

Land Suitability for Establishing Rainwater Harvesting Systems for Fighting Wildfires¹

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Abstract

Rainwater harvesting systems (RHSs) can be used to improve the efficiency of helicopter fire-fighting operations. To this end, RHSs need to be strategically located in areas with high wildfire occurrence to maximize their usefulness. In this study, spatial analysis was carried out to determine suitable sites for establishing RHSs intended for air attack operations in three municipalities (Chalco, Ixtapaluca and Tlalmanalco) located in the eastern part of the state of Mexico, Mexico. Five variables were used for site selection: wind speed, distance to roads, runoff, evaporation and wildfire density. Each variable was graded by consulting experts and multi-criteria decision analysis was performed to integrate them on a map. Potential RHS sites that met most of the criteria established are in the north and south of the study area. The method used in this study to identify suitable sites for establishing RHSs is a useful tool. Expert knowledge and field visits would also be helpful in selecting the best RHS site and design, in order to reduce costs and environmental impacts.

Keywords: curve number, multi-criteria analysis, wildfire fighting.

Introduction

Mexico, like other countries, has been impacted by the increasing occurrence of forest fires and mega-fires, exacerbated by the effects of global climate change. On average 10,521 fires occur in Mexico each year, affecting some 292,701 ha (Rodríguez *and others*, 2000). PROBOSQUE, a pro-forest alliance in the State of Mexico, has identified the Itza-Popo region in the state as being at high risk for wildfires and, in particular, the municipalities of Chalco, Ixtapaluca and Thalmanalco in number and area affected. To cope with the fire season, among other activities, air

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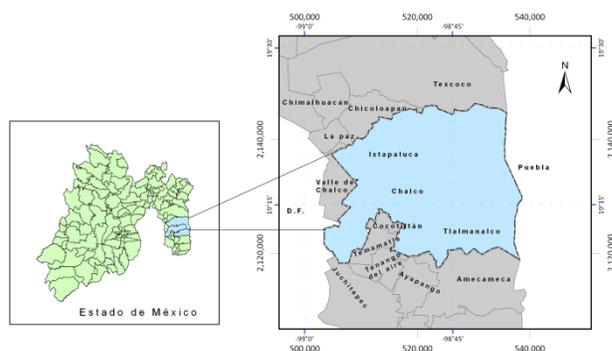
attack operations are conducted, but their efficiency is limited by the lack of nearby water sources.

Rainwater harvesting systems (RHS), which describe all methods to concentrate, store and collect rainwater runoff (De Winnaar and others 2007), are renowned for their versatility to solve water shortage problems, although their location may depend on many factors, so geographic information systems (GIS) are used to address this complexity (Mbilinyi and others 2007). Numerous studies have been undertaken to determine suitable RHS sites: Sekar and Randhir (2007) designed a spatial method to identify suitable rainwater harvesting sites based on groundwater recharge potentials; Mohtar and others (2006) presented a GIS-based system to locate suitable water harvesting reservoirs in a local watershed.

The objectives of this study are: a) the selection and geographic treatment by GIS of the variables that affect the location of suitable RHS sites and b) the weighting and integration of these variables using a participatory hierarchical process and a multi-criteria method.

Methods

The study area is located in the east of the state of Mexico, comprising the municipalities of Chalco, Tlamanalco and Ixtapaluca (Figure 1) and covering an area of 70,668.09 ha.



Figure—1 Study area location.

According to Escamilla and others (2010), the air operations officer for Mexico's national forestry commission (CONAFOR)⁵ and related studies (Weerasinghe and others 2010), the most important variables in water loading and RHS functionality in air control of wildfires are as follows : a) wind speed, b) fire density c) proximity to roads, d) visibility (fog), e) air temperature, f) altitude; g) surface runoff, h) slopes and i) evaporation. After a detailed analysis of the information, the variables visibility, air temperature, slope and altitude were

discarded, while the remaining ones were processed in the GIS, generating the following maps:

- a) Wind speed: eight AWS (automated weather stations) were geographically referenced in ArcGIS 9.2; the arithmetic means of the winds in the fire season (December to July) were obtained and the IDW (Inverse Distance Weighting) interpolation method was used. The map was reclassified according to the Beaufort scale.
- b) Fire density: the map was generated from 456 records in the study area for the 2005- 2010 period, using the ArcGis 9.2 point density module (Vilar del Hoyo 2007).
- c) Proximity of roads: the roads were digitized on SPOT 5 images and the Euclidean distance module in ArcGIS 9.2 was applied to generate vertical distances in meters.
- d) Surface runoff: it was calculated with the curve number (CN) method used by the USDA Soil Conservation Service (SCS); the rainfall information required in the calculation was obtained in two steps: 1) for each weather station, the length of records needed to ensure the data mean had a probability of 90% was determined, and 2) the rain distribution function values were adjusted to calculate the return period to 1.1 years and ensure a 90% probability in the precipitation range (Campos 1998).

