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Optimizing watchtower locations for forest fire monitoring using location models

Shitai Bao [a], Ningchuan Xiao [b,*], Zehui Lai [a], Heyuan Zhang [c], Changjoo Kim [d]

[a] Department of Geographic Information, South China Agricultural University, 483 Wushan Road, Guangzhou, Guangdong Province 510642, China
[b] Department of Geography, The Ohio State University, 1036 Derby Hall, 154 North Oval Mall, Columbus, OH 43210, USA
[c] Department of Science and Information Technology, Administration of Forestry and Gardening of Guangzhou Municipality, 348 Huanshi East Road, Guangzhou, Guangdong Province 510060, China
[d] Department of Geography, University of Cincinnati, 400B Braunstein Hall, Cincinnati, OH 45221, USA

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ABSTRACT

Automated forest fire monitoring systems can be constructed using forest fire watchtowers equipped with laser night vision cameras or high-definition video cameras. In order to minimize the construction cost and to maximize the monitoring coverage of forest fires, efficiently placing the watchtowers is critical. This paper examines efficient watchtower locations by integrating visibility analysis and location-allocation models. Specifically, based on the classical location set covering problem and maximum covering location problem, three optimization models are developed to satisfy three kinds of requirements of forest fire monitoring in practice: minimizing cost with full coverage, maximizing coverage with a fixed budget, and maximizing coverage while minimizing the cost. The models are tested using integer programming and a multi-objective genetic algorithm, with an application in a forest park in Guangzhou, China. The results suggest that this model-based optimization approach to watchtower location can be used to improve the efficiency of forest fire alarm systems.

1. Introduction

Forest fire is a severe natural disaster and public emergency of the world. Fire incidents are often abrupt, spread rapidly, difficult to control, and highly disastrous, and have become a serious threat to forest resources globally as they affect forest ecosystem succession and global climate change. According to a report of Greenpeace Research Laboratories and climate change research of United States Environmental Protection Agency, there has been an increase in the number of forest fires because of global warming and intense human activities [1,2]. In recent years, forest fires, known as wildfires, consumed more than 6.25 million acres of forest in Alaska (roughly equal to the area of Massachusetts) [2]. Climate change is projected to increase the extent, intensity, and frequency of wildfires in certain areas of our earth. Forest fires have also become a major concern in China in recent decades because of the increasingly serious damage they have done to the environment and the loss of societal wealth incurred. According to a report on Chinese forestry development, a total of 3966 forest fire incidences were identified in 2012, and China spent ¥342,000,000 fighting forest fire, and the government invested more than 2 billion Yuan on 190 construction projects to prevent forest fire [3].

Among many preventive measures, early detection and suppression of forest fires are the main ways to minimizing damage. The critical issue in forest fire monitoring systems is the immediate response in order to minimize the scale of destructions. Many countries that have recognized the significant importance of forest fire monitoring have developed effective technologies, including monitoring via observation towers, cruising aircrafts, remote sensing using meteorological satellites, and sensor networks, to improve their response ability [4–8]. Forest fire monitoring technology was implemented belatedly in China but has experienced a rapid growth, with watchtowers being the first selection for forest fire monitoring in the country. In the light of the 2013 report of Chinese forestry development, for example, various preventive and monitoring measures have been implemented, and the coverage rate of forest fire monitoring has increased from 45.3 to 63.1 percent in China [3]. Since December 2013, the Administration of Forestry and Gardening of Guangzhou Municipality launched a project of 74 million Yuan to monitor fire of key forest zones and green parks by video cameras, which will equip 941 cameras to cover 8 parks, 3 forest farms, and 2 forest and wild animal protection areas [9].

* Corresponding author. Fax: +1 614 292 6213.
E-mail address: xiao.37@osu.edu (N. Xiao).

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Protecting wild animals, forests, and the environment from forest fires has long been a major concern in environment and natural resources management [10]. In the past, forest personnel monitored fires from watchtowers that were located on hilltops in forests so that forest fires could be discovered and alarmed as soon as possible [6,7]. However, living conditions are often difficult at lookout towers for human observations who may also lack the consistency and reliability required for constant monitoring. As a result, vision techniques such as automatic video surveillance systems (AVSS) were proposed to monitor small forests [8]. Many medium and large-scale fire surveillance systems currently do not accomplish timely detection because of low resolution or long periods between scans [6,7]. With developments in technology, high definition video cameras and sensor networks are now being used to equip watchtowers and automate forest fire monitoring. Further, watchtowers can be equipped with solar panels that supply power to support the compression of images and real-time transmissions to command centers via wireless networks. Forest fire watchtowers equipped with laser night vision cameras or high-definition video cameras can constitute an automated forest fire monitoring system that has a wide coverage of monitoring viewsheds and can quickly respond to forest fire alarms (Fig. 1).

Determination of the optimum location of permanent fire watchtowers in a given forest area has been, and continues to be, of significant interest to both the practitioners and research communities [11,12]. The efficient location of watchtowers equipped with cameras has become increasingly important as it can directly influence the construction cost of watchtowers and the monitoring coverage of forest fires [13]. It is a combinatorial optimization problem and, consequently, is difficult to obtain optimal location solutions using simple enumeration and search methods or viewshed analysis based on geographic information systems (GIS). Further, watchtowers need to be sited optimally to meet forest fire monitoring requirements such as full coverage, maximal coverage, minimal cost, and/or minimum overlap for forest fire monitoring. There are also specific constraints such as terrain limitations and the effective detection range of cameras installed on watchtowers of various heights.

