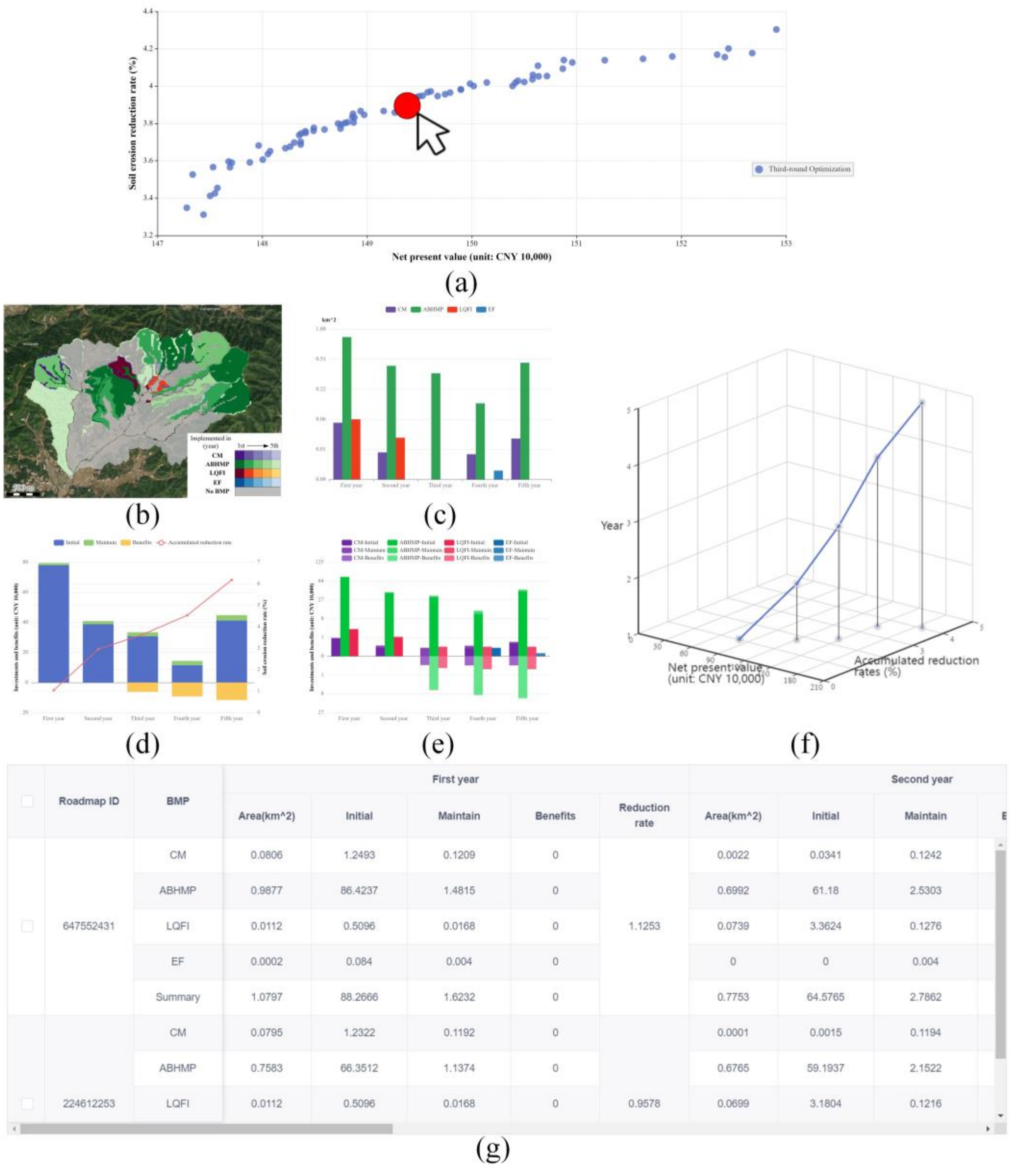
2.3 Integrating BMP roadmap optimization method

The BMP roadmap optimization method proposed by Shen et al. (2023) is intended to be a universal modeling framework that includes several independent and sequenced functional components, such as data preprocessing tools, watershed model and BMP scenario cost model, optimization algorithm tools, and postprocessing tools (Figure 1a and Figure 2). That means this framework can be implemented by different watershed models and optimization algorithms and applied for various BMPs and watershed management goals. The implementations of these components generally do not have user interfaces. They can be invoked in the API from other programs or command lines, which is unfriendly to non-expert users but convenient for system integration.

