

**GIS APPLICATION IN FLOOD MANAGEMENT – A CASE STUDY:  
PARAIBA DO SUL BASIN, SOUTHEAST BRAZIL  
UTILIZACIÓN DE GIS EN EL MANEJO DE INUNDACIONES – CASO DE ESTUDIO:  
CUENCA DE PARAÍBA DEL SUR, SUDESTE DE BRASIL**

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**Abstract**

In different regions of Brazil, floods have increased dramatically, affecting millions of people and inflicting huge economical damage. Flood hazard maps are important to integrate geospatial and temporal data in a same computational environment that allows risk assessment, modeling and decision support. This paper discusses different levels of integration approaches between GIS and hydrological models and presents a case study, in which all the tasks of creating model input, editing data, running the model, and displaying output results are available within a GIS. The study area corresponds to the upper section of the Paraíba do Sul basin (Sao Paulo State portion), comprising nearly 15,300 km<sup>2</sup> and situated in the Southeast of Brazil. Paraíba do Sul basin has a large importance in the history, culture and economy of Brazil with high urbanization and industrial activities along a part of the main river. The case study presented in this paper has a database which is suitable for the basin dimension including digitized topographic maps. From ArcGIS®/ArcHydro Data Modeler a geometric network called HydroNetwork was created to produce different raster maps. This first grid derived from the digital elevation model grid (DEM) is the flow direction map followed by flow accumulation, stream and catchment maps. The next steps in this research are to incorporate rainfall time series data from about forty stations to build a hydrologic data model within a GIS environment and to combine ArcGIS®/ArcHydro and HEC-HMS model, in order to produce a spatial-temporal model for floodplain analysis at a regional scale.

**Keywords:** Geographic Information Systems (GIS); Hydrologic Models; Flood Inundation Model; Paraíba do Sul River Basin

**Resumen**

Las inundaciones han aumentado dramáticamente en diferentes regiones de Brasil generando consecuencias para millones de personas y causando un enorme daño económico. Los mapas de riesgo de inundación son importantes para integrar datos geoespaciales y temporales en un mismo entorno computacional, permitiendo de este modo decidir, modelar y evaluar los riesgos. Este artículo analiza los diferentes niveles de integración entre SIG y modelos hidrológicos. Se presenta un estudio de caso en el cual todas las tareas para crear un modelo de entrada, edición de datos y visualización de resultados de salida estén disponibles dentro de un SIG. El área de estudio corresponde a la parte superior de la cuenca de Paraíba del Sur (porción del Estado de San Pablo), que comprende aproximadamente 15.300 km<sup>2</sup> y está ubicada en el sudeste de Brasil. La cuenca del Río Paraíba del Sur tiene una gran importancia en la historia, cultura y economía del Brasil. A lo largo del río principal tienen lugar un gran número de actividades urbanas e industriales. Esta región cuenta con una base de datos adecuada para la dimensión de la cuenca que incluye mapas topográficos georeferenciados. Se utilizó el software ArcGIS®/ArcHydro, que tiene una red geométrica llamada HydroNetwork creada que fuera a su vez creada para producir varios mapas con formato "raster". Este primer cuadro derivado del cuadro modelo de elevación digital (DEM) se corresponde con el mapa de la dirección del flujo seguido por mapas de acumulación, drenaje y sub-cuencas. Los próximos pasos en esta investigación serán incorporar datos de series temporales de lluvias de unas cuarenta estaciones para construir un modelo de datos hidrológicos e integrar el software ArcHydro con el modelo lluvia-escorrentía HEC-HMS para producir un modelo espacial y temporal para el análisis de inundaciones de llanuras a escala regional. **Palabras clave:** Información geográfica, Sistemas (GIS); Modelos hidrológicos; Modelo de Inundaciones; Cuenca acuífera de Paraíba do Sul

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## 1. INTRODUCTION

Studies in different parts of the world suggest that the number of disasters associated with extreme weather and climate, such as floods, has increased through the 20th century (Changnon et al., 2000; Ashmore and Church, 2001; Guha-Sapir et al., 2004; Luger et al., 2010). This trend likely reflects different factors, such as a shift in the precipitation pattern, and the fact of a growing amount of the population living in flood-prone areas is increasing. Residents that lived in low land or close to river banks are often highly vulnerable to flood hazard, especially when it happens in urban areas. For all these reasons, floodwater management and analysis became a growing topic of discussion among the government, communities and researchers worldwide.

