8 Advances in Geomatics and Geospatial Technology for Solving the Water Problem in Mexico

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8.1 Introduction[1]

The problem of water is complex, and the occurrence of hydrological cycle variables and the other factors involved have an observable geographic reference and spatial and temporal variability. Based on this territorial perspective, studies aimed at solving the problem must consider a systemic approach, and this requires information and knowledge that reflect the spatial and temporal nature of such variables and factors.

Geomatics is a scientific discipline that has emerged from the convergence of earlier disciplines such as geographical information systems, spatial analysis, cartography, remote sensing, geodesy and photogrammetry. In general terms, it involves a series of methods for the acquisition, processing, representation, analysis and systematization of information and knowledge with geographic references (specific localization and spatial surroundings). The discipline sees society as the principal beneficiary of its studies and development projects; it includes society in its models of knowledge for the functioning of a territory by identifying the factors that influence both natural and human-induced changes. The systemic approach and the generation of information from remote sensors and geospatial models increase the possibilities for analysing and communicating how the processes that occur in a territory function, and for decision making. This scientific discipline is assisted by geospatial technology, that is, the use of technology to visualize, measure and analyse phenomena that occur on the land's surface and its immediate underlying layers.

This article presents the relevant tools (methods, information and knowledge) provided by geomatics and geospatial technology (which is included in geomatics) to help solve the water problem. Each one is described in summary form and supported by bibliographic sources and internet links that can be consulted for more detailed information. Among the most notable is the use of products from the LANDSAT, SPOT and MODIS missions, and other more specialized ones such as SRTM, TRMM and GOES. Geospatial analysis and modelling techniques are also important tools with great potential for application in the area of water science. This chapter also briefly describes and refers to examples of these techniques, such as a model for defining surface hydrological connectivity of territories based on *Digital Elevation Model* (DEM) analysis. Also mentioned are the design, implementation and utilization of the artefacts of geomatics developed in the area of water science, including the *Geographical Information System* (GIS) for the Mexico Hydrographic Basin, the Cybercartographic Atlas of Chapala Lake and the System for the Management of Urban Ravines in Mexico City. Remote sensing techniques for studying and monitoring hydrological variables are also highlighted and described with respect to their usefulness in water-related issues.

More than one billion people worldwide do not have access to clean water, and 2.6 million have no sanitary services (UNDP, 2006). The combination of various social, environmental and socio-economic pressures often results in increased use of and competition for water and in its contamination, as well as in inefficient water supply practices (UN-WWAP, 2006). The use of biophysical and socio-economic indicators that combine measurable data relevant to public policies provides the basis for diagnosing the current status of the problem and for decision-making (MA 2005, chapter 1). Unfortunately, in the context of probable climate change, it will be substantially more difficult to quantify the range of possible modifications in the hydrological cycle than in the context of global mean temperature (Allen/Ingram 2002). Natu-

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[1] Keywords: spatial analysis, remote sensing, cyber-cartographic artefacts, systemic approach, territorial perspective

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ral and socio-economic factors that characterize, influence and interact in the problem of water comprise a series of processes that are difficult to understand, even with the most comprehensive perspective possible.

The water cycle and water usage are phenomena that are intrinsically associated with space. Hydrology is therefore defined as a geographic science. The components of the cycle, and other factors involved in the complex problem of water, have an observable geographic reference and spatial and temporal variability. From a territorial perspective, studies aimed at influencing the solution must consider a systemic approach, and they require information and knowledge that reflect the spatial and temporal variability of the factors involved. In the context of a territorial approach, a systemic perspective must have the characteristic of identifying the elements that comprise the hydrological system in question (a basin or catchment area or a specific territory defined by other types of criteria, for example, the political), and analysing the relations and dynamics of change that are observable among these elements.

8.2 Objective and Methodology

8.2.1 Objective

There are an enormous number of investigations that study water issues based on the disciplines included in geomatics. Hence, this chapter gathers together a sample (not exhaustive) of studies so that the capacities of this science and its convergent disciplines can be appreciated; the aim is to support the study of the variables of the hydrological cycle based on a territorial analysis of the water problem so that initiatives and public policies that help solve the problem may be generated.

8.2.2 Methodology

The first section is a primarily conceptual perspective on the possibilities of geomatics (its systemic approach, remote sensing techniques and spatial analysis) for the study of complex water issues. Next, a summary of the water problem in Mexico is presented, followed by a section that highlights the application of research results, with a review of the methods, information and knowledge that geomatics and geospatial technology (primarily remote sensors) provide for the solution of the problem described in the previous section. Methods discussed include the use of remote sensing products from the LANDSAT and MODIS (*Moderate Resolution Imaging Spectroradiometer*) missions, and other more specialized products such as SRTM (*Shuttle Radar Topographic Mission*) and TRMM (*Tropical Rainfall Measurement Mission*). Also mentioned are geospatial analysis and modelling techniques that have great potential for application in the study of water issues, including the model for defining a territory's hydrological surface connectivity based on *Digital Elevation Model* (DEM) analysis, as proposed by Jenson and Domingue (1988). The integration of GIS information is also discussed in this section. The last section describes cybercartography and its possibilities in the area of water science. Included are descriptions of geomatic artefacts developed in Mexico, such as the Geographical Information System for Mexico's Hydrographic Basins, the Cybercartographic Atlas of Lake Chapala and the System for the Management of Urban Ravines in Mexico City. General conclusions are then presented.

8.3 Results

The results of the review as well as the ideas for developing the issues mentioned in the methodology section are presented in the order in which they appear above.

8.3.1 Geomatics for Studying the Complexity of Water Issues

Since it is difficult to define a complex system (Bourgine/Johnson, 2006*)*, the reference quoted only observes that a region's hydrological problem fulfils the primary characteristics of a complex system. This includes evolution and adaptation due to external and internal interactions (such as climate, population and economic pressures), and possible changes in the boundaries of a system and the links between a system and its surroundings (for example, the case of Mexico City, where alternative supply sources from other regions continue to be sought). We observe that the hydrological cycle is composed of a set of physical elements or processes (the components of the hydrological cycle) that are joined together interdependently. The cycle has input and output variables from the perspective of balance in a particular geographic zone or territorial unit (a block, neighbourhood, city, state, country, a rainwater catchment area, or a river basin).

Precipitation is the best known and most important hydrological input variable, observed as water in the form of rain, sleet or falling snow. This hydrological variable shows a large degree of spatial and temporal variability, as do the others. Thus, on specific days and places, different amounts of precipitation are observed. Important output variables are surface run-off and evaporation. Complex relations between hydrological variables (which can be considered as subsystems) are observed – for example, in the study of evaporation. This variable depends in a complex way on the behaviour of other hydrological variables (for example, the amount of precipitated water and the amount that manages to infiltrate) and on complicated interrelations with other factors (such as climate). In addition, the accelerated process of change in land use is a factor that directly affects infiltration, run-off and evaporation variables.

The attempt to capture the spatial and temporal variability of precipitation has traditionally been made through point measurements. These measurements are used to generate climatic reports to provide information for recording moderate, strong or extreme precipitation. Geomatic techniques serve an important function, beginning with the acquisition and processing of such climate information. Since the records obtained using measurement stations have spatial and temporal references, they are valuable and useful for knowing, with certainty, the time and space in which the phenomena of interest have occurred.

However, it is commonly assumed that point measurements of precipitation and other climatic parameters are valid only within a radius of a few kilometres, as indicated by Daly (2006) for mountain areas. And since measurement stations are separated by tens, if not hundreds, of kilometres, this presents a problem for spatial representativeness in the generation of surfaces based on point measurements. Geomatics provides a series of interpolation methods for such a purpose. This type of geostatical method is described by Goovaerts (1997), for example. Auxiliary variables, such as terrain heights normally represented by *Digital Elevation Models* (DEMs), are commonly used in interpolation processes for point measurements of precipitation, for which Goovaerts (2000) proposes the Kriging with External Drift technique. This technique can be used to generate combined precipitation products between land radars and point measurements, as described by Goudenhoofdt and Delobbe (2008). Geomatics also provides more sophisticated techniques for measuring precipitation with remote sensors. International advanced missions, such as TRMM, estimate precipitation on a global level based on sensor packages: the first *space precipitation radar* (TPR), a *microwave sensor* (TMI) and a *visible ultraviolet scanner* (VIRS).