This paper proposes a modeling approach to optimizing the spatial coverage of watchtowers equipped with cameras in forest zones. This approach integrates coverage models and visibility analysis into a spatial optimization framework and applies the result to forest fire monitoring. The aim of the approach is to develop a procedure for finding optimal solutions of locating watchtower that satisfy a set of objectives and specific constraints of forest fire monitoring in practice. In the remainder of this paper, Section 2 analyzes technical problems associated with forest fire electronic monitoring, Section 3 presents the three proposed optimization models, Section 4 outlines the implementation procedure for the three models and discusses the application results obtained, and Section 5 summarizes and concludes this paper.

2. Problem analysis

When a watchtower is planned for construction on an undulating terrain, a major concern is the tower's viewshed, meaning a set of locations on the terrain that are visible from the watchtower extending out to the maximum visibility distance of the camera. Viewshed analysis is an important function of GIS as a method of visibility analysis based on the terrain and has been successfully applied in many applications [14–17]. The viewshed of a watchtower is computed and analyzed at each candidate location based on a digital elevation model (DEM) from which the elevation of each cell is used to determine the visibility to or from a candidate position when applied to forest fire monitoring [17]. Usually the candidate positions for building watchtowers are the many hilltops in the forest, as illustrated in Fig. 2. The viewshed of a watchtower is subject to the height and position of the hilltop and tower, the maximum visibility distance of the camera, and the undulating terrain in a given forest area. A location or a cell in the DEM is considered to be covered if it is within the viewshed of a watchtower, in which a cell value of one signifies the primary coverage meaning the cell is covered by only one tower. Cells with a value of zero are gaps between viewsheds, and fire monitoring blind zones that are at risk of forest fire disaster.

Watchtowers need to be sited optimally to obtain maximal coverage or minimal cost for forest fire monitoring, taking into account terrain conditions and the effective detection range of the cameras mounted on watchtowers at various heights. While viewshed analysis can be used to provide useful information for siting watchtowers, the method alone cannot generate optimal watchtower locations. Instead, optimization models must be used to help search for watchtower locations in order to satisfy a set of requirements of watchtower regarding monitoring coverage and construction costs. Two optimization models are of particular importance in this research. When watchtowers must monitor the entire forest area, the location set covering problem or LSCP [18] can be used to minimize the total construction cost while guaranteeing that each cell is covered at least once. ReVelle [18] also studied the use of multiple types of facility to fully cover the demands with an objective to minimize the number of facilities in the LSCP as a way of minimizing the cost. While complete coverage of watchtowers to cover all demands is ideal, it is sometimes economically infeasible due to budget constraints. In this case, the maximal covering location problem, or MCLP, is used so that the

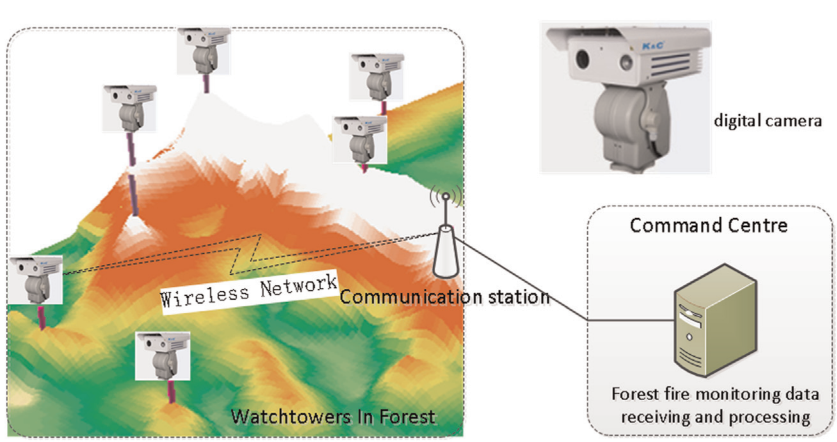

Fig. 1. Automated forest fire monitoring system.

goal is to maximize the coverage under certain budgetary constraints [19].

Much research has been successfully conducted on the optimization methods using the set covering problem [20]. Goodchild and Lee [21] and Lee [22], for example, investigated terrain coverage problems on topographic surfaces by applying the location set covering and maximal covering location problems and solving them using greedy heuristic approaches. Bagheri [23] explored coverage problems for forest fire detection and showed that the problem is NP-hard. Kaucic and Zalik [24] developed optimal models for K-guarding of polyhedral terrain based on the set covering problem and solved them using heuristic solution techniques. Bao et al. [25] presented a practical solution to the full coverage problem in terms of the ratio of the covered area and cost for all candidate watchtowers. While these optimization models have been widely used in the facility location and operations research literature, their use in locating watchtower for forest fire monitoring has not been fully examined. In this paper, we discuss how these models can be extended for our research goals and demonstrate how they can be used in locating watchtowers for an application area.

