GIS TECHNOLOGY IN WATER AVAILABILITY USING ARCHYDRO DATA MODEL

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Abstract

We proposed to show the methodology in using The ArcHydro data model as the data repository to calculate the surface water amount in a basin. The Arc Hydro Data Model is considered as a geographic database containing a GIS representation of a Hydrological Information System under a case-specific database design. It includes a set of tools providing raster, vector, and time series functionality like rain, temperature, evaporation, uses of water. The estimation of the available surface water is based on the Official Mexican Norm NOM-011-CNA-2000, "Water resource conservation" (Conagua 2005), that uses the continuity equation.

INTRODUCTION

Knowing the water quality and quantity available in a certain area is essential for assigning this vital liquid to the existing and new stakeholders; this task becomes difficult when information about quality and quantity is scarce or null. Water resources managers need to have accurate data to take decisions and also need tools that help them know the water availability in an easier and accurate way.

Time series and additional data required to estimate surface water availability are extensive, therefore it is complex to store, organize and handle that information within a logical and flexible data structure. The ArcHydro data model allows implementing a database with a standard and flexible structure to store all the data related to water resources. This database is a useful tool since it provides the necessary data for estimating water availability, stores the results obtained and makes easy to query and display data within a geographic information system (GIS).

OBJECTIVE

The objectives established in this work were: developing a software tool to estimate surface water availability, implementing a database using the ArcHydro structure to store the results and all the information required for computing the water availability and using the developed software tool to estimate the water availability in a Mexican watershed.

METHODOLOGY

ESTIMATION OF SURFACE WATER AVAILABILITY

In order to calculate the surface water availability in a system composed by a set of connected watersheds it is recommended to follow three steps: a) estimation of downstream runoff; b) to distribute the demand water from lower watersheds to upper watersheds and c) estimation of water availability.

ESTIMATION OF DOWNSTREAM RUNOFF

We estimate the downstream runoff by using the continuity equation, which can be expressed as:

$$\frac{dV}{dt} = I - O \qquad (1)$$

Where the volume change *dV* over the time interval *dt* depends of the input and output flows *I* and *O*, respectively. The time interval considered for estimating surface water availability is one year, and the units are expressed in cubic hectometers (we use these units for the sake of convenience). By considering the surface level, equation (1) turns into:

$$Ab = (Cp + Ar + Im + R) - (Ev + Ex + Uc + \Delta V) \qquad (2)$$

Where: *Ab* is the downstream runoff going out a watershed. The inputs are: *Cp*, runoff produced by the watershed itself; *Ar*, upstream runoff; *Im* water imports from other watersheds; and *R*, flow returns. The outputs are; *Ev*, evaporation in water bodies and areas without vegetation; *Ex*, water exports to other watersheds; *Uc*, consumptive uses; and *ΔV is s*torage change in the surface.

In equation 1, the variables that are measured in situ are: storage change (*ΔV)*, consumptive uses (*Uc*), and water imports (*Im*) and exports (*Ex*). Others variables are measured with indirect methods like evaporation (*Ev*), upstream runoff (*Ar*) and flow returns (*R*). In case of not having measurements of *Ab* in a defined control point in the watershed under study, the variable *Cp* is firstly calculated by using an indirect method and then the variable *Ab* is isolated from equation 2.

For estimating the surface water availability, equation (2) is applied successively to each watershed beginning from upper watersheds to finish in the lower watersheds. It should be made clear that the estimation of water availability in this work takes into account the average water supply, represented by the annual average virgin runoff (Cp) in a watershed. The remaining variables involved in equation 2 are calculated for the specific year for which the availability analysis is carried out.

WATER DISTRIBUTION TO THE UPSTREAM DEMANDS AND CALCULATION OF RESERVED AND AVAILABLE VOLUME.

Apparently all the runoff going out a sub watershed could be used inside it; nevertheless, if there are stakeholders downstream of it, a fraction of this volume must be used to satisfy partially these users. We say “partially” because the demands existing in a sub watershed are satisfied with the runoff coming from upper sub watersheds, the volume originating inside the sub

watershed (virgin runoff) and water imports, if they exist. In this way, all the sub watersheds, with exception of the highest one, depend in greater or smaller degree of the volumes that receive from sub watersheds located upstream of each.

