Title

The application of spatial analysis in the implementation of a qualitative infiltration model to evaluate the aquifer's potential recharge for conservation areas of Mexico City

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Abstract

Mexico City is undergoing a rapid process of urbanization, occupying remnant rural and conservation areas. The land use change of natural areas begins normally with a conversion to agriculture, which has a "bulldozer" fragmentation effect, eliminating forest zones, and making them susceptible for residential use. A growing land cover modification process has an important effect on the hydrological cycle, and then by increasing sealed areas to water infiltration, this process alters significantly the aquifer's recharge, highly reducing the capacity of the aquifer to offer more than 70% of the water consumption of the city.

Based on the application of spatial analysis methods, a water-infiltration model was implemented in a geographical information system, in order to evaluate the recharge potential of some areas of Mexico City's aquifer. This is a qualitative and spatial model that includes a watershed delineation, -based on a digital elevation model- along with information on soil, precipitation and land cover spatial data. Throughout the application of the model, relevant information is generated in order to identify areas of high and low recharge potential. This information can be then used to define a general policy for the sustainable land use management of the City, restricting the inadequate land use changes. The water-infiltration model has been developed using a strategy from algorithms theory called "*divide and conque*r", for which the fundamental factors that determine the aquifer's recharge process have been abstracted, and, later on, analyzed individually. The strategy begins by defining the spatial and temporal variability of these factors, in order to reduce the problem complexity without losing or ignoring relevant information. Finally, the results derived from the individual analysis were summarized to obtain a single indicator of potential aquifer's recharge model.

Out of the total surface of the studied area with the model, 22% was characterized as low infiltration, 57% of medium infiltration and the remaining 21% of high infiltration. According to the results, 78% of the analyzed area still offers a very important environmental service based on groundwater recharge. However, there is a very high risk of degrading the areas of high infiltration, because they belong to forest areas and agricultural zones prone to urbanization, following the observed process of land use change and resulting in low infiltration areas.

Article text

1. Introduction

Mexico City faces enormous challenges to provide enough water to a population of more than 20 million people. Human activity in this geographic area has resulted in significant landscape changes that are expressed in increases of surface sealing, water pollution and green areas reduction. Land cover modification has accelerated the process by which the ability to catch and to store the vital liquid have being gradually diminished in surrounding watersheds. Considering the enormous amount of water that must be extracted, conduced, consumed, treated, and drained from the city, the characterization of its hydrologic phenomena is an activity of great relevance, especially to monitor and avaluate the water that can be infiltrated to the aquifers. This information can contribute with elements of analysis for a better operation of its geographic space in terms water management. In this context, the analysis and research of the hydrological functioning is a key element for decision making, and this can be implemented throughout spatial modeling efforts. However, it has not been able to develop a consistent methodology, or method that can be follow as a specific guide for hydrological research. One of the major constraints in implementing hydrological spatial analysys is the lack of basic data . For that reason, spatial analysis and hydrological studies for specific conditions, can be often adapted from studies made over different and wider geographic regions. In the process of refining the models, more detailed information is needed, and is only when geographic analysis tools such as remote sensing techniques, geostatistics interpolation methods, raster modeling, map algebra, can be combined with the the analysis of hydraulic connectivity of surfaces for the definition of the superficial hydrological system.

The use of quantitative methods for the analysis of the groundwater-recharge process can be a very complex task, and often requires a group of parameters that might not be always available. A quantitative approach for hydrological analysis has been developed and implemented in commercial models like Modflow or MIKE SHE but these face the difficulty of choosing the appropiate technique to parameterize the selected model (Scanlon and Healy 2002). For an adequate model initialization and parameterization a technique that included space/time scales, range, and reliability of recharge estimation has to be considered. The difficulty of modeling and parameterization is so complex that comprehensive methods for measuring the certainty level of the results by quantitative modeling have been developed (Décourt & Madsen 2002). Consequently, the generation of these parameters can be very time consuming and expensive, restricting then the utility of this type of models and therefore their applicability (Madsen & Kristensen 2002). Furthermore, only if the parameterization process was sufficiently rigorous it is possible to get reliable quantitative results (Mirghani 2001). As an alternative to quantitative model parameterization, qualitative modeling methods allow to make enough reliable predictions of a particular problem without having to implement comprehensive procedures to obtaining the unavailable parameters. Generally, qualitative models are more flexible and easier to apply .

The goal of this scientific report is to offer a description of the analysis methods used for the implementation of a spatial qualitative infiltration model. The methodology is a development from the "divide and conquer" strategy, arised from the field of algorithms design. For this particular case, the strategy begins with analysis and identification of the available factors (or factor groups) that could be combined/included (or even ignored) in a specific step of the analytical process. The exclusion of a particular factorcan be justified in terms of:

a) reduced spatial variability
b) the parameter exerts an unwanted effect on the final characteristic to be defined (objective variable)
c) the parameter effect is associated whit another parameter (for example: dependence between climatic variables).

At the first stage of this research, factors that normally exert a specific influence on the objective variable were analyzed separately. These factors are:

a) geology
b) soil types
c) land cover
d) precipitation and temperatures
e) catchment areas as a logical operation of the territory (based on relief generation of runoffs towards channels in deeper surfaces).