3. Watchtower location models

Based on the LSCP and MCLP models, we developed three application models specifically for locating watchtowers in a context of forest fire monitoring. We incorporate multiple types of watchtowers that can be equipped with cameras with different specifications. The indices and constants used in our models are listed below:

t=index of a watchtower type ($0 \le t \le T-1$),
i=index of a potential location for building a tower ($0 \le i \le M-1$)j=index of a demand cell in the grid that needs to be monitored ($0 \le j \le N-1$),
C_{it} = cost of building a type t tower at location i,

$$a_{ijt} = \begin{cases} 1 & \text{if a tower of type } t \text{ at location } i \text{ can cover cell } j \\ 0 & \text{otherwise} \end{cases}, \text{ and}$$

B=a constant budget of building watchtowers.
And the decision variables used in the models are defined

$$\text{as} x_{it} = \begin{cases} 1 & \text{if a type } t \text{ tower is located at cell } i \\ 0 & \text{otherwise} \end{cases}, \text{ and}$$

$$Z_j = \begin{cases} 1 & \text{if cell } j \text{ is covered by at least one tower} \\ 0 & \text{otherwise} \end{cases}.$$

3.1. Minimum cost with full coverage

In this model we minimize the total cost of watchtower construction. This model is similar the location set covering problem. To fit the forest fire monitoring setting of this paper, we include the support of multiple watchtower types as has been reviewed in the literature [18,26].

$$\min \sum_{t=1}^{T}\sum_{i=1}^{M} C_{it}x_{it} \tag{1}$$

subject to

$$\sum_{t=1}^{T}\sum_{i=1}^{M} a_{ijt}x_{it} \ge 1 \quad \forall\ j \tag{2}$$

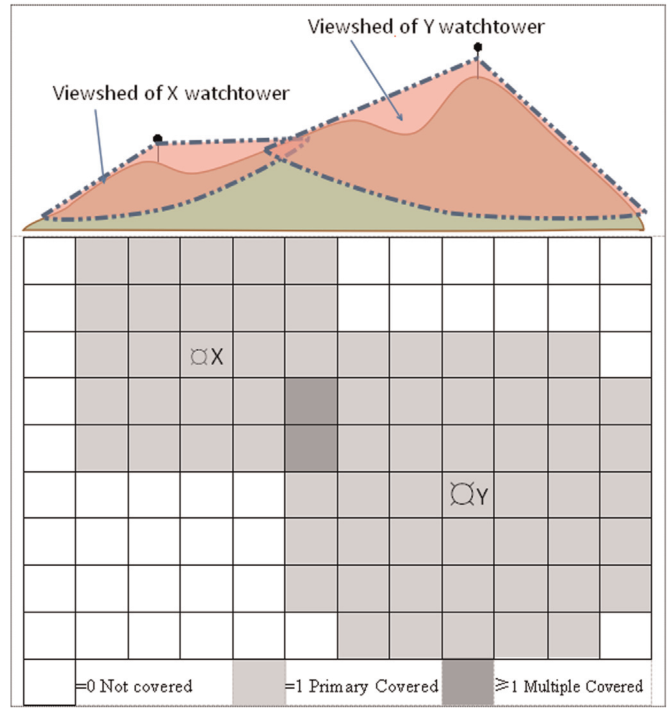

Fig. 2. Viewshed analysis of multiple watchtowers based on the DEM.

$$\sum_{t=1}^{T} x_{it} \le 1 \quad \forall\ i \tag{3}$$

$$x_{it} \in \{0,\ 1\} \quad \forall\ i, t \tag{4}$$

Objective function (1) seeks to minimize the cost of building the towers. Constraints (2) ensure that every grid is covered by at least one tower. Constraints (3) ensure that only one type of tower is built at candidate location i. Constraints (4) specify binary decision variables.

3.2. Maximal coverage with a budget

Because of budget constraints in practice, it may be difficult to fully cover a forest by arranging a large number of watchtowers. Here we extend the maximal covering location problem (MCLP) so that multiple tower types can be used in forest fire monitoring:

$$\max \sum_{j=1}^{N} Z_j \tag{5}$$

subject to

$$\sum_{t=1}^{T}\sum_{i=1}^{M} c_{it}x_{it} \le B \tag{6}$$

$$z_j \le \sum_{t=1}^{T}\sum_{i=1}^{M} a_{ijt}x_{it} \quad \forall\ j \tag{7}$$

$$\sum_{t=1}^{T} x_{it} \le 1 \quad \forall\ i \tag{8}$$

$$x_{it} \in \{0,\ 1\} \quad \forall\ i, t \tag{9}$$

$$Z_j \in \{0,\ 1\} \quad \forall\ j \tag{10}$$

Objective function (5) seeks to maximize the covered grid demand. Constraint (6) makes sure the total construction cost is within the budget (B). Constraints (7) make sure that if cell j is covered, a tower must be located at a location that can cover j. Constraints (8) make sure that no more than 1 tower is built at each candidate location. Constraints (9) and (10) specify binary decision variables.