Therefore, several general APIs are designed for the interactions between the BMP roadmap optimization suite with other components, such as executing the optimization task with the user-specific investment plan and parsing optimized roadmap for visualization data. When building the watershed planning system for a specific case study, the specialized modeling processes according to the management goals should be pre-prepared by professional modelers and integrated with these general APIs. 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 1b). More details about the BMP roadmap optimization method can be found in Shen et al. (2023).

2.4 Multi-perspective visualization of roadmaps

Effective spatiotemporal data visualization is crucial for stakeholders to understand, analyze, and reach agreed-upon roadmaps. The linked visualization method ensures consistent data display as stakeholders explore roadmaps (Figure 3). By selecting a point in the Pareto front (Figure 3a), stakeholders can view multi-perspective data, including maps, bar and line charts, and tables. The mapping method considers the temporal information of BMP roadmaps, using different color tones to represent BMP types and color saturations to represent implementation time (Figure 3b). Bar charts express statistical staged information, such as annual construction area for each BMP type (Figure 3c) and annual economic data (Figures 3d and 3e). A three-dimensional line chart shows the effect of an implementation plan at each stage (Figure 3f), and any roadmap can be added to a well-designed data table for comparison (Figure 3g).



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

Figure 3 Spatiotemporal data visualization for selected roadmap: (a) visualization and interactive mode of Pareto front; (b) a map of multistage BMP spatial 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 used management modes of special funds for watershed management projects, 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 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 study of an agricultural watershed planning system for mitigating soil erosion

Based on the above overall design, we chose a small agricultural watershed planning case study for soil erosion reduction as an example to develop the watershed planning system, which can be accessed via http://easygeoc.net:9091/. This system is open-source via Github (refer to Data and code availability section for more details). The 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. (2023), as shown detailed in Figure 4.