Kummerow et al. (1988) provide a detailed description of the sensors that make up TRMM, as well as a preliminary determination of its effectiveness. Estimates from this mission have facilitated climatic analysis studies and the management of water resources (Chiu et al. 2006). One of the results of TRMM is a database with 9 years of rainfall and cloud cover information, accessible to the public by downloading. This is a noteworthy source of information for the analysis of precipitation in tropical zones (Liu et al. 2008). In addition, techniques to improve the precision of these precipitation calculations, aided by satellite images, are being researched to generate precipitation maps that combine field and satellite measurements (Adler et al. 2000). Thus, geomatics has enabled a series of significant advances to occur in defining with a greater degree of precision the amount of water that precipitates over the territorial units of interest. Scientific disciplines included in geomatics (cartography and cybercartography as described in section 8.3.4) facilitate correct cartographical expression (maps and other types of spatial expressions) and a geographic and comprehensive analysis that considers cross-cutting socio-economic and natural factors.

What is observed after precipitation occurs depends on the spatial configuration (primarily the types of land use and ground cover) of the territorial unit being studied. If it is a highly permeable zone with little influence from human activity, a large part of the water will most likely infiltrate it (and some part of this would reach the aquifer springs) and another part would evaporate off the vegetation surfaces and ground layers. On the other hand, if the zone involved is highly urbanized and impermeabilized or deforested, greater quantities of run-off water are generated along natural beds (rivers and streams) or artificial ones (streets and highways), and this can unleash tragedies of great magnitude.

Between these two opposite situations is a wide variety of ground cover and other types of land that largely define the division of pluvial precipitation between infiltration and recharge of aquifer springs, run-off, and evaporation. Geomatics also plays a fundamental role in the study of these processes. The most rapid, certain, and economical way to define types of ground cover is through the interpretation of satellite images. Each type of ground cover has a different response (expressed as absorption, transmission and reflectance) to the incident light (usually solar light) registered by satellite images. LANDSAT satellites and other missions, such as SPOT, have frequently been used in Mexico to define ground cover precisely. Indeed, the use of LANDSAT could increase, since this mission's products have been available at no cost since the end of 2008 (<http://edcsns17.cr.usgs.gov/EarthExplorer/>). In one year, it is possible to have four or more LANDSAT images from the same region and a similar number of SPOT images. Consequently, it is feasible to follow the temporal ground cover changes very adequately. The spatial resolution of these images, that is, the minimal territory detected by a SPOT or LANDSAT image, varies between 15*15 and 30*30 m^2, and this enables sufficiently detailed studies to be conducted. In addition, there are spatial images with even greater spatial resolution (such as IKONOS with pixels of less than 1 m^2). MODIS is also a mission of great interest to the study of hydrological variables. This sensor registers information according to 36 spectral bands and, therefore, has more possibilities for monitoring biophysical variables than other sensors such as LANDSAT, although the spatial resolution of this sensor (250*250 m^2, 500*500 m^2 and 1000*1000 m^2, depending on the spectral band) is less than that of LANDSAT and of SPOT.

Techniques developed in the field of geomatics also enable the direction in which water runs to be assessed, once it has precipitated and where it is located on a surface with low permeability. This is accomplished using *Digital Elevation Models* (DEMs). In addition, this process allows the areas in which water accumulates to be detected. DEMs are likewise produced by techniques generated by the scientific disciplines that make up geomatics. A notable source for DEMs on a global level is NASA's *Shuttle Radar Topography Mission* (SRTM 2003). The available DEMs produced by this mission, with 90 m of spatial resolution, are also available for downloading from the internet at no cost (ftp://e0srp01u.ecs. nasa.gov). For special cases (available by request), it is possible to obtain 30-m DEMs, the spatial resolution at which the DEMs from this mission were originally produced based on radar signals. A model for defining hydrological surface connectivity that is widely known and used is that proposed by Jenson and Domingue (1988). The fundamental premise of this model is that water flows in the direction of the greatest slope. A first processing step for DEM is to remove artificial depths, known as fill sinks. In order to do this, interpolation is conducted before creating the raster map for flow direction. This is done because artificial depressions (not real but, rather, produced by errors in the generation of the DEM) can significantly alter the directions of flow. According to the system proposed by Jenson and Domingue (1998), there are at least eight cells that border each cell in a DEM and, therefore, flow in any one of those eight directions is possible. These are determined, by convention, as 2^x where x = {0,1,...7}. The calculation of flow directions is based on the definition of the steepest gradient from the centre of each cell towards the centre of its neighbouring cells. In the Jenson and Domingue (1998) model, the definition of flow accumulations is the next step for defining the hydrological surface connectivity system. The corresponding map is created from the directions of flow and registers the quantity of cells that flow towards one particular cell. The flow from one cell may not reach the exit point of the basin or collection area because of errors resulting from errors in the generation of the DEM or because the DEM scales are not sufficient to register the changes in slope and, therefore, the drainage lines. In this case, Maidment (2000) recommends applying the procedures for correcting such imprecision in the model, such as 'DEM burning', which results in an artificial 'elevation' of the watershed, or 'sinking' of the low or flow accumulation zones, so that flow towards these zones is assured.

Evaporation is another relevant hydrological variable. This variable is fundamental for studies based on hydrologic balance and water availability. Its determination is complex, and advances in geomatics provide elements for a more precise and diversified determination of this variable, such as methods that are available related to the use of biophysical variables obtained from remote sensors. Among the most well known are SEBAL (*Surface Energy Balance Algorithm for Land*, Bastiaanssen et al., 1998) and METRIC (*Mapping Evapotranspiration at high Resolution with Internalized Calibration,* Allen et al. 2007). Both methods are based on obtaining the evaporative term from the surface energy balance.

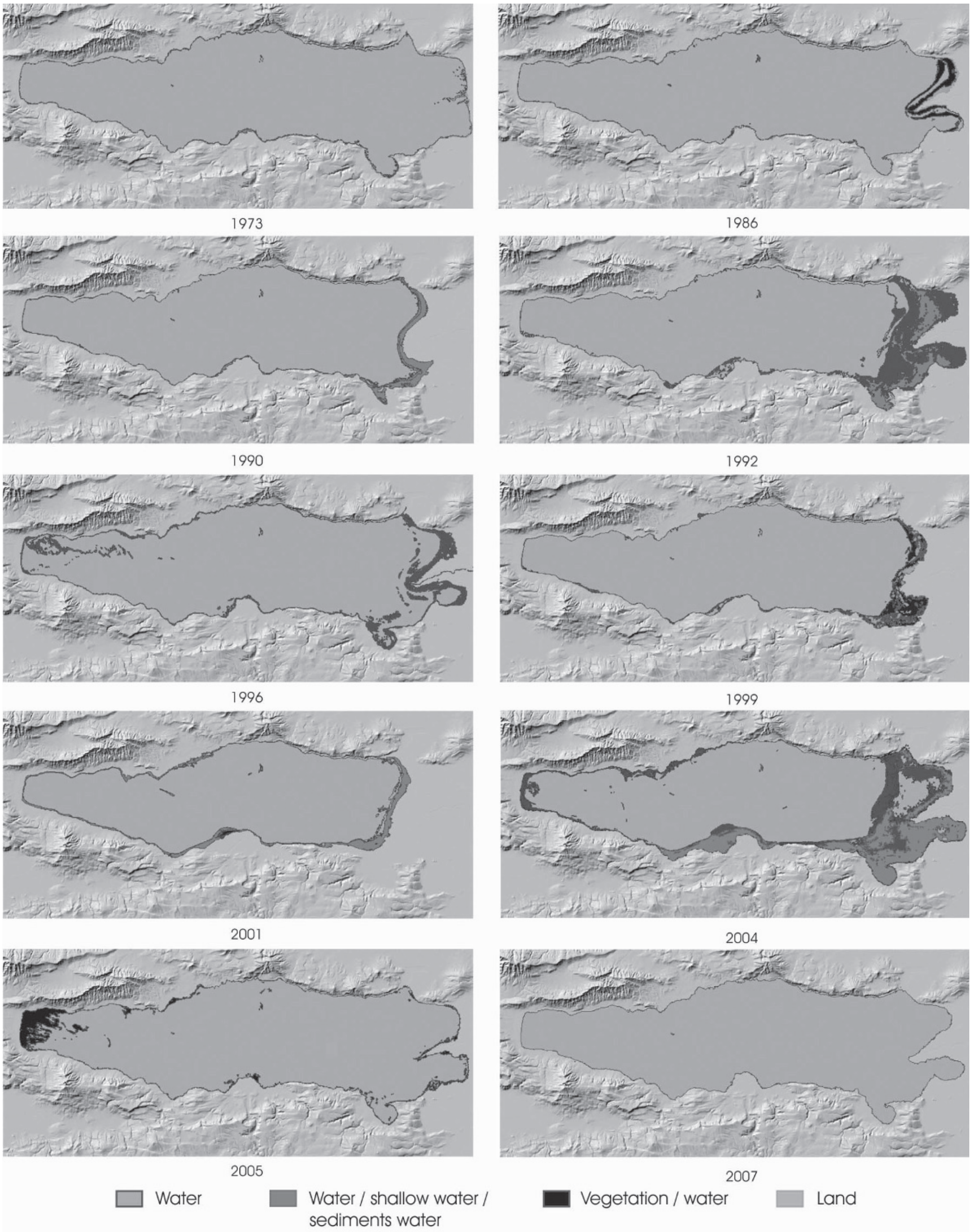
SSEB (Senay et al., 2007) is another example of this type of methodology. In general terms, this is a method based on remote sensing that enables obtaining a reduction function to obtain a real value for evaporation based on a reference or potential evapotranspiration value. In SSEB sets of hot and cold pixels are used to obtain this reduction function. Cold pixels are selected based on those with *low surface temperature* (LST) and a high vegetation index (NDVI), and hot pixels are selected according to the opposite criteria. Some of the biophysical variables required by these models (LST and NDVI) are available at no cost, for example, as satellite products such as MODIS. LST is a good indicator of surface energy balance and is therefore used to estimate evaporation. NDVI is an indicator of the density and health of existing vegetation and is also an important value for the calculation of evaporation using remote sensing. Applications of these models in Mexico are included in 8.3.3.