To conclude this research, a combined analysis of these factors was implemented in order to generate a final infiltration model. The methodology for the model generation is described in the following paragraphs

2. Geologic characteristics (Tlalpan, Mexico City)

Most of the geological characteristics of the area in which the model was going to be developed include material of volcanic origin such as basaltic or andesitic type. These characteristics in turn determine a high permeability as hydrogeologic characteristic. Permeability is produced by the fractures originated during the cooling process of the expelled lava (Mooser, Montiel, Zúñiga 1996). Spatial variability in the geological layer is determined by the presence of small volcanic cones of a reduced number of elevations in the zone. Spatial variability due to volcanic cones were included in the analysis at the end of the process because they were determinants in defining zones of low aptitude to infiltration. Additionally this type of surfaces normally belong to upper parts of the delimited catchment areas, which not necessarily determines a differentiated spatial analysis from the geologic material point of view. Then, the assumption that the parameter geology is not a restriction of the infiltration process of the zone of study, justifying its exclusion of the analysis.

3. Land cover spatial variability

Land cover variability plays a very important role in defining the current situation and the potential recharge and soil and sediment retention in catchment areas. Land cover spatial variability was determined by remote sensing satellite imagery. A land cover map was derived by a supervised classification of a Landsat 7 image data (fig 1). Additional precison was gained by integrating information derived from an orthophoto of the same year with a space resolution of 0.5 m. Land cover data was then transformed to infiltration information by a reclassification of land cover types into infiltration classes, defing areas going from lower to higher infiltration rates and potential recharge.

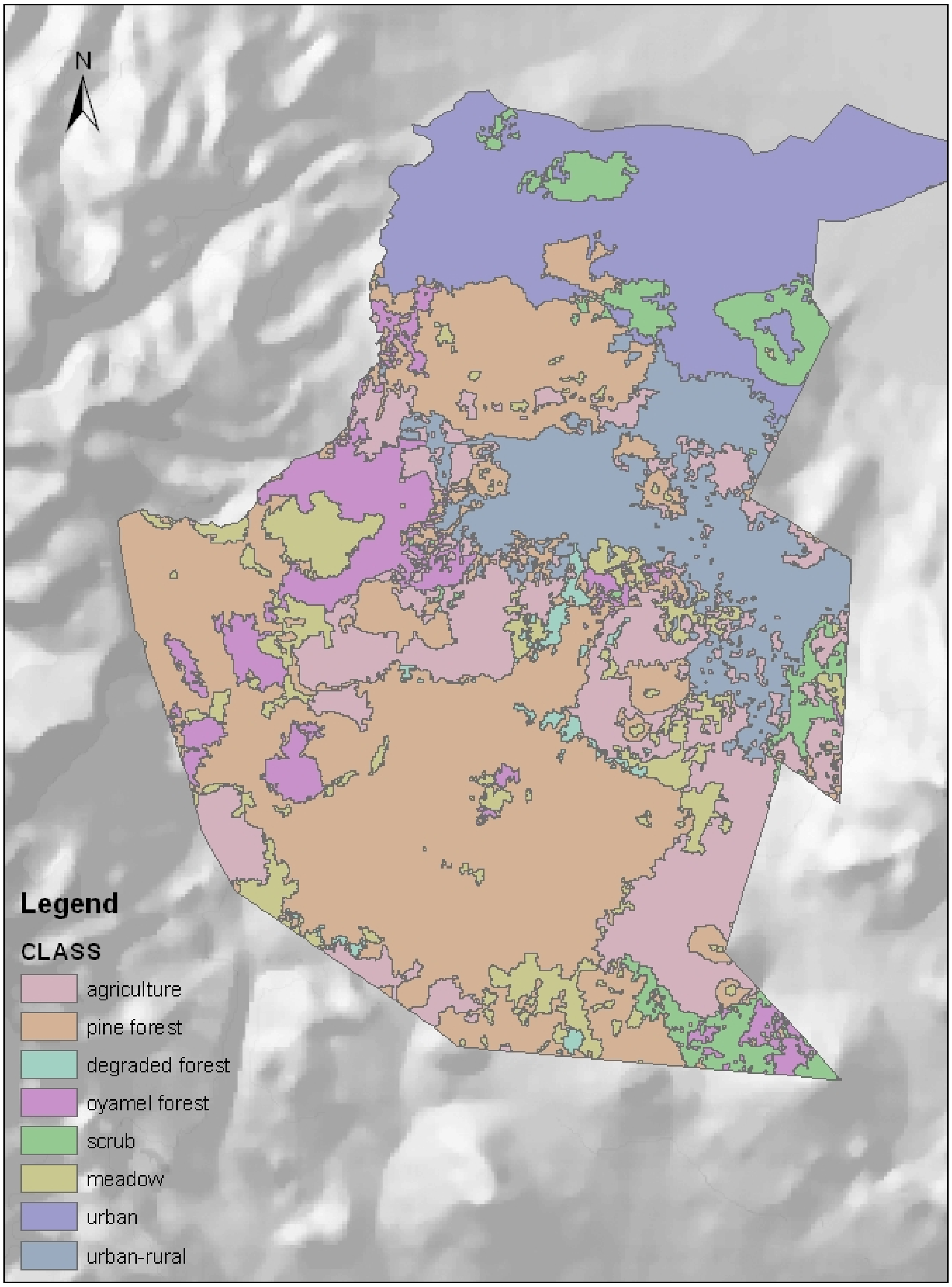

Fig. 1: Land covers map obtained by a supervised classification of an landsat 7 image verified by aerial photography for Tlalpan DF

According to the land cover map, about 57% of the total area (26.032 ha) is forest land (includes also scrubs and meadows); about 36% is dedicated to agriculture and about 7% is urban cover.