3.3. Bi-objective watchtower location model

Each of the two previous models can address a certain situation when a decision maker explicitly wants to cover the entire area or knows exactly the budget to cover as much of the area as possible. However there are cases when the decision maker and stakeholders wish to explore the relationship between coverage and cost. It can be argued that one can control the value of budget (B) in the second model by systematically changing the B value so different coverage can be obtained. This can work as a rough estimate. However, the budget value does not replace the actual cost and the relationship between budget and coverage may be nonlinear that makes it difficult to numerically control how budget should be changed. For these reasons, we propose a bi-objective optimization model that explicitly has total cost and coverage as two objectives:

$$\min \sum_{t=1}^{T}\sum_{i=1}^{M} C_{it}x_{it} \tag{11}$$

$$\max \sum_{j=1}^{N} Z_j \tag{12}$$

subject to

$$z_j \le \sum_{t=1}^{T}\sum_{i=1}^{M} a_{ijt}x_{it} \quad \forall j \tag{13}$$

$$\sum_{t=1}^{T} x_{it} \le 1 \quad \forall\ i \tag{14}$$

$$x_{it} \in \{0,\ 1\} \quad \forall\ i, t \tag{15}$$

$$Z_j \in \{0, 1\} \quad \forall j \tag{16}$$

This model is similar to the second model described above. But here we convert the budget constraint (6) to be an objective (11), while all the other constraints remain the same.

4. Computational experiments

The study area is located at Longdong Forest Park that is part of the southern end of the Dayu Mountains, in the northeast of the city of Guangzhou, China. Forest covers 96 percent of the park, causing the area to be at high risk of forest fires during the dry seasons. The fire risk period in the Guangzhou region is from mid-September to the end of April next year, with November to March as a critical period. The size of the Forest Park is nearly 10 square kilometers, including more than 50 hilltops. Our study area is a subset of the park centered at 23.21°N and 113.35°E and is entirely covered by forest. All the experiments described in this paper were conducted on an Intel Core i3 2.4 GHz computer with 4 GB of RAM running the 64-bit Windows 8.1 operating system.

Laser night vision cameras with monitoring distances from 1000 m to 1500 m are installed on the watchtowers, which are also equipped with 1/2 in. CCD with color resolution of 570 TV lines and black-white resolution of 600 TV lines, and KOWA lens 1/2 in. F4.630–750 mm. It should be noted that these nigh vision cameras have shorter distance range than daylight vision cameras. If daylight cameras were used, we should expect significantly different results to be obtained. The cameras can be continuously controlled electrically, with 360° pan movement and vertical tilt in the range of +10° to –90°.

Table 1
Forest fire monitoring watchtower parameters.

Tower type	Tower height (m)	Maximum visible distance of camera (m)	Average cost per tower (¥)
x	10	1000	40,000
y	15	1500	60,000

The cameras were supposed to be installed on two types of towers and we named them x tower and y tower. The specifications for the two types of towers are listed in Table 1. The average cost per tower was in Chinese Yuan and included the building tower material cost, labor, and equipment. Here we did not further differentiate the construction cost of the towers at each candidate location, mainly due to the fact that towers are typically built on hilltops that have similar conditions for new constructions (hence $C_{i0} = 40,000$ and $C_{i1} = 60,000$ for all location i).

We subdivided the study area into a grid of 13,886 cells in 131 columns and 106 rows; the resolution was 30 m by 30 m. The candidate positions for the watchtowers were primarily situated on the peaks or ridges of hills in order to achieve maximum visibility from the watchtowers. There were two existing y-type towers in the area, and we identified 30 additional candidate locations where watchtowers can be built, as depicted in Fig. 3. Specifically, for decision variables x_{it}, we had i ranging from 0 to 31 and t from 0 to 1 for tower types x and y. The two existing y-type towers were at locations 19 and 24. Consequently, to incorporate the existing towers, we added the following two additional constraints to all the above models so that they were always included in the solution.

$$x_{19,1} = 1, \tag{17}$$

$$x_{24,1} = 1. \tag{18}$$

The next step was to compute the viewsheds of every candidate location for each watchtower type using the DEM. We wrote a Python program to automatically derive these viewsheds in ArcGIS 10 [27]. The three important visibility analysis parameters used in this process are listed in Table 2. The viewshed of every watchtower in a candidate position was translated into the a_{ijt} values in the location models described above. For example, if cell j in the DEM is in the viewshed of a candidate cell at i for the type x tower, we have $a_{ij0} = 1$, otherwise if j is outside the viewshed of i for type x tower, we have $a_{ij0} = 0$.

Finally, optimal solutions were obtained. The first (minimal cost with full coverage) and second (maximal coverage with limit cost) models are integer programs, and we used an open source solver called LP_Solve [28] to find optimal solutions. Because the bi-objective model has multiple objectives, it often has many, instead of one, optimal solutions. For example, let us consider an optimal solution to our problem that has a cost of c_1 and coverage of z_1. There may exist another solution with a lower cost of $c_2 < c_1$, but a coverage smaller than z_1. Since none of the two is better than the other, they both are optimal or none dominated. The set of all optimal solutions to the problem together is called the Pareto front, representing the tradeoffs between the two objectives. Thus solving such a multiobjective optimization problem requires us to find as many, if not all, optimal solutions to the problem. A range