In order to consider the situation pointed out above, besides doing the traditional availability analysis, beginning from highest sub watersheds to finish in the lowest ones, it is also necessary to do the analysis following an opposite direction. In this second analysis, we will assign water volumes to the different stakeholders proportionally to the volume available of each component inside the sub watershed. In this way, we will obtain the reserved volume corresponding to each one of these components.

ESTIMATION OF WATER AVAILABILITY

The available volume coming out of a watershed, D_{xy}, is calculated by subtracting the reserved volume, $R_{xy,}$ to the downstream runoff going out a watershed, Ab_x:

$$D_{xy} = Ab_x - R_{xy} \qquad (3)$$

Where D_{xy} is the available volume coming out of a watershed ***x***, Ab_x is the downstream runoff and R_{xy} is the reserved volume at the outlet of watershed ***x*** to satisfy partially the demands in watershed ***y***.

In a similar way, the available volume in a watershed, D_{xx}, is calculated by subtracting the reserved volume, R_{xx}, to the virgin runoff produced by the watershed itself, Cp_x:

$$D_{xx} = Cp_x - R_{xx} \qquad (4)$$

Where D_{xx} is the available volume in watershed ***x***, Cp_x is the virgin runoff produced by the same watershed, and R_{xx} is the reserved volume used to satisfy demands in the same watershed.

ARCHYDRO DATABASE

A data model is basically a specification to describe a real world system by using a structured set of data; the ArcHydro data model was developed by the Center for Research in Water Resources (CRWR) of the University of Texas at Austin, and is a proposal to store information concerning to water resources inside a geographic database (geodatabase). The ArcHydro model has been adopted by several agencies and has rapidly become a standard, (Maidment, 2002). Data associated to water resources is mainly of two types:

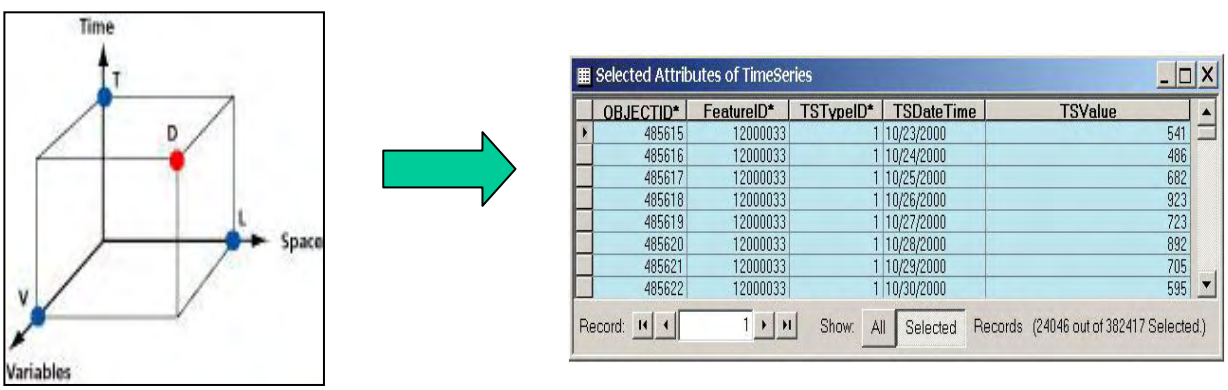
- Geospatial information .- It is composed by features of the terrestrial surface related to water resources like hydrography, watershed limit, location of monitoring and gage points, etc. This information is stored in vector or matrix form.
- Time series.- They are historic data resulting from the measurement of variables or parameters related to water resources, in a specific location and period of time. Some examples are precipitation, evaporation, pH, biochemical demand of oxygen, etc.

ArcHydro proposes to store both kinds of data inside a geodatabase, which is a relational database that stores geospatial coordinate and alphanumeric data. ArcHydro is designed to be implemented with the GIS software ArcGIS, which allows the creation of three types of geodatabase: **Personal (**implemented in Access), **File geodatabase** (implemented with a data structure proposed by ESRI, the company that developed ArcGIS) and **Enterprise (**implemented using a multiuser relational database manager system like SQL Server or Oracle, for example).In this project we implemented a personal geodatabase.