In different regions of Brazil, floods have increased dramatically, affecting millions of people and inflicting huge economic damage. The situation is particularly dramatic in Southeast region, involving the states of São Paulo, Minas Gerais and Rio de Janeiro, which are responsible for more than 50% of the GDP in Brazil. Inundation has been recurrent in São Paulo, Rio de Janeiro, Belo Horizonte and other important cities. In January 2011, Brazil had its worst and deadliest natural disaster since 1900, where a heavy rain caused the floods and the mudslides in mountain towns situated in the north of the city of Rio Janeiro.

Despite this situation, there are no national (and regional) projects by promoting flood hazard mapping for flood-prone areas in the urban environment, which could provide general knowledge of the flood hazard and could establish a measure for the management and prediction of these risk areas. National flood hazard maps have been created in different countries, such as the "Flood Hazard Mapping for Urban Areas (FHUA)" for Malaysia (Toriman et al., 2009) and the "Digital Flood Insurance Rate Maps (DFIRMs)" elaborated by FEMA (Federal Emergency Management Agency), for the USA (National Research Council, 2007).

Producing flood hazard maps is important to integrate geospatial and temporal data in a same computational environment that allows risk assessment, modeling and decision support. The scope and scale of flood problems makes the Geographical Information System (GIS) software a powerful tool for its integrated management process. GIS is ideally suited for various floodplain management activities, such as base mapping, topographic mapping, and post-disaster verification of mapped floodplain extents and depths.

In this way, this paper aims describing a GIS application for flood management and it presents a case study for the Paraíba do Sul basin situated in the Southeastern Brazil. This basin is one of most important in the country linking the major cities of the São Paulo and Rio de Janeiro.

## 2. A FOCUS ON GIS MODELING

Since the mid-1970's, specialized computer systems have been developed to process geographical information in various ways, searching to connect digital maps and alphanumeric data that describe the features on the maps. The new generation of the GIS can store and analyze the topology of the data, i.e. the understanding of the context of spatial and attribute data (Delaney and Niel, 2007). Each spatial feature in a GIS has a unique geographic location, specified by its coordinates, and a unique identifying number by which it is connected to descriptive data in a relational database. GIS generally uses a Structured Query Language (SQL), which is standard computer language designed specifically for accessing, querying and manipulating geodatabases in a powerful database management system.

As mentioned by Bernhardsen (2002), the GIS technology signifies much more than a software system that processes, stores, and analyzes geographical data; nowadays, the GIS development is allied to the power of the computer, opening an enormous range of possibilities for modeling and accurate decision.

Figure 1 shows different GIS domains and the importance of archiving, manipulation and a data-intensive analysis of the GIS (management components), as well as the modeling, the decision and the process-intensive GIS control (scientific component). However, process-intensive and data-intensive domains are no contradictory ones, and should be shared and integrated to the hydrology and the water resources (Kovar and Nachtnebel, 1993). Therefore, for those that study water resources, it is necessary to find a balance between the process-intensive (modeling) and the data-intensive (archival; management)



Figure 1 – A concept of GIS domains (Clark, 2000).

Within the large broad domain of water resources sciences, the priorities of GIS will depend upon context, in which modeling occupies a key position (Clark, 2000). This is because hydrology, catchment and fluvial systems interact closely in time and space. On the other hand, hydrological models simulate the flow of water, sediment, nutrients, whose physical diversity and complexity of the landscape should be considered and, consequently, tend to strengthen the spatial dimension.

Although the elements of hydrological modeling pre-date GIS by more than a century (Maidment, 1993), GIS and modeling have converted strongly over the last 20 years. Clark (2000) highlights that almost 60% of the whole papers in the 1993 and 1996 HydroGIS conference proceedings include the terms modeling, simulation or forecasting. Because the uncertainty of water resources management under climate change tends to increase, modeling and simulation are valuable tools for building alternative future scenarios.

However, geographic reality is continuous and infinitely complex when comparing with computer, which are relatively simple and can only deal with digital data. Therefore, difficult choices have to be made about how things are modeled in a GIS and how are they represented.

