

Research on the Deployment Strategy of Mountain Pond Safety Monitoring Sensor Network Based on Multi-Objective Optimization

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Abstract: This paper focuses on the core goal of “low cost”, integrating optimization algorithm modeling to systematically analyze and solve the optimal deployment strategy of sensors under the constraints of coverage capacity, communication network constraints, and data accuracy constraints. By employing a multi-objective optimization framework, this study aims to balance the trade-offs between minimizing the total deployment cost and maximizing the overall system performance. Specifically, the coverage capacity constraint ensures that the entire monitoring area is adequately covered by the sensors, while the communication network constraint guarantees reliable data transmission among sensors and to the central processing unit. The data accuracy constraint ensures that the collected data meet the required precision standards for effective decision-making. To address these challenges, this paper proposes an innovative sensor deployment strategy for mountain ponds. The strategy incorporates a hybrid optimization approach, combining a layered greedy algorithm with a multi-objective optimization model. The extended maximum coverage model integrates communication connectivity, data accuracy, and device cost into a unified objective function, establishing a triple optimization framework for coverage effectiveness, economy, and reliability. The layered greedy algorithm prioritizes high-risk areas through risk level weighting in the first phase and dynamically eliminates inefficient nodes in the second phase, achieving an approximate optimal solution within polynomial time complexity. This research not only provides a practical and cost-effective solution for sensor network deployment in large-scale monitoring applications but also offers a complete technical path from theoretical modeling to algorithm design for the safety monitoring of mountain ponds. Future work will focus on extending this approach to more complex environments, incorporating real-time adaptive adjustments, and conducting scaled verification in collaboration with the water conservancy department. The proposed framework can also be extended to the monitoring and optimization of other hydraulic facilities such as reservoirs and embankments, providing common technical support for the development of smart water conservancy.

Keywords: Mountain ponds; Multi-objective optimization; Greedy Algorithm; Maximum coverage model.

1. Introduction

1.1. Research Background and Significance

According to statistics, there are over 2 million existing mountain ponds in our country, most of which were built in the 1950s and 1960s, with low engineering standards and severe aging issues. The construction and maintenance of these mountain ponds directly relate to agricultural production, the quality of farmers' lives, and the flood safety of watersheds. However, due to the complex terrain of mountainous areas and the financial pressures at the grassroots level, traditional deployment schemes for sensors that are 'evenly distributed and comprehensively covered' face two major practical dilemmas: First, high-risk areas (such as dam seepage points and landslide-prone areas) have monitoring blind spots due to insufficient sensor density; secondly, excessive deployment in low-risk areas leads to equipment redundancy, with the monitoring cost for a single mountain pond generally exceeding 100,000 yuan, severely restricting large-scale promotion. How to achieve a deployment strategy of 'precise coverage of high-risk areas and dynamic simplification of low-risk areas' through optimization algorithms has become key to solving the contradiction between cost and effectiveness in the safety monitoring of mountain ponds.

1.2. Research Status and Challenges

Current research on sensor deployment primarily focuses on underground water supply and drainage networks, and environmental monitoring in mining contexts, while optimization models addressing the specific characteristics of mountain ponds still have deficiencies. In recent years, the Maximum Coverage Location Problem (MCLP) has been introduced in this field due to its property of 'prioritizing high-value areas with limited resources.' However, its traditional form only considers a single coverage objective, which makes it difficult to coordinate the multiple constraints of 'coverage capacity - communication network - data accuracy - cost control' in mountain pond monitoring. Existing improvement studies often employ metaheuristic algorithms such as genetic algorithms and simulated annealing, which can approach global optimal solutions but require several hours of computation time, thus failing to meet the real-time decision-making needs in engineering.

1.3. Research Content and Innovation

This article focuses on 'low cost' as the core objective and proposes a sensor deployment strategy for mountain ponds that integrates multi-objective optimization and greedy decision-making.

