Optimal Planning of a Weather Radar Network

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ABSTRACT

An approach to the optimal planning of a weather radar network is presented. In the approach, several aspects affecting the planning decision, including terrain blockage, the need to measure with two Doppler weather radars in some regions, and the environmental impact of their installation, are taken into account using a proper mathematical formulation. The decisional problem takes on a form that closely resembles a well-known combinatorial optimization problem, that is, the weighted set-covering problem. The proposed mathematical approach can serve as a methodological basis of a decision support system, the function of which is to assist decision makers in the selection of optimal sites for the installation of weather radars in a given region. In this paper, the methodology is presented, as are the preliminary results stemming from its application to the planning of the forthcoming Italian weather radar network.

1. Introduction

The Italian Civil Protection Department is responsible for the issuing of early warnings for flash floods and diffuse landslides. In order to enhance its severe weather forecasting abilities, the department is currently financing the redeployment of a real-time rain gauge and hydro-metric network at ground level and the extension of its network of weather radars (WRs).

Ground WRs are, in fact, increasingly applied to ensure reliable weather forecasts, principally when they are organized as a group of contiguous installations, that is, as a weather radar network (WRN), operating over a defined territory. The benefits stemming from a WRN are considerable, especially for mesoscale weather predictions and nowcasting over territories with a complex orography, such as alpine regions (German and Joss 2000; Joss and German 2000). More generally, WRNs allow a better understanding of many regional weather phenomena (Colle and Mass 1998; Doyle 1997). A WRN may thus represent a valuable resource to guarantee an exhaustive, real-time, nowcasting description of weather dynamics, which becomes crucial, especially when integrated with other weather information sources, to support the decisions of emergency managers in critical situations (Siccardi 1996; Subramaniam and Kerpedjiev 1998). Compared to satellite observations, which focus mainly on cloud tops, and to surface point sensors, such as rain gauges that may describe point phenomena, a WR, especially a Doppler WR, can provide a more accurate measurement of the observed phenomena over a wide spatial region.

Realizing the benefits that can derive from a WRN for purposes of civil protection operations management, the Italian government has recently undertaken to plan and to install a national WRN.

As far as the integration of radar technology with other information is concerned, many recent works provide useful guidelines and exhaustive details on the state of the art. For European Union countries, relevant information on this issue can be found in the results of some recent research projects: COST-73 (Collier 1992), COST-75 (Collier 2000), OPERA (Köck et al. 2000), and COST-717 (Meischner and Hagen 2000; Rossa 2000; Bruen 2000). These works clearly evince that the common European standard of operational WRs is a Doppler system at C band (Meischner and Hagen 2000). However, in some countries, such as Spain, S-band systems are predominant; in addition, both in general and specifically for alpine regions, new dual-polarization X-band and K-band systems are quite promising in order to reduce attenuation issues, and a few installations in European Alpine environment are presently under test.

By contrast, the literature does not seem to be so exhaustive on guidelines or on methodologies that can, from a geographic standpoint, assist decision makers in their planning of networks. The fundamental questions entail

1) the selection of criteria to be assessed for the positioning of a WR installation, and
2) the appropriate methods to optimize the planning of a regional/national WRN.

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In fact, for the Next Generation Weather Radar (NEXRAD), now the Weather Surveillance Radar–1988 Doppler (WSR-88D) network in the United States, a systematic and objective approach was used to optimize the siting of the 136 WRs currently in operation (Leone et al. 1989). In that work, the main criteria taken into account to support the planning decision were

1) identification of priority coverage areas for population centers based on the expected paths of storms and their travel speed,
2) radar viewing of the priority coverage areas down to low altitudes [610 m above ground level (AGL), 2000 ft],
3) terrain features and local obstructions,
4) locations of airways of civilian and military airports,
5) electromagnetic interference,
6) integration of NEXRAD data into the national weather system,
7) environmental impacts, and
8) costs.

Although such a work contributed significantly to the definition of practical, objective criteria for the selection and evaluation of eligible radar sites, it did not provide any planning algorithm to support the siting of one or more sets of radar installations.

A more recent work focused on a much smaller WRN planning problem in Iran (Golestani et al. 2000). Here, several similar planning considerations, based on the regional hydrology and climatology, on the urban population requirements, and on the complex topography of the region, were proposed as issues to be taken into account in the site selection process. In this work, the territory was first divided into 10 areas, and then, to assess a priority, climate statistics were analyzed. This approach defined the three regions where WRs were needed with higher priority. However, although this work represents a further important step toward the formalization of the decisional criteria to be taken into account in the design of a WRN, it is still far from the definition of a general methodology to support the practical decision process for the selection of one or more sets of WR sites.