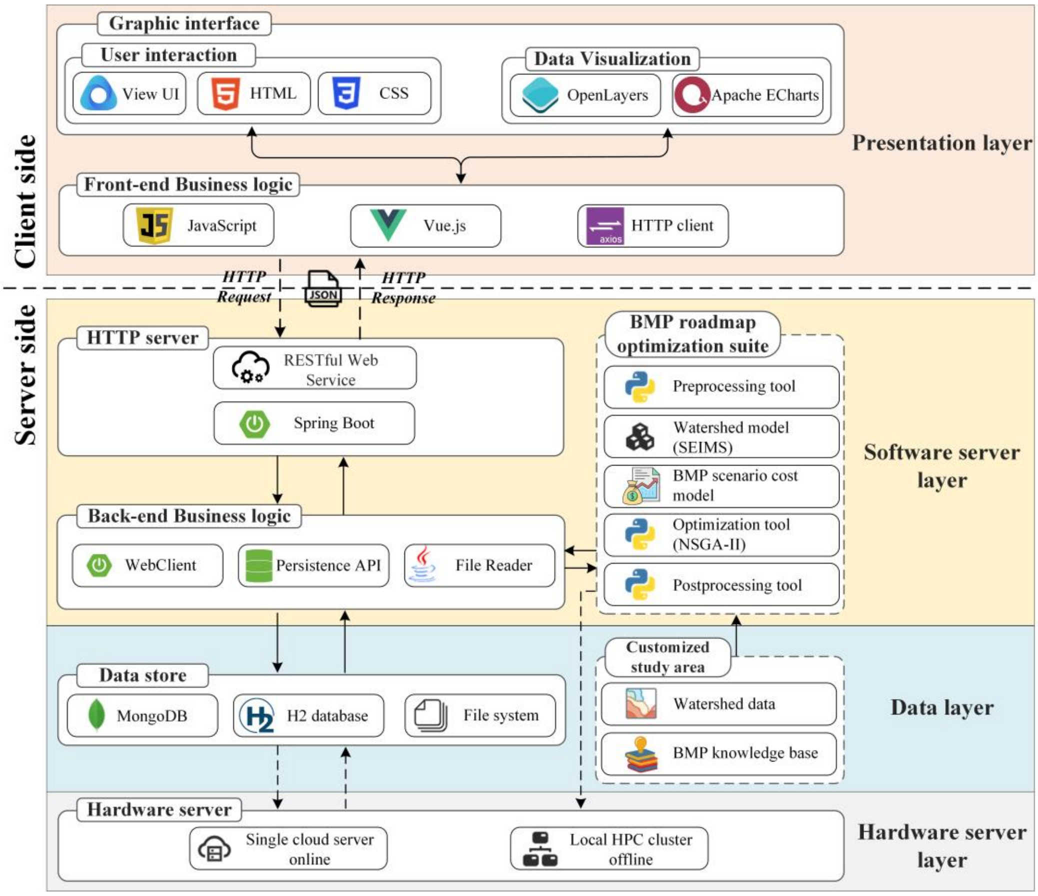


Figure 4 Overall technical schematic diagram of the watershed planning system implemented in the Youwuzhen watershed case study

3.1 Overall implementation

On the server side, the implementation of the BMP roadmap optimization suite by Zhu and Shen et al. (2022) 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., 2023). According to the available modeling data and settings of the previous study (Shen et al., 2023), the period for watershed simulations was from 2011 to 2017, and the implementation period for BMP roadmaps was from 2012 to 2016. The process of executing the optimization task via Python APIs is as follows (Figure 4): 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 the 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 tasks. When the optimization task 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 30 m 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.

On the client side, the entire graphical interface (Figure 5) 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 OpenLayers and Apache Echarts were used to visualize the roadmap spatial dimensions and bar and three-dimensional line charts, respectively.

