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A decision support system for the optimal planning of a weather radar network: a case study

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Abstract. A methodology that allows defining the optimal planning of a weather radar network (WRN) is presented. This methodology allows defining the optimal siting of a WRN selecting up to W optimal sites out of N eligible sites according to the optimization of a planning cost function. 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, i.e., the weighted set-covering problem. The proposed mathematical approach can serve as a methodological basis of a decision support system, whose function 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 and an application to the case study of the planning of the forthcoming Italian WRN is presented.

1 Introduction

While many recent works provide exhaustive details on the state-of-the-art of weather radar (WR) technology, methodologies for the planning of weather radar networks (WRN) are not so frequent in literature. The fundamental questions entailed in WRN planning are:

1. WR specificity, related to the assessment of the quality in positioning each WR installation on its own;

2. WR cooperativity, related to the appropriate methods to optimize the quality of the WRN planning, taking into account the ability of a proper set of WR to provide, cooperatively, exhaustive observed weather data on a given territory.

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In fact, for the NEXRAD (Next Generation Weather Radar) – now WSR-88D (Weather Surveillance Radar – 1988 Doppler) – network in the United States, a systematic approach was used to optimize the radar siting (Leone et al., 1989). In that work, several criteria were taken into account to support the planning decision and radar viewing of the priority coverage areas down to low altitudes (610 m above ground level (AGL), 2000 ft) played an important role. Although this work as well as a few others (Westrick et al., 1999; Golestani et al., 2000) contributed significantly to the definition of practical, objective criteria for the selection and evaluation of eligible radar sites, they did not provide any planning algorithm to support the radar siting.

In this work, the definition of a methodology to support the decisions entailed in the optimal WR siting in the planning of a WRN over a defined territory is presented. The methodology is based on a mathematical formalization of the problem, in terms of costs, constraints, and decision variables. Preliminary results obtained from the application of this methodology to the Italian territory are reported.

2 Methods

Supposing that N eligible sites have been identified for a new WR installation, the problem is related to the election of W (W<N) sites where a WR is effectively to be put in place, in order to plan a WRN that is able to cover adequately a territory. In the approach proposed here, 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 this reason, an explicit enumeration method is unfeasible, and an implicit enumeration approach is necessary.

This problem, defined here as WRN coverage problem (WRN-CP), can be related to a weighted set-covering problem (SCP). A weighted SCP is an 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; Ohlsson et al., 2001), properly developed for the SCP, should be applied. SCP formulation fits many real-world resource location/allocation problems.

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

$$\min \sum_{i=1}^{N} c_j x_j \tag{1}$$

$$A\mathbf{x} \geq \mathbf{1} \tag{2}$$

$$\mathbf{x} \in \{0,\, 1\}^N \tag{3}$$

where A is a M×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 certain predefined feasible subsets. The generic element of such a matrix, namely a_{ij}, is equal to 1 if the i-th element is covered by the j-th subset, 0 otherwise. The j-th component of vector $\boldsymbol{x}$ is a decisional variable whose value is 1 if the j-th subset is selected, 0 otherwise. $\mathbf{1}$= col(1,..., 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.

The 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. For each of the eligible sites, a "covering map" at the four layers of interest is known. 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 above sea level (a.s.l.). The coverage at these elevations will be termed hereafter as covering layers. 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. 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 coverings layers are evaluated, four matrices A^z, (z =1, 2, 3, 4) are needed, where z index is associated to the coverage at the various elevations of interest (1000, 1500, 2000 and 3000 m a.s.l.). This is the first modification to the basic formulation of the weighted SCP. The generic element of matrix A^z is denoted as a^z_{ij} . Obviously, the cost c_j corresponds to the overall cost related to the installation of a WR in position j.

