Mexico´s National Map of Small Watersheds

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Abstract

In agreement with policies for rural development, the National Program of Micro Watersheds (NPMW) was created in Mexico at the Federal level by the current administration. The NPMW uses the small watershed for the integrated management of natural resources. For each watershed, the basic instrument is a management and conservation plan known as Plan Rector de Producción y Conservación (PRPC) or Rector Plan for Production and Conservation. However, each PRPC requires the generation of the Micro Watershed National Map for the Mexican Republic (MWNM-MR), and a GIS-based consultation management system. The objective of this paper is to present the automated methodology for the elaboration of the MWNM-MR and the GIS-based consultation management system (GCMS). The GCMS was developed in ArcView and Avenue and it contains a national database of micro watersheds.

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Introduction

Watersheds have been managed hydrologically – frequently in a fractionated form rather than as an integrated unit – for the control of flooding and as a source of water for irrigation or for improving river navigation. Most of the world rivers have been modified by the construction of channels, dams, or drainage systems in wetlands, often with a great benefit for society.

However, watersheds are not seen or managed as units. Integrated management of both economical and ecological attributes of a watershed is very difficult because its boundaries often are not the same as the economical and administrative boundaries and, in some cases, international limits. Sectarian, regional and cultural crossover is essential for the management of watersheds in order to maintain their ability to provide, in a sustainable way, ecological, hydrological and economical services.

In order to provide a quantitative basis for the integrated management approach, it is required to be able to characterize the watersheds and to measure the nature and patterns of the risks in a quantitative way. Human population, plants and animals distribution, the patterns of economical activities and other relevant variables have not been managed, neither analyzed, in an integrated way for each watershed, which makes the goals in a management plan difficult to achieve. Therefore, the very first step in a management plan has to be a precise and exact delimitation of boundaries for the study area, in this case, the small or micro watersheds. Counting on a Micro Watershed National Map for the Mexican republic (MWNM-MR) is a key element in the planning process at the national level. For this reason, it is very important to carry out a project like this one.

General Methodology for the Delimitation of Micro Watersheds

Without any doubt, the main input to delineate a hydrological unit, such as a watershed, sub-watershed or micro watershed, using a Geographical Information Systems (GIS) is a Digital Elevation Model (DEM).

Generation of the Digital Elevation Model
A DEM can be defined as a regular grid of terrain elevation values that represent the form of the Earth surface. In a more generic way, there exists the Terrain Digital Models (TDM). According to Felicimo (1994), a terrain digital model is a numerical structure of data representing the spatial distribution of a quantitative and continuous variable (for example soil pH, precipitation, evaporation, etc). When this variable is terrain elevation then we are referring more specifically to a Digital Elevation Model (DEM). Following the consideration of Felícimo (1994), these models have some requirements that other models lack, such as:

a) Do not have ambiguity
b) Do have the possibility of modeling processes.
c) They can be verified
d) There is repeatability in the results

Traditionally, watershed delineation has been done using conventional cartography with elevations in a topographical map, mostly in the form of contour lines. However, with digital cartography it is possible, in addition to that, to create a set of models derived or elaborated from the information contained in a DEM. The simplest derived models can be created exclusively with information from a DEM and they can reflect simple morphological features such as slope, orientation and shadowing of the relief. Incorporating extra information, such as terrain morphology and numeric simulations of physical processes, allows the elaboration of more complex models.

Input of topographical information is the first step in the process of constructing a DEM. This process includes transforming geographical reality into a digital data structure. This is a very important step forward since the main limiting factor for later analysis is the quality of data.

On the other hand, utilization of Geographical Information Systems (GIS) is a more efficient way to create a DEM. The firs element needed in this case is the availability of cartographical information in digital format and in a structure such that can be interpreted by the GIS. We will now consider the creation of the DEM and from there, how to delineate a hydrographic watershed, starting from the fact that the original available information is a topographical map with contour lines in paper.

Transformation from paper to digital format requires of a digitizing process of contour lines contained in the topographical map. This is a slow and time consuming process. Fortunately, in the case of Mexico this process has been done already by INEGI, the Mexican Institute for Statistics, Geography and Informatics. This information is commercially available in CAD format and covers all the country at a 1:250,000 scale. For Central Mexico, approximately 1/3 of the national territory, the same digital topographical information is available at a 1:50,000 scale. Some areas, but not all, in the North and the South have also 1:50,000 digital topographical maps.

For the purpose of this work 1:50,000 vector topographical maps for Central Mexico and 1:250,000 for the rest of the country were used. Then, Arcview 3.2 (ESRI, 1999) was used to create the DEM's. The process consisted of an interpolation of vector points from the digitized contour lines.

The final result of this process is a grid file with terrain elevation data in every point interpolated or known. Therefore, it is necessary to define the cell size, which depends on the scale of the original information, and the area to be covered. The cell size will define how detailed the grid will be in the DEM. In general terms, and for a Pentium III-type computer, GIS such as ArcView execute the operations very quickly with a grid of up to 10000 cells (for example: 500 rows and 200 columns grid). Some more modern and powerful computers can operated at higher speeds with grids up to 1,000,000 cells. Under these considerations, and depending of the study region, Maidment (ESRI, 1999) suggest the following classification of scale application based on for the size of cell (Table 1).