4. Landscape subdivision in catchment areas with runoff generation and flow accumulation zones

It was necessary to identify the catchment areas that are being sealed as a consequence of the anthropic intervention. Urbanization has a compactation effect on soils and therefore reduces the possibilities of aquifer’s recharge. The upper and low areas of runoffs within catchment areas were identified applying the Arc-Gis Hydro model of superficial hydrological connectivity analysis. A digital elevation model (DEM) was used as input for Arc_GIS hydro for the extraction of the topographic structure (Jenson and Domingue 1998). Catchment areas were delimited at two hierarchic levels (fig 2). Areas with a minor referential size (1.5 km^2) were used units of infiltration aptitude. A reclassification of the catchment areas was done based on an arbitrary thickness of 500 m for the limits of the catchment areas. With this procedure, the internal catchments areas (core) were identified. Considering that core areas are more suitable to the infiltration than the upper parts of the catchments, core areas determined the highest infiltration aptitude value.

5. Estimation of the spatial variability of zones with high precipitation on a monthly basis

Precipitation data used for the model were expressed as year averages in the analysis to define the aptitude to aquifer’s recharge in specific geographic areas. However, yearly averages can increase the estimation error, compared to procedures based on analysis of shorter periods of time, like for example by monthly averages. For that reason, the use of monthly averages instead of year averages was chosen. An analysis for the years 1970 to 1990 was done in order to find the rain season period of the Mexico City valley (April to October) with the greatest average values of daily precipitation intensities. Spatial variability of precipitation data was analyzed with a geostatistic method (universal kriging) by processing the precipitation data of 51 climatic stations of Mexico City. The average quadratic error (RMSE) in the interpolation was of 10.3%. As a result of this analysis (s. annex) we defined that the daily precipitation average of August for the years 1970 to 1990 was a good indicator of the intensity of the spatial variability of precipitation (fig 3).

6. Soils spatial variability

The soil parameters that affect the infiltration process for this model were: soil depths, soil textures and texture modifiers. A universal kriging procedure with spherical function was applied to the values of soil depth in order to define its spatial variability (RMSE = 12.4%). A qualitative cartographic model procedure was programmed on the Arc Info-Grid module to characterize soils aptitude to the infiltration process. The method consisted on calculating the arithmetic mean from the available soils parameters, that were previously expressed spatially in maps (s. fig 4). Generally the soils do not present great difficulties to the infiltration process.