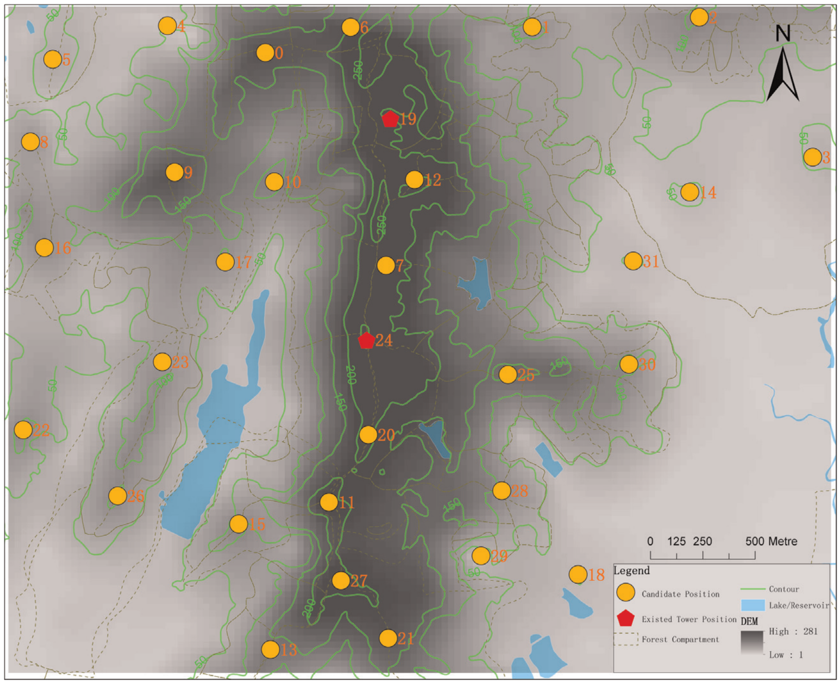

Fig. 3. The study area and candidate locations for watchtowers.

Table 2
Visibility analysis parameters.

Parameter	Parameter meaning
SPOT	The height of the observation point, i.e., the sum of terrain height and tree height from the forest resource map.
OffsetA	The distance between the observation point and the surface, i.e., the height of the watchtower.
Radius2	The maximum visibility distance of the camera equipped on the watchtower.

of methods has been developed to solve multiobjective optimization problems exactly [29]. The weighted sum method, for example, applies a set of weights to the objectives so that they are converted into a single objective. By systematically changing the weights, it is possible to find the optimal solutions on the Pareto front. However, the Pareto front may be discrete and its shape may not be convex, which makes it difficult to determine the weights. Recent studies in the optimization literature have demonstrated the effectiveness of genetic algorithms (GAs) in solving multi-objective problems [29–34]. In this study, we used the genetic algorithm in the optimization toolbox in Matlab [35].

The key of using multi-objective genetic algorithms is to construct a fitness function and set population parameters. The fitness function evaluates a solution by simultaneously using the number of cells covered by the towers and the cost of building towers. Each individual solution is encoded as a binary string of 64 bits in Matlab, and the population size is 900. An important feature in multiobjective optimization is to find a diverse set of optimal solutions to the problem so that the Pareto front can be approximated. To improve the diversity of the solutions found, the GA function implemented in the Matlab toolbox utilizes two mechanisms called elitism and sharing that dynamically maintain the best solution found in each iteration while encourage the search to explore areas in the solution space that have not been searched. For more detail about the use of GAs in solving multiobjective optimization problems, we refer the reader to the relevant literature [29].

4.1. Results of minimizing costs with full coverage

The optimal location solution to the first model that minimizes the total cost with full coverage is presented in Table 3 and Fig. 4. The total construction cost to build these towers is ¥1,020,000 including the cost of the two existing y type towers and all cells are covered by the selected towers. There are 1984 primary covered cells (the cells that are only covered once), 2875 cells that are covered twice, and 3928 cells that are covered thrice. The sum of the cells covered between four and eight times is 5099. This means that more than 85 percent of the cells are covered by more than one tower and there is a significant overlap of coverage between the selected watchtowers. This situation also leads to a question: is it possible to drop a small amount of coverage but cut a substantial amount of the construction cost? In other words, we wish to explore the relationship between coverage and cost to gain a better understanding of the impact watchtower locations.

4.2. Results of maximizing coverage under budget

To use the second model to find the maximum number of covered cells, we test 4 budgetary scenarios ranging from ¥301,999 to ¥841,999 (Table 4). When the budget is set at

Table 3
Full coverage optimization result.

Tower type	Optimal locations (i)	Total cost of optimal solution (¥)	Coverage (%)	Primary covered (%)	Twice covered (%)	Iterations	Time (s)
$t=0$ (x) $t=1$ (y)	$i=1, 4, 8, 12, 13, 15, 28, 29, 30$ $i=0, 2, 6, 9, 18, 19, 21, 22, 24, 25, 27$	1,020,000	100	14.3	20.7	121	1.20