8.3.2 Summary of the Water Problem in Mexico

Water was initially considered to be a renewable natural resource (at least in the collective imagination of Mexico), but this is no longer the case. Another negative aspect is the emergence of problems generated by changes in precipitation patterns (which are not even predictable, according to Allen and Ingram, 2002) as a consequence of climate change. These changes are expressed by a greater incidence of extreme phenomena (droughts and intense rains) and by a destabilization in precipitation regimes (Easterling, 2000). In addition, complications exist as a result of the decrease in and contamination of aquifers and bodies of surface water (see below). These events indicate that in the context of poorly planned human intervention on the land, water cannot alone maintain itself as a vital resource for life and the development of human society and the ecosystem on which it exists. The following are some of the more significant cross-cutting hydrological problems observed on a national scale:

- Incidences of torrential rains and surface impermeabilization that create floods and landslides and impede aquifer recharge. With regard to hurricanes, CONAGUA (2007) observed that 47 hurricanes occurred between 1980 and 2006 and that between 2001 and 2006, phenomena of category 3 or higher have been more frequently recorded. With respect to impermeabilization, a good deal of research is lacking in order to discover the current extent of this process in our country, though the degree of impermeable surfaces has been determined for some cities, including Campeche, León and Mexicali; this was carried out by CentroGeo (2007), as mentioned in section 8.3.3.
- Drying up and contamination of aquifers (104 out of 653, see CONAGUA, 2007) due to over-exploitation and serious deficiencies in planned land use.
- Wasting rainwater and its contamination from becoming mixed with sewage. CONAGUA (2007) reported that 36 per cent of municipal water is treated; however, treatment levels of plants vary a great deal and treatment is usually performed at a primary level (CONAGUA, 2007).
- Contamination of surface water by residual waste contaminants. According to CONAGUA (2007), based on monitoring three quality parameters (biochemical oxygen demand, chemical oxygen demand and total suspended solids), between 8 and 30 per cent of total surface run-off is contaminated.
- Increase in river flows produced by deforestation and a decrease in water above the basins as a result of poorly planned usage. Investigation is needed to precisely define the current situation. Only preliminary results are available, such as the study conducted by Tapia Silva et al. (2007a; figure 8.3) of deforestation in the south-eastern basins and its relation with increased run-off, as well as that by Preciado et al. (2004) of the Quelite basin on the Guatemala border.
- Poor efficiency in the use of water in agricultural and urban zones. CONAGUA (2007) reported a total use for agricultural purposes of roughly 80 per cent of the national total, which suggests the need to improve the efficiency of irrigation through water-saving technologies. Nevertheless, CONAGUA (2007) also reported increased productivity in the use of water (quotient between total crops and total applied irrigation volume, expressing the amount of kg of crops obtained per m^3 of water) of 1.11 during the 1995–1995 agricultural cycle and 1.41 between 2004 and 2005.
- Reduction and disappearance of water bodies as a result of negative balances between inputs (from precipitation and surface and subterranean water flows) and outputs (caused by evaporation and anthropogenic uses). Studies to define the current general situation for this issue are also lacking. Those that exist deal with specific bodies of water, such as that conducted of Chapala Lake (López Caloca et al., 2008; figure 8.1). Section 8.3.3 presents a sequence for that area from 1973 to 2007, describing how geomatics and geospatial technology can contribute to solving this problematic situation, and gives examples of some of the related investigations.

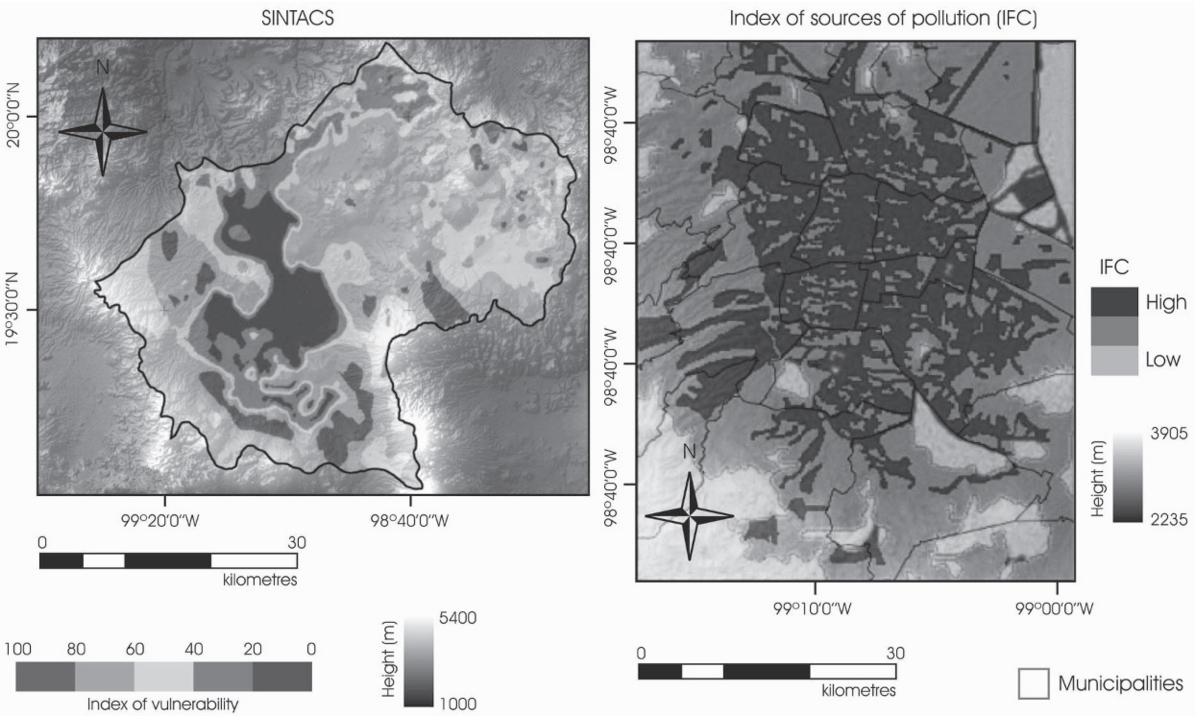
Figure 8.1: Changes in the area of Chapala Lake, monitored by LANDSAT and SPOT. **Source:** López Caloca et al. (2008).



8.3.3 Examples of the Application of Geomatics and Remote Sensors to Solving the Water Problem

The studies included here (most of which were conducted on a regional or local scale in Mexico) indicate how geomatics and the disciplines it encompasses facilitate the generation of information and knowledge for creating projects and tools for public policies that will contribute to solving the complex water problem summarized above. The information and knowledge acquired can support decision making to

Figure 8.2: Left: Aquifer vulnerability to contamination in the Mexico Valley Basin. Right: index of sources of contamination for the Mexico City urban sprawl zone. **Source:** Ramos Leal et al. (2010).