Table 1. Size of Cell and Scale of Application

Size of Cell (meters)	Scale of Application
1-10 m	Ecological or Industrial Areas
10-30 m	City or Micro Watershed Scale
30-100 m	Small of Medium Size Watershed
100-500 m	State or National Level
1 km	Continental or World Scale

The selection of cell size also depends on the type of process that will be studied. For example, if a terrain surface is to be studied, it is known that this property has a great spatial variability and a smaller cell size is needed. In climatic studies (temperature, precipitation, etc.) the level of variability, especially on small areas, is smaller, and bigger cells can be used. For the purpose of delineating micro watersheds, a 25-m cell size for the 1:50,000 topographical maps and a 100- m cell size for the 1:250,000 same type of map were used. Obviously, due to the size of the area to cover (area extension of Mexico is approximately 1.95×10^6 km^2), it is almost impossible to create only one digital elevation model for the whole country using the scales mentioned above. Because of this, digital elevation models were obtained at the Hydrological Regions level. Figure 1 is an example of the DEM created for a portion of Hydrological Model Region No. 12.
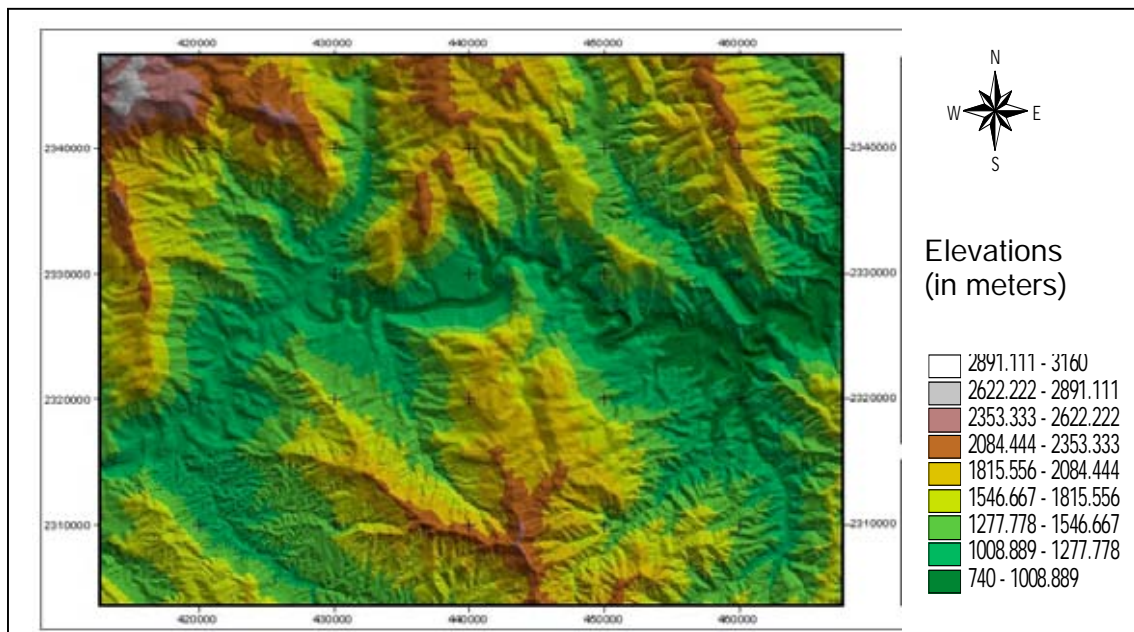

Figure 1. DEM generated for a portion of Hydrological Region No. 12

Pre-processing of DEM

In this part of the study, the analysis and processing of DEM's is presented, taking advantage of the potential capabilities of the GIS system used for the hydrological analysis, with the purpose of doing an automated delineation of

micro watersheds. The idea of this work was to let the GIS do all operations in an automated way. However, the process requires other calculations such as the preprocessing of the DEM and determination of flow direction and accumulation.

For the delineation of watersheds, it is very uncommon to execute all operations without doing modifications before. The idea is to adjust the DEM for later processing and be certain that the data will be reliable. This modification do not implies the distortion of reality contained in the DEM, instead, is a way to get closed to it. The reason for this is that the same process of creating DEM's introduces deviations in the relief that do not correspond to the natural conditions. These deviations can also be produced from the conversion of primary sources (aerial photographs, classic cartography, etc) of data, previous to the elaboration of the DEM and therefore these deviations have to be eliminated in the preprocessing step of making the DEM. Among these deviations are the so called "depressions", which are elements that in reality correspond to areas of reservoirs or water retention structures. Such "accidents" make difficult or limit the correct calculation of parameters, due to the fact that they stop the correct water flow advance along hill slopes, affecting all later calculations. This water flow advance towards maximum slope direction is the base for many, if not all, of the most important hydrological and related calculations.