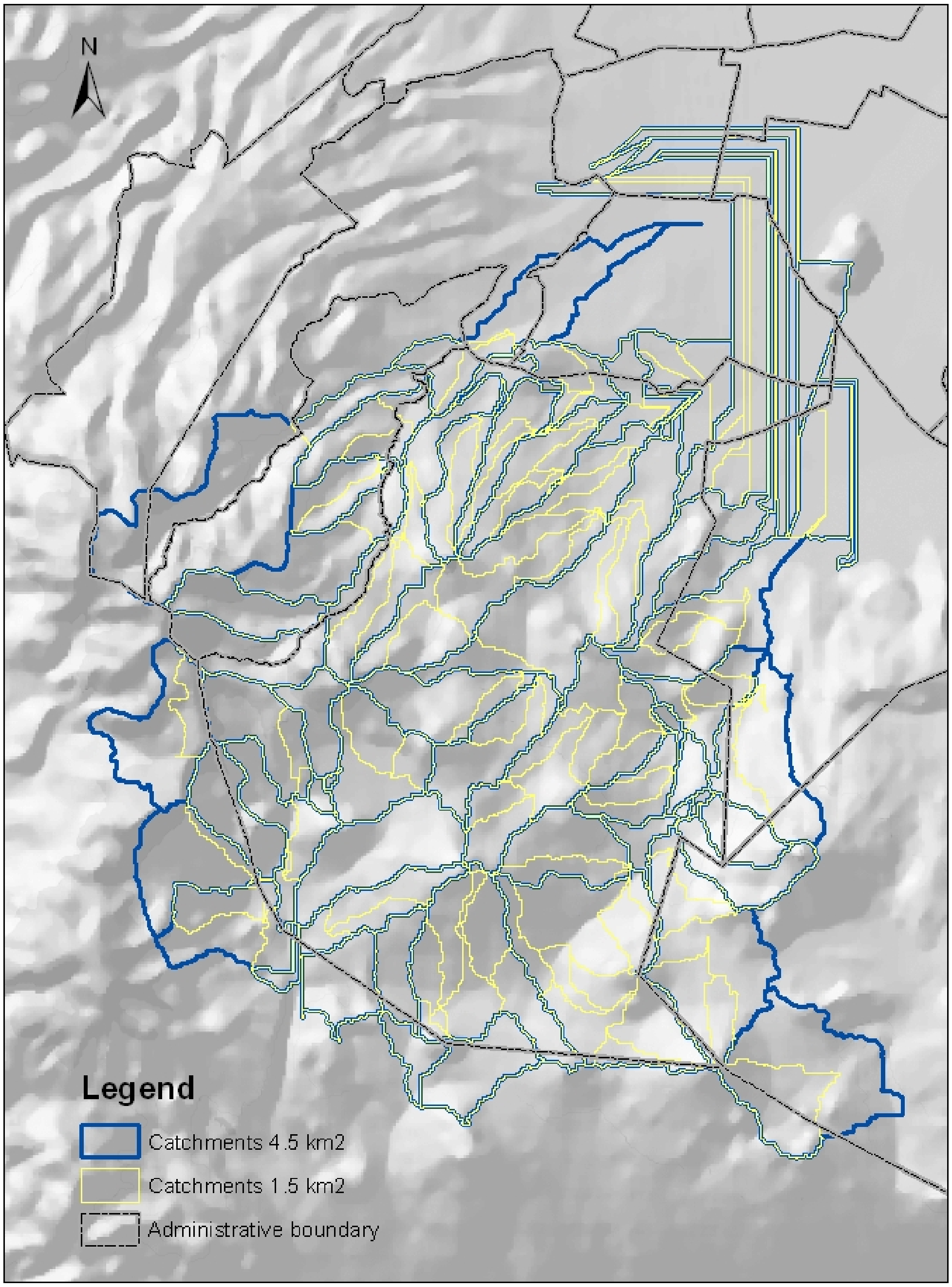

Fig. 2: Catchment areas of referential size of 1.5 and 4.5 km^2, delimited by means of the ArcHydro model according to Jenson & Domingue (1988) for Tlalpán (Mexico City) from a DEM to 30 ms

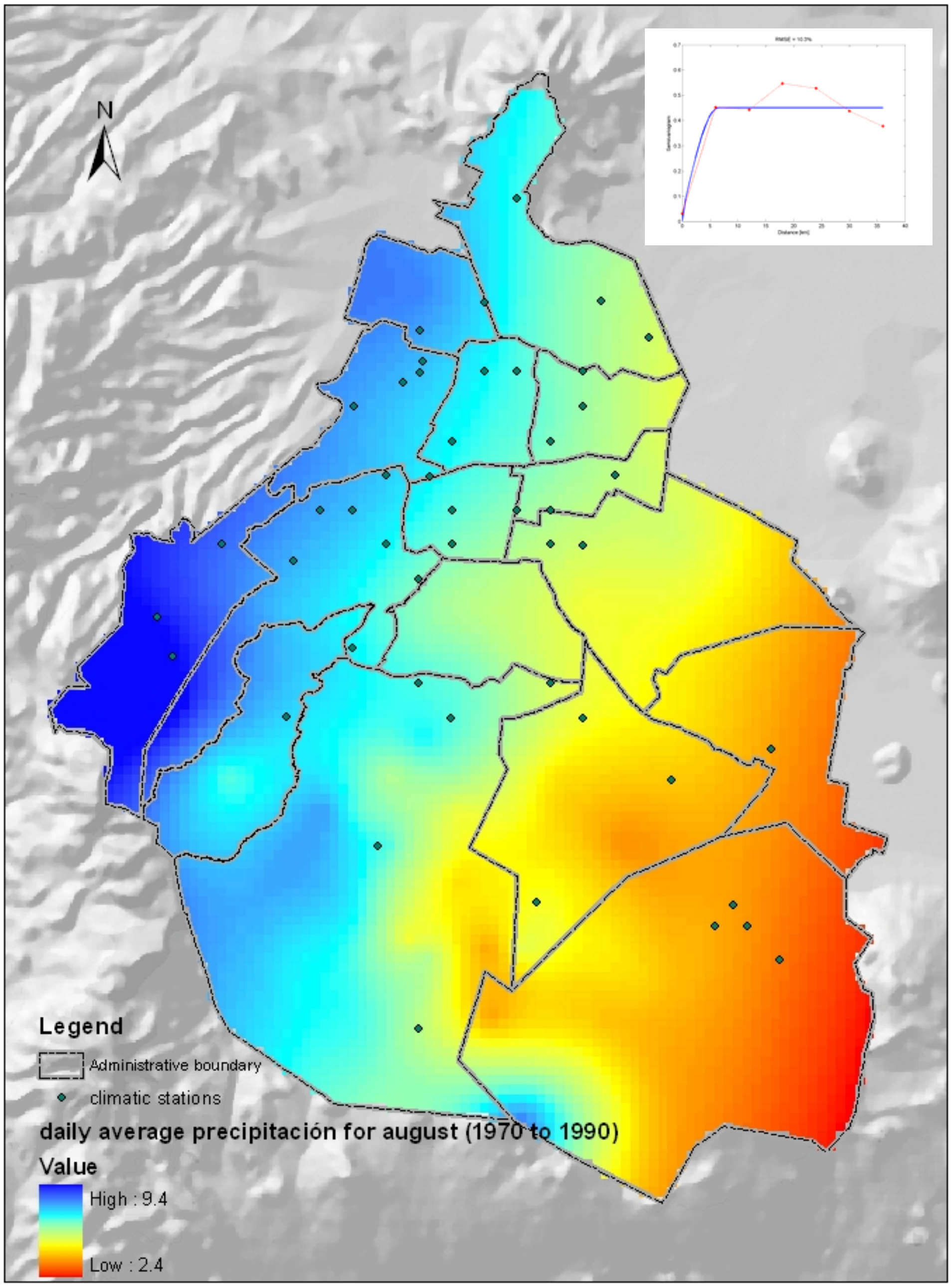

Fig. 3: Spatial Variability of intense precipitations for the territory of Mexico City, daily data average for August from 1970 to 1990 (universal kriging interpolation)