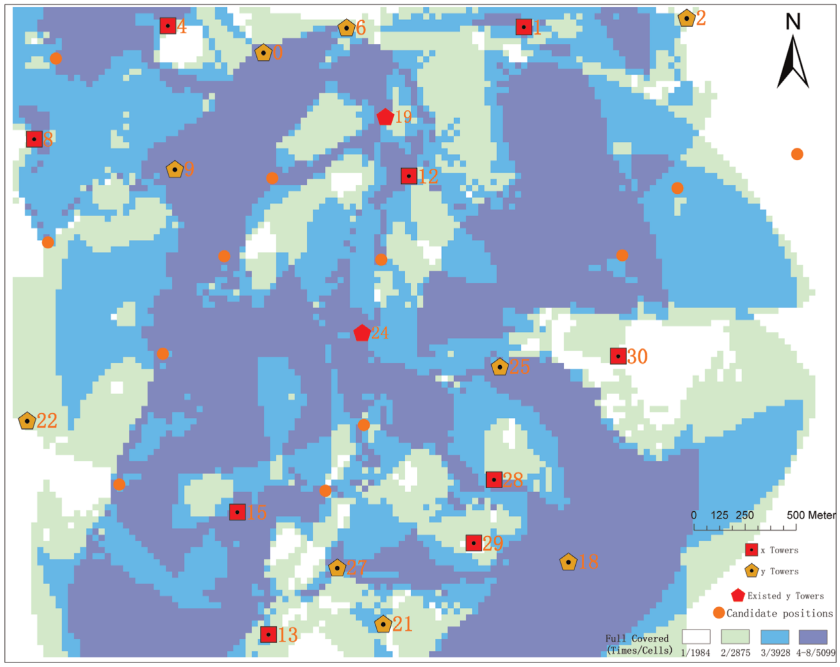

Fig. 4. The optimal result based on the location set covering model.

Table 4
Results of maximum optimal coverage with different budgets.

Budget (¥)	Optimal locations (x_{it})	Cost (¥)	Sum of covered cells	Covered cells (%)	Not covered (%)	Primary covered (%)	Iterations	Time (s)
301,999	$t=0$, $i=9$, 18, 26 $t=1$, $i=14$, 19, 24	300,000	12,137	87.4	12.6	57.7	17,419	101.4
481,999	$t=0$, $i=21$, 25, 30 $t=1$, $i=2$, 9, 18, 19, 24, 26	480,000	13,544	97.5	2.5	43.8	7829	49.7
661,999	$t=0$, $i=1$, 2, 5, 6, 21, 28 $t=1$, $i=9$, 11, 18, 19, 22, 24, 30	660,000	13,794	99.3	0.7	20.8	4743	35.6
841,999	$t=0$, $i=4$, 9, 13, 21, 25, 29 $t=1$, $i=1$, 2, 6, 8, 11, 18, 19, 22, 24, 30	840,000	13,870	99.9	0.1	14.4	2058	19.0

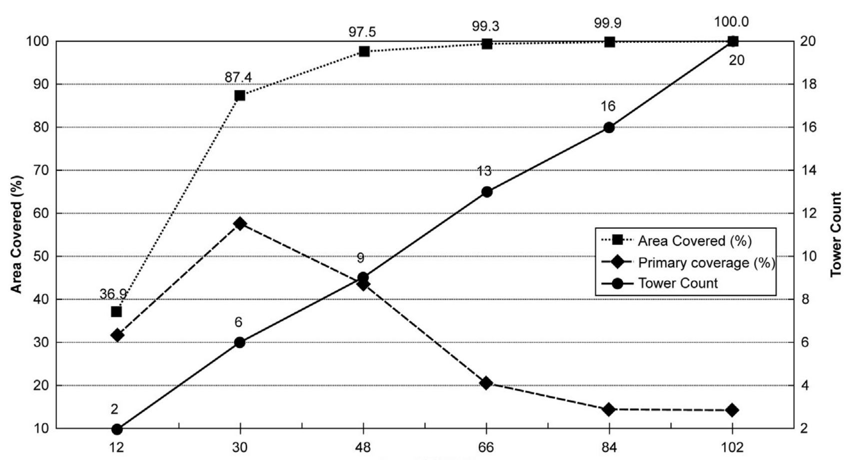

Fig. 5. Relationship between cost, coverage and number of watchtowers.

¥301,999, the solution indicates a coverage of 87.4 percent of the cells. With the increase in the budget, candidate towers are added, resulting in the increase in percentage of covered cells and decrease in that of primary covered cells and the computing time. When budget equals ¥841,999, only 0.1 percent of cells are not covered by the 17 optimal watchtowers.

Table 4 shows both the budget specified for the model and the cost calculated given the number of optimal watchtowers. It is noteworthy the gap between these two numbers. We further explore the relationship between construction cost and area coverage and number of towers in Fig. 5 where a diminishing gain of coverage can be observed when the cost and number of towers