Some peculiarities of the WRN-CP may suggest the introduction of further modifications. First of all, the covering constraints may not be easily satisfied, owing to the complex orography of the considered territory. Thus, it is reasonable to convert them into objectives, that is, 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 where it is important to have more detailed data, e.g., the definition of the vector wind fields, at least a second Doppler WR covering is required (Doviak and Zrnic, 1984, chapter 9, page 288–304). Finally, the decision maker, 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 his/her hands on the decision process in order to: 1) verify the feasibility of certain configurations; 2) produce several optimal solutions; 3) modify the specifications of the parameters that characterize the formulation of the problem; and 4) analyze the sensitivity of such solutions 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 to upgrade 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:

$$\min\; k_1 \underbrace{\sum_{j=1}^{N} c_j x_j}_{J_1} + k_2 \underbrace{\sum_{z=1}^{4} p^z \sum_{i=j}^{N} RI_i \cdot y_i^z}_{J_2}$$

$$+ k_3 \underbrace{\sum_{z=1}^{4} pp^z \sum_{i=1}^{N} RI_i \cdot w_i^z}_{J_3} \tag{4}$$

The first component J_1 takes into account the generalized cost of installing WRs in the eligible 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. Coefficients k_1, k_2 and k_3 are weighting coefficients which can be used by the decision maker to take more or less into account the various components of the objective function. The objective function is subject to:

$$\sum_{j=1}^{N} x_j \leq W \tag{5}$$

$$\sum_{i=l}^{M} y_I^z \leq (1-\varphi^z)\cdot M \qquad z = 1, \dots 4 \tag{6}$$

$$\sum_{i=1}^{M} w_i^z \leq (1-\omega^z)\cdot M \qquad z = 1, \dots 4 \tag{7}$$

$$y_i^z \geq 1 - \sum_{j=1}^{N} a_{ij}^z \cdot x_j \qquad i = 1, \dots M,\; z = 1, \dots 4 \tag{8}$$

$$w_i^z \geq 2 - \sum_{j=1}^{N} a_{ij}^z \cdot x_j - y_i^z \quad i = 1, \dots M,\; z = 1, \dots 4 \tag{9}$$

Table 1. Definition of the WRN-CP parameters and variables

Paramaters/Variables		Description
x_j		Binary decisional variable, related to the decision to install ($x_j = 1$) or not ($x_j = 0$) a WR in site j
W		Maximum number of WRs that can be installed ($W<N$)
M		Number of subregions in which the territory is divided
N		Number of eligible WR sites
k_1, k_2, k_3		Weighting coefficients
i		Index i=1...N related to the subregions considerd
j		Index j=1...M related to the eligible WR sites considered
z		Index $z \in \{1000,1500,2000,3000\}$, identifying the quotes, in m asl, of the covering layers
c_j: in this formulation $c_j = \eta_0 \cdot (Q_j - Q_0)^2 + \eta_1 \cdot \delta_j + \eta_2 \cdot CR_j + \eta_3 \cdot d_j$		generalized cost, corresponding to the placement of a WR in the j-th eligible site
	$\eta_0, \eta_1, \eta_2, \eta_3$	weighting parameters
	Q_j	parameter expressing the elevation (in m asl) of site j
	Q_0	"optimal" elevation (in m asl; in this work $Q_0 = 1500$ m asl) for a WR
	δ_j	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
	CR_j	parameter related to the economic cost of installing a WR in site *j*
	d_j	parameter related either to the inconvenience or to the distance from site j of a road accessible to truck traffic
RI_i		positive parameter related to the priority of covering subregion *i*;
p^z		positive parameters related to the importance of covering the layer at elevation *z*
y_i^z		0-1 variables whose value is 1 if subregion i is not covered at elevation *z* by any WR, and zero otherwise
pp^z		positive parameters related to the importance of covering the layer at least twice at elevation *z*;
w_i^z		0-1 variables whose value is 1 if area i is not jointly covered at elevation *z* by at least two WRs, and zero otherwise,
$\varphi^z \in [0,1]$		parameter that specifies the admissible minimum fraction of subregions covered at layer *z*
$\omega^z \in [0,1]$		parameter that specifies the admissible minimum fraction of subregions covered at least twice at layer *z*;

Constraint (5) requires that the number of WRs actually to be placed is upper-bounded. Constraints (6) impose a lower bound on the percentage of covered subregions required at each covering layer. Constraints (7) impose a lower bound on the percentage of subregions covered at least twice at each layer. Constraints (8) are needed to relate variables y_i^z to variables x_j. Similarly, constraints (9) are needed to relate variables w_i^z to variables x_j. The parameters and the variables in (4)–(9) are described in Table 1.

