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# Select Optimal Treatment Modes and Priority Villages for Investments on Rural Sewage Treatment in China

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**Abstract:** Rural sewage treatment (RST) has emerged as a critical issue in the restoration of China's environment. In comparison to urban areas, the planning and management of RST in rural settings are significantly more complex and often constrained by limited budgets. It is significant and urgent for provincial or municipal governments to identify the optimal treatment modes and the most "priority" villages for RST investment. Decision-makers face a series of questions that require quantitative answers. This study proposes a generic decision-making model aimed at selecting priority villages for investment, considering economic and ecological benefits as well as life-cycle costs. Case studies were conducted across Guangdong, Henan, and Hunan Provinces in China, encompassing a total of 48,000 villages. The model successfully generated RST treatment modes maps and priority maps. Results indicate that the return on investment (ROI) for the top 5% of villages selected by this decision-making model in Guangdong Province reached 1.75, which is 20.3% higher than returns from random investments. Furthermore, the corresponding average revenue was 6 times greater than that of randomly selected villages. The model also demonstrated strong performance in the other 2 provinces. Factor importance analysis—utilizing random forest regression models alongside SHAP methodology—reveals that population size is the most influential factor affecting prioritization within these areas. The proposed decision-making model offers scientific and efficient solutions for optimizing a fixed number of RST investment with predetermined investments while maximizing marginal benefits from those investments. Overall, this approach significantly enhances the efficiency of special funds allocated for ecological environmental protection.

**Keywords**: Rural sewage treatment, multiple objective optimizations, cost-benefit analysis

## 1. Introduction

Rural sewage treatment in China faces significant challenges due to the imbalance between sewage discharge and treatment facilities, with rural areas significantly lower than urban areas. This has led to environmental issue such as eutrophication and health risks. RST rates vary widely across regions in China, with the eastern region at 36.3%, and the central and western regions at 19.3% and 16.8%, respectively. It is significant and in emergency for provincial or municipal government to select the best modes for RST and the most "priority" villages.

Therefore, this research aims to establish a national wide decision-making model to select priority villages for RST investment. The model integrates the economic and ecological benefits, life-cycle costs of RST investment for three sewage treatment modes (decentralized, joint-village and single-village centralized), which also considers the impact of rural population, location, income, and topographic slope. Case studies in Guangdong, Henan, and Hunan provinces will produce modes distribution maps and priority zoning maps.

Decision makers will address specific questions: Q1. *Which sewage treatment mode is the best for a village?* Q2. *How to select the optimal village sets to achieve the maximum benefit or lowest cost when the number of projects or investment amount is fixed?* Q3. *Marginal benefit analysis of investments, for example, which villages have the return of investment (ROI) larger than one?* Q4. *What features of the village impact the priority ranking most?*

## 2. Methods and results

The framework of the cost-benefit analysis model is shown below.

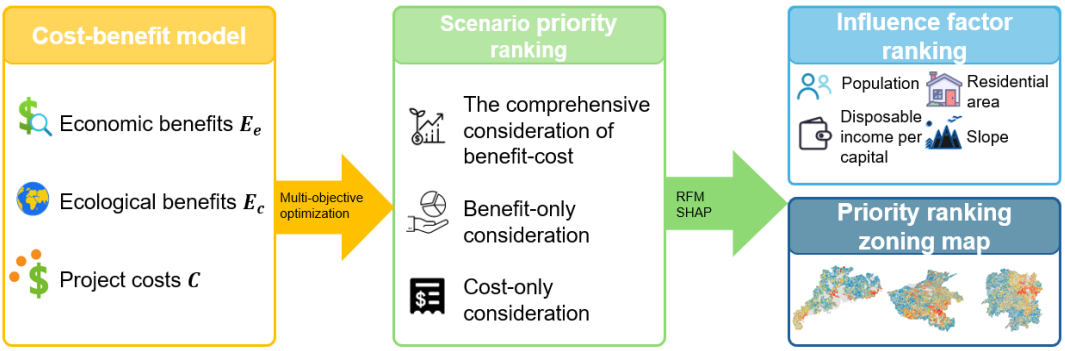


**Figure 2.1** The framework of the rural sewage treatment benefit-cost analysis model.

In this study, priority of a village is determined by a function, where decision-makers pursue maximizing benefits E while minimizing costs C.