The present work focuses on the definition and implementation of a methodology to support the decisions entailed in the optimal planning of a WRN over a defined territory. The main distinguishing feature of this methodology is that it is based on a mathematical formalization of the problem, in terms of costs, constraints, and decision variables. Even though the formalization described herein cannot by any means be considered exhaustive, it represents a first effort toward the development of a comprehensive approach for WRN planning in which the various requirements and constraints affecting the decision process are simultaneously taken into account at a certain level of detail. Preliminary results obtained from the application of this decision support methodology to the Italian territory are reported.

2. Methods

The problem entails the planning of a WRN over a region, that is, the assessment of convenient sites for the installation of WRs. Weather radar technology is assumed as a necessary investment on the considered territory, and the possibility to evaluate or to integrate them with other technologies (such as, e.g., the evaluation of the allocation of money on a WRN instead of, say, satellite sensors) has not been taken into account since it exceeds the scope of the paper.

In the adopted approach, radar technology is presumed to be the same for all the WRs to be installed (C-band Doppler WRs). The WRs are also expected to allow for any positive, 0, and negative elevations of the 1° radar beam at discrete values of elevations expressed in degree (e.g., $-1^\circ$, $0^\circ$, $1^\circ$, . . .).

The proposed methodology to support the WRN planning consists of four steps (Fig. 1).

1) In the first step, a set of $N$ eligible sites is defined according to certain feasibility criteria.
2) In the second step, the $N$ eligible sites are characterized and quantitatively evaluated according to criteria that either favor or do not support their choice.
3) In the third step, the optimization problem is formalized and an optimal solution is found; that is, up to $W$ sites ($W < N$) are selected.
4) In the fourth step, a sensitivity analysis is carried out, by suitably varying the values of the set of parameters characterizing the statement of the problem. In this way, a set of “preferred” solutions is determined. Each of such solutions is optimal in connection with a certain specification of the parameters characterizing the problem statement. Such a set of solutions is then provided to the decision maker for the final selection.

a. Definition of eligible sites

In this step, $N$ eligible sites are identified throughout the region. The definition of a sufficient number of eligible sites and their distribution over the territory is heavily contingent on the region’s natural, climatic, and anthropic characteristics. Obviously, a greater $N$ is desirable, as this provides a larger set of alternatives from which step 3 can identify better solutions to the overall problem. On the other hand, choosing a large number of eligible sites may require more computational time and additional “in situ” investigations that can make the planning a slow and costly process.

The selection of these sites should be based on preliminary investigations of different aspects that affect their eligibility. Some of these investigations may also be examined further at the end of the third and fourth steps of the methodology, for those sites that are actually selected.

The following main criteria have been used to assess
FIG. 1. WRN planning as an iteration of four steps.

1) The site should have a qualitatively acceptable view, without any significant terrain blockage. However, the elevation should not exceed a threshold based on the seasonal oscillation in freezing level. Following this criterion, mountain tops below 2000 m MSL that are free of any evident or great terrain blockage in the surroundings may be deemed eligible sites if the other following criteria are satisfactorily met.

2) The site should not be subject to any zoning or environmental regulations, which may prevent the installation of a WR.

3) The site should be stable from a geological point of view.

4) The site should be sufficiently distant from built-up areas in order to comply with all laws concerning electromagnetic pollution. Ideally, an eligible site should lay at least 1 km from any built-up area.

5) The site should have a flat operational area of at least 400 m², without electricity pylons or other electromagnetic sources within a range of 20–50 m.

6) Communications to the site, namely, accessible roads, electrical lines, phone lines enabled for data connections, water supply, etc., should be readily available.

b. Evaluation of each single eligible site

All of the eligible sites selected in the previous step should be described according to specific criteria that can affect their choice. The first criterion is the elevation of the site. Sites at an elevation of less than 1500 m MSL should be preferred, due to the radar brightband problems caused by the melting layer. Sites lying in environmentally protected areas, even when these do not prohibit the construction of a WR, should be avoided. Sites where antennas and/or other electromagnetic sources can produce noise should also be dismissed in order to reduce signal analysis problems. The quality of the infrastructure and communications facilities, mentioned earlier, should be also taken into account in the decision process. The most important criterion to evaluate is the effective coverage of a WR placed in each eligible site. Above all, the WR coverage should be effective at elevations where the observation of the dynamics of weather phenomena is important. Specifically, a major factor in siting each WR is to obtain unobstructed radar coverage down to low elevations (Leone et al. 1989). This is necessary because low-altitude coverage reveals circulations in the lower parts of the clouds that are most likely associated with particularly severe low-level phenomena (Wilson et al. 1980). For planning purposes of the NEXRAD WRN (Leone et al. 1989), the altitude of 610 m AGL (2000 ft AGL) was selected as a goal for the base of the volumes covered. In that work, this choice also implied that priority areas were within a distance of 102 km from a WR (Leone et al. 1989). Radar coverage at higher elevations (e.g., 1830 m AGL, 6000 ft AGL) was also evaluated for air traffic monitoring.