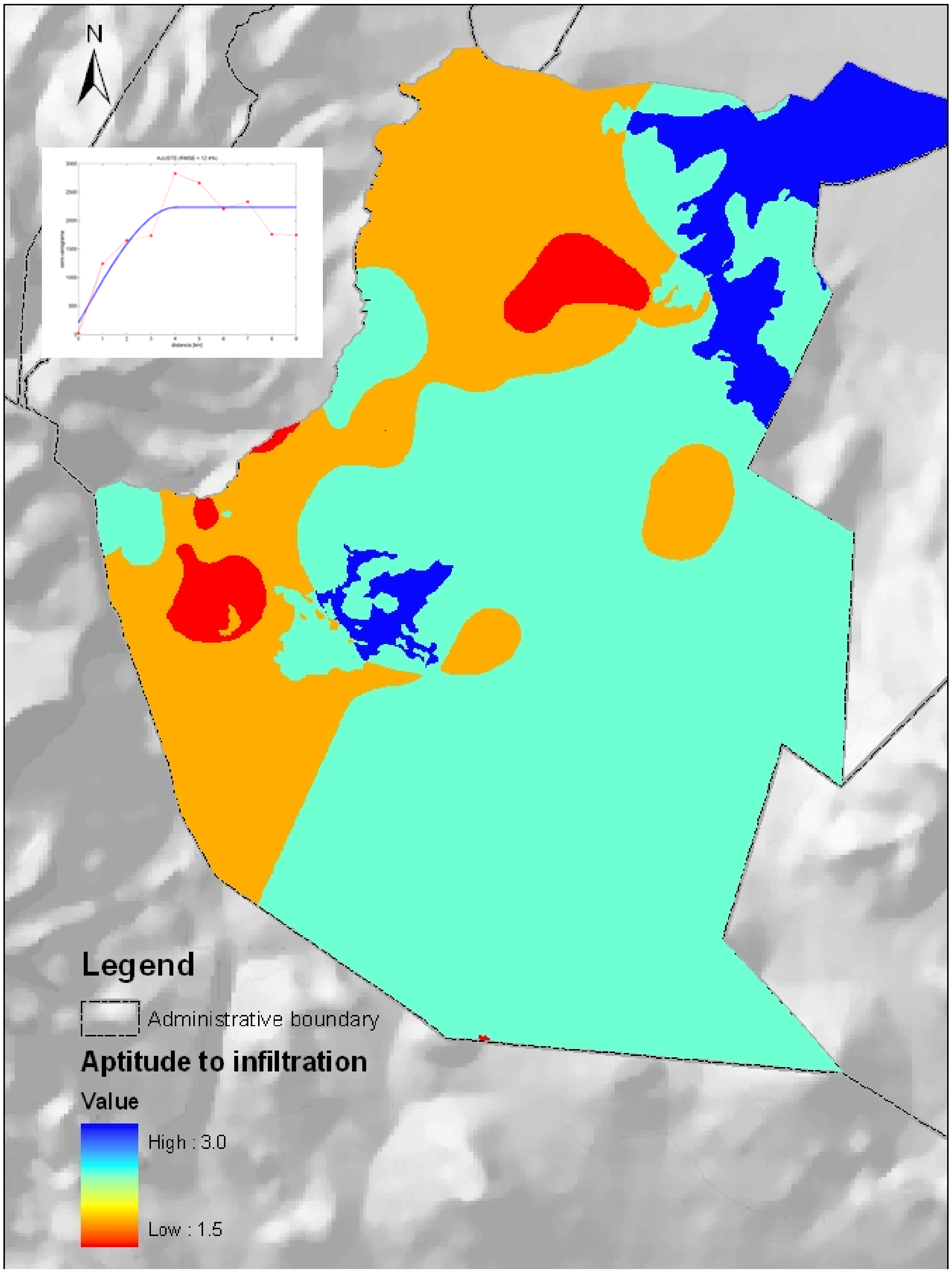

Fig. 4: Soil infiltration aptitude in Tlalpan (Mexico City) considering depths, textures and texture modifiers

7. Qualitative definition of the spatial variability of the infiltration process in the zone of Tlalpan

Most of the territory of Tlalpan does not have great restrictions to the infiltration process (fig 5). A highly permeable geologic material, the analyzed soil characteristics and the high precipitation rates have a positive influence on the aquifer's recharge process. In the catchment areas with low human intervention (mainly corresponding to forest or scrubs zones) the soil permeability and the underlying geologic layers have not allowed the formation of rivers or streams. On the other hand, areas with high human intervention are generating a considerable amount of impervious surfaces, that result in soil and water losses from the upper zones to the low areas. Important runoffs are generated by upper zones of catchment areas with a predominant forest cover. In these cases, the water infiltrates quickly in the low parts located in the low zones. Normally it is only possible to observe some water and soils losses of the high parts that flow towards the low ones, where the soils remain protected by their own vegetal cover.