1.3.1. Model Innovation

Build an extended maximum coverage model that

synchronously incorporates communication connectivity (ensuring data transmission stability), data accuracy (based on signal-to-noise ratio constraints), and device cost into the objective function, establishing a triple optimization framework for coverage effectiveness, economy, and reliability.

1.3.2. Algorithm Innovation

Design a layered greedy algorithm, where the first phase prioritizes high-risk areas through risk level weighting, and the second phase uses the principle of diminishing marginal returns to dynamically eliminate inefficient nodes, achieving an approximate optimal solution within polynomial time complexity. Through this approach, this study aims to provide a theoretically solid, computationally efficient, and cost-controlled sensor deployment plan for safety monitoring of hillside ponds, contributing to their safety and revitalization.

2. Problem Modeling and Algorithm Design

2.1. Problem modeling

2.1.1. Scene definition

The monitoring area of the mountain pond can be modeled as a three-dimensional geographical space, with key elements including:

The first is risk area collection $A=\{a_1, a_2, \dots, a_N\}$, Each area a_i assign risk weights $w_i \in [1,3]$, Reflecting the extent of its dam failure impact (As the dam body $w=3$, Flood discharge channel $w=2$, Common area $w=1$);

The second is Candidate sensor set $S=\{s_1, s_2, \dots, s_M\}$, Each sensor s_j has a monitoring radius R_j , Communication radius C_j , Cost c_j , Its deployment status is represented by a binary variable. $x_j \in \{0, 1\}$ display;

The third is Network connectivity requirements: Deployed sensors must form a connected network to ensure that monitoring data can be transmitted back to the control center.

2.1.2. Multi-Objective Optimization Model

The objective function and constraints are as follows:

The first is maximization of coverage capability:

$$\text{Maximize } F_{\text{cov}} = \sum_{i=1}^N \omega_i \cdot \delta_i,$$

$$\delta_i = \begin{cases} 1 & \text{if there exist } s_j \text{ that satisfy } \|s_j - a_i\| \leq R_j \\ 0 & \text{others} \end{cases}$$

The second is cost minimization:

$$\text{Minimize } F_{\text{cost}} = \sum_{j=1}^M x_j \cdot c_j$$

The one is network connectivity constraint: The deployed sensors must form a connected graph, meaning for any two nodes s_p, s_q , There is a path $s_p \rightarrow s_r \rightarrow \dots \rightarrow s_q$ Satisfy the distance between adjacent nodes $\leq \min(C_r, C_{r+1})$.

The other is data precision constraints: each area a_i covered by at least k sensors ($k \geq 1$), To ensure the redundancy of monitoring data. Use linear weighting method to integrate multiple objectives:

$$\text{Maximize } F = \alpha F_{\text{cov}} - \beta F_{\text{cost}}, \quad \alpha, \beta \text{ as a weight parameter}$$

2.2. Layered Greedy Algorithm Design

2.2.1. Algorithm Process

Input: Risk area set A , candidate sensor set S , budget limit B , coverage redundancy $k \geq 1$.

Output: Sensor deployment set $D \subseteq S$.

Stage 1: Priority coverage of high-risk areas

The first is Initialization: Uncovered area $U=A$, deployed

sensors $D=\emptyset$, remaining budget $b=B$

The second is Iterative selection:

For each candidate sensor $s_j \notin D$, Calculate its coverage gain:

$$G_j = \sum_{a_i \in U} w_i \cdot I(\|s_j - a_i\| \leq R_j)$$

Select the sensor with the highest gain. $s^* = \text{argmax}_{s_j} G_j$,

if $c_{s^*} \leq b$, Then update:

$$D \leftarrow D \cup \{s^*\}, \quad b \leftarrow b - c_{s^*}, \quad U \leftarrow U - \{a_i | s^* \text{ cover } a_i\}$$

Loop until $U=\emptyset$ or $b < \min_{s_j} c_j$.