On the other hand, a more recent objective assessment of the current WSR-88D radar coverage (Westrick et al. 1999) has revealed that only one-fourth to one-third of the land surface of the mountainous U.S. west coast has sufficient radar coverage for precipitation estimation, taking into account that previous studies of orographic precipitation (Houze et al. 1981; Marwitz 1983; Rauber 1992; Bruinjes et al. 1994) showed that much of the orographic precipitation development occurs within a 1–2-km layer above terrain.

The approach presented in this paper is oriented toward an effective application over the Italian territory, which has a quite complex orography that includes the highest European mountains. In this respect, the follow-
ing modeling for the evaluation of the WR coverage has been adopted.

The region over which the WRN works is divided into subregions of mesoscale dimension (about 1500 km²). Each subregion is characterized by its georeferenced shape and by a priority related to the importance to receive an effective coverage. Examples of subregions may be the administrative partitions of the territory (either counties or districts), river basins, or rectangles of land falling within certain ranges of latitude and longitude. This last geographic partition has been adopted in the results section of this work.

In this approach, the effectiveness of the coverage is sampled on circles with a fixed radius of 100 km whose center is the eligible site, and laying on four elevations at 1000, 1500, 2000, and 3000 m MSL. In other words, for each WR eligible site and evaluating the possible terrain blockage, “the view” from that site has been computed at a constant elevation of X m MSL in a circle of 100 km; four significant sampling elevations (that are X equal to 1000, 1500, 2000, 3000 m MSL) have been taken into account. The coverage at these elevations will be termed hereafter as covering layers. The operational range of 100 km is chosen because of Doppler efficiency in observing wind components. However, rainband observation is also possible beyond the limit, with decreasing accuracy, but this aspect has not been taken into account. In any case, a different choice of the value of the operational range does not change the structure of the proposed decision procedure. In addition, taking into account observations with decreasing accuracy beyond a given limit would only require a modification of the rule to establish the coverage of a given subregion.

For each site, the covering layers have been computed taking into account the terrain blockages shown by the digital elevation model (DEM) that are met by the beam trajectories at different elevation angles of a WR positioned in that site.

With simplifying conditions, such as horizontally homogeneous temperature and humidity and small elevation angles, the height h of a ray leaving the WR at an elevation angle θ, is defined by Eq. (1) (Doviak and Zrnic 1984, p. 21):

\[ h = \left( r^2 + \frac{4}{3} a^2 \right)^{1/2} - \frac{4}{3} a \sin \theta \tag{1} \]

where \( r \) is the slant range of the WR beam and \( a \) is the earth radius. In the approach proposed in this paper, a subregion is defined as being covered at elevation \( h \) by a WR if at least 60% of its area is covered at that elevation, including important parts of land defined by expert visual inspection where meteorological phenomena can contribute to the occurrence of relevant hydrogeologic risks. If this is not achieved, the region is defined as not covered.

\[ \text{c. The formalization of the optimization problem} \]

1) THE WRN COVERAGE PROBLEM AS A WEIGHTED SET-COVERING PROBLEM

In the third step, the elected sites are determined according to an optimality criterion, and by taking into account a suitable set of constraints. First of all, it is worth noting that, without the use of an adequate method, the determination of the elected sites by direct enumeration gives rise to unsustainable computational time even for a medium size WRN; for example, designating 35 optimal WR locations out of 100 eligible WR sites requires evaluation of more than \( 10^{27} \) possible sets. For this reason, an explicit enumeration method is unfeasible, and an implicit enumeration approach is necessary.

The very same words that define the problem immediately prompt the likening of WRN planning to a weighted set-covering problem (SCP), a well-known complex combinatorial optimization problem (Gilmore and Gomory 1961; Etcheberry 1977) whose formulation fits many real-world resource location/allocation problems. A weighted SCP is a special kind of integer (binary) linear programming problem that can, at least for modestly sized problems, be optimally solved by making use of standard approaches for integer linear programming (e.g., branch and bound). For problems having a larger dimension, special algorithms (among others, Johnson 1974; Chvátal 1979; Beasley 1987; Ohls-son et al. 2001), properly developed for the SCP, should be applied.