For understanding the modeling process related to a GIS (or *GIS data model*), we can think about different levels of data model abstraction (Figure 2). First, the *reality*, represents the real-world phenomena (buildings, streets, rivers, forests) and includes all the aspects that may or not be perceived by individuals. Second, the *conceptual model*, represents selected objects and processes that are considered relevant for a specific proposal. Third, the *logical model* is an implementation-oriented representation of the reality that is often represented as a diagram or lists. Lastly, the *physical model* (or computational model) corresponds to an implementation in a GIS, and often comprises tables stored as files or databases (Longley et al., 2008). Note that the expression *physical model* applied above is different of considering the expression *hydrologic physical model*, whose hydrological

system is represented for formal mathematics terms. Physically-based models are the most suitable when studying internal catchment scenarios (Olsson and Pilesjö, 2002).

The central role of the GIS in the modeling process may vary in different grades and stages. The set of possible relationships depends on the different application of the linkage as suggests Maidment (1993) and showed below.

- Hydrological assessment to represent hazard or vulnerability (using arithmetic operators and weights for evaluating influences of significant factors);
- Hydrological parameters determination, whereby the GIS provides inputs to the model in terms of parameters, such as surface slope, channel length, land use and soil characteristics
- Hydrological modeling within the GIS, where temporal data are involved;
- Linking the GIS and hydrological models to utilize the GIS as an input and display device including real-time process monitoring.

Therefore, the relationship between GIS and modeling assumes different levels of integration and this issue will be discussed further.

### 3. DATA COLLECTION

A major problem that hydrologist and environmental professionals will treat during the next several years is *information overload* that means the inability to

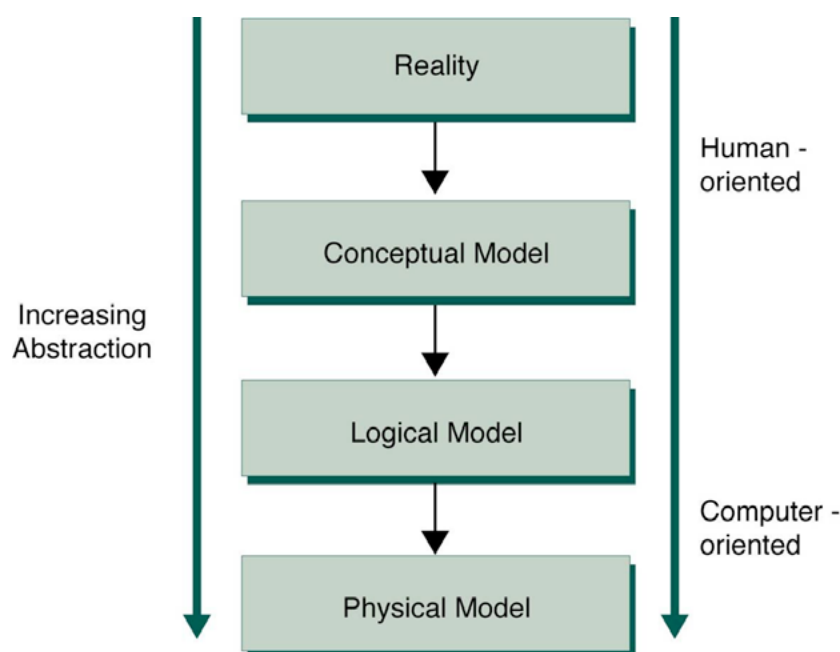


Figure 2 – Levels of abstraction relevant to GIS data model (Longley et al., 2008)

deal with available information using present methods (Dodson, 1993). In the early days of GIS, when geographic data were scarce, data collection was the main project task. Even today, data collection still remains a time-consuming, tedious and expensive process. Obviously, effectively using large sets will require a more integrated approach involving a series of sequential stages, as those displayed in figure 3. Sequential stages could be used at different types of project, regardless of its level of complexity. A workflow commences with planning, followed by preparation, digitizing/transfer, editing and improvement and finally evaluation (Longley et al., 2008).