The most classical and used solution to this problem consists in refilling the depressions. This process is known as "pit-filling", which generates flat surfaces on which calculations can be done forcing the flow direction according to different theories. It is important to mention that, generally, assignation of flow directions over flat surfaces is based on establishing a distance from the main stream from higher to lower elevations areas. There is many new algorithms for this purpose, such as the algorithm of Garbretch and Martz (1997), implemented in the powerful analysis software called TOPAZ (TOpographic PArametriZation). Refilling the depressions and sinks is therefore a previous step for later hydrological calculations, which are the basis for watershed delineation.
In this work, this process was carried out using Arcview, which adapts Jenson and Domingue (1988) algorithm for the modification of elevations that correspond to the depressions. The functioning of this algorithm is based on the natural behavior that a water stream will do if it finds in its course a depression. Initially, the stream will filling up such depression, then drain the excess into the lowest elevation end.

Once the DEM has been processed, and all artificial depressions of the terrain have been filled up, there is a possibility to delineate the boundaries of hydrological watersheds. However, this process has to be taken in steps. First, it is required to determine flow directions. This aspect will be considered next.

The basis for this step s very simple and consists on the evaluation of the existing slopes between the analyzed cell and the eight neighboring cells. This process is known as D8 or *Deterministic eight* (Jenson and Domingue, 1988). Calculating flow directions means determining the direction of runoff in each of

the cells that made up the DEM. Following the D8 model the flow can take any of the 8 possible directions, as shown in Figure 2. The selected direction will be the one with the stepper slope between the cell in consideration and the neighbor cell where runoff flows into. In Figure 2 it can be appreciated as an example, that number 1 means flow directions to the East, number 64 represents the North, 4 represents the South and so on. The algorithm to do the above procedure comes included in many of the GIS programs and Arcview is not the exception.
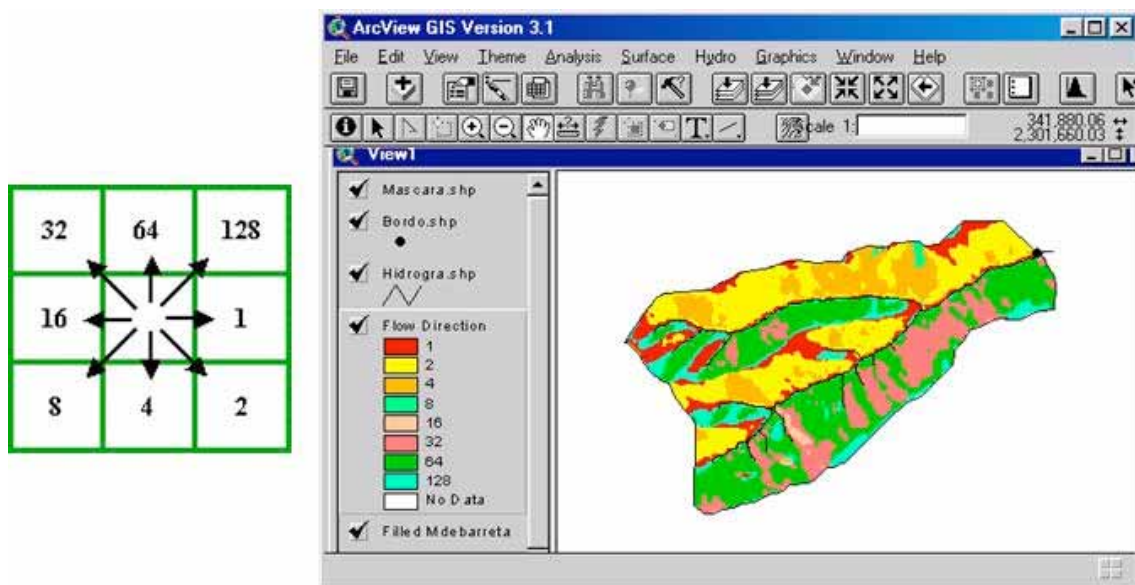
Figure 2. Determination of water flow directions