The ArcHydro data model is defined in two versions: a compact version, named ArcHydro Framework, and a complete version. The compact version allows storing the more important geospatial data that describes a water resources system: hydrography, waterbodies, watersheds and monitoring point.

In ArcHydro the historic data (time series) is stored in the database according to the dimensional model that is used in data warehouses. In this model, data is modeled as a cube where each axis of it represents a dimension of interest. The cube shown in figure 1 has tree dimensions: time, variable and space, so that a point in the cube (shown as a red point) represents the value of a variable measured in a certain location and date.

This design produces a very simple database table (named TimeSeries), with four fields: FeatureID, used to store the primary key of the station where the value was measured; TSTypeID, used to store the primary key corresponding to the variable measured; TSDateTime, used to store the date; and TSValue, where the measured value is stored. Figure 1 also shows an example of the TimeSeries table in Access. More fields can be added (each one represents a dimension) to store another data of interest, for example, the source where the data comes from.



OBJECTID*	FeatureID*	TSTypeID*	TSDateTime	TSValue
485615	12000033	1	10/23/2000	541
485616	12000033	1	10/24/2000	486
485617	12000033	1	10/25/2000	682
485618	12000033	1	10/26/2000	923
485619	12000033	1	10/27/2000	723
485620	12000033	1	10/28/2000	892
485621	12000033	1	10/29/2000	705
485622	12000033	1	10/30/2000	595

Figure 1. Dimensional model used in ArcHydro to store times series (Patino, et al, 2007)

The geographic layers that were included in the ArcHydro database were water bodies, gage points, climatic and water quality stations, surface water rights and water discharges from the Mexican Public Registry of Water Rights (REPDA) and context information like states and counties, for example. The geographic information considered was the one at scale 1:50,000 and the geographic projection used was Lambert (datum ITRF92) with the parameters proposed by The National Institute of Statistics and Geography (INEGI) for Mexico. The time series that

were included were precipitation and evaporation accumulated in 24 hr., maximum and minimum temperature in the day and temperature measured at 8 a.m. each day.

For the creation of the geodatabase we use the Framework version of the ArcHydro model with time series. In order to store additional geographic and numeric information that was required for the availability analysis, we considered more geographic layers and database tables which are showed in tables 1 and 2.

SOFTWARE TOOL TO ESTIMATE SURFACE WATER AVAILABILITY

In this part of the work we developed a computer program composed of a user interface and routines to access the ArcHydro geodatabase, make the availability calculation and show the results in graphical form. The program was developed in *Visual Basic for Applications (VBA)* with the software ArcGIS, version 9.2. It should be mentioned that the program can be used with the basic level of this software (ArcView), nevertheless, the creation of the database with the ArcHydro structure requires the ArcEditor or ArcInfo level.

Geographic layer (feature class)	Description
WaterWithdrawal	It is used to store the surface water rights reported in the REPDA.
WaterDischarge	It was used to store the water discharges reported in the REPDA.
Dam	It was used to store the information concerning to dams.

Table 1 Additional layers used to store geographic information required to estimate surface water availability

Besides, Database tables defined in the database to store additional numerical information used in the surface water availability analysis, for example: *WaterImportsExports* stores the volumes transferred between watersheds, *ElevationAreaCapacity* stores the elevation, area and capacity curve of each dam, *AnnualTimeSeries* stores variables required in the availability analysis. They are calculated per year and for each sub watershed, *WaterAvailabilityTopology* stores the configuration that it indicates as the river basins are connected.

RESULTS AND EXAMPLE OF APPLICATION

The computational tool starts estimating the runoff from the highest sub watersheds to the lowest ones and later, in a second step, does the same process following an inverse direction. This tool is included within an ArcMap project (a file with *.mxd* extension), which is one application of the ArcGIS software. The ArcMap project shows all the geographic layers necessary to carry out the estimation of surface water availability and context layers like states, counties and other layers. The options to estimate the water availability are contained in a tool bar inside the mentioned ArcMap project; figure 2 shows the main window of the project.

The program has the option to add a new consumptive use, in which the user specifies the required volume, the use type (agriculture, urban, etc.) and the location of it (latitude and

longitude). Once aggregated, the system creates a new element within the geographic layer of consumptives uses (represented as a map of points), makes a spatial intersection to determine the sub watershed where the element is located and proceeds to estimate the water availability to determine if the requested use can be granted.