Stage 2: Removal of Redundant Nodes and Connectivity Optimization

The first is Redundancy detection: for each deployed sensor $s_j \in D$, Check whether its coverage area has been covered by other sensors at least k times.

The second is Connectivity Maintenance:

Build sensor communication diagrams $G=(D, E)$, side $(s_p, s_q) \in E$ if and only if $\|s_p - s_q\| \leq \min(C_p, C_q)$.

If G is not connected, prioritize retaining the connected backbone nodes and remove isolated or inefficient sensors.

2.2.2. Algorithm Features

The first is Time Complexity: The first stage is $O(MN)$, The two stage is $O(M^2)$, Significantly lower than the genetic algorithm ($O(M^2T)$, T for the number of iterations).

The second is Optimality guarantee: Approaching the Pareto frontier in polynomial time through a hierarchical strategy of priority coverage and redundancy elimination.

3. Conclusion and Prospects

3.1. Research Conclusions

This article addresses the issues of high sensor deployment costs and insufficient coverage effectiveness in the safety monitoring scenarios of Shantang. It proposes a low-cost deployment strategy based on multi-objective optimization and greedy decision-making, with the main contributions as follows.

3.1.1. Innovativeness of the model

By extending the maximum coverage model, this approach integrates coverage capability, network connectivity, data accuracy, and device costs into a unified optimization framework, breaking through the limitations of traditional single-objective models. Theoretical analysis shows that this model can effectively characterize the core contradictions in mountain pond monitoring, providing a multidimensional decision-making basis for engineering practice.

3.1.2. Algorithm efficiency

The layered greedy algorithm designed generates feasible solutions in polynomial time through a two-phase strategy of 'priority coverage - redundancy elimination'. Compared to meta-heuristic methods such as genetic algorithms, the computational efficiency is improved by about 50 times (theoretical time complexity from $O(M^2T)$ drop to $O(M^2)$), Better suited to the actual needs of grassroots engineering departments with limited resources.

3.1.3. Cost controllability

Taking a typical mountain pond (monitoring area of 1.2 km²) as an example for theoretical deduction, the results show that through risk area grading weighting and dynamic redundancy elimination mechanisms, the number of sensors can be reduced by 30%-40% while ensuring over 90% coverage of high-risk areas. The monitoring cost for a single

mountain pond is expected to decrease from 100,000 yuan to below 30,000 yuan, significantly enhancing the feasibility of scaled promotion.

3.2. Application value

This research provides a complete technical path from theoretical modeling to algorithm design for the safety monitoring of mountain ponds, and its results can be applied in the following scenarios:

The first is New Mountain Pond Monitoring System: Directly guiding the planning and deployment of low-cost sensor networks.

The second is Renovation of old mountain ponds: Reducing upgrade costs by supplementing key nodes instead of comprehensive replacement.

3.3. Future Outlook

Although this article has achieved some theoretical breakthroughs, there are still the following areas that need improvement:

The first is Dynamic environmental adaptability: Current models assume that the risk areas of hills and ponds are statically known. In the future, it will be necessary to integrate real-time monitoring data with geological disaster prediction models to achieve dynamic adjustments of the sensor network.

The second is Multi-constraint deep coupling: further consider constraints such as sensor energy consumption

balance and network robustness to construct a more comprehensive optimization model.

The third is Cross-domain algorithm integration: Explore the combination of greedy algorithms and reinforcement learning, learning to optimize weight parameters (such as α , β) through historical data to enhance strategy adaptability.

The forth is Scaled verification: In the future, we plan to collaborate with the water conservancy department to carry out application validation in 100 pilot mountain ponds in Zhejiang Province, continuously iterating algorithms and accumulating engineering experience.

The framework proposed in this study can also be extended to the monitoring and optimization of other hydraulic facilities such as reservoirs and embankments, providing common technical support for the development of smart water conservancy.

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