Flow Accumulation Calculation

Next step in watershed delineation is the calculation of what is known as flow accumulation. The idea is to get the corrected cells connected following the flow direction. The procedure involves counting the number of cells upstream that drain into the cell of interest. To understand this process, in Figure 3(a) all the cells located in the first row and first column have a zero (0) as indicator. This means there is no more cells upstream draining into them. Cell (2,3), for example, has an attribute of 2, which means there is two cells training into it located upstream: cells (1,2) and (1,3). The result of this calculation is then a new grid that contains as attributes the number of draining cells. Obviously, the cell representing the outlet in the watershed will have as attribute the total number of cells that cover the watershed under consideration.
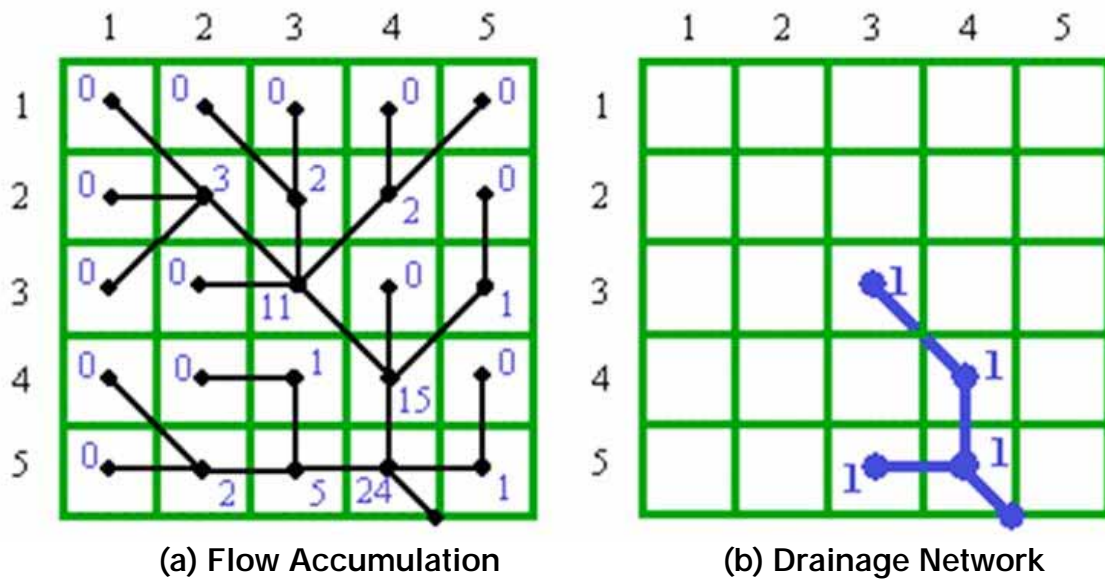
(a) Flow Accumulation   (b) Drainage Network

Figure 3. Sequence of flow accumulation (Taken from Maidment, 1999)

Drainage Network

By using the layer of flow accumulation, the drainage network can be obtained for the whole watershed. The concept of current cell is used for this purpose. A current cell is the one that has an attribute equal or greater than a given limit. This limit represents the minimum amount of cells upstream that will contribute with runoff. Under this consideration, a limit of 100 means that for the generation of runoff in a given cell, so it can be considered a current cell, it needs to have a minimum attribute equal or greater than 100 in the layer of flow accumulation. In this way, drainage network is constructed by connecting all the current cells in accordance to the layer of flow direction. For example, if we take 5 as limit for the case in Figure 3a, only cells with a value equal or greater than 5 will appear as part of the drainage network. This can be appreciated clearly in Figure 3b with the cells (3,3), (4,4), (5,3) and (5,4). All the resulting current cells will have an attribute of 1 for their identification, while the rest of the cells will not have any attribute.

To delineate the watershed boundary, the drainage network is segmented in sections of streams, known in Arcview as "stream links". For each of them, the end point is identified, and the "watershed" function in the Hydro menu of ArcView is applied. This leads to the delineation of watersheds and sub-watersheds, defined to the end points of each stream links. For this, a previous definition of the limit or threshold is very important, since this value will determine the size of watersheds, sub-watersheds or micro-watersheds to be delineated. The greater the value of the limit is the bigger the size of the defined hydrological units will be. Therefore, a small limit value will be used for defining micro-watersheds, while a big value will be useful in delineating watersheds. As an example and for the same part of DEM shown in Figure 1, the drainage network and the limits of micro-watersheds for the limit of 50,000 are shown in Figure 4.
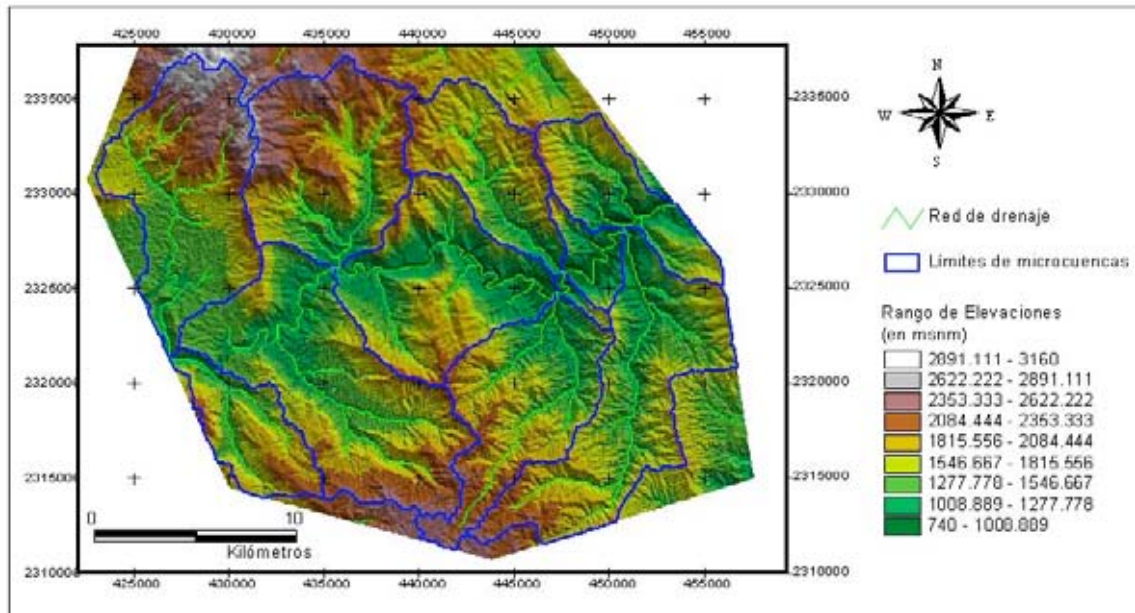
Figure 4. Boundaries of microwatersheds obtained for the DEM presented in Figure 1.