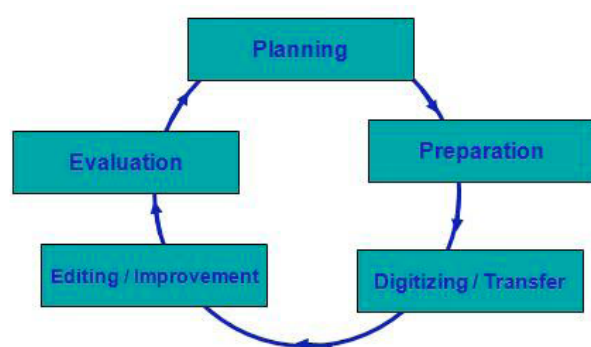


Figure 3 – Sequential stages of planning (Longley et al. 2008)

GIS can contain a wide variety of geographic data types originated from many diverse sources. From the perspective of creating geographic databases, it is convenient to classify geographic data as raster and vector and as primary and secondary, as well. (Table 1).

Table 1 – Different types of data (Longley et al., 2008, modified)

	Raster	Vector
Primary	Digital remote sensing images	GPS measurements
	Digital aerial photographs	Survey measurements
Secondary	Scanned maps	Topographic surveys
	DEMs from maps	Toponymy data sets

Primary data sources are those collected in digital format for using in a GIS project. Typical examples of primary GIS sources include raster satellite image such as Landsat, Aster® and Ikonos® images, and

vector survey measurements which are captured using, for instance, highly accurate total station. Typical secondary sources include raster scanned color aerial photographs or analog maps covering, for example, an urban area or a watershed of different sizes.

A major limitation to the application of GIS to hydrologic parameters computation is the lack of sufficient data on important characteristics such as land uses and soil. The LUCC (Land Use and Cover Change), a current joint project of IHDP (International Human Dimension of Global Environmental Change Program) and IGBP (International Geosphere-Biosphere Program) has a set of digital files covering different regions of the world. NATSGO is an example of soil database designed for regional and national planning for the USA. Similar soil database have been developed only in a few countries such as Canada, France and Netherlands (Nizeyimana et al., 2002). Therefore, unfortunately, there are no consistent national or regional set of soil maps available in digital form in many parts of the world. This way, important hydrologic parameter, such as infiltration, is difficult to obtain because soil maps are not available at the suitable scale.

The analysis of floodplains includes a large volume and variety of both primary and secondary sources data, which could be divided into geospatial and hydrologic data. This data can be obtained from different sources. Some of the main geospatial data used in floodplain management are discussed below.

### 3.1. Topographic Data

Much has changed since the early topographic maps made by hand or “old” procedures based on paper map (analog cartography). Advances in survey techniques, instrumentation, and printing technologies, as well as the use of remote sensing products, have dramatically improved mapping coverage, accuracy, and efficiency. The information age has introduced a new cartographic product that is changing the face of mapping: digital data for computerized mapping and analysis. As mentioned by Robinson et al. (1995), the computer revolution in cartography preserves the basic elements of science but it provides two new functions: the *digital database*, replacing the printed map, and the *cartographic visualization* on many different media.

However, in spite of these amazing technological advances, in many countries large scale and accurate digital maps are not available for extent regions. Developed countries usually have 1:25,000-scale topographic digital maps - or even more accurate - covering large contiguous areas. In contrast, in many countries, typical mapping scales are at regional level (between 1:100,000 and 1:1,000,000). At this level, the areas to be investigated are large, covering several thousands of square kilometers, and the use of GIS for flooding management could be useful in

the early phases of regional projects or in large engineering projects (Westen, 2002).

At local level (or municipality level), typical mapping scales are between 1:5,000 and 1:25,000 and the hazard maps may present a high quality accurate information. At this scale level – or higher –GIS software with 3D visualization tools could be of great use.

The absence in many countries of a higher-level cartography program supported by large governmental subsidies clearly change the order of magnitude cost analysis of the projects, especially the smaller ones (see item 3.4).