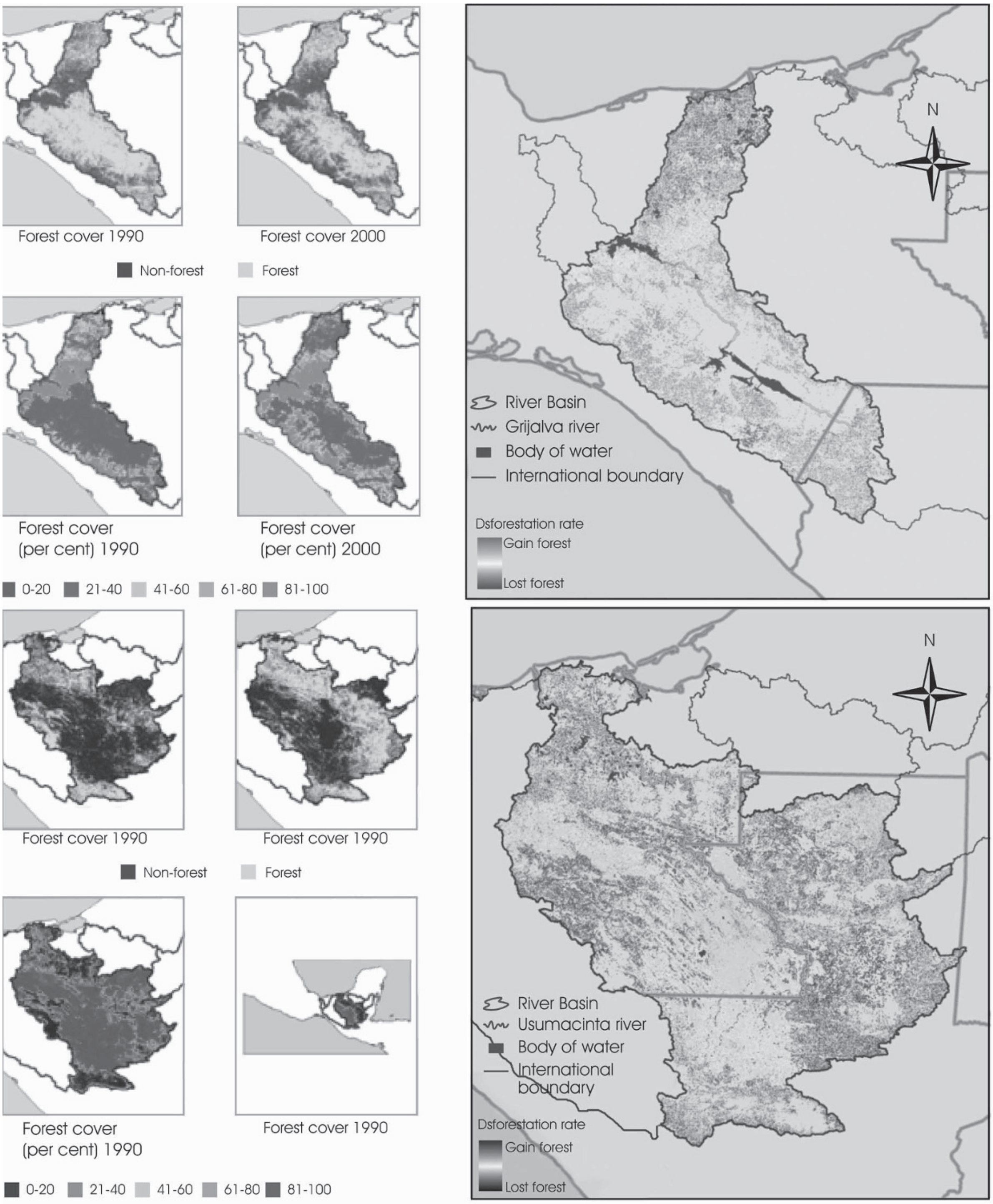
improve the management and conservation of this valuable resource. Based on GIS, these studies integrate geospatial information from various sources (including remote sensing). Other geomatic disciplines, such as cartography, spatial analysis and cybercartography (see 8.3.4) provide elements for generating and communicating information and knowledge about the water issue.

In geomatics, it is possible to conduct studies about the sealing of permeable surfaces and those that are capable of aquifer recharge (Tapia Silva/ Mora, 2004). With regard to impermeable surfaces, it is possible to create methodologies using SPOT-5 images to study precarious settlements, such as that performed by CentroGeo (2007) for the Secretary of Social Development in Mexico. This methodology includes the application of the VIS (*vegetation-impervious surface-soil*; Ridd, 1995) model. This is an empirical model that relates ground cover data obtained with remote sensing to the biophysical aspects of urban environments within a hierarchical decision-making strategy. Another option in geomatics is monitoring changes in the areas of lakes and relating them to trends in hydrological and climatic variables, as well as to others such as water extraction and availability from bodies of surface water. One example is the Chapala Lake study conducted by López Caloca et al. (2008), which presents a temporal sequence showing changes in the area of Chapala Lake, monitored by LANDSAT and SPOT (figure 8.1).

This study and that by Lira (2006) apply segmentation methods based on the interpolation of water indices such as NDWI (*Normalized Difference Water Index)*. Lira (2006) defines lakes such as Patzcuaro, the Centla marsh, and lakes in Mexico City. It is also possible to propose the location of well recharge restoration points for aquifers or collection points for rainwater or surface water, as did Saraf et al. (2004). Another very recent application of geomatic techniques is for defining zones prone to flash flooding. One example of this type of study is that performed by Tapia Silva et al. (2007b) for the urban ravines zone in Mexico City. It is even possible to generate real-time maps of flood zones that allow for the planning of immediate responses to disasters, as reported by Matgen et al. (2007). Another example is the flood maps of Tabasco published by UNOSAT (2007) which, on 7 November 2007, provided information that was fundamental to responding to the disaster that began one week before and ended in the last days of November. In this case, the sensors used were MODIS and SRTM.

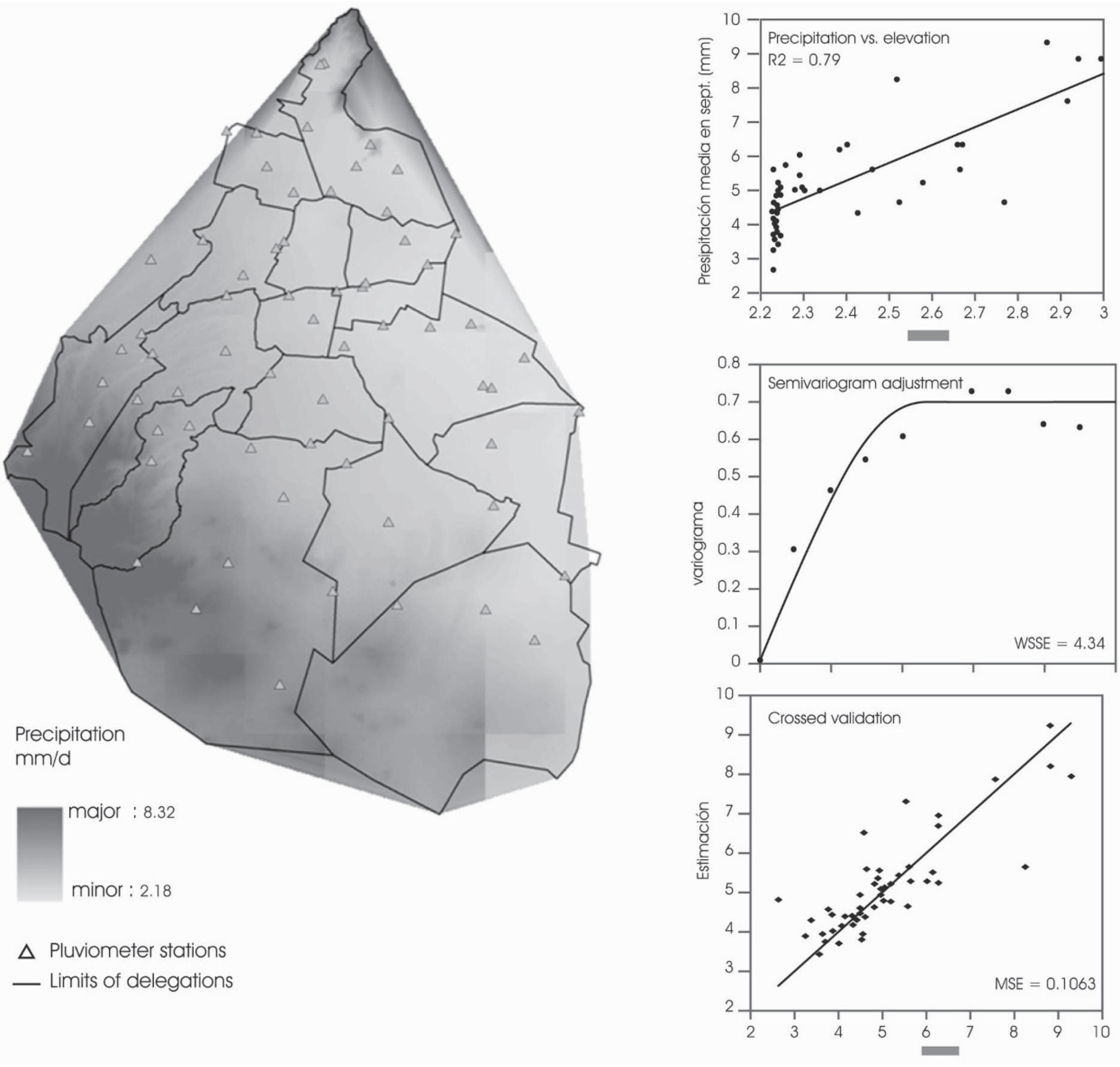
With regard to assuring organized land use from a hydrological perspective, geomatics makes it possible

Figure 8.3: Deforestation rate between 1990 and 2000 for large hydrological basins in south-east Mexico, obtained from LANDSAT images. Left: Grijalva; Right: Usumacinta. **Source:** Tapia Silva et al. (2007a).



to identify the zones with the best capacity for aquifer recharge that should be maintained intact, or not be urbanized or occupied for habitation purposes, since they can represent serious dangers from run-off accumulation. An example of this is the study by Tapia Silva and Arauz (2007a). Likewise, it is possible to determine the spatial variability of the vulnerability of an aquifer to contamination and the location of

Figure 8.4: Spatial variability of multi-annual precipitation for September in Mexico City, resulting from Kriging with External Drift interpolation, using the linear dependency between the digital elevation model and precipitation values. **Source:** Designed by the author based on research data.