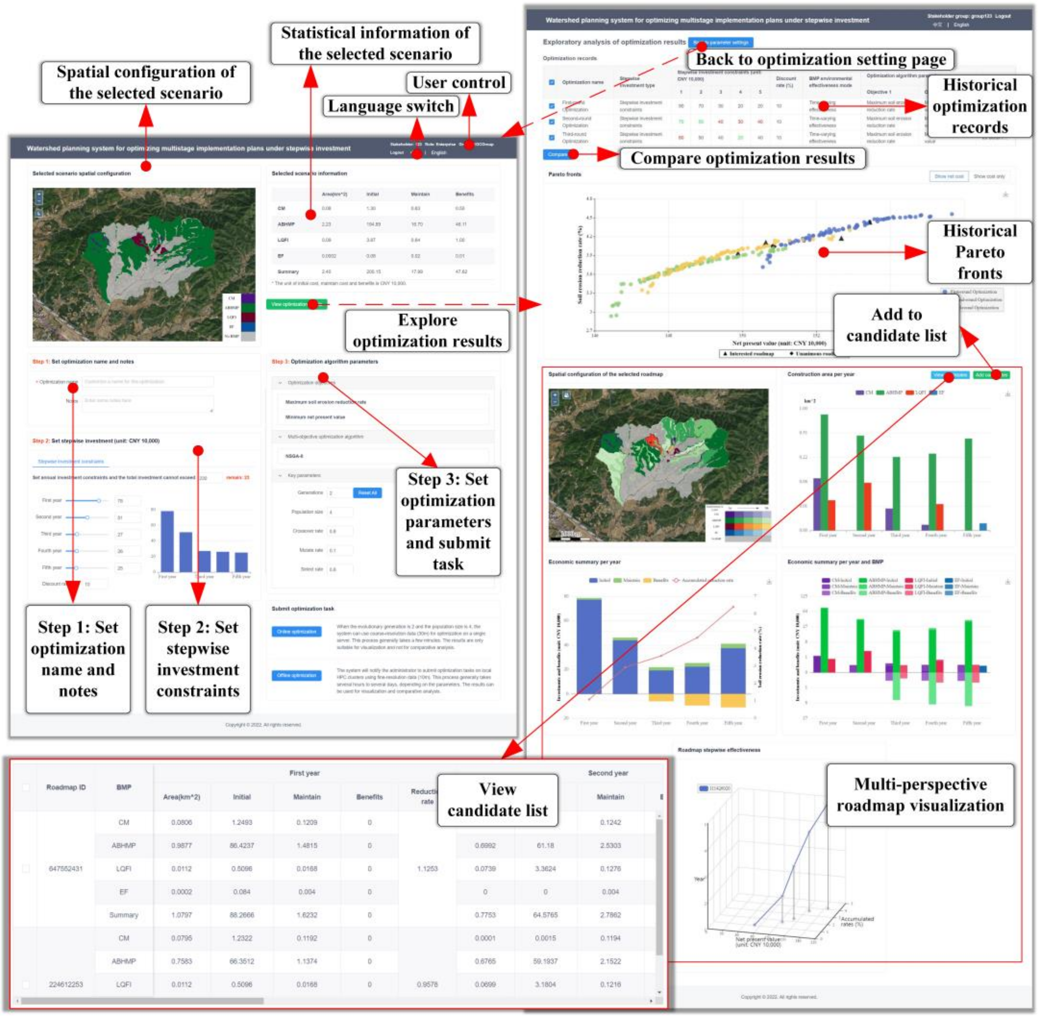


Figure 5 The client-side graphical user interface of the Youwuzhen watershed planning system

3.2 Study area and watershed management goal

The Youwuzhen watershed (approximately 5.39 km^2) in Changting County, Fujian Province, China, was chosen as the study area (Figure 6). The primary geomorphological characteristics are the low mountains and hills with steep slopes (up to 52.9° and with an average slope of 16.8° in the watershed) and broad alluvial valleys (Qin et al., 2018). The study area has a mid-subtropical monsoon moist climate, with an annual average temperature of 18.3 °C and precipitation of 1697 mm. Precipitation is characterized by concentrated and intense thunderstorm events, contributing about three-quarters of the annual precipitation from March to August. 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*). The soil types were red soil (78.4%), majorly distributed in hilly regions, and paddy soil (21.6%) in valleys (Chen et al., 2013, 2017). The red soil, originating from granite, underwent substantial weathering, rendering it inherently lacking essential nutrients, deficient organic matter content, and limited capacity to hold water and thus vulnerable to erosion. As a result of the above natural conditions and long-term human activities (e.g., forest destruction), this area has become one of the most severely eroded counties in the granite-red soil region of southern China (Chen et al., 2013).

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. (2023) and is briefly introduced in the following subsection.