In order to make the availability estimation, the user must firstly specify the year for which he wishes to know it. Secondly, the program accesses the ArcHydro database to obtain the values corresponding to that year of the variables that take part in equation 2. The values of these variables are stored in the database table named AnnualTimeSeries, Velazquez A., (2002).

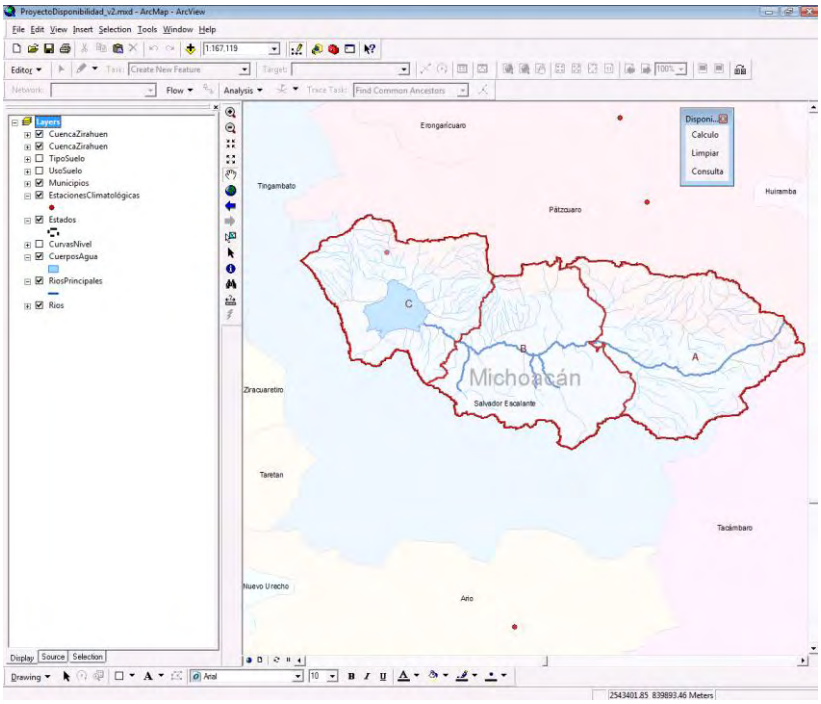
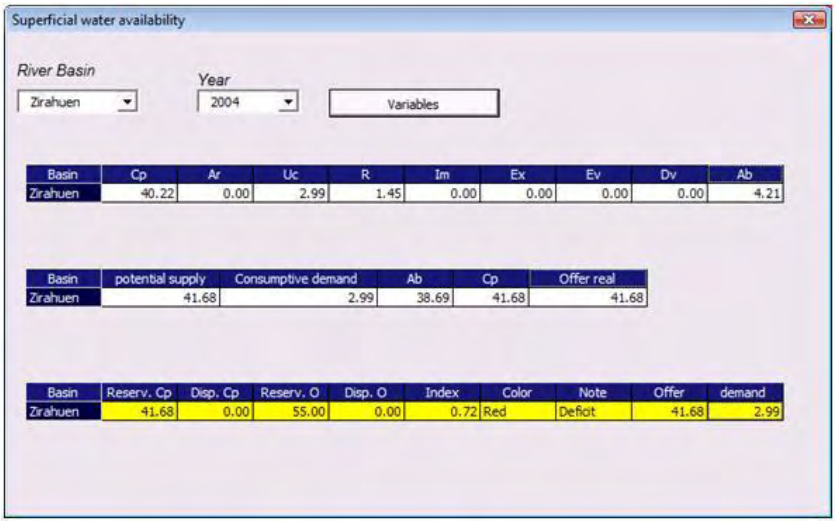