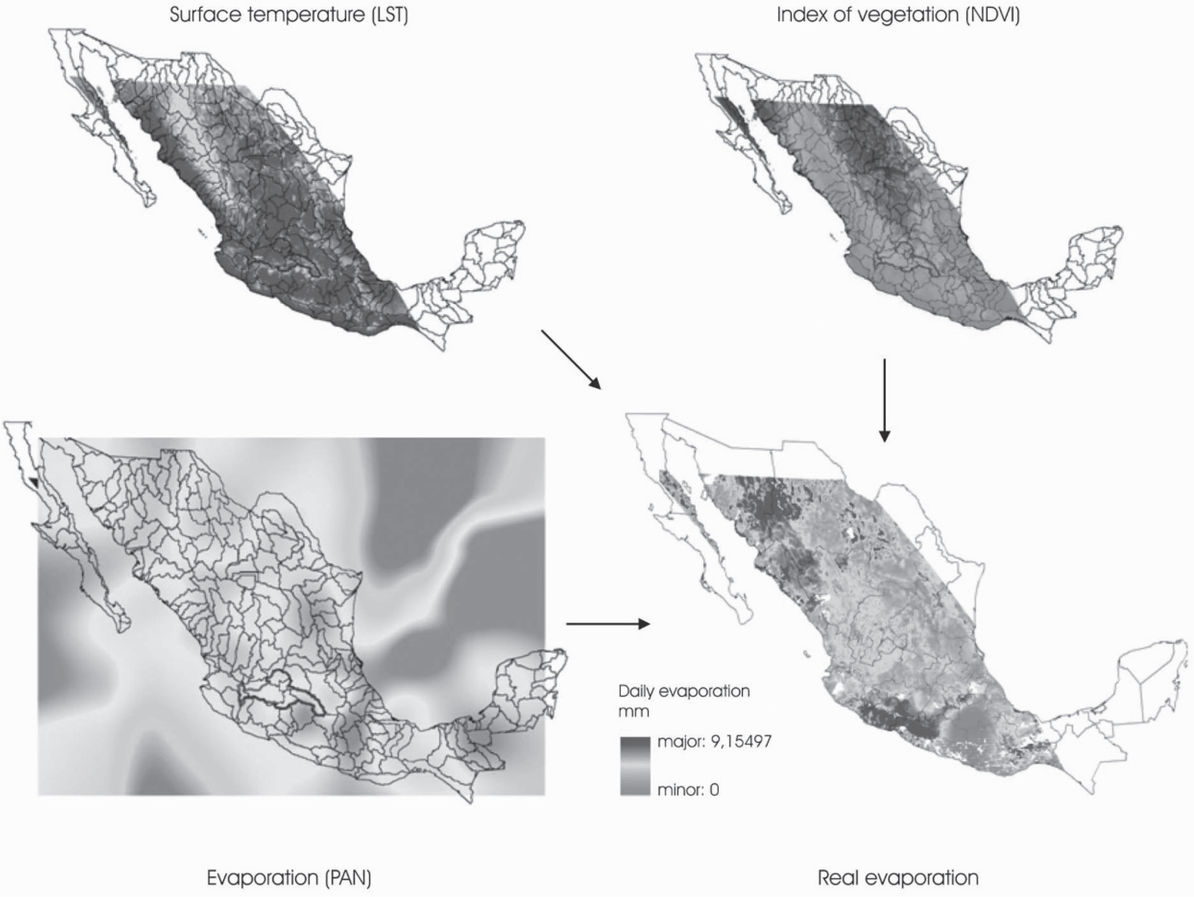


sources (geographic points or zones) of contamination of bodies of surface or subterranean water. This was conducted for Mexico City and its metropolitan zone by Ramos Leal et al. (2010). Figure 8.2 shows images from this study, indicating the zones that are prone to contamination and an index of sources of contamination.

Studies on the availability of resources by hydrogeologic basins are also greatly valuable. For example, Ramos Leal and Hernández Moreno (2008) conducted a series of reflections on the usefulness of a regional approach to the study and management of hydrogeologic basins in San Luis Potosí and the Mexico Valley. It is also possible to determine the influence of deforestation on increased run-off, as illustrated by Benitez et al. (2004). Figure 8.3 includes images from Tapia Silva et al. (2007a) for the Grijalva and Usumacinta basins (south-east Mexico and Guatemala), showing deforestation rates calculated between 1990 and 2000 based on LANDSAT images. A similar study was conducted by Preciado et al. (2004) for the Quelite basin on the Guatemala border.

The generation of cartography for spatial and temporal hydrologic and climatic variables is also possible in geomatics. Gochis et al. (2007) present an analysis of the spatial and temporal characteristics of the

Figure 8.5: Calculation of real evaporation in Mexico according to SSEB (Senay et al., 2007) for the winter of 2002, calculated using MODIS products and PAN evaporation measurements. **Source:** Coronel et al. (2008).



intensity of precipitation in north-east Mexico for the period 2002 to 2004. Golicher et al. (2004) use Universal Kriging to define precipitation and temperature patterns related to the 'el Niño' phenomenon on the southern border. Figure 8.4 presents results from an interpolation procedure for multi-annual daily precipitation for September in Mexico City. The method used Kriging with External Drift, taking into account the linear dependency between precipitation and elevation values.

The study of zones with low indices for efficient water use and the generation of proposals to increase these indices is another viable activity. Mo et al. (2005) use geographic land use layers, DEM, soil textures and an index for leaf area index taken from AVHRR (*Advanced Very High Resolution Radiometer*), in addition to interpolated climatic data to calculate crops, water consumption and an index for the efficient use of water. Aquifer studies as hydrologic balance and consumption of groundwater resources are supported by studies to calculate evaporation using PR (Bastiaanssen et al., 2005). For example, Zwart et al. (2006) used SEBAL to calculate water productivity for wheat crops in the Yaqui Valley in Sonora, Mexico. Garatuza Payan et al. (2001) used GOES *(Geostationary Operational Environmental Satellites*) images to obtain radiation values and then used those to calculate evapotranspiration according to Makkink's formula. Values derived from the satellite images were roughly 9 per cent less than those from field measurements. In addition to the above, Garatuza Payan et al. (2005) calculated crop coefficients as a function of vegetation indices (NDVI and SAVI: *Soil Adjusted Vegetation Index*), based on which they derived real evapotranspiration using reference evapotranspiration. Scott et al. (2003) validated the use of SEBAL for the calculation of soil moisture in an agricultural zone in Cortazar Guanajuato and analysed their results in the context of resource management. With regard to desertification, Lira (2004) proposed a model based on TSAVI (*Transformed Soil-Adjusted Vegetation Index*) and applied it to a portion of a LANDSAT image from 1996 in the northern zone of the country. Coronel et al. (2008) calculated real evaporation for the Mexican territory using SEBAL (Bastiaanssen et al., 1998) and SSEB (Senay et al., 2007) methods, in addition to data from MODIS products and PAN evaporation measurements (figure 8.5).

8.3.4 Cybercartography and its Possibilities for Water-related Problems

Cybercartography, through its practical expression in geomatic artefacts, can influence the solution to the complex and problematic water situation. It is worth noting that a substantial part of the theoretical advances in this discipline and many of its applications have occurred in Mexico at CentroGeo. Another relevant aspect is that the information and knowledge from studies such as those reviewed in the previous section can be integrated and structured as artefacts so as to maximize their usefulness to decision-making processes.