High infiltration zones correspond to forest zones located outside the upper parts of the catchment areas, that present low soil depth and coarse textures. The medium infiltration zones include areas located at the upper part of forest zones or zones with agricultural use or meadows, with mainly low depth soils and medium textures. The low infiltration zones belong to urban areas with highly impervious surfaces located at the upper part of the catchments or to areas used for agricultural or meadow purposes, which allows the generation of increased runoffs because of the absence of a stable soil cover.

Out of the total area, 22% is considered to be of low infiltration, 57% of medium infiltration and the last 21% of high infiltration. Although 78% of the studied area is still offering the environmental service aquifer recharge, the risk of degrading these infiltration areas, to low infiltration zones is very high.

8. Conclusion

By the application of a qualitative spatial analysis it was possible to generate a qualitative infiltration model for the city of Mexico. This model is focused to support the decision making process to define policies of sustainable water management of the conservation zone. The qualitative aspect of the model allowed to contribute even-though there was not enough basic information.

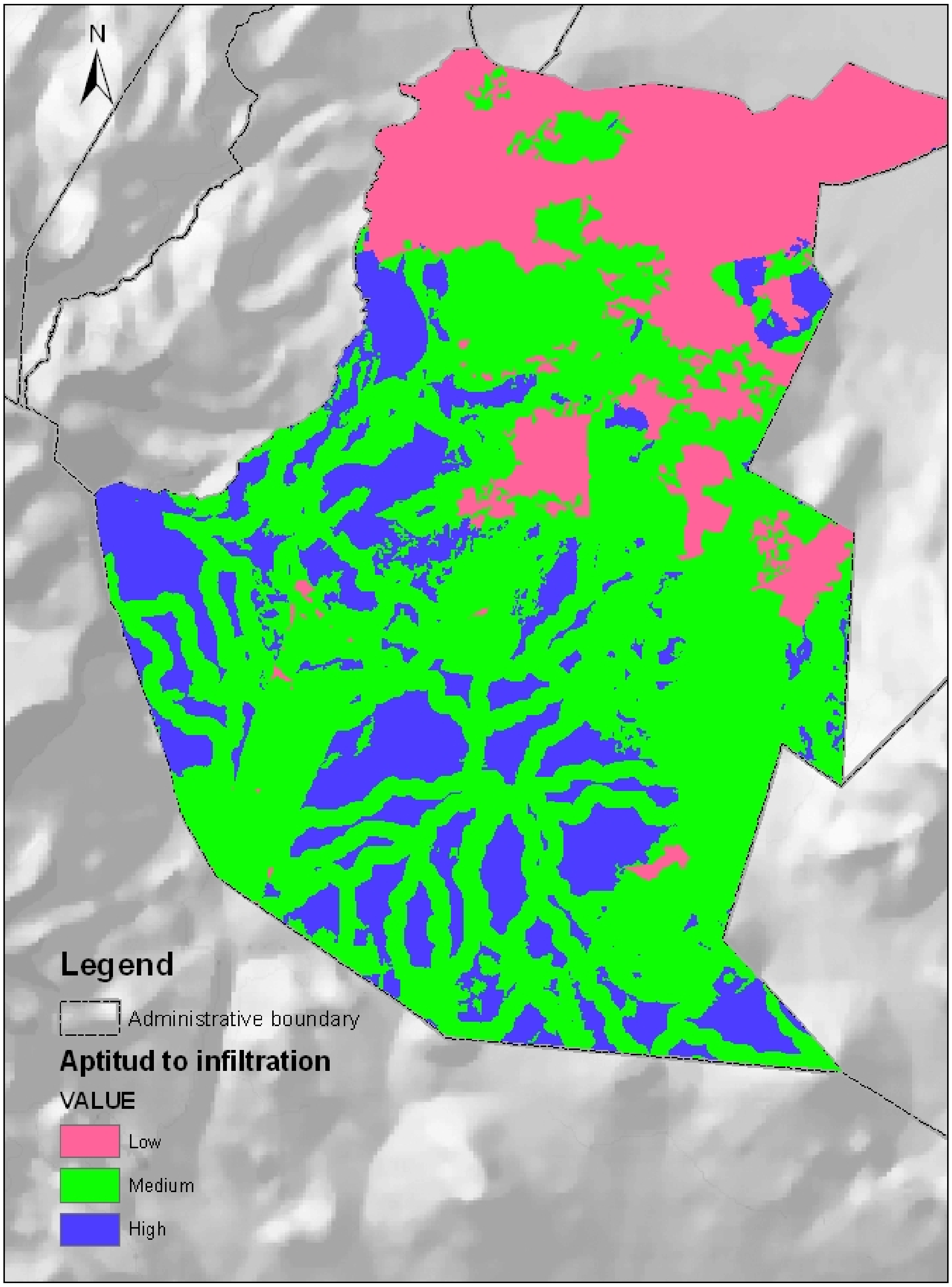

Fig. 5: Qualitative spatial variability of aptitude to infiltration in Tlalpan (Mexico City)