Note that the objective function to be minimized (4) and the constraints (5)–(9) 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 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 Italian territory has a quite complex orography and an overall area of more than 300 000 km^2. In this approach, N = 107 eligible sites (Fig. 1) 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. This number of eligible sites seems to represent an adequate set of choices that are sufficiently geographically distributed over the Italian territory. The 87 eligible sites were chosen in collaboration with senior experts of the Italian Civil Protection Agency and Air Force. This work is still ongoing: specific criteria, e.g., the presence of a flat working area, have been directly verified for only a few sites, on the understanding that they will be checked again in case of an actual selection.

The Italian territory has been divided into subregions of mesoscale dimension (about 1500 km^2). Each subregion is characterized by its georeferred 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 a.s.l. For each site, these covering layers have been computed taking into account the terrain blockages shown by the DEM that are met by the beam trajectories at different elevation angles of a WR positioned in that site. In the approach proposed in this paper, a subregion is defined as being covered at elevation z 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.

The 107 sites were characterized by the following parameters:

- the elevation Q_j of the site expressed in m a.s.l.;
- a parameter $\delta_j \in [0, 10]$ 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_j evaluated by the expert and related to the presence of infrastructures; in the current approach, d_j was simplified to represent only the distance (in km) 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 was discretized into M=285 rectangular subregions (30′ longitude, 20′ latitude) as defined by the Italian Military Geographic Institute (IGM). The area of each subregion varies from North to South, from 1397 km^2 to 1644 km^2, and, on average, is equivalent to about 5% of

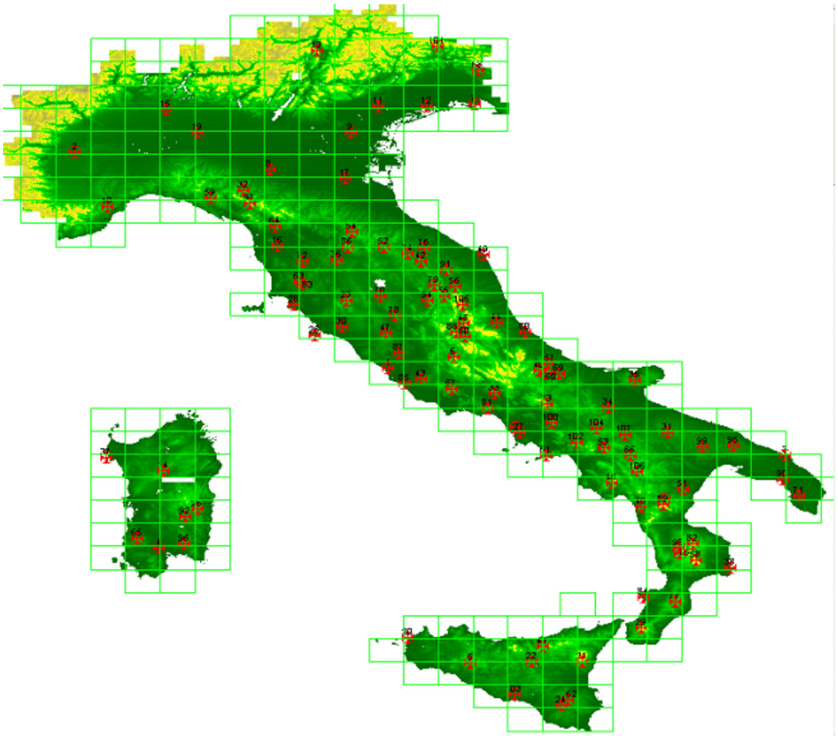

Fig. 1. The 107 sites that have been considered in the work. Radars from 1 to 20 are already installed or about to be installed. The grid defining M=285 rectangular subregions (30′ longitude, 20′ latitude) as defined by the Italian Military Geographic Institute (IGM) is also shown.

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 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 are stored in a database.

Finally, each subregion was characterized by a salience parameter RI_i related to the priority of covering a subregion. To define this salience, the AVI (Guzzetti et al., 1994; Guzzetti, 2000) database was consulted. 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 in hydrogeological risk, it was possible to classify the subregions into five categories, assigning $RI_i = 1,$,...5 from lower to higher salience.