According to Taylor (1997) at the *International Cartography Association* (ICA) in Stockholm, cybercartography "transforms socio-economic, scientific and environmental data into interactive representations that allow the user to explore and understand spatial patterns and relationships in new ways". Reyes (2005) proposed the first theoretical conceptual framework for cybercartography, which establishes cybernetics, modelling and systems theory as the pillars of this new science. This approach represents an observed situation in terms of a conceptual model that comprehensively describes its generic structure using a systemic focus in order to facilitate the representation of the observed situation as diverse structural levels and the selection of the elements or agents involved (Reyes, 2005). Reyes (2005: 78) states that geospatial information is expressed using different languages, such as "maps, graphics, images, diagrams, videos, photographs, text, sounds and music (and potentially via touch and smell)", that should be "designed, in-tegrated and presented in such a way that the user receives the geospatial information". A fundamental aspect of the definitions provided by Reyes (2005) is the incorporation of the development of geomatics into social and organizational processes so that it becomes dynamic, or 'vivid', in the sense that "it can evolves according to the users' wishes" (Reyes et al., 2006: 12).

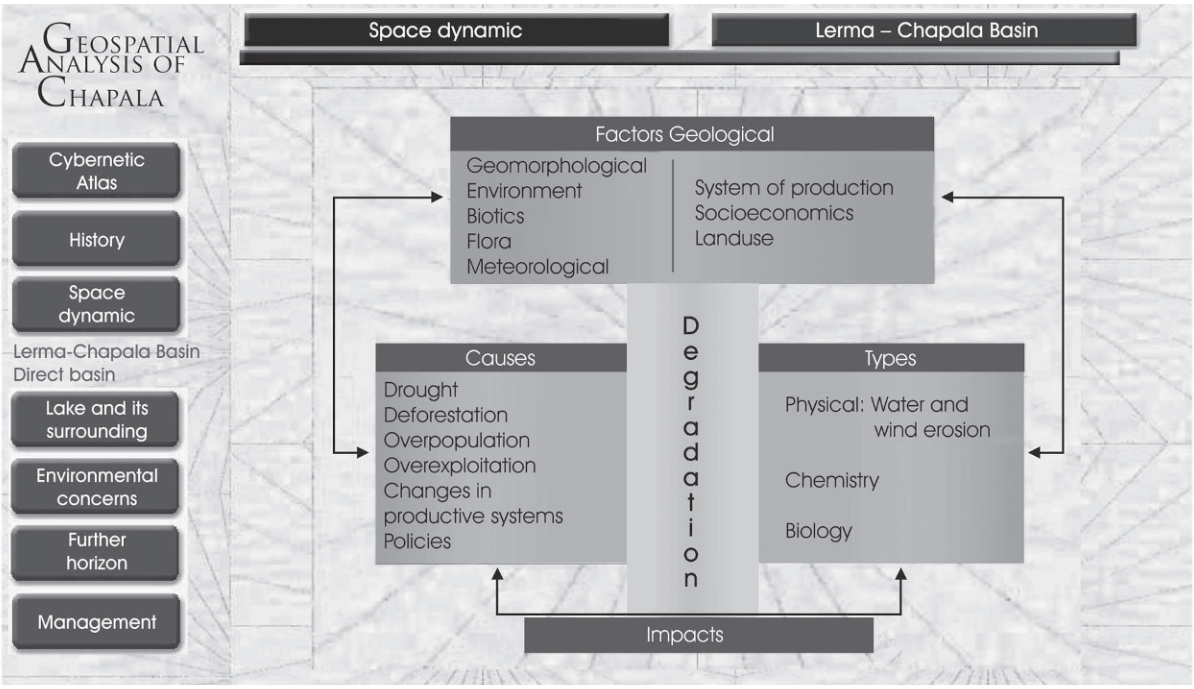
Geomatic artefacts (for personal computers or in their web version) may be geomatics' most significant contribution to the solution of cross-cutting hydrological problems with other types of societal concerns. Geomatic artefacts refer to cybernetic developments, prototypes and applications that provide feedback to geospatial knowledge and information – for example, atlases, documents, systems and solutions in geomatics. Their development combines a series of elements that make possible bidirectional communication processes with users who, in turn, access the elements that enable them to observe themselves as actors within each application's specific environment. This process is called second-order cybernetics (Martínez/Reyes, 2005).

Thus, it has been observed that while using geomatic artefacts, a process occurs that modifies the perspective of the user of the artefact. The users then propose improvements to the artefacts that permit them to re-access another series of concepts, information and ideas; and thus the perspective towards the problematic object of the artefact, and its solution, continue to evolve. An important characteristic of geomatic artefacts is their comprehensive and systemic perspective regarding the problems, or phenomena, that they represent. One of the principal components of this perspective is the requirement to observe and represent the phenomenon in question while taking socio-economic and technical-natural aspects or characteristics into account. Thus, the problem to be addressed in the environment of the artefact is comprehensively observed and analysed, maximizing the possibilities of identifying solutions that may be socio-economic, technical, biophysical, or a combination of these. The systemic approach and the inclusion of knowledge models allow the complexity of the hydrological problem to be represented.

Since its founding approximately 10 years ago, CentroGeo has developed a series of geomatic artefacts for the purpose of organizing knowledge and information that facilitate initiatives to solve cross-cutting hydrological problems. The applications developed, framed theoretically in the context of cybercartography, exemplify the possibilities and reaches of the practice and science of geomatics for solving specific societal problems. Included among such artefacts are the Geographic Information Systems of the Hydrographic Basins of Mexico (figures 8.6 and 8.7), the Cybercartographic Atlas of Chapala Lake (figure 8.8), the Educational Atlas of Chapala Lake, the Cybercartographic Atlas of the Lacandona Forest, the Cybercartographic Atlas of Lake Pátzcuaro, the Cybercartographic Atlas of the Sea of Cortes and an application for the Management of Ur-

Figure 8.6: Principal screen of a geomatic artefact on the web (under development). **Source**: Mexican Geographic Information System of Water Basins; at: <http://xsei.centrogeo.org.mx/ine/>.

Figure 8.7: Screen for the Cybercartographic Atlas of Chapala Lake. **Source**: http://mapas.centrogeo.org.mx/website/chapala/chapdegradacion/viewer.htm.



ban Ravines in Mexico City (SGBUCM, Tapia Silva et al., 2007c; figure 8.8).

As mentioned, geomatic artefacts are based on explicit knowledge models for the specific phenomena they represent. This facilitates the definition of future

Figure 8.8: Example of screens for the application of geomatics in the Cybercartographic Atlas of Chapala Lake. **Source:** Cybercartographic Atlas of Chapala Lake; at: <http://mapas.centrogeo.org.mx/website/chapala/chapdegradacion/viewer.htm>.

This map is included in the cybernetic atlas of the Geo Centro of Chapala (C) 1999-2009

scenarios of the consequences of new management and organizational strategies for the processes studied. The process of generating new proposals supported by artefacts influences the evolution and transformation of the modelling system. Geomatic artefacts, especially versions that are educational or for the dissemination of information, such as those developed for Chapala Lake, have proved to be an effective means for communications about the problem and for raising public awareness about trends related to the degradation of society's resources. In addition, the internet represents a significant evolutionary change in geomatic artefacts, providing up-to-date investigations, with some of the artefacts currently available online, such as those related to the urban ravines in the western part of Mexico City (Tapia Silva et al., 2007c) and the Hydrographic Basins (figure 8.9).[2]

8.4 Conclusions

Studies conducted in the field of geomatics can provide knowledge and analytical methods that contribute to the process of improving the management of water resources. Spatial analysis techniques and obtaining information and knowledge through remote sensing allow for the study of hydrological and related variables, making it possible to identify appropriate solutions to specific conditions in the geographical regions studied. Geomatic artefacts are based on knowledge models and on a systemic and comprehensive perspective towards the problems to be resolved. They integrate information and knowledge from investigations based on remote sensing and spatial analysis, and may be geomatics' most significant contribution to raising public awareness and to the search for solutions. Through such artefacts, it is possible to generate second-order cybernetic processes that enable the definition of new alternatives for land management. The dissemination of these types of systems should be increased so as to maximize their potential for the management of water resources and for the generation of public policies and social initiatives that support the sustainable use and management of resources.