Delineation of watersheds does not end at this point, since the development of the NMMW requires also preparing a table of attributes where important characteristics of watershed morphometry are specified. Morphometry of watersheds may include area, perimeter, axial distance, shape factor, average slope, and drainage density. Calculations of these elements can be done by using a GIS. In consideration to the space given for this paper, the algorithms for such calculations are not presented in this paper. It is important to mention however, that the attributes table in the NMWM has a minimum amount of these characteristics that will be complemented in future versions with the idea of including both physical and socioeconomic information for each micro-watershed.

The coordinate system utilized in the delineation of this work is projected to the "Lambert Azimuthal Equal Area" system, with the idea of maintaining a precision in the calculation of micro-watersheds areas.

Results for the Micro Watersheds Delineation

Using the methodology explained above, the final NMWM obtained for Mexico is shown in Figure 5. For a more detailed display, Figure 6 shows the micro watersheds delineated for the State of Colima, a small Mexican state located in West Central Mexico near the Pacific Ocean. For the whole country, the total number of micro watersheds in the national map was, for this first version, 15391 hydrographic units, with surface areas ranging from 2500 to 15000 hectares (see frequency histogram in Figure 7). Some micro watersheds are above the superior limit, but this is mostly because of the presence of big water bodies such as the Chapala Lake, the biggest in Mexico, and other big reservoirs used for the generation of hydroelectric power.
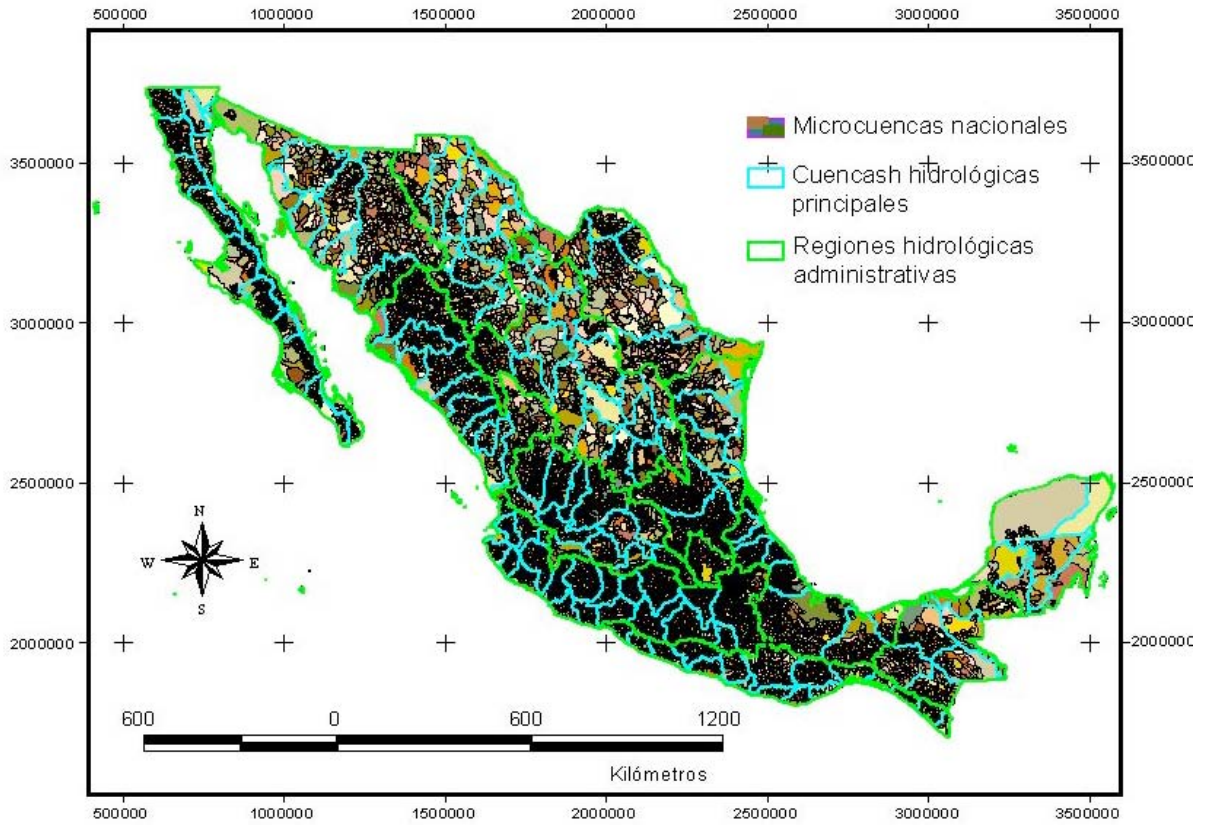
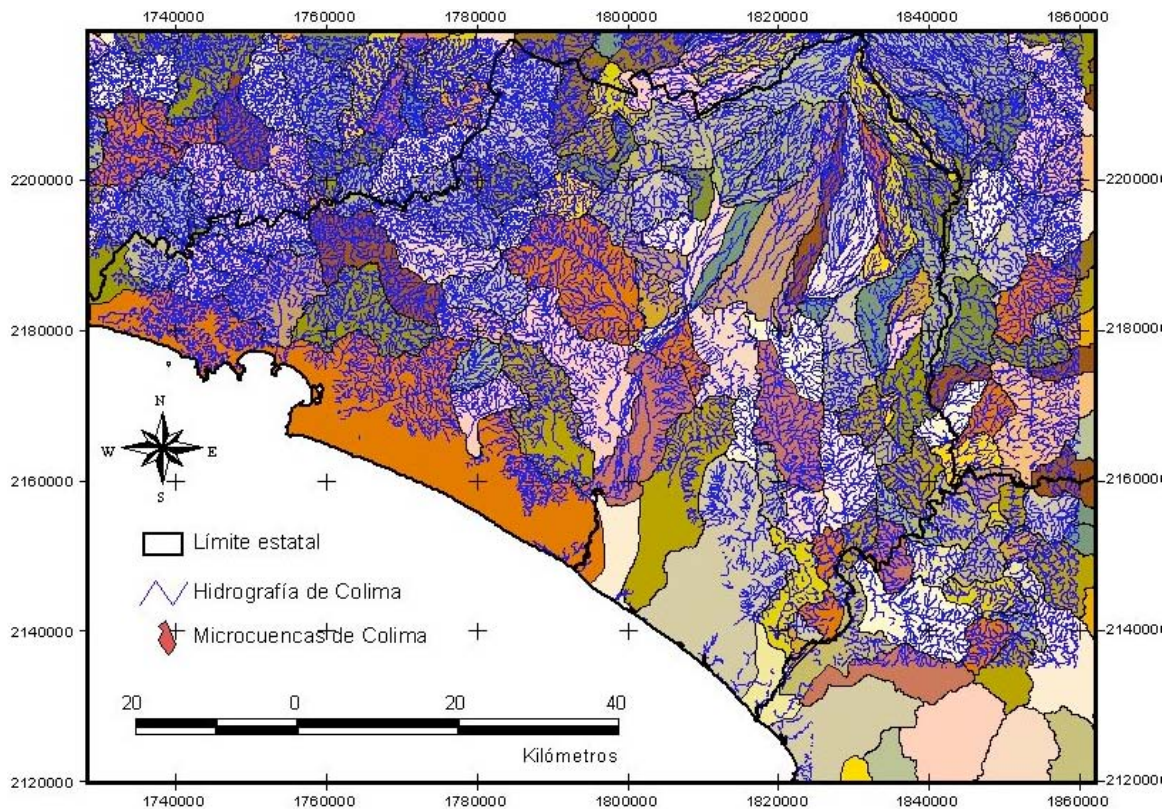*Figure 5. National Micro Watersheds Map (NMWM) for Mexico*

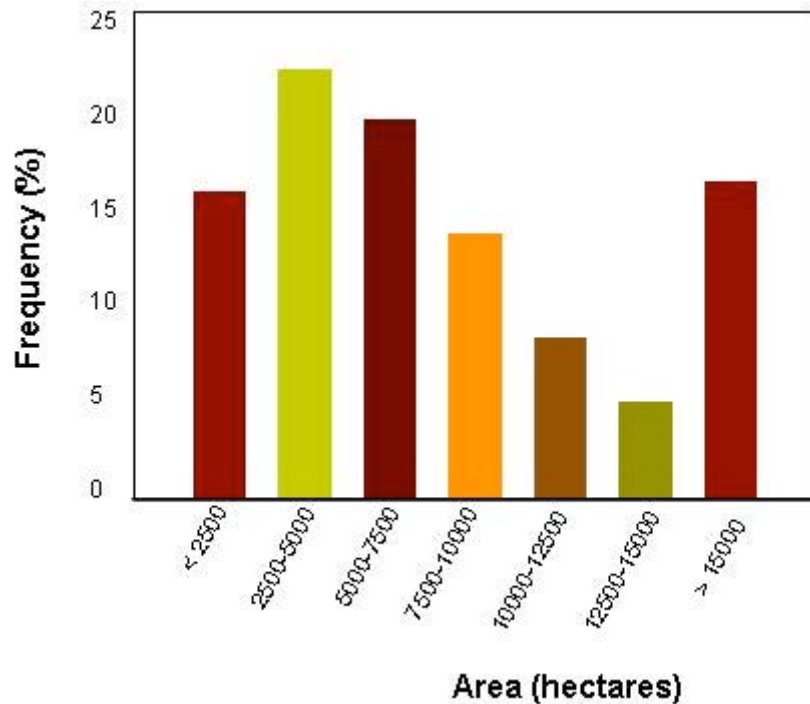*Figure 7. Micro watersheds for the State of Colima, Mexico.*

Figure 7. Histogram of micro-watershed areas.