The general formulation of the weighted SCP as a binary linear programming problem is

\[ \text{min} \sum_{j=1}^{N} c_j x_j \tag{2} \]

\[ \mathbf{A} \mathbf{x} \leq \mathbf{1} \tag{3} \]

\[ \mathbf{x} \in \{0, 1\}^N, \tag{4} \]

where \( \mathbf{A} \) is an \( M \times N \) 0–1 matrix, denoted as the covering matrix, whose rows correspond to the elements of a set to be covered and whose columns correspond to a set of predefined feasible subsets. The generic element of such a matrix, namely, \( a_{ij} \), is equal to 1 if the \( i \)-th element is included (i.e., is covered by) the \( j \)-th subset, and 0 otherwise. The \( j \)-th component of vector \( x \) is a decisional variable whose value is 1 if the \( j \)-th subset is selected, and 0 otherwise. Here \( \mathbf{1} = \text{col}[1, \ldots, 1] \) is a vector of \( M \) ones. The vector inequality constraint imposes that each element in the set is covered by at least one of the selected subsets. Finally, the parameter \( c_j \) represents the cost related to the selection of the \( j \)-th subset in the optimal solution.

Clearly, the WRN coverage problem (WRN CP) bears many similarities to the weighted SCP. In the WRN CP, \( N \) eligible sites located over a territory are to be evaluated for the possible positioning of a maximum of \( W \)
WR stations \((W < N)\). The territory is supposed to be partitioned in \(M\) subregions (see previous section). For each of the eligible sites, a covering map at the four layers of interest is known (see previous section). Specifically, each area \(j\) may be covered by a WR positioned in site \(i\) \((a_{ij} = 1)\) or not \((a_{ij} = 0)\). However, since four covering layers are evaluated, four matrices \(\bar{A}^z\) \((z = 1, 2, 3, 4)\) are needed, where \(z\) index is associated with the coverage at the various elevations (interest \((1000, 1500, 2000, \text{and } 3000 \text{ m MSL})\). This is the first modification to the basic formulation of the weighted SCP. The generic element of matrix \(\bar{A}^z\) is denoted as \(a_{ij}^z\). Obviously, the cost \(c_j\) corresponds to the overall cost related to the installation of a WR in position \(j\).

2) THE FORMULATION OF THE WEATHER RADAR NETWORK COVERAGE PROBLEM

Some peculiarities of the WRN CP may suggest the introduction of further modifications to the formulation of the weighted SCP. First of all, the covering constraints may not be easily satisfied, owing to the complex orography of the considered territory. Thus, it is necessary to convert them into objectives. In other words, it is necessary to introduce in the overall cost function to be minimized some terms penalizing the violation of such constraints. In addition, in some subregions about which it is important to have more detailed data, for example, the definition of the vector wind fields, at least a second Doppler WR covering is required (Doviak and Zrnic 1984, 288–304). Finally, the decision makers, as in previous works (Leone et al. 1989; Golestani et al. 2000), and as usually occurs in decision making processes, is likely to wish to put their hands on the decision process in order to 1) verify the feasibility of certain configurations, 2) formalize the decision problem and determine an optimal solution, 3) modify the specifications of the parameters that characterize the formulation of the problem, and 4) analyze the sensitivity of the optimal solution with respect to the choice of these parameters. For instance, a decision maker may want to search for solutions with at least a certain percentage of subregions covered at a specific covering layer, or to verify the possibility of upgrading an existing or planned WRN, etc.

On this basis, the overall WRN CP objective to be minimized may be written as the weighted sum of three components:

\[
J = k_1 J_1 + k_2 J_2 + k_3 J_3. \tag{5}
\]

The first component, \(J_1\), takes into account the (generalized) cost of installing WRs in the designated sites. The second component, \(J_2\), takes into account the weighted cost relevant to the subregions that are not covered by any WR for any of the covering layers. The third component, \(J_3\), takes into account the weighted cost relevant to the subregions that are not covered by at least two WRs for any of the covering layers. Co-efficients \(k_1, k_2, \text{and } k_3\) are weighting coefficients that can be used by the decision maker to drive the optimal solution to take more or less into account the various components of the objective function.

The first component can be expressed as

\[
J_1 = \sum_{j=1}^{N} c_j x_j, \tag{6}
\]

where the generalized cost \(c_j\), corresponding to the placement of a WR in the \(j\)th eligible site, is given by

\[
c_j = \eta_h (Q_j - Q_0)^2 + \eta_d \delta_j + \eta_c CR_j + \eta_d d_j, \tag{7}
\]

where the variables are defined as follows:

- \(\eta_h, k = 0, 1, 2, 3,\) are weighting parameters;
- \(Q_j\) is a parameter expressing the elevation (in meters MSL) of site \(j\);
- \(Q_0\) is an “ideal” elevation (in meters MSL; in this work \(Q_0 = 1500 \text{ m MSL}\)) for a WR;
- \(\delta_j\) is a positive parameter expressing the adequacy of the installation of a WR in site \(j\) from an environmental impact standpoint (lower values), or not (higher values); in the application, reported in section 3, a variability range 0–10 has been chosen for \(\delta_j\);
- \(CR_j\) is a parameter related to the economic cost of installing a WR in site \(j\); as all the WRs of the planned WRN are presumed to be technologically identical, the difference in such a cost depends on the infrastructure and power availability\(^1\) features of the different sites that can influence the WR installations; and
- \(d_j\) is a parameter related either to the inconvenience to or to the distance from site \(j\) of a road accessible to truck traffic; this parameter is important, as it allows the quantification of an estimate of maintenance costs of a WR placed at the \(j\)th site.