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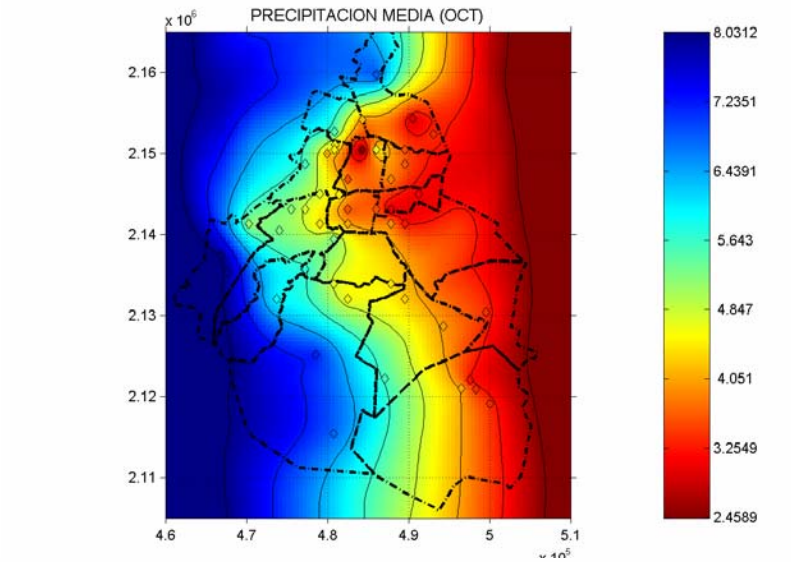
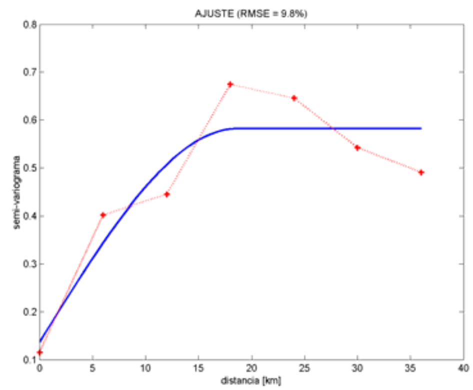
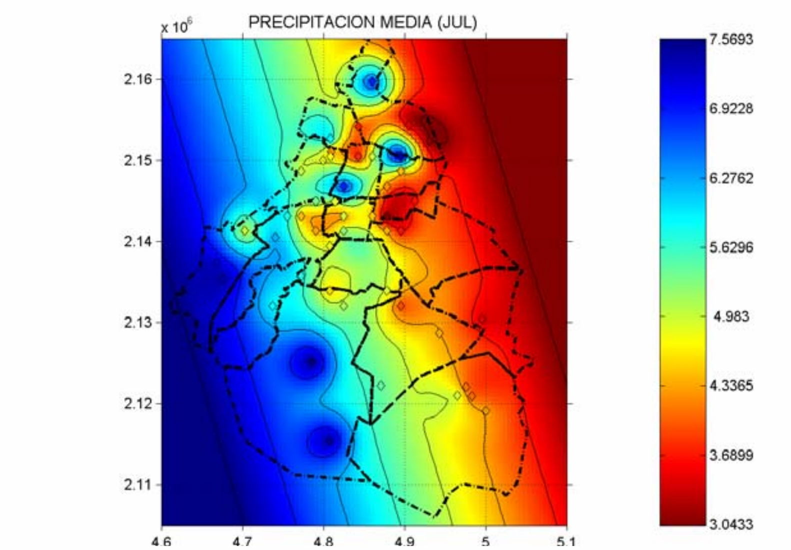
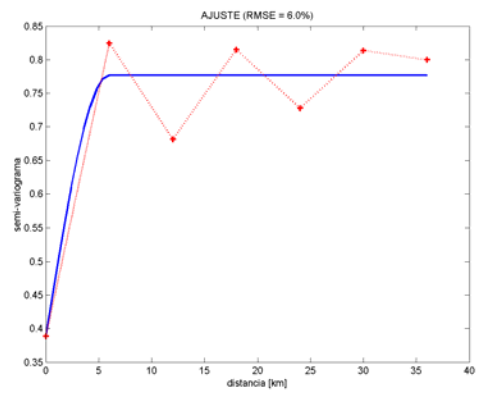
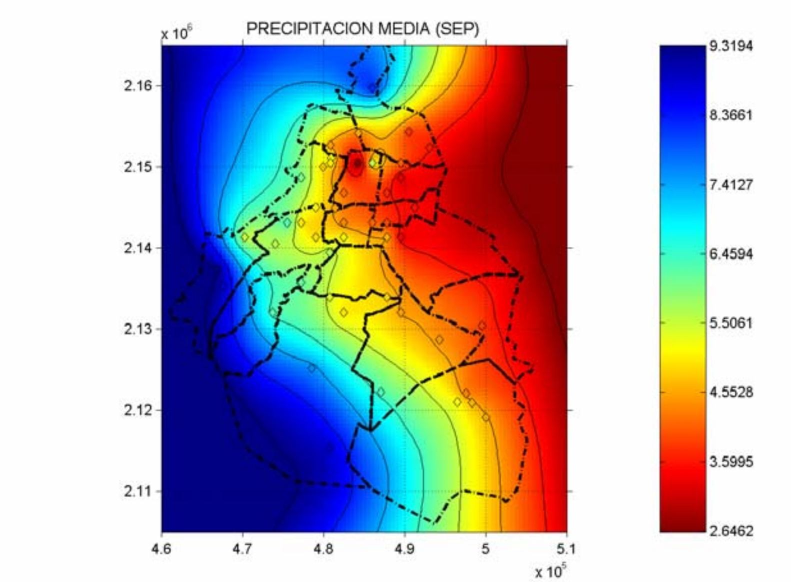
Annex. Interpolation results by means of universal kriging with spherical function for daily average of precipitation for April to October from 1970 to 1990.