Consulting System

To use de NMWM, an interface in ArcView that works as a consulting system for user was developed. The search of micro-watersheds in the NMMW can be done at the hydrological region, watershed, or sub-watershed level defined for the country. Also, the system allows a search of micro-watersheds by State or Municipality. The system was defined and thought to be an instrument to facilitate the planning activities of the micro-watershed offices at the state agencies of FIRCO (An organization for sharing the risk in productive activities that is under the Mexican Department of Agriculture (SAGARPA).

The consulting system for the micro-watersheds map of Mexico is based on Arcview 3.2 as operating base platform. Arcview 3.2 is software that allows visualization, editing, analysis and processing of geographical information spatially. The computer minimum requirements for this software are listed in Table 2.

Table 2. Minimum requirements for ARCVIEW 3.2*.

Processor	Intel (based) 800 MHz
RAM Memory	32 MB
Conventional Memory	150 MB
Selection device	Mouse
Operating System	Microsoft Windows 98/98E, Windows ME, Windows NT 4.0, Windows 2000, Windows XP Home Edition and Professional

* Information contained in the consulting system requires more advanced hardware
  since it displays raster images and vector databases of big size.

Spatial information is always associated to a database (attributes table). Working on a spatial environment allows a better comprehension of the existing relationships between the characteristics of the object and the processes occurring around it, so the decision making process to solve problems is fast and accurate.

The consulting system in Arcview was programmed in Avenue, which is an object oriented language based on sub routines or procedures that operate with names of generic variables that fit into any format and content of the active documents inside an Arcview project. This language allows customizing and editing of tools and standard commands.

By being programmed in Avenue, databases can be consulted directly in the main screen (shown in Figure 8). Once in the system, options in the screen allow to search for micro-watersheds at the hydrological regions, watersheds, or sub watersheds level. Also, a search can be performed by state or municipality (See search screen in Figure 9). Once a selection is chosen, the interface displays the selected area and opens the thematic layers associated to the selected micro watershed.

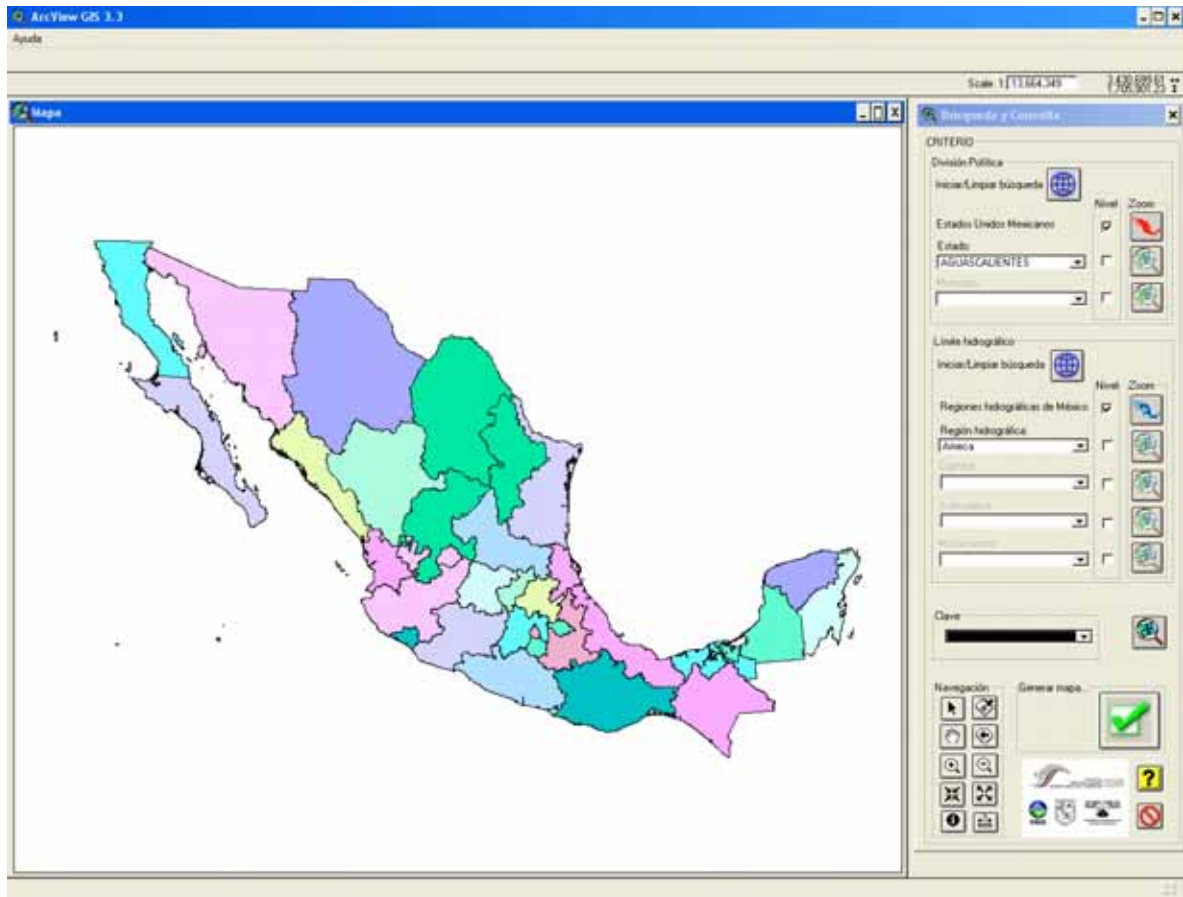*Figure 8. Welcoming screen in the consulting system.*