### 3.2. Digital Elevation Model

The inclusion of topographic features, using digital elevation models (DEM) structures allows more physically realistic models. The global model GTOPO30 reflects a significant improvement in the quality and resolution of DEMs (Reed et al., 2002). GTOPO30 or local digital topographic survey can be used for computing floodplain elevations and mapping floodplain boundaries. TIN (Triangulated Irregular Network) data structure has the ability to precisely represent linear (banks, channel bottom, ridges) and point features (hills and sinks), which are critical to accurately define the channel and the floodplain geometry. Moreover, TIN associated with raster data (remote sensing) or vector data (topographic maps) provides an increase in the flexibility of modeling of surface from raster modeling (DeMers, 2002) using, for example, the Spatial Analyst/Arc GIS®, the GRASS, the IDRISI® and the ERDAS® softwares.

### 3.3. Remote Sensing

In the last decades, satellite data have been successfully used in most phases of the flood disaster management (CEOS/IGOS, 1999). Earth observations satellites can be used in many phases of disaster prevention, by mapping geomorphologic elements, historical events and sequential inundation phases, including duration, depth of inundation, and direction of currents (Westen, 2002). Floodplains have been delineated by using remotely sensed data to infer their extent from different criteria such as, topographic, pedologic, and botanical features (Dunne and Leopold, 1978). For the prediction of floods, low resolution NOAA AVHRR images, combined with radar data are used to estimate intensity and amount of precipitation, and coverage, and to determine ground effects such as the surface of soil moisture. Medium resolution Landsat and SPOT satellites have been used for producing flood-prone maps at scales varying between 1:30,000 and 1:100,000. High resolution IKONOS® and Quickbird® satellite images can

be reasonably expected to produce more accurate delineation of flood prone areas, although the cost of data can also be prohibitive for a single project or organization. At the local scale, a large number of hydrological and hydraulic factors can be integrated with spatial resolution imagery using GIS, especially the generation of detailed topographic information using high precision digital elevation models derived from aerial photography, SPOT® or LiDAR® (Light detection And Range). An important feature of satellite and aerial photography systems is that they can provide stereo imagery from overlapping pairs of images. These maps are used to create a 3-D model from which contours and elevation maps can be created. Therefore, these data can be used in two or three dimensional finite element models for the prediction of floods in river channels and floodplains.

### 3.4. GIS data sources

As previously discussed, there are many sources and types of geographic data used for water resource projects in general and floodplain management more specifically. However, GIS data comes in many different forms and levels of accuracy and a large variety of prices. In spite of a decrease of the GIS data cost in the latest years, it can represent more than 40% of the total project, especially the smaller one. Therefore, developing your own datasets allows you to have total control over the content and accuracy but it can involve a substantial portion of cost of a GIS project.

In order to reduce the cost, Internet is the best alternative to obtain GIS data. The data include specialist geographic data catalogs as well as the sites of specific geographic data. There are many organizations that maintain comprehensive environmental database such as, Environmental System Research Institute (ESRI), Center for Information Earth Science Information Network (CIESIN), and Canadian Geospatial Data Infrastructure (CGDI). Table 2 shows some of the main organizations where useful data for floodplain management could be found. Elevation data can be obtained from different sources and a large variety of spatial resolution. Hydrologic database includes precipitation records, stream flow, and gauge records. Climatologic and hydrologic data set is represented by time-series data, which represent sequences of real-world observations or calculation. The hydro database of the Brazilian National Water Agency (ANA, in Portuguese) is an example of a comprehensive national hydrological database, which includes more than 2,000 streamflow stations associated with Brazilian streams. This database includes rainfall, evaporation, water quality and sediment data.

**Table 2 – Type of data and source used to floodplain management**

Type	Source <sup>(1)</sup>	Details
Elevation	NGA, USGS, SPOT image, NASA, INPE	DEMs, contours at local, regional, and global levels
Hydrology	Government agencies and national hydrological databases available for many countries (e.g. NHD/USGS, USA, ANA, Brazil)	including spatial rainfall and streamflow gage data
Soil type data	Government agencies (e.g. STATSGO/USA)	Very limited for many regions often depending on local surveys
Land use / land cover	LUCC, AVHRR/NOAA	High level of detail depends on large-scale aerial photography and commercial satellite remote-sensing
Flood zones	Many national and regional government agencies, e.g. FEMA/USA	National Hydrological databases are available for many countries

<sup>(1)</sup> NGA – National Geospatial-Intelligence Agency, USGS – United State Geological Survey, INPE – Brazilian Agency for Space Research, NHD – The National Hydrography Database, STATSGO – Soil Survey Geographic Data, United State

Department of Agriculture, AVHRR/NOAA – Advanced very High Resolution Radiometer/National Oceanic and Atmospheric Organisation, FEMA – Federal Emergency Management Agency/USA.