$$\max \sum_{i}^{n} x_i \left(\frac{E_i}{C_i}\right)/n, subject\ to \sum_{i}^{n} x_i C \leq Cp, x_i = 0,1 \text{ (Equation 1)}$$

$$\max \sum_{i}^{n} x_i (E_i - C_i)/n, subject\ to \sum_{i}^{n} x_i C \leq Cp, x_i = 0,1 \text{ (Equation 2)}$$

$$\max \sum_{i}^{n} x_i (E_i - C_i),\ subject\ to \sum_{i}^{n} x_i \leq Np, x_i = 0,1 \text{ (Equation 3)}$$

The life-cycle cost encompasses equipment construction, installation, and operation maintenance expense. There are three sewage treatment modes equations: (4) is decentralized treatment, (5) is single-village centralized treatment, (6) is joint-village centralized treatment.

$$f = \frac{P}{3} \quad \{1.56A + 11.47[\alpha_1(G - 18700) + 450]\} \text{ (Equation 4)}$$

$$g^a = \lambda P[a_2(G - 18700) + 3600] + P\lambda m_1 t + 10^{-4} \sum_{i=0,1} L_{ai} C_i \text{ (Equation 5)}$$

$$g^b = \lambda P[a_3(G - 10000) + 5000] + P\lambda m_1 t + 10^{-4} \sum_{i=0,1} L_{bi} C_i \text{ ) (Equation 6)}$$

The economic benefits are income from the collection of sanitation fees ($E_{e_1}$), the sale of reuse water ($E_{e_2}$), and selling sludge composting($E_{e_3}$). The ecological benefits ($E_c$) are calculated based on the volume of sewage treated and the price of urban water supply.

$$E_{e_1} = F_1 \times Q_{\text{input}} \times (P/A, i, n) \text{ (Equation 7)}$$

$$E_{e_2} = P_{\text{reused}} - C_{\text{reused}} = \left(F_2 \times Q_{reused} - \alpha {Q_{reused}}^{\beta}\right) \times (P/A, i, n) \text{ (Equation 8)}$$

$$E_{e_3} = F_3 \times Q_{\text{sludge}} \times (P/A, i, n) \text{ (Equation 9)}$$

$$E_c = \left(Y_2 - Y_2^{'}\right) \times 1.06 \text{ (Equation 10)}$$

Furthermore, this study takes the rural areas of Guangdong Province, Hunan Province, and Henan Province in China as case studies to explore wastewater treatment projects under different geographical features, economic, and population conditions.