Figure 9. Search screen in the consulting system.

A report can also be generated from the same search screen for the set of micro-watersheds in the area selected (See Figure 10). The elements considered in the report may include: number of micro-watersheds per municipality, micro-watersheds with a Rector Plan for Production and Conservation (PRPC), amount of investment in conservation practices for each micro-watershed, etc. The user has the option of previewing a sheet with all the layers of the selected area before printing out the report. Then make a decision of whether to print or not the information obtained.

Finally, the integrated databases allow the following tasks:

- Rapid consulting of databases, spatially or numerically, in the system.
- Make quick analytical tests and repeat conceptual models in spatial display.
- Make analysis that otherwise will be tedious and complicated.
- Integrate, in the near future, complementary and relevant information related to the original database.
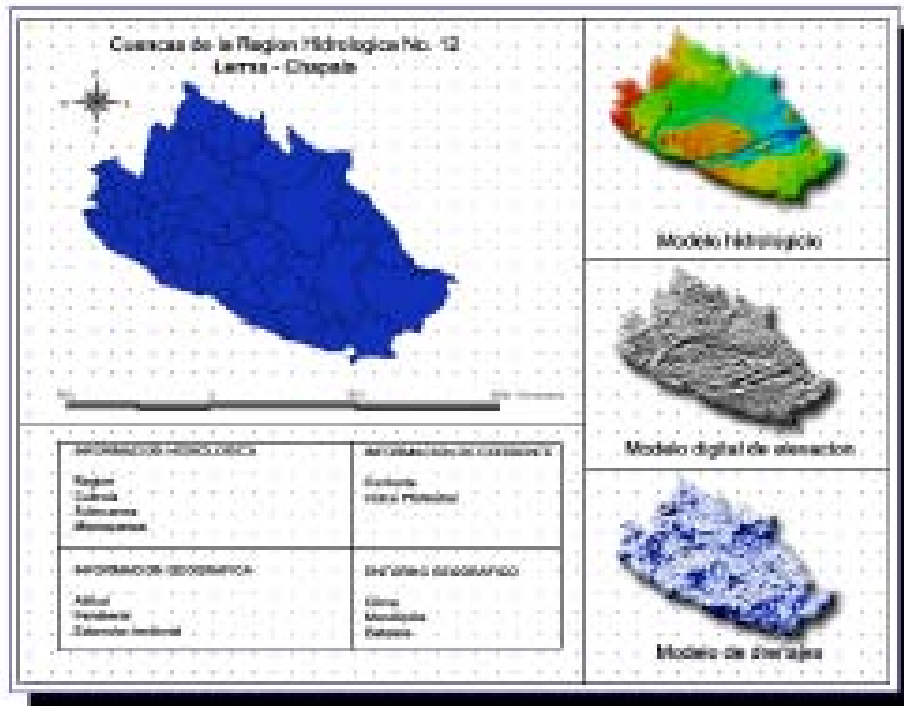
Figure 10. Print out example from the system.

Conclusions

The elaboration of the National Map of Micro Watersheds (NMMW) allows defining the most detailed level of classification for terrestrial units of hydrological type, the micro-watershed. On top of this level the sub-watershed, watershed and hydrological region levels can also be defined. Making the NMMW required a lot of efforts to generate DEM's from 1:250,000 and 1:50,000 scale topographical maps of Mexico. Pre-processing and data analysis for the definition of hydrological units with areas often smaller than 15000 hectares was a challenge. A total of 15,391 micro watersheds were obtained. Consulting micro-watersheds in Mexico is now possible with a dynamic consulting system in ArcView and programmed using Avenue. The system will allow the use of tools to increase the design and evaluation of planning instruments, such as the Rector Plan for Production and Conservation (PRPC), used by the Mexican agency for shared risk in productive activities (FIRCO) under the supervision of the Mexican Department of Agriculture (SAGARPA).

Acknowledgements

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