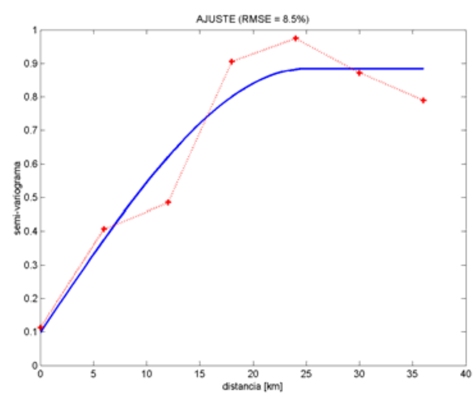


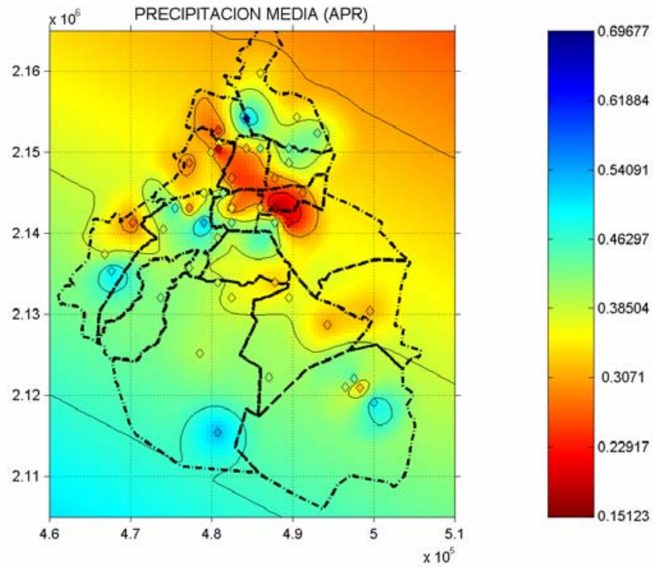








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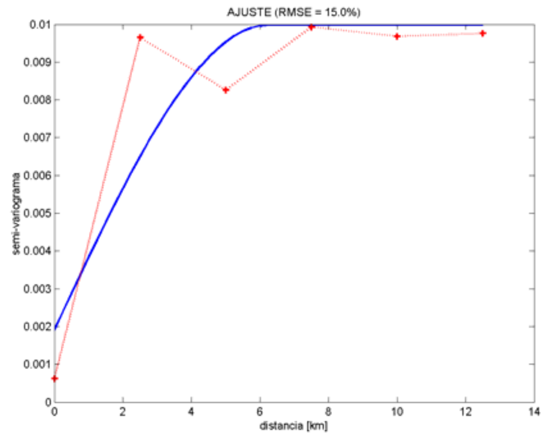
AJUSTE (RMSE = 15.0%)
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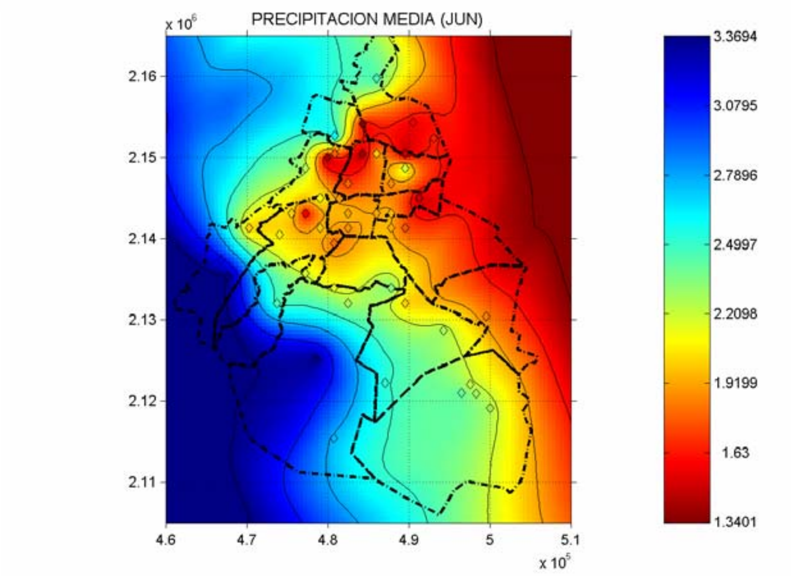
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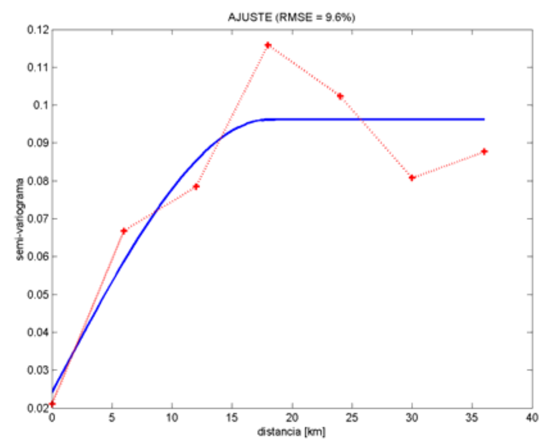
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