The hydrologic group was assigned to each soil unit according to USDA SCS tables and vegetation cover, updated to 2010, was classified by its hydrological condition; both were superimposed on the ArcView 3.2 program and assigned the corresponding NC for antecedent moisture type II, 12.7 - 38.1 mm, (Ramakrishnan and others 2009). Surface runoff was multiplied by the cell surface (900 m²) to obtain the result in cubic meters.

- e) Evaporation: for calculating it, the average annual values were interpolated by the IDW method in Arc GIS 9.2.

To develop the land suitability map, maps of the fire density, surface runoff, evaporation, wind speed and distance to roads variables were reclassified into four categories, then each category was prioritized according to the expert and its weighting values immediately indicated; they were obtained from the method of addition and reciprocal (SEMARNAT - INE 2006): 0.33, 0.27, 0.20, 0.13 and 0.07, respectively. The maps were integrated by weighted linear combination (Bojórquez-Tapia and others 2003). The suitability map was standardized on a scale of 0 to 10.

Results

Maps were prepared in Arc Gis 9.2 for the five selected variables:

a) Wind speed: the most severe were found in higher altitude areas in the northeast, and the lowest in the lower areas in the southwest. The optimal class chosen for establishing RHSs was 29 to 49 km h⁻¹ (Table 1).

Table 1—Classes, areas and prioritization of the wind speed variable

Variable	Prioritization	Classes	Area	Surface area occupied
		km/h	ha	%
Wind speed	1	75 - 117	28 269.53	40.00
	2	62 - 74	8200.26	11.60
	3	50 - 61	13 832.61	19.57
	4	29 - 49	20 365.70	28.82
			70 668	100

b) Distance to roads: the study area presented, in a little over 94% of its area, distances from 0 to 1000 m that were selected as optimal (Table 2).

Table 2—Classes, areas and prioritization of the variable distance to roads

Variable	Prioritization	Classes	Area	On the Ground Distribution
		m	ha	%
Distance to roads	1	2000 - 2500	453.15	0.64
	2	1500 - 2000	786.96	1.11
	3	1000 - 1500	2348.46	3.32
	4	0 - 1000	67 078.62	94.92
			70 668	100

c) Surface runoff: the highest volumes (415-667 m³) were identified south of Tlalmanalco and was selected as optimal (Table 3); by contrast, to the north, in Ixtapaluca, the lowest inputs were located (163-280 m³).

Table 3—Classes, areas and prioritization of the variable surface runoff

Variable	Prioritization	Classes	Area	On the Ground Distribution
Surface runoff		m3	ha	%
	1	163 - 280	1836.24	2.60
	2	280 - 402	41 958.08	59.45
	3	402- 415	15 346.02	21.74
	4	415 – 667	11 432.91	16.20
			70 668	100

d) Evaporation: values between 1080 and 1968 mm were found as the annual average (Table 4). Class 1080 - 1302 mm was selected as the optimum.

Table 4— Classes, area and prioritization of the variable evaporation

Variable	Prioritization	Classes	Area	On the Ground Distribution
Evaporation		mm	ha	%
	1	1745 - 1968	13 390.56	18.95
	2	1524 - 1745	12 738.51	18.03
	3	1302 - 1524	11 103.03	15.71
	4	1080 - 1302	33 437.79	47.32
			70 668	100

d) Fire density: there were from 0 to 3.3 fires km⁻² and densities of 2.4 to 3.3 were selected as optimal (Table 5).

Table 5— Classes, areas and prioritization of the variable fire density

Variable	Prioritization	Classes	Area	On the Ground Distribution
Fire density		fires km-2	ha	%
	1	0-0.8	55 193.72	78.10
	2	0.8-1.6	6949.52	9.83
	3	1.6-2.4	5484.25	7.76
	4	2.4-3.3	3043.71	4.31
			70 668	100

The maximum land suitability for RHSs intended for the control of forest fires was located to the northeast, in Ixtapaluca, and the south in Tlalmanalco (Figure 4). Most of the area, 30.49%, was placed in category five (Table 6).