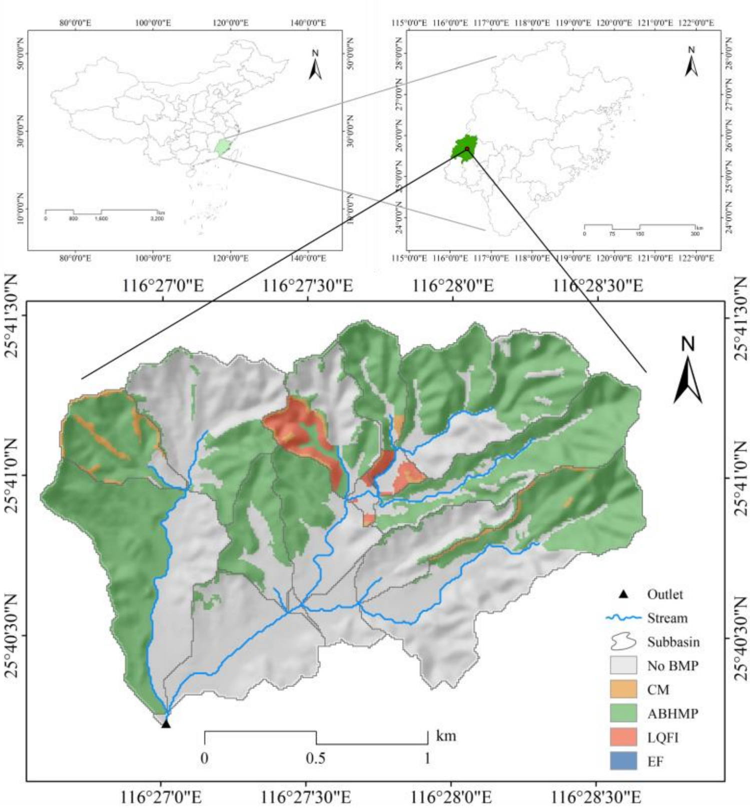


Figure 6 Map of Youwuzhen watershed in Changting County, Fujian Province, China, and spatial distribution of the fundamental best management practice (BMP) scenario based on slope position units derived from Zhu et al. (2019b). Four BMPs are included: closing measures (CM), arbor–bush–herb mixed plantation (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) (refer to Data and code availability section for more details). 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 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 used for spatial optimization of BMPs to derive the cost-effective BMP scenario (Zhu et al., 2019b). The pre-optimized BMP scenario is included in this case study for roadmap optimization. Detailed BMP environmental effectiveness and cost-benefit data adapted from Shen et al. (2023) can be found in Table A.2 of the Appendix. 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 scenario for roadmap optimization

We constructed and calibrated a daily SEIMS-based watershed model 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).

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).

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., 2023). A generalized roadmap spatial optimization problem can be formulated as：

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

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

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

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

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

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., 2023).

4 Experimental design and evaluation

4.1 Experimental design

A multistakeholder role-playing 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 agreed-upon roadmaps. The experiment assumed three stakeholder roles (see Section 2.5) and analyzed possible participatory behaviors from the perspective of their role characteristics and specific needs. 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 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 participatory process was designed as follows:

1) The government stakeholder is the primary investor who leads the first-round optimization and discussion with the standpoint 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 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).

2) The second-round optimization is launched by the enterprise stakeholder based on the elected roadmaps 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.

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.

4.2 Experimental results and discussions

4.2.1 Effectiveness of iterative optimization process in the system

After each of the above optimizations and discussions among stakeholders, a candidate range of multi-objective can be built by stakeholders, from which agreed-upon roadmaps can be determined. Figure 7 depicts the Pareto fronts derived from the three optimization rounds in turn, with the candidate ranges of multi-objective marked as red rectangles. The process of each optimization round is described in detail below.

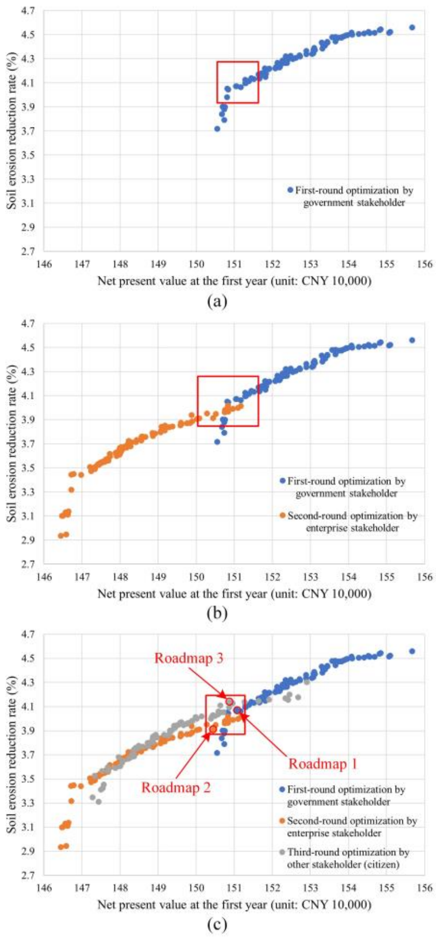


Figure 7 Pareto fronts of the three optimization rounds launched by three stakeholder groups