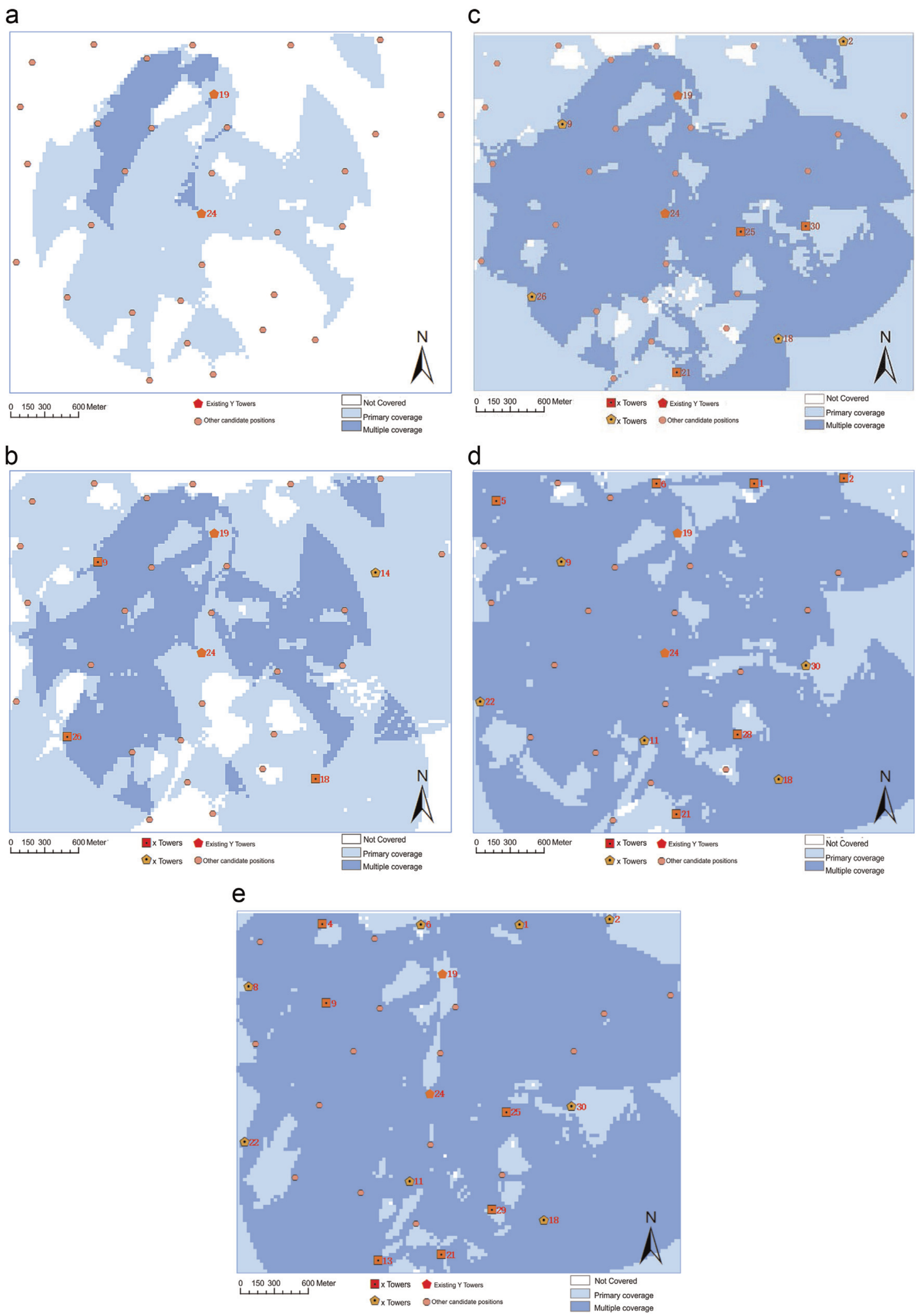

Fig. 6. Coverage maps of the two existing y towers (a), and of optimal solutions under budgets of (b) ¥301,999, (c) ¥481,999, (d) ¥661,999, and (e) ¥841,999.

increase. For example, for an additional cost of ¥18,000, a gain of 10.1 percent in coverage increase can be achieved when the cost increases from ¥300,000 to ¥480,000, while a mere 1.8 percent increase in area coverage is reached when the cost goes up ¥18,000 from ¥480,000 to ¥660,000. A similar trend can be observed between the number of towers and area coverage. This indicates that a high degree of coverage may be possible by increasing the number of towers (or investment cost), but may be at an increasingly highly cost per unit. As a reflection of such a relationship, we can observe the overall decrease of primary

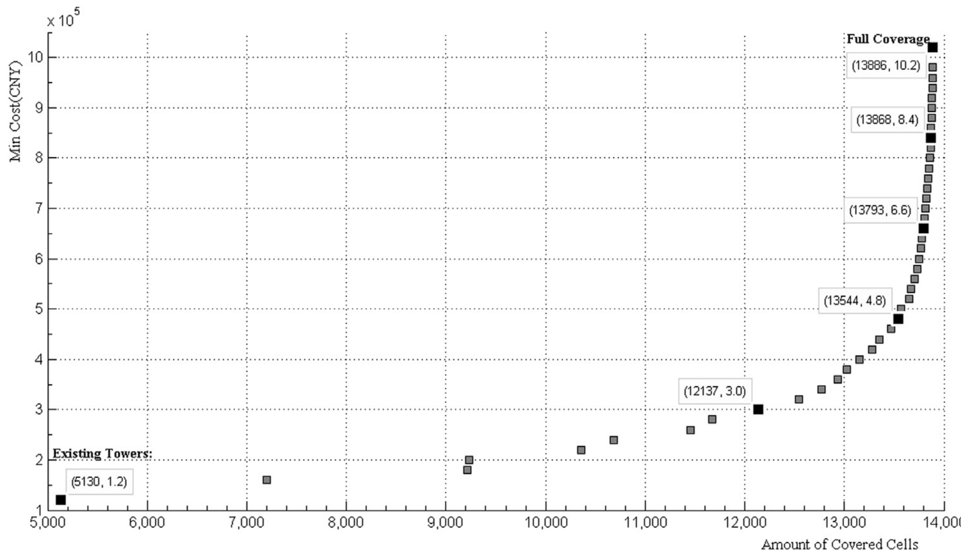

Fig. 7. Pareto front of multi-objective optimization based on genetic algorithms.

Table 5
Results of global optimization and partial optimization.