The second component can be expressed as

\[
J_2 = \sum_{i=1}^{I} p_i \sum_{j=1}^{M} RI_i y_j, \tag{8}
\]

where the variables are defined as follows:

- \(p_i\) is a positive parameter related to the importance of covering the layer at elevation \(z\);
- \(RI_i\) is a positive parameter related to the priority of covering subregion \(i\); this parameter is likely to be related to the hydrogeological risk characterizing that region or the regions immediately downstream; and
- \(y_j\) is a 0–1 variable whose value is 1 if subregion \(i\) is not covered at elevation \(z\) by any WR, and 0 otherwise; \(i = 1 \cdots M, z = 1 \cdots 4\).

Finally, the third component can be expressed as

\(^1\) Data transmission from each WR installation is via satellite link.
\[ J_3 = \sum_{j=1}^{4} pp_j \sum_{i=1}^{N} RI_jw_i, \quad (9) \]

where

- \( pp_j \) is a positive parameter related to the importance of covering the layer at least twice at elevation \( z \); and
- \( w_i \) is a 0–1 variable whose value is 1 if area \( i \) is not jointly covered at elevation \( z \) by at least two WRs, and 0 otherwise; \( i = 1 \cdots M, z = 1 \cdots 4 \).

The formulation of the WRN CP requires the introduction of several constraints.

1) The number of WRs actually to be placed is upper bounded:

\[ \sum_{j=1}^{N} x_j \leq W. \quad (10) \]

2) There is a lower bound in the percentage of covered subregions required at each covering layer:

\[ \sum_{j=1}^{N} y_j^z \geq (1 - \varphi^z)M \quad z = 1, \ldots, 4, \quad (11) \]

where \( \varphi^z \in [0, 1] \) is a parameter that specifies the admissible minimum fraction of subregions covered at layer \( z \).

3) There is a lower bound in the percentage of subregions covered at least twice at each layer:

\[ \sum_{j=1}^{N} w_j^z \geq (1 - \omega^z)M \quad z = 1, \ldots, 4, \quad (12) \]

where \( \omega^z \in [0, 1] \) is a parameter that specifies the admissible minimum fraction of subregions covered at least twice at layer \( z \).

4) An additional set of constraints is needed to relate variables \( y_j^z \) to variables \( x_j \), namely,

\[ y_j^z \geq 1 - \sum_{j=1}^{N} a_{ji}x_j \quad i = 1, \ldots, M, \quad z = 1, \ldots, 4, \quad (13) \]

Such a constraint requires that the binary variable \( y_j^z \) is at least 1 when subregion \( i \) is not covered at layer \( z \) by any WR, and greater than or equal to 0 when subregion \( i \) is covered at layer \( z \) by at least one WR. Moreover, note that the structure of the second term \( J_3 \) of the cost to be minimized actually requires that the value of \( y_j^z \) is 0 in the latter case, and 1 in the former one; thus, \( y_j^z \) actually takes on values as required by its definition.

5) Similarly, a further set \( j \) of constraints is needed to relate variables \( w_j^z \) to variables \( x_j \), namely,

\[ w_j^z \geq 2 - \sum_{j=1}^{N} a_{ji}x_j - y_j^z \quad i = 1, \ldots, M, \quad z = 1, \ldots, 4, \quad (14) \]

in order to make the values taken by \( w_j^z \) correspond to its definition.

In addition, some further simple constraints may be present in the problem formulation, namely,

\[ x_s = 1 \quad (15) \]

for all sites \( s \) where a WR is already either present or planned;

\[ y_s^z = 0 \quad (16) \]

for all subregions \( r \) where a covering at layer \( z \) must be ensured; and

\[ w_s^z = 0 \quad (17) \]

for all subregions \( r \) where a double covering at layer \( z \) must be ensured.

Note that the objective function to be minimized and the constraints of the WRN CP are all linear in the variables, which are all binary. The solution of such a problem could be achieved by introducing some modifications into existing (and above mentioned) algorithmic approaches originally developed for the weighted SCP. However, since the dimensions of the considered case studies (at least those referring to the Italian territory) are not too great, it is possible to use standard software tools developed for general binary programming problems.