#### 4. GIS AND FLOODPLAIN MODEL DATA

GIS is ideally suited for floodplain management and prevision for its capacity of linking and integrating geospatial and temporal data. Moreover, the integration of the GIS with floodplain computer models allows users to devote more time to understanding flooding problems and less time to the mechanical tasks of preparing input data and interpreting output.

The primary challenge lies as the difficulty in integrating GIS and hydrological data models in a combined program. Shamsi (2002) defines a useful taxonomy to define the different ways that a GIS can be linked to computer models and how simulation or prediction will be handled by a non-GIS hydrological model that is coupled to the GIS data input or output data. The three methods of GIS linkage suggested by Shamsi (2002) are:

- Interchange method - This method employs a batch processing approach to interchange a GIS and a computer model. Both the GIS and the model are run separately and independently. This is the easiest method and the mostly used nowadays. The GIS software is used to extract the floodplain cross-section from the DEM data, runoff curve numbers from land use or soil layers are some examples of the interchange methods.

- Interface Methods - The model is executed independently from the GIS; however, the input file is created, at least partially, from within the GIS. The main difference between the interchange and interface methods is the automatic creation of a model input file. The HEC-HMS (Hydrologic Modeling System – Hydrologic Modelling System) model developed by U.S. Army Corps of Engineering associated with GIS packages is a good example of the interface method. HEC-HMS has a graphical user interface that allows the users to edit, execute and view model data in a windows environment.
- Integration method – It is a combination of a model and a GIS in a way that the combined program offers both the GIS and the modeling functions. This method represents the closest relationship between the GIS and the floodplain models. Two integration approaches are possible: 1) *GIS Model Integration* – all the four tasks of creating model input, editing data, running the model, and displaying output results are available in GIS. 2) *Model Based Integration* – GIS modules are developed in or are called from a computer model.

#### 5. FLOODPLAIN MAPPING SOFTWARE

There are several well-known floodplains mapping software currently in use elsewhere. Each individual component process of these models can vary significantly because they could serve for a different pur-



pose. Some floodplain mapping and modeling software examples are presented below.

**MIKE FLOOD®** is a complete toolbox for flood modeling, including a wide selection of 1D and 2D flood simulation engines, enabling to virtually model flood problem, whether it involves rivers and floodplains in different environments. Typical MIKE FLOOD® applications include rapid flood assessment and flood hazard mapping. MIKE FLOOD® also has GIS linkage capabilities, which can be used to produce inundation maps as a result of levee or embankment failures. **HEC-GeoRAS** system is a free software composed of a set of procedures, tools, and utilities for processing geospatial data in ArcGIS®, which intends to calculate water surface profiles in a full network of channels, a dendritic system or a single river reach. Water surface profile data and velocity data exported from hydraulic modeling such as HEC-RAS may be processed by HEC-GeoRAS for GIS analysis (see next topics) for floodplain mapping, flood damage computations, ecosystem restoration, and flood warning response (see next topic). **RiverCAD®** is a river modeling software that supports HEC-RAS and HEC-2 within AutoCAD®. RiverCAD® computes water surface profiles for modeling bridges, culverts, levees, floodway delineation, stream diversions and so on. RiverCAD allows the creation of 3D CAD drawings of HEC-RAS showing the extent of water surface regarding the ground topography. **ArcGIS Hydro Data Model** is an ArcGIS® geodatabase model, which provides a standardized framework, into which, the data forms an integrated water resources modeling and mapping database. Because it will be presented a case study using ArcGIS® ArcHydro Data Model, this software will be discussed in more details below.

## 6. THE ARCHYDRO DATA MODEL

ArcHydro is a geospatial and temporal data model for water resources that operate within ArcGIS®. ArcHydro has an associated set of tools, built jointly by ESRI (Environmental System Research Institute) and CRWR (Center for Research in Water Resources), which interconnect features and different data layers, and support hydrologic analysis (Maidment, 2002). ArcHydro is a data structure that support hydrographic simulation models, but it is not itself a simulation model. ArcHydro focuses on the description of surface water hydrology, despite the fact that there is a separate data model called ArcHydro Groundwater Data Model that should enable the integration of surface and groundwater information.