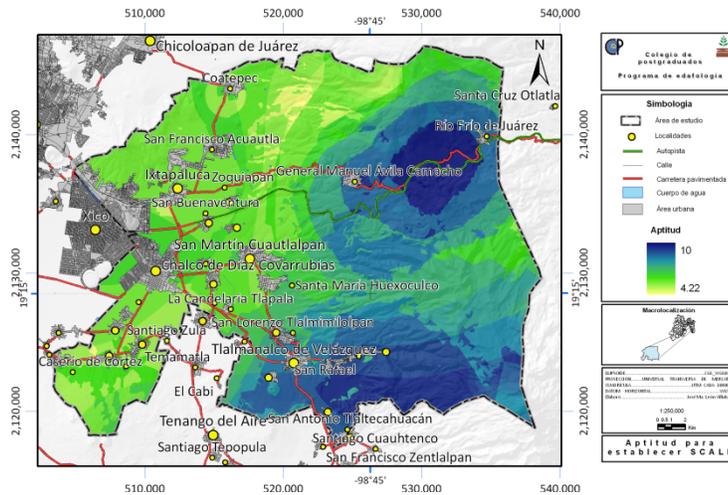


Figure 4—Land suitability for RHSs for forest fire control

Table 6—Area of each suitability category found in the study area

Suitability scale	Area	On the Ground Distribution
	(ha)	(%)
4	939.51	1.33
5	21 512.43	30.49
6	13 579.11	19.24
7	14 383.71	20.39
8	14 229.45	20.17
9	5829.93	8.26
10	85.86	0.12
	70 668	100%

Discussion

Other researchers with a similar approach rely on the analysis of two variables: a) surface runoff (Gutpa and others 1997) and b) slopes (Mbilinyi and others 2007), simplifying the selection criteria, as observed by Ramakrishnan and others (2009).

Although for most studies the slope variable is important, it was discarded from the model because of its low weight value. By contrast, Gutpa and others (1997) indicate that slope is a key variable due to its influence on the amount of runoff; however, this claim has limited validity on a regional scale as is the case in this study. Elevation was also eliminated from the model because air fire control has been performed successfully at altitudes over 4,000 m.

Surface runoff presented great variability, 163-667 m³, on the map; for example, the northeast showed high curve numbers (70, 73 and 86) and significant runoff

volumes (415-667 m³), which were related to regosol soils and 600 mm of rainfall annually.

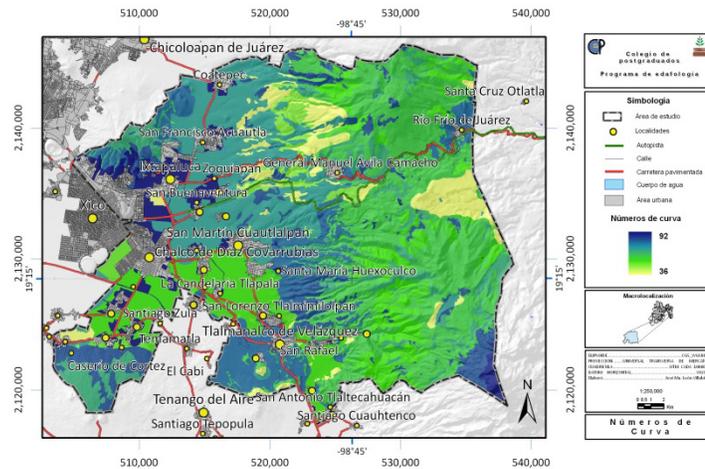


Figure 3—Curve number per unit of soil and vegetation type

This was also observed by Sekar and others (2007) in a similar study, where soil types and their infiltration capacity directly affected the curve number values and subsequent runoff values.

Distances to RHSs intended for agricultural use have been set at between 1000 and 2000 m (De Winnaar and others 2007); by contrast, this proposal requires greater proximity to roads. The optimal class kept a positive relationship with high suitability due to the adequacy of the road network in the fire areas. Furthermore, sites found to be suitable for RHSs intended for forest fire control respond, on one hand, to the weighting values of each variable, and on the other, to the optimum classes of each one, as is the case with the fire density, runoff and evaporation variables, which define the suitable sites in the north area. This was also observed by Weerasinghe and others (2010), whose potential RHS sites depended on the weight values and the optimum classes of each variable. Instead, there was a negative relationship with the wind speed variable in the north area, which is consistent with the observations of Simiu (1978), who stated that the records of wind under 10 do not produce accurate results.

Although you may consider other factors of social, economic and environmental, they can be validated in the establishment of RHS site according to terrain and layout of the structure (De Winnaar and others 2007, Sekar and Randhir 2007, Ramakrishnan and others 2009).

Summary

This research evaluated the territorial capacity in three municipalities in the eastern part of the state of Mexico, RHS intended to establish air control of wildfires, combining variables affecting the water loading of the helicopter and the same RHS by multicriteria evaluation in GIS, finding good skills in over 28% of the study area, in two areas: north, in Ixtapaluca, and south in Tlalmanalco. Variables responded mostly with a positive, except for wind speed. Identified fitness provides a useful framework for making decisions, which will have to add economic and social elements to decide on the type of structure (design) that is more affordable and cause the least environmental impact.

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