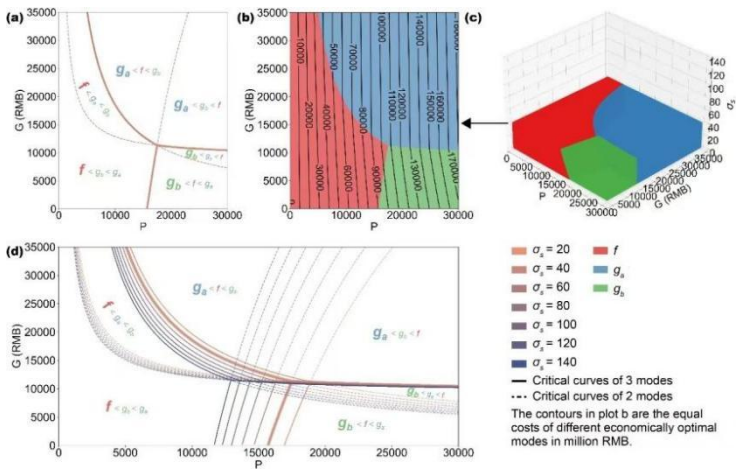


**Figure 2.2** Example of critical curves of 3 RST modes

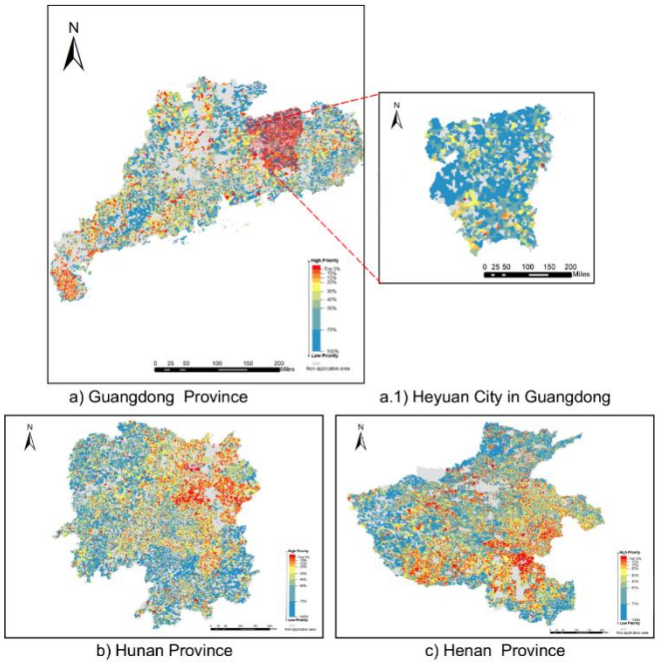


**Figure 2.3.** Priority ranking map of rural sewage treatment projects in three provinces under the comprehensive consideration of benefit-cost

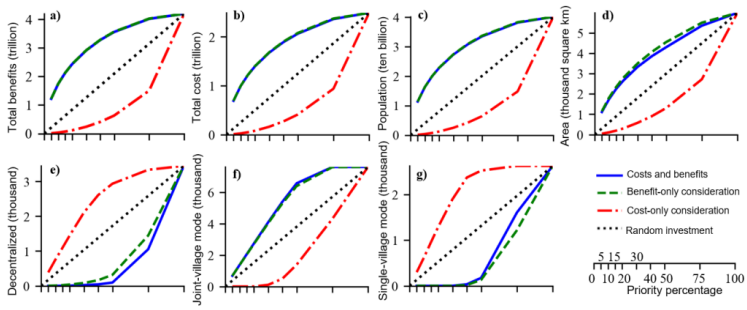


**Figure 2.4.** The margin benefit for rural sewage treatment projects in Guangdong Province based on the multiple-objective optimization (a) Total benefits (b) Total costs (c) Population covered by projects (d) Residential area covered by projects (e) Number of decentralized treatment projects (f) Number of single-village centralized treatment projects (g) Number of village joint-village centralized treatment projects

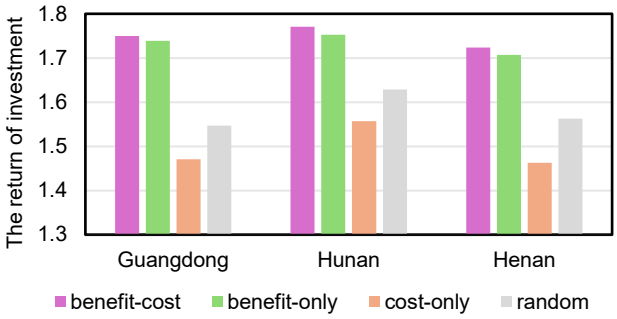


**Figure 2.5.** The ROI of Top 5% Prioritized Rural Sewage Treatment Projects in Guangdong, Hunan, and Henan Provinces under four Scenarios.

The results show the priority map of RST investment in three provinces. The red areas represent high-priority degree of RST. The model can address decision-making questions. If a city plans to invest 500 million RMB, the model provides the information including the number of villages, the population covered, the expected revenue, and the Return on Investment. The areas with smaller population are more suitable for decentralized sewage treatment. Discussions are also presented about the marginal benefits of RST investment and the importance of influencing factors.

## 3. Conclusion

A decision-making model for RST mode optimization is established based on life cycle cost estimation. It evaluates three treatment patterns and four impact factors. Then the decision-making model for selecting priority villages for RST investment is established considering economic and ecological benefits. In Guangdong, the top 5% projects showed an ROI of 1.75, outperforming random investments by 20.3%. The population is the most influencing factor in this model. The model's feasibility varies by region. Adjustments are made for constants like RST charging standards, economic return from reused sewage and so on. The result of the other three provinces will be completed. The model supports efficient national rural wastewater project planning. This study provides an analytical decision-making tool, supporting national rural sewage project planning and management. It generates significant investment efficiency.

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