The first-round optimization by government stakeholders showed 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., 2023). 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 enterprise stakeholder proposed 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. As shown in 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 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 other stakeholders 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. The optimization results 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 standpoints and investment proposals of all stakeholder groups. The progressive shifts in the three optimized roadmap sets can well reflect the differences in standpoints among stakeholders and facilitate the reach of agreed-upon solutions, demonstrating the effectiveness of the iterative 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 solutions can be reached. In this experiment, the scope of this candidate area was focused step by step (the red box in Figures 7a–c) and the investment-environmental effectiveness differences between the roadmaps in the area were no longer apparent, indicating that the agreed-upon roadmaps 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.

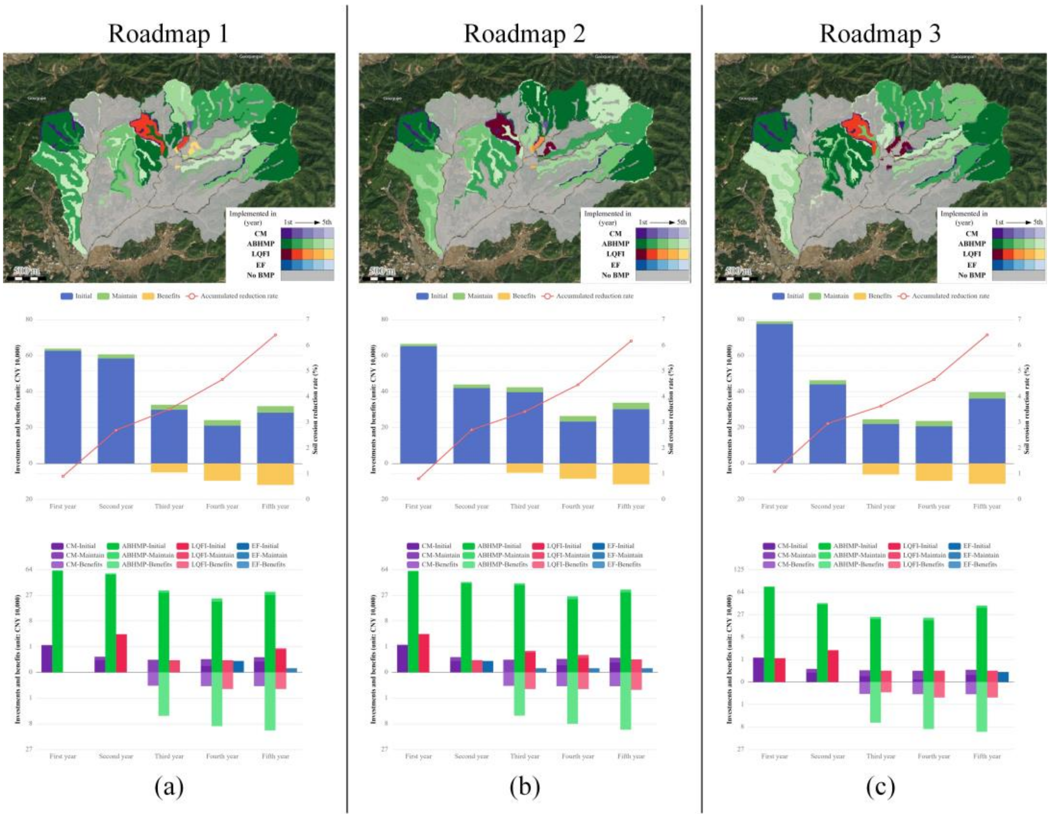


Figure 8 Three representative roadmaps selected from candidate area after three round optimizations, one for each Pareto front. The map in the first row demonstrates the BMP spatiotemporal configuration in the roadmap. The bar chart in the second row demonstrates the annual investment and income, and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

Compared with roadmap#1 derived by the government stakeholder, roadmap#2 by the enterprise stakeholder reduced investment in the second year (also in the first two years) and thus led to a lower environmental effectiveness. Roadmap#3 from the third-round optimization obtained the highest environmental effectiveness with a maximum first-year investment, lowest fourth-year investment, and highest fifth-year investment. Thus, roadmap#3 or similar roadmaps are more likely to become the final agreed-upon roadmap.