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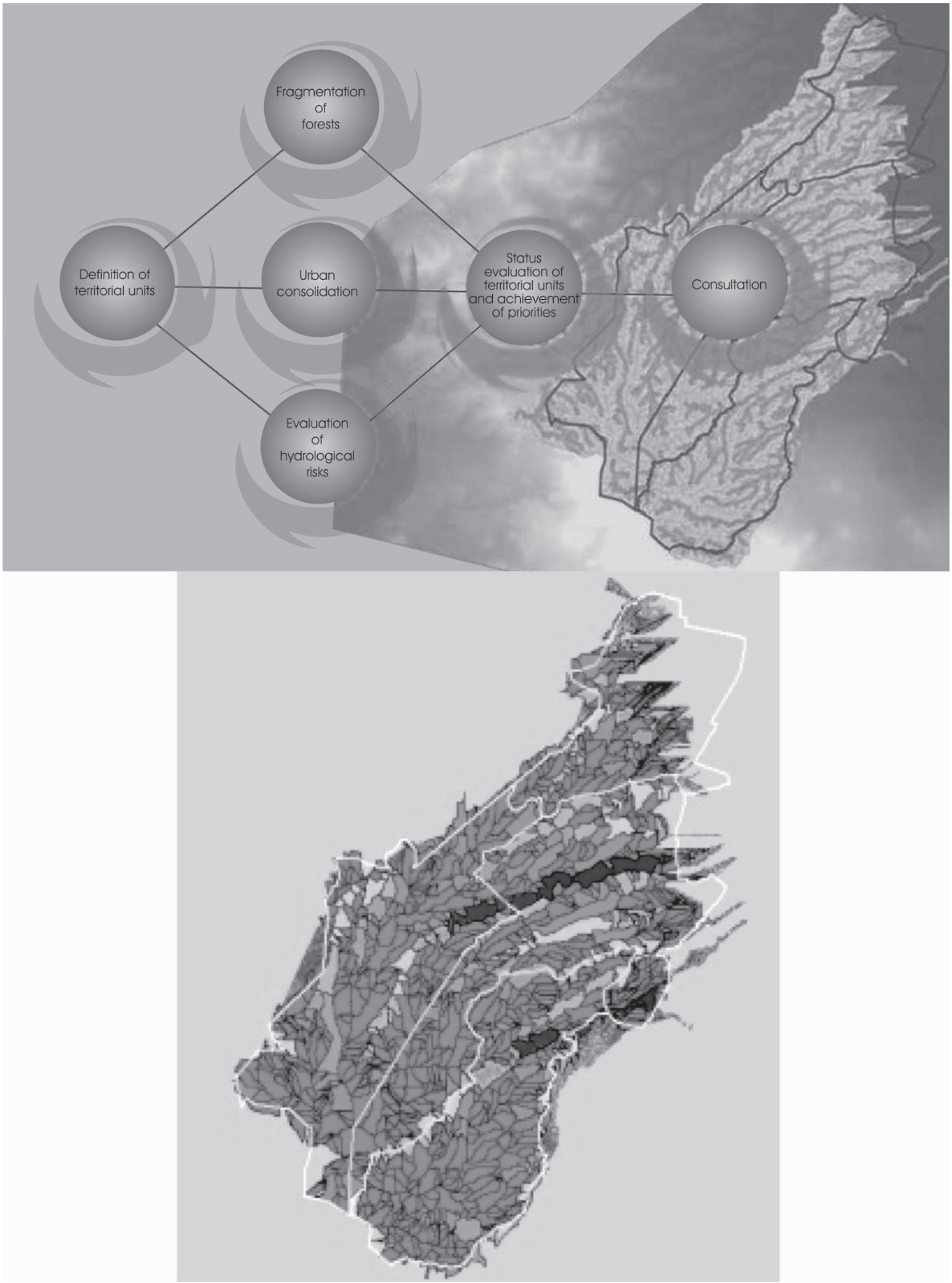
[2] These can be accessed at: <http://xsei.centrogeo.org.mx/>.

Figure 8.9: Example of screens for the application of geomatics in the system for the management of ravines. **Source:** Tapia Silva et al. (2007c)



References

Adler, R.F., G.J. Huffman, D.T. Bolvin, S. Curtis and E.J. Nelkin (2000), "Tropical Rainfall Distributions Determined Using TRMM Combined with Other Satellite and Rain Gauge Information", in *Journal of Applied Meteorology*, vol. 39, no. 12, pp. 2007–2023.

Allen, M.R. and W.J. Ingram (2002), "Constraints on Future Changes in Climate and the Hydrologic Cycle", in *Nature*, no. 419, pp. 224–232.

Allen, R.G., M. Tasumi and R. Trezza (2007), "Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (Metric)-Model", in *ASCE Journal of Irrigation and Drainage Engineering*, vol. 133, no. 4, July-August, pp. 380–394.

Bastiaanssen W.G.M., M. Menenti, R.A. Feddes and A.A.M. Holtslag (1998), "A Remote Sensing Surface Energy Balance Algorithm for Land (Sebal): 1. Formulation", in *Journal of Hydrology*, vols. 212–213, pp. 198–212.

Bastiaanssen, W.G.M., E.J.M. Noordman, H. Pelgrum, G. Davids, B.P. Thoreson and G.R. Allen (2005), "Sebal Model with Remotely Sensed Data to Improve Water-Resources Management under Actual Field Conditions", in *Journal of Irrigation and Drainage Engineering*, vol. 131, no. 1, pp. 85-93.

Benítez, J.A., H. Sanvicente, J. Lafragua, P. Zamora, L.M. Morales, C.J.F. Mas, G. García, S.A. Couturier, R. Zetina, R.A. Calan Yam, S.L. Amabilis, C.I. Acuña and M.C. Mejenes (2004), "Sistema de Información Geográfica de la cuenca del río Candelaria: reconstrucción histórica de los cambios en la cobertura forestal y su efecto sobre la hidrología y calidad del agua", in Kauffer, M.E.F. (ed.) (2004), *El agua en la frontera México-Guatemala-Belice*, San Cristobal de Las Casas, Chiapas, El Colegio de la Frontera Sur.

Bourgine P. and J. Johnson (2006), *Living Roadmap for Complex Systems Science*, Version 1.22, Report Project (FP6-IST 29814) IST-FET Coordination Action, Open Network of Centres of Excellence in Complex Systems.

CentroGeo (2007), "Metodología para el mapeo y caracterización de asentamientos precarios" (2007), CentroGeo, at: <http://xsei.centrogeo.org.mx/ap/campeche/Main CMP.htm> (11 December 2008).

Chiu, L.S., D.B. Shin and J. Kwiatkowski (2006), "Surface Rain Rates from Tropical Rainfall Measuring Mission Satellite Algorithm", in J. Qu John, Gao Wei, Kafatos Menas, Robert E. Murphy and Vincent Salomonson (eds.), *Earth Science Satellite Remote Sensing*, vol. I, Science and Instruments, vol. V, Berlin, Springer, chapter 17.

CONAGUA [Comisión Nacional del Agua] (2007), *Estadísticas del Agua en México*, Mexico, CONAGUA.

Coronel, C., E. Rosales, F. Mora, A.A. Lopez Caloca, F.O. Tapia Silva and G. Hernández (2008), "Monitoring Evapotranspiration at the Landscape Scale in Mexico: Applying the Energy Balance Model Using Remote Sensing Data", in *Proceedings of SPIE Europe Remote Sensing 2008*, vol. 7104, Remote Sensing for Agriculture, Ecosystems, and Hydrology X.

Daly, C. (2006), "Guidelines for assessing the suitability of spatial climate data sets", in *International Journal of Climatology*, vol. 26, pp. 707-721.

Easterling, D. R., G.A. Meehl, C. Parmesan, S.A. Changnon, T.R. Karl and L.O. Mearns (2000), "Climate Extremes: Observations, Modeling, and Impacts", in *Science*, vol. 289, no. 5487, pp. 2068–2074.

Garatuza Payán, J. and C.J. Watts (2005), "The Use of Remote Sensing for Estimating ET of Irrigated Wheat and Cotton in Northwest Mexico", in *Irrigation and Drainage Systems*, vol. 19, no. 3-4, pp. 301–320.

__, R.T. Pinker, W.J. Shuttleworth and C.J. Watts (2001), "Solar Radiation and Evapotranspiration in Northern Mexico Estimated from Remotely Sensed Measurements of Cloudiness", in *Hydrological Sciences*, vol. 46, no. 3, pp. 465-468.

Gochis, D.J., C.J. Watts, J. Garatuza Payán and J.C. Rodríguez (2007), "Spatial and Temporal Patterns of Precipitation Intensity as Observed by the Name Event Rain Gauge Network from 2002 to 2004", in *Journal of Climate*, vol. 20, no. 9, pp. 1734–1750.

Golicher, J. D. (1997), *Geostatistics for Natural Resources Evaluation*, New York, Oxford University Press.

__, and J. Morales (2004), "Correlations Between Precipitation Patterns in the State of Chiapas and the El Niño Sea Surface Temperature Index", in Kauffer, M.E.F. (ed.) (2004), *El agua en la frontera México-Guatemala-Belice*, San Cristobal de Las Casas, Chiapas, El Colegio de la Frontera Sur.

Goovaerts, P. (1997), *Geostatistics for Natural Resources Evaluation*, New York, Oxford University Press.

__ (2000), "Geostatistical Approaches for Incorporating Elevation into the Spatial Interpolation of Rainfall", in *Journal of Hydrology*, vol. 228, no. 1–2, pp. 113–129.

Goudenhoofdt, E. and L. Delobbe (2008), "Evaluation of Radar-Gauge Merging Methods for Quantitative Precipitation Estimates", in *Hydrology and Earth System Sciences Discussions*, no. 5, pp. 2975–3003.