Figure 2 shows the subregions of southern Italy and a colored representation of their salience RI_i. 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.

The optimization problem was modeled and implemented using specific software that allows linear and non-linear problem definition and solving (Lingo 6.0, http://www.lindo.com). To solve this problem, which is linear with binary variables, the branch-and-bound technique is used.

Since 20 WRs are already or about to be installed, 87 decisional binary x_j variables are present in this problem. Since M = 285 subregions (Fig. 1) and 4 covering layers have been taken into account, 1140 binary y_i^z and 1140 binary w_i^z 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); 1140 of type (15); 20 of type (16). Thus, on the whole, 3449 linear constraints are present. Several tests of the overall approach have been performed. In the following, the tests to determine an optimal planning solution for a WRN with 34 WRs are presented. In all cases, the importance of the coverage at the four different layers has been weighted according to the suggestions of WR experts, assigning more importance to covering lower levels (as p^z and pp^z values).

Having specified such parameter values, a first test (Test-1) has been 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 have been set to $k_1 = k_3 = 0$, $k_2 = 1$, $\varphi^z = 0$, $\omega^z = 0$, $z=$ 1, 2, 3, 4. Thus, the first row of Table 2 displays the values of the J_1 and J_2 components of the objective function (J_3 is omitted since, having set $k_3 = 0$, its evaluation is not significant), and the single and double covering at the four considered covering layers.

A further test (Test-2) has been 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

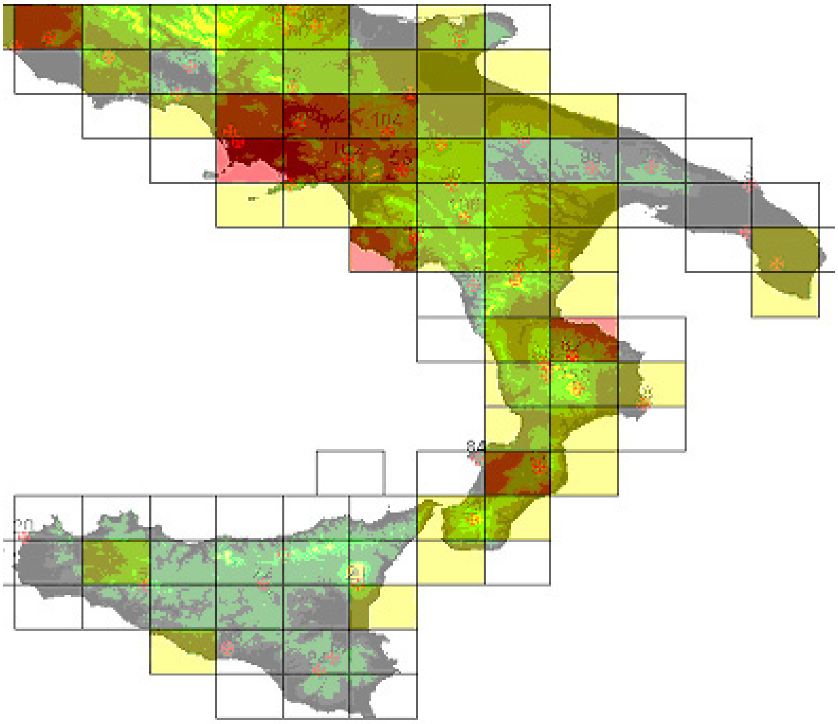

Fig. 2. A zoom of the Italian Southern regions showing in darker color the subregions with higher priority of WR covering.

by setting $k_1 = 200$ $k_2 = 2$ and $k_3 = 1$, and $\omega^{1000} = 0.3$, $\omega^{1500} = 0.35$, $\omega^{2000} = 0.4$, $\omega^{3000} = 0.5$. The differences in k_u coefficients allow obtaining a contribution in the cost function that is quite similar for all J_u components. Nine out of the 14 WRs obtained are common to the previous optimal solution. Although the coverage percentages are similar to those obtained for Test-1, this solution is worse than the previous one from a single coverage perspective (note that the component J_2 has to be computed taking into account priority coefficients of the various subregions).