The roadmap optimization results affected by stepwise investment plans can 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 investment as the fifth-year investment after discounting is smaller than investments in other years.

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.

From the stakeholder-oriented perspective, with the focus of assisting the participation of multistakeholder 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 to simulate the role-playing experiment. The case study indicated that this system could provide effective comprehensibility of optimized roadmaps through spatiotemporal data visualization. The successful role-playing experiment designed and conducted according to 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 provides sufficient technical support for the sequential participation of the three stakeholder groups in the case study. 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, the proposed design and case study of a watershed planning system could effectively promote the application of the state-of-the-art BMP roadmap optimization method among multiple stakeholders with different standpoints. Technically, any selected BMPs and customized watershed model in any study area aiming at various watershed management needs can be applied to the method proposed by Shen et al. (2023) and the system proposed in this study. Except for the basic structure of the system, including the encapsulated roadmap optimization suite on the back end and the user-friendly interactive workflow and spatiotemporal data visualization, many details of the system implementation can be adjusted by developers. For example, watershed management goals, the accordingly customized multi-objective optimization tool (e.g., Kumeda et al., 2021), the watershed model (e.g., SWAT model), and selected BMPs and their representation in the watershed model.

5. Conclusions and future works

This study proposed the design and evaluation of a web-based participatory watershed planning system for optimizing multistage implementation plans of BMPs, i.e., from the BMP scenario to roadmaps. The system is oriented to the practical watershed management needs for agreed-upon roadmaps involving multiple stakeholders and aiming at promoting the application of the state-of-the-art BMP roadmap optimization method. The design separates easy-to-use interfaces for non-expert stakeholders from specialized models pre-prepared by professional modelers and encapsulated on the back end. The system implementation comprises server and client sides with independent technical routes. The design was demonstrated in an agricultural watershed planning case study for soil erosion reduction. The validity and practicality of the case study system were verified through the role-playing experimental design of three stakeholder groups (i.e., government, enterprise, and other stakeholders such as citizens).

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 having similar functionality. The loosely coupled frontend and backend design allows 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 serve as a suitable platform for inspiring the simulation-and-optimization-based decision-making thinking of students taking environmental management-related courses.

As intended to be a general watershed planning system providing roadmap planning for non-expert stakeholders, several issues or limitations 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 cannot 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. Besides, we appeal to enhance long-term monitoring of the time-varying effectiveness of BMP routinely after implementation and applying the data in related studies of BMP scenario analysis.

Data and code availability

The source code of the Youwuzhen watershed planning system is open-source at GitHub (https://github.com/lreis2415/WatershedPlanningSystem), and the front- and back-end projects are located in the mip-wps-web and mip-wps-service folders, respectively. The improved SEIMS programs and the prepared data encapsulated in the back end are freely available at Shen and Zhu (2022). The Youwuzhen watershed spatiotemporal datasets are in the /SEIMS/data/youwuzhen/data_prepare folder, including meteorological data, property lookup tables of landuse/landcover and soil, spatial data, and BMP knowledge data, etc.

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Supplementary materials on brief descriptions, environmental effectiveness data, and cost-benefit data of the four best management practices (BMPs) considered in this study

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)). These representative BMPs have been widely implemented for soil and water conservation in this study area.

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.

Shen Shen: Conceptualization, Methodology, Software, and Writing - Original Draft. **Cheng-Zhi Qin:** Conceptualization, Supervision, Writing - Review & Editing, and Funding acquisition. **Liang-Jun Zhu:** Conceptualization, Methodology, Writing - Review & Editing, and Funding acquisition. **A-Xing Zhu:** Supervision and Funding acquisition.