Jenson, S.K. and O. Domingue (1988), "Extracting Topografic Structure from Digital Elevation Data for Geographic Information System Analysis", in *Photogrammetric Engineering & Remote Sensing*, vol. 54, no. 11, pp. 1593–1600.

Kauffer, M.E.F. (ed.) (2004), *El agua en la frontera México-Guatemala-Belice*, San Cristóbal de Las Casas, Chiapas, El Colegio de la Frontera Sur.

Kobrick, M. (2006), "On the Toes of Giants – How SRTM was Born", in *Photogrammetric Engineering Remote Sensing*, vol. 72, no. 3, pp. 206–211.

Kummerov, C., W. Barnes, T. Kozu, J. Shiue and J. Simpson (1998), "The Tropical Rainfall Measuring Mission (TRMM) Sensor Package", in *Journal of Atmospheric Oceanic Technology*, vol. 15, pp. 809–816.

Lira, J. (2004), "A Model of Desertification Process in a Semi-Arid Environment Using Employing Multi-Espectral Images", in Alberto Sanfeliu, José, Francisco Martínez Trinidad and Jesús Ariel Carrasco Ochoa (2004), *Progress in Pattern Recognition, Image Analysis and Applications*, 9th Iberoamerican Congress on Pattern Recognition (CIARP), Berlin, Springer.

__ (2006), "Segmentation and Morphology of Open Water Bodies from Multispectral Images", in *International Journal of Remote Sensing*, vol. 27, no. 18, pp. 4015-4038.

Liu, C., E.J. Zipser, D.J. Cecil, S.W. Nesbitt and S. Sherwood (2008), "A Cloud and Precipitation Feature Database from Nine Years of TRMM Observations", in *Journal of Applied Meteorology and Climatology*, vol. 47, no. 10, pp. 2712–2728.

López Caloca, A.A., F.O. Tapia Silva and B. Escalante (2008), "Lake Chapala Change Detection Using Time Series", in *Proceedings of SPIE Europe Remote Sensing 2008*, vol. 7104, Remote Sensing for Agriculture, Ecosystems, and Hydrology X.

Maidment, D.V. (ed.) (2000), "ArcGIS Hydro Data Mode. Draft Data Model and Manuscript", *Proceedings 20th Annual ESRI User Conference*, San Diego, CA.

Martínez, E. and C. Reyes C. (2005), "Cybercartography and Society", in F. Taylor (ed.), *Cybercartography: Theory and Practice*, Amsterdam, Elsevier.

Matgen, P., G. Schumann, Henry, J.-B. Hoffmann and L. Pfister (2007), "Integration of SAR-Derived River Inundation Areas, High-Precision Topographic Data and a River Flow Model toward Near Real-Time Flood Management", in *International Journal of Applied Earth Observation and Geoinformation*, vol. 9, no. 3, pp. 247–263.

MA [Millennium Ecosystem Assessment] (2005), "Ecosystems and Human Well-Being: Current State and Trends. Findings of the Condition and Trends Working Group", Publisher Island Press, at: <http://www.millenniumassessment.org/en/Condition.aspx> (15 March 2009).

Mo, X., S. Liu, Z. Lin, Y. Xu, Y. Xiang and T.R. McVicar (2005), "Prediction of Crop Yield, Water Consumption and Water Use Efficiency with a SVAT-Crop Growth Model Using Remotely Sensed Data on the North China Plain", in *Ecological Modelling*, vol. 183, no. 2–3, pp. 301–322.

Preciado, M.E., A.I. Ramírez and A.R. Ocón (2004), "Metodología para el uso de los sistemas de información geográfica para la estimación de la pérdida de bosque y el cálculo de los números de escurrimiento. Caso de aplicación: la cuenca del río El Quelite", in Kauffer, M.E.F. (ed.) (2004), *El agua en la frontera México-Guatemala-Belice*, San Cristobal de Las Casas, Chiapas, El Colegio de la Frontera Sur.

Ramos Leal, J.A. and J.I. Hernández Moreno (2008), "Las cuencas hidrogeológicas desde el punto de vista regional", in *Aquaforum*, vol. 12, no. 48, pp. 14–18.

__, M.C. Noyola Medrano and F.O. Tapia Silva (2010), "Aquifer Vulnerability and Groundwater Quality in Mega Cities: Case of the Mexico Basin", in *Environmental Earth Sciences*, at: <http://www.springerlink.com/content/u097001107266k02/> (3 February 2010).

Reyes, C. (2005), "Cybercartography from a Modeling Perspective", in F. Taylor (ed.) (2005), *Cybercartography: Theory and Practice*, Amsterdam, Elsevier.

Reyes, Carmen C., D.R.F. Taylor, E. Martínez, F. López Caloca (2006), "Geo-cybernetics: A New Avenue of Research in Geomatics?", in *Cartographica*, vol. 41, no. 1, pp. 7–20.

Ridd, M.K. (1995), "Exploring a V-I-S (Vegetation-Impervious-Surface-Soil) Model for Urban Ecosystem Analysis through Remote Sensing: Comparative Anatomy for Cities", in *International Journal of Remote Sensing*, vol. 16, no. 12, pp. 2165–2185.

Saraf, A.K., P.R. Choudhury, B. Roy, B. Sarma, S. Vijay and S. Choudhury (2004), "GIS Based Surface Hydrological Modelling in Identification of Groundwater Recharge Zones", in *International Journal of Remote Sensing*, vol. 25, no. 24, pp. 5759–5770.

Scott, A.C., W.G.M. Bastiaanssen and M.U.D. Ahmad (2003), "Mapping Root Zone Soil Moisture Using Remotely Sensed Optical Imagery", in *Journal of Irrigation and Drainage Engineering ASCE*, vol. 129, no. 5, September/October, pp. 326–335.

Senay, G.B., M. Budde, J.P. Verdin and A.M. Melesse (2007), "A Coupled Remote Sensing and Simplified Surface Energy Balance Approach to Estimate Actual Evapotranspiration from Irrigated Fields", in *Sensors*, vol. 7, no. 6, pp. 979–1000.

SRTM [Shuttle Radar Topography Mission] (2003). "The Shuttle Radar Topography Mission SRTM-30, Global 1km Digital Elevation Model", at: <ftp://e0srp01u.ecs.nasa.gov/srtm/version1/SRTM30/SRTM30_Documentation> (19 December 2008).

Tapia Silva, F.O. and F. Mora (2004), "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", *Proceedings of the 19th International CODATA Conference*, Berlin, The Information Society, New Horizons for Science.

__ and G. Arauz (2007a), "Geomatics Procedure to Allocate Infiltration Areas and to Relate them with Green Areas in the Mexico Basin", *Proceedings 32nd International Symposium on Remote Sensing of Environment*, San José de Costa Rica, International Society of Photogrammetry and Remote Sensing and International Center for Remote Sensing of Environment.

__, F. Mora and J.M. Núñez (2007b), "Characterization of Tropical River Basins in Mexico and Central America by Remote Sensing and Hydrological Spatial Analysis", *Proceedings 32nd International Symposium on Remote Sensing of Environment*, San Jose, Costa Rica, International Society of Photogrammetry and Remote Sensing, International Center for Remote Sensing of Environment.

__, J.M. Núñez and D. López López (2007c), "Using SRTM DEM, Landsat ETM+ Images and a Distributed Rainfall-Runoff Model to Define Inundation Hazard Maps on Urban Canyons", *Proceedings 32nd International Symposium on Remote Sensing of Environment*, San Jose, Costa Rica, International Society of Photogrammetry and Remote Sensing, International Center for Remote Sensing of Environment.

__, E. Rosales and A. Mohar (2007d), "Aplicación de geomática para el Sistema de gestión de barrancas urbanas del DF", 1er foro de Geomática, CP, Mexico.

Taylor, D.R.F. (1997), "Maps and Mapping in the Information Era", in L. Ottoson (ed.). *ICC Proceedings*, vol. 1, Stockholm, Swedish Cartographic Society, pp. 1–10.

UN-WWAP [The United Nations, World Water Assessment Program] (2006), *Executive Summary. Water a Shared Responsibility*, New York, World Water Development, Report 2.

UNDP (United Nations Development Programme) (2006), *Summary. Human Development Report 2006. Beyond scarcity: Power, Poverty and the Global Water Crisis*, New York, UNDP.

UNOSAT (2007), "Mexico Maps", at: <http://unosat.web.cern.ch/unosat/asp/prod_free.asp?id=70> (21 January 2009).

Zwart, S.J., W.G.M. Bastiaanssen, J. Garatuza Payán and C.J. Watts (2006), "Sebal For Detecting Spatial Variation Of Water Productivity For Wheat in the Yaqui Valley, Mexico", in *AIP Conference Proceedings*, vol. 852, no. 154, pp. 154–161.