Finally, a third test (Test-3) was conducted using the same parameters of Test-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. Thirteen out of 14 WRs obtained are common to the previous optimal solution. 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 3 shows the elected WRs of southern Italy by Test-3 solution.

4 Conclusions

The most important innovation of this methodology is the definition of the optimal planning of the WRN over a territory, i.e., 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 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. So, the approach is also independent of the radar technology that has been adopted.

In the software 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 optimal positioning of 14 WRs according to different weighting of the components of the objective function. The results obtained, however, are only preliminary, since other sites are currently being evaluated and added to the set of eligible sites, and, at the same time, the several aspects characterizing each site in component J_1 of the objective function have to be refined by direct on-site inspections.

A possible enhancement of the approach would be to reformulate the WRN-CP solving methodology as a decisional multiobjective problem (Wierzbicki et al., 2000), since its definition would require allowing a greater involvement of decision makers in the various steps needed to achieve the final solution.

Table 2. Results obtained on three different computations to define an optimal WRN with W = 34 WRs, 20 of which are already (or about to be) installed. The tests are:

– TEST-1: the 34 WRs achieving the maximum single coverage

– TEST-2: the 34 WRs achieving the minimum cost under constraints refined by experts

– TEST-3: as before, but giving more importance to the first component, J_1, of the objective function.

The covering (single and double) obtained at the 4 different covering layers are expressed as a percentage of the subregions that are effectively covered by at least one (single) or at least two (double) WRs.

Test	J_1	J_2	J_3	$cover^{1000}$	$cover^{1500}$	$cover^{2000}$	$cover^{3000}$	$dcover^{1000}$	$dcover^{1500}$	$dcover^{2000}$	$dcover^{3000}$
Test-1	75.728	1515.5	–	65.6%	77.2%	83.9%	89.8%	–	–	–	–
Test-2	64.654	1608	3461	65.3%	75.1%	80.7%	90.2%	32.6%	45.6%	54.0%	63.9%
Test-3	64.274	1608	3549	65.3%	75.1%	80.7%	90.2%	30.9%	43.9%	52.3%	62.8%

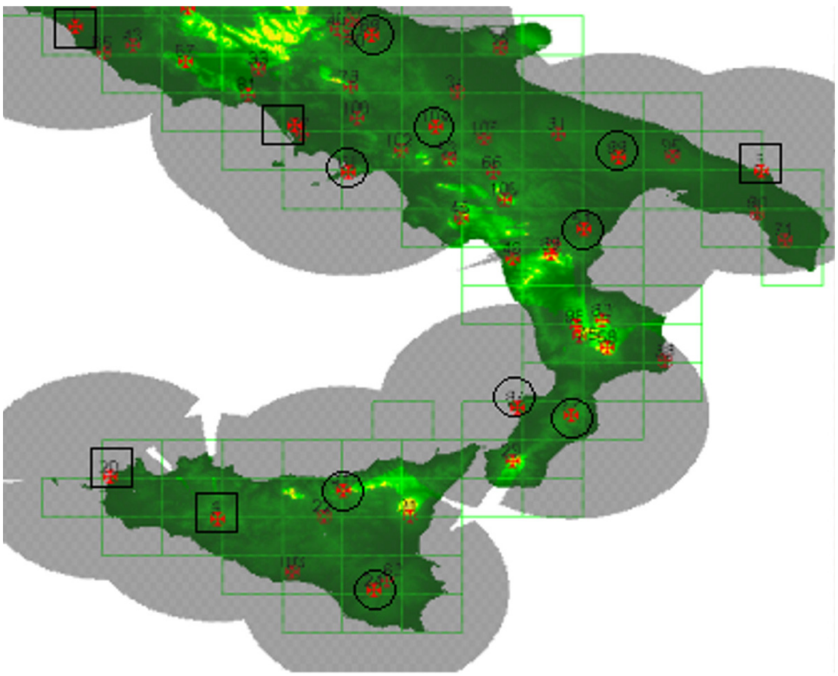

Fig. 3. The same area of Fig. 2 showing the covering at 1500 m a.s.l. obtained by the set of elected WRs that are solution of Test-3. In squares are pointed out the sites that are already installed in the territory, while the elected new WRs are circled.

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