Solution	Optimal result of candidate towers	Cost (¥)	Covered cells (%)	Primary covered (%)	Multiple covered (%)
A1	$t=0$, $i=9$, 18, 26 $t=1$, $i=14$, 19, 24	300,000	87.4	57.7	29.7
A2	$t=0$, $i=1$, 14, 25 $t=1$, $i=9$, 18, 26	480,000	93.4	65.8	27.6
B1	$t=0$, $i=21$, 25, 30 $t=1$, $i=2$, 9, 18, 19, 24, 26		97.5	43.8	53.7
B2	$t=0$, $i=1$, 5, 6, 11, 21, 25 $t=1$, $i=9$, 14, 18, 26		98.3	44.1	54.2
C1	$t=0$, $i=1$, 4, 8, 12, 13, 15, 28, 29, 30 $t=1$, $i=0$, 2, 6, 9, 18, 19, 21, 22, 24, 25, 27	1,020,000	100	14.3	85.7
C2	$t=0$, $i=1$, 4, 8, 13, 15, 28, 29, 30 $t=1$, $i=0$, 2, 6, 9, 12, 18, 21, 22, 24, 25, 27	980,000	100	13.6	86.4

coverage percent (percent of cells covered by one tower) with cost, indicating the increase of cost on duplicating the coverage. Fig. 6 illustrates the coverage of different number of towers. It clearly reinforces the observation on the diminishing gain of coverage as the area in dark blue increases dramatically from map (a) to (c), but then slowly from map (c) to (e).

4.3. Results of the bi-objective model

In Fig. 7, each point represents an optimal solution found by the multiobjective genetic algorithm and we highlight 6 solutions along with their objective function values in the pair of parentheses. Five of these highlighted solutions exactly match the optimal solutions we found in the previous two models and the last one matches the case for the two existing towers. For example, the solution at the very upper-right end covers 13,885 cells (all the cells in the study area) with a cost of ¥1,020,000, exactly as found by the first model (Table 3). For this reason, we believe that the solutions found by the GA are indeed optimal and they form the Pareto front for our bi-objective watchtower location problem. The overall shape of the Pareto front indicates the same trend of diminishing gain of coverage with the total cost. The Pareto front for our problem is discrete, but more importantly, we also notice the non-convex shape of the front that is clearly shown when the number of covered cells is around 9200 where the front takes an abrupt turn. As suggested in the literature [29,32,34], it is often difficult to use the weighted sum method to solve a multiobjective problem with a Pareto front as this.

4.4. Relaxing fixed existing towers

We now examine the impact of existing towers by assuming they can be relocated. In this sense, we relax the two constrains in Eqs. (11) and (12) so that all the 32 candidate locations will be considered. We test three scenarios here: the maximum coverage location model with budgets of ¥301,999 and ¥481,999, and the full coverage model using the location set covering problem. Table 5 summarized the results. Under a budget of ¥301,999, solutions A1 and A2 are obtained by assuming the existing towers cannot (A1) or can (A2) be relocated. Both solutions have the same total cost, but more cells can be covered if the existing locations can be relocated to new locations, which can be achieved by including more cells that are not covered under solution A1 and by reducing cells that are covered by multiple towers. Solutions B1 (with existing tower fixed) and B2 (existing towers can move) are under a budget of ¥481,999 and have the same total cost. However, solution B2 has a slightly higher total coverage. For full coverage solutions, C1 (fixed existing towers) and C2, solution C2 has one fewer tower than C1 and therefore has a lower cost, meaning that it is possible to reduce the total number of watchtowers and reach the objective of full coverage if the existing towers could have been built at different locations.

5. Conclusions and discussion

This paper suggested that integrating location models and visibility analysis can help efficiently place watchtowers for forest fire monitoring on the terrain. We discussed the procedure of data preparation using viewshed analysis in a GIS and optimization models based the location set covering problem and the maximum covering location problem. We demonstrated how multiple types of watchtower can be incorporated in the optimization models and how a bi-objective optimization model can be used to help explore the trade-off between two fundamental goals (coverage and cost) of locating forest fire monitoring facilities. While we mainly focused on a particular monitoring devise (laser night vision cameras), the models developed in this paper can be applied in a broader context where other devises are used. The key to applying our models in a different situation is to determine the coverage of the devise. In our research, viewshed analysis was used to determine whether a location can be covered by testing if that location can be visible from a facility. This relationship of being visible can be extended to other devises as long as it is possible to determine whether a location can be sensed from the facility. We also note that while DEM is used to compute the viewshed in this paper, fires sometimes can be detected by their rising smoke plumes that are higher than the elevations on the DEM cells. While this does not change how the optimization models can be developed, it indeed presents a significant challenge to the data preparation process.

Though the study area used in this paper is completely covered by forest, there might be case studies where locations in the area must be treated specially. For example, some applications may require certain critical locations to be constantly monitored, while some locations such as water bodies may not need to be monitored. The literature in location modeling has an extensive discussion about these cases [36,37]. In our case, it is straightforward to formulate additional constraints so that a location u falling into the must protected areas will have its Z_u value be set to 1 and a watchtower must be placed in at least one location what can cover location u (i.e., $\sum_{t=1}^{T}\sum_{i=1}^{M} a_{iut}x_{it} \geq 1$). For vulnerable locations that require more secured monitoring, it may be necessary to ensure that they are covered by more than one watchtower so that equipment failure at individual towers will not be likely to affect the monitoring process. In the bi-objective model, we can also explore the impact of security gained on the overall cost by duplicating coverage, which will help decision makers decide the level of security for special cases.

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