Figure 2. Main window of the ArcMap project to estimate water availability

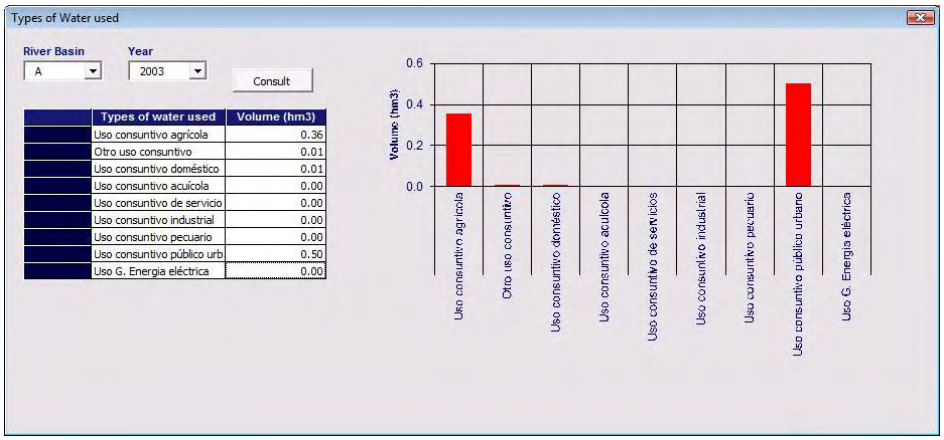
Finally, with the data obtained in the previous process, the system calculates each one of the variables necessary to obtain *the potential supply*, *consumptive demand* and *the real supply***.** With this information the user can determine if it is possible to grant the new requested use. The system shows the results in a table and highlights in yellow color the surface water availability for the selected sub watershed, also the different water uses can be queried by sub watershed river basin, depending on the year of study (see Fig. 3).



Basin	Cp	Ar	Uc	R	Im	Ex	Ev	Dv	Ab
Zirahuen	40.22	0.00	2.99	1.45	0.00	0.00	0.00	0.00	4.21

Basin	potential supply	Consumptive demand	Ab	Cp	Offer real
Zirahuen	41.68	2.99	38.69	41.68	41.68

Basin	Reserv. Cp	Disp. Cp	Reserv. O	Disp. O	Index	Color	Note	Offer	demand
Zirahuen	41.68	0.00	55.00	0.00	0.72	Red	Deficit	41.68	2.99



Types of water used	Volume (hm3)
Uso consuntivo agrícola	0.36
Otro uso consuntivo	0.01
Uso consuntivo doméstico	0.01
Uso consuntivo acuícola	0.00
Uso consuntivo de servicio	0.00
Uso consuntivo industrial	0.00
Uso consuntivo pecuario	0.00
Uso consuntivo público urb	0.50
Uso G. Energía eléctrica	0.00

Figure 3. Windows showing results obtained by the system and queries

By way of an example we used the software tool developed in this work to estimate the surface water availability in the Zirahuen sub watershed. It is a small endorheic sub watershed where water resources play an important role in the touristic activity that exists in this zone. It is located between the north parallels 19°20 ' and 19°30 ' and the west meridians 101°30 ' and 101°50 ', south of the Patzcuaro Lake. This sub watershed has 282.64 km^2 of surface and occupies 0.24% of the Balsas river hydrologic region, which it belongs to, and 0.014% of Mexico (fig. 4).

Figure 4. Location of the Zirahuen river basin

The Zirahuen river basin produces an annual average natural runoff, also named "virgin" runoff, of de 40.22 hm^3 (it is the variable Cp that participates in equation 2), the return flows are about 1.45 hm^3 and the consumptive uses represent a volume of 2.99 hm^3. By considering this figures and applying equation 2, we have:

$$Ab = (Cp + Ar + R + Im) - (Uc + Ev + Ex + \Delta V) = (40.22 + 0.00 + 1.45 + 0.00) - (2.99 + 0.00 + 0.00 + 0.00) = 38.69\ hm^3$$

The available volume (D) is: $Cp_x - R_{xx} = 41.68 - 55.00^* = 0.00\ hm^3$

*The reserved volume (R_{xx}) for this closed watershed was obtained from the Mexico official journal published on December 29th, 2003, in which the limits of aquifers, the results of studies realized to determine annual average surface water availability and maps are made known.

CONCLUSIONS

The ArcHydro data model allowed integrating all geographic data and time series required to estimate the surface water availability, as well as storing the results obtained from this analysis. The data structure that the model proposes is simple, standard, flexible and adaptable to the requirements of the calculation. On the other hand, the user interface allowed to automate and to facilitate the estimation, and constitutes a useful tool for decision makers in charge of water

resources management in a given area. Finally, it is important to revise and to analyze the data with the purpose of detecting and correcting errors in order to obtain reliable results.

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