3. Results

The four-step methodology described in section 2 has been applied to the Italian territory implementing specific software tools. Preliminary results are reported below.

a. Identification of eligible sites on the Italian territory

The Italian territory has a quite complex orography and an overall area of more than 300 000 km². In this approach, \( N = 107 \) eligible sites were preliminarily identified, 20 of which are already (or about to be) equipped with a WR; as such, the elected sites should be chosen from only 87 eligible sites. Installing one radar at each of these 87 sites, supposing no terrain blockage and taking into account a 100-km WR beam range, would cover Italy more than 11 times at each of the four elevations.

The 87 eligible sites were chosen in collaboration with senior experts of the Italian Civil Protection Department and Air Force following the criteria described in section 2a.

b. Evaluation of each single eligible site previously defined

According to sections 2a,b, the 107 sites were characterized by the following parameters:

- the elevation \( Q_i \) of the site expressed in meters MSL;
• a parameter $\delta_i \in [0, 10]$ assessed by the expert and related to the environmental impact of that site (e.g., if the site is located in a natural park);
• a parameter $d_i$ evaluated by the expert and related to the presence of infrastructures; in the current approach, $d_i$ was simplified to represent only the distance (in kilometers) of the site from the nearest road accessible to truck traffic;
• the installation costs were presumed to be similar for all the sites, such that the $CR_j$ contribution was omitted.

The Italian territory official maps are discretized into $M = 285$ rectangular subregions (20' latitude, 30' longitude). The area of each subregion varies from north to south, from 1397 to 1644 km$^2$, and, on average, is equivalent to about 5% of an area covered by a WR with a presumed range of 100 km. To evaluate terrain blockages, a DEM of the Italian territory was used (Reichenbach et al. 1993).

The evaluation of the coverage over the subregions, according to section 2b, was performed using a specific Geographic Information System (GIS)–based software package implemented “ad hoc” for this application [Weather Radar Network Planning Decision Support System (WRNP DSS)]. Results needed by the optimization model (see following section) were stored in a database. Figure 2 shows the DEM in Plate Carrée projection, the subregions considered, and the geographical distribution of the eligible sites.

Figure 3 shows the result of the computation, at the 1500-m covering layer, of the area covered by WR Settepani (WR18 in the result section). The computation of the WR coverage exemplified in Fig. 3 was performed for all 107 eligible sites and for all four covering layers.

This number of eligible sites seems to represent an adequate set of choices that are sufficiently geographically distributed over the Italian territory. Table 1 shows the number of subregions effectively covered both at least once and at least twice, and presuming that all 107 sites could have a WR installed. Table 2 shows the mean, median, maximum, and minimum coverage by eligible WR sites.

Finally, each subregion was characterized by a salience parameter ($RI_i$ in section 2c) related to the priority of covering a subregion. To define this salience, the Aree Vulnerate Italiane (AVI; Guzzetti et al. 1994; Guzzetti 2000) databases were consulted. AVI is an Italian civil protection project that has produced the databases of the Italian inundation and landslide events of the past century, which had a damage impact on the Italian territory (in terms, e.g., of loss of life, damage to property, and disruption to local services and business). Hydrogeological events that did not produce damage, such as a flood or landslide in a remote, unpopulated area, are not stored in these databases. Using this database it is possible to define the number of relevant landslide and flood events that have occurred over the past century in each subregion. Weighting these two numbers into a salience coefficient, normalizing it, using proper thresholds, and submitting it to the final revision by an expert evaluating the hydrogeological risk characterizing each subregion or the subregions immediately downstream, it was possible to classify the subregions into five categories, assigning $RI_i = 1, \ldots, 5$ from lower to higher salience. Since $RI_i$ is a multiplicative coefficient, this scale implies that the coverage of a subregion with the highest salience is equivalent, from the objective function viewpoint, to the coverage of five subregions of lowest salience. Figure 4 shows the geographic distribution of the subregion salience from lower (white) to higher (darkest).

c. Selection of the elected sites on the Italian territory

The optimization problem as defined in section 2 was modeled and implemented using specific software that allows linear and nonlinear problem definition and solving (Lingo 6.0; online at http://www.lindo.com). To solve this problem, which is linear with binary variables, the branch-and-bound technique is used. This model can access the necessary data, which was previously computed by the GIS module of the WRNP DSS software and stored in a database.

Since 20 WRs are already or are about to be installed, 87 decisional 0–1 $x_j$ variables are present in this problem. Since $M = 285$ subregions and four covering layers have been taken into account, 1140 0–1 $y_j$ and 1140 0–1 $w_j$ variables are present. Thus, the decision (binary) variables of this problem total 2367. The constraints are: 1 of type (10); 4 of type (11); 4 of type (12); 1140 of type (13); 1140 of type (14); and 20 of type (15). Thus, on the whole, 2309 linear constraints are present.
Several tests of the overall approach were performed. In the following, the most relevant tests are presented and classified as follows:

1) sizing the Italian WRN; and
2) determination of an optimal planning solution for a WRN with 34 WRs.

All the tests were performed taking into account four fixed matrices \( M = 285 \times N = 107 \) each previously computed as described in section 3a. The parameters, and their values as these were refined by the decision makers, are shown in Table 3.

In addition to the assessment of the objective function values \( J_1, J_2, \) and \( J_3, \) the single and double coverage are also quite important from the decision maker standpoint. Therefore, the following coefficients are also shown for performance evaluation purposes:

- the percentage of subregions covered at least once at covering layer \( z, \) indicated as
  \[
  \text{cover}^z = \frac{\left(M - \sum_{i=1}^{M} y_i^z\right)}{M} \times 100\% \quad \text{and} \quad (18)
  \]
- the percentage of subregions covered at least twice at covering layer \( z, \) indicated as
  \[
  \text{dcover}^z = \frac{\left(M - \sum_{i=1}^{M} w_i^z\right)}{M} \times 100\% \quad \text{and} \quad (19)
  \]

### Table 1. Number of subregions effectively covered both at least once and at least twice at the four considered covering layers (CLs), presuming all 107 sites could have a WR installed.

<table>
<thead>
<tr>
<th>Subregions</th>
<th>1000 CL</th>
<th>1500 CL</th>
<th>2000 CL</th>
<th>3000 CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covered at least once</td>
<td>199</td>
<td>234</td>
<td>244</td>
<td>262</td>
</tr>
<tr>
<td>(69.8%)</td>
<td>(82.1%)</td>
<td>(85.6%)</td>
<td>(91.9%)</td>
<td></td>
</tr>
<tr>
<td>Covered at least twice</td>
<td>171</td>
<td>213</td>
<td>228</td>
<td>241</td>
</tr>
<tr>
<td>(60.0%)</td>
<td>(74.7%)</td>
<td>(80.0%)</td>
<td>(84.6%)</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Mean, median, max, and min coverage at the four considered covering layers (CLs) obtained by the 107 eligible WR sites.

<table>
<thead>
<tr>
<th>Number of subregions covered by eligible WRs</th>
<th>1000 CL</th>
<th>1500 CL</th>
<th>2000 CL</th>
<th>3000 CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.9</td>
<td>4.1</td>
<td>4.9</td>
<td>5.8</td>
</tr>
<tr>
<td>Median</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Max</td>
<td>14</td>
<td>15</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
1) SIZING THE ITALIAN WRN

The first tests were oriented to size the number of the WRs that could provide an adequate single coverage of the Italian territory. To this end, a first set of examples of the WRCP was solved by specifying

- the different values of the maximum number of allowed radars $W$;
- the presence in the objective function (5) of the second component (8) only, setting $k_1 = k_3 = 0$, and $k_2 = 1$, that is, paying no attention to double covering or to the costs of radar siting;
- the relaxation of constraints (11) and (12), by setting $\varphi = 0$ and $\omega = 0$, $z = 1, \ldots, 4$, that is, imposing no minimum single and double covering percentage; and
- no special preference for covering specific subregions, which corresponds to setting $R_i = 1 \forall i$.

Moreover, the WRCPs were solved (a) independently for each layer $z^*$ (the set of parameters is reported in Table 3, row WRN-S1); and (b) jointly for all layers, weighting equally the coverage at the different layers (Table 3, row WRN-S2). Figures 5a (related to WRN-S1) and 5b (related to WRN-S2) show the coverage parameter for some values of $W$ (in abscissa) at the four different covering layers. The two graphics are very similar, since the different covering layers for each site are closely related. Optimizing the coverage at each layer independently (WRN-S1), 43, 40, 35, 29 WRs are sufficient (including the 20 already positioned WRs) to attain the maximum coverage, at 1000, 1500, 2000, 3000 m MSL, respectively. Optimizing jointly the covering layers (WRN-S2), 49 WRs are needed to attain the maximum coverage for all the four layers.

2) OPTIMIZING THE PLACEMENT OF 14 ADDITIONAL WRs IN A 34 WRN

Subsequently, the problem of optimizing the placement of 14 additional WRs in a network where 20 WRs are already installed or about to be installed was considered. Several problem examples were solved and only a few significant results are reported here. The configurations of the parameters used in these examples, as well as the parameters characterizing them, are reported in Table 3 (WRN34 tests). In all cases, the importance
of the coverage at the four different layers was weighted according to the suggestions of WR experts, assigning more importance to covering lower levels (see \(p^z\) and \(pp^z\) values). The salience parameters \(RI_i\) for the subregions were computed as described in section 3b. The \(W = 34\) WRs are identified by a progressive number, where the already existing/planned WRs are numbered from 1 to 20.

Having specified such parameter values, a first test (WRN34-1) was carried out with the objective of determining the maximum attainable single coverage of a WRN with 34 WRs. For such a test, the following parameter values were kept at the same values as for the previous section, namely, \(k_1 = k_3 = 0, k_2 = 1, \varphi^z = 0, \omega^z = 0, z = 1, 2, 3, 4\). Thus, the first row of Table 4a displays the optimal solution in this case, and Table 4b shows the values of the \(J_i\) and \(J_j\) components of the objective function (\(J_3\) is omitted since, having set \(k_3 = 0\), its evaluation is not significant).

A further test (WRN34-2) was performed by specifying \(\varphi^{1000} = 0.65, \varphi^{1500} = 0.75, \varphi^{2000} = 0.8, \varphi^{3000} = 0.85\), taking into account all three components of the cost function by setting \(k_1 = 200, k_2 = 2, k_3 = 1, \omega^{1000} = 0.3, \omega^{1500} = 0.35, \omega^{2000} = 0.4, \omega^{3000} = 0.5\). The differences in \(k_i\) coefficients allow obtaining a contribution in the cost function that is comparable for all \(J_i\) components. The second row of Table 4a shows the
optimal solution obtained for such an example of the WRCP. Nine out of 14 WRs are common to the previous optimal solution. Although the coverage percentages are similar to those obtained for WRN34-1 (about 65%), this solution is worse than the previous one from a single coverage perspective (note that the component \( J_1 \) has to be computed taking into account priority coefficients of the various subregions).

Finally, a third test (WRN34-3) was conducted using the same parameters of WRN34-2, but with \( k_1 = 400, k_2 = 2, \) and \( k_3 = 1, \) that is, by evaluating to a greater extent the first component \( J_1. \) The solution has the same single coverage characteristics, worse performance for double coverage, but better characteristics for the costs related to \( J_1. \) The same configuration was also obtained with \( k_1 = 800. \) Figure 6 shows the coverage obtained by WRN34-3 at the 1000 m MSL covering layer.

4. Conclusions

A four-step methodology to plan a WRN has been presented. The most important innovation of this methodology is the definition of the optimal planning of the WRN over a territory, that is, the selection of a defined number of WR sites from a set of eligible ones using a mathematical programming approach. The approach, defined as WRN-CP, was modeled as a weighted SCP with some modifications due to the peculiarities of the problem.

This approach, which can be viewed as a natural evolution of previous efforts to provide guidelines for WRN planning (Leone et al. 1989; Westrick et al. 1999; Golestani et al. 2000), offers a methodology that aims to support the efforts of the planner in selecting the most convenient WR sites according to different formulations of the problem while simultaneously enhancing objectivity of the same planning process. The approach is not dependent on the way in which the WR coverage of a region is assessed, and can be applied to regions of differing shape and size, taking into account as well varying WR ranges. In addition, the approach is also independent of the radar technology that has been adopted.

Using this methodology, a specific software package, WRNP DSS, has been implemented and tested on the Italian territory. This package allows the selection of an eligible site and the computation of the coverage, at four altitudes needed to solve the problem, by a GIS interface. This computation, whose results are stored in a database, allows the definition of the \( A \) matrixes needed to solve the problem by the software module implementing the WRN CP.

In the module defining the WRN CP, the decision maker can refine the parameters in order to obtain several examples of the problem as well as several pertinent optimal solutions. Specifically, the examples illustrated in this work are related to tests conducted to define the sizing of a WRN needed to adequately cover the Italian territory, as well as the optimal positioning of 14 WRs according to different weighting of the components of the objective function.

A possible enhancement of the approach would be to reformulate the WRN CP solving methodology as a decisional interactive multiobjective problem. As a matter of fact, decision support systems related to environmental problems are usually related to several criteria that affect the decision. In many cases, as in the one considered in this work, the decision maker pursues different objectives of different nature (in this case, related to environmental, monetary, and covering aspects). Combining different objectives in a single function to be optimized is a possible way to treat the multiobjective decision problem. However, interactive and multiobjective methodologies exist (Wierzbicki et al. 2000), allowing the separate evaluation of different objectives, involving the decision maker interactively in the decision process. This approach is currently under development.

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FIG. 6. The coverage achieved by WRN34-3 at the 1000-m MSL covering layer. Shaded rectangles represent subregions assessed as being covered. The effective coverage achieved by WRN34-3 is shown by the gray overlapping parts of ellipses.

sample data are available by direct e-mail to the corresponding author.

REFERENCES

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