The design of the ArcHydro is a hydrologic information system, which is a synthesis of geospatial and temporal data supporting hydrologic analysis. Therefore, ArcHydro provides a systematic way to link time series data on water management to geospatial data on the location. ArcHydro can even be applied at the scale of a small urban subdivision to study runoff

pattern through buildings and storm sewers (Maidment, 2002). The ArcHydro, also, allows hydrological models to be linked with GIS through a common data storage system. For a long time, hydrologists have wanted to apply GIS data using spreadsheet (Merwade and Maidment, 2002). In this way, ArcHydro facilitates the integration with hydrologic modeling, since the ArcHydro personal geodatabase is a Microsoft Access and Microsoft Excel and Microsoft Access are interchangeable (Figure 4).

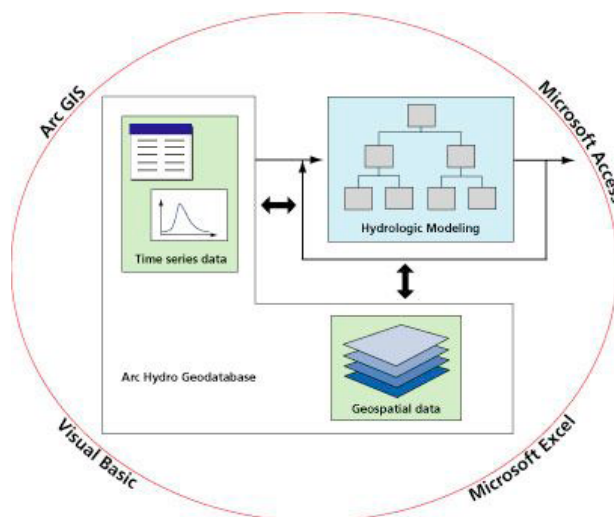


Figure 4– Interfaces for hydrologic modeling (Merwade & Maidment, 2002)

HEC-HMS is considered a standard model for the design of drainage systems making it possible, for example, to quantify the effects of land use change on flooding (Singh and Frevert, 2006). A hydrologic model such as HEC-HMS transforms storm rainfall input to streamflow discharge output using watershed characteristics, such as drainage area, slope, land cover and soil type. Many of these types of data can be estimated from a GIS database. The runoff information from the hydrologic model can then be combined with stream cross-section information model such as HEC-RAS, to determine flooding parameters. An interesting example of GIS and HEC-RAS integration was presented by Kraus (2000) for a small watershed situated in Texas, USA. The floodplain data developed in ArcView (a former version of ArcGIS) was imported into the HEC-RAS, where it was combined with field data in order to construct a full floodplain cross section.

HEC-HMS and HEC-RAS are written in object-oriented programming languages and, during the 1990s, special purpose GIS interface was constructed to supply geospatial data such as HEC-GeoHMS/HEC-GeoRAS systems. HEC-GeoRAS allows a professional with little GIS training to use the ArcGIS to develop geometric data for import in the HEC-RAS and view water surface profile data (Ackerman, et al., 2000).

An interesting application involving an integration of ArcHydro database and HEC-GeoHMS tools was developed by Kawasaki et al. (2008) for analyzing the effects of precipitation change and land use change in the LowerMekongRiver. Spatial and temporal data were used to create 2025 and 2050 scenarios considering the potential impacts of climate change and socio-economic development.

## 7. CASE STUDY

### 7.1. Study area characteristics

Different types of flooding (river floods, flash floods, coastal floods) have different characteristics with respect to the areal extent. Topographic maps and remote sensing images can be used for mapping geomorphologic elements of the landforms and the fluvial system supports wherever possible by information on past flood and high-scale topographic maps, where terraces and levees can be recognized (Westen, 2002). However, detailed geomorphological features are not available for large hydrographic basins worldwide.

One of the main problems of integrating GIS and hydrologic modeling regarding floodplain management and flood mapping is that a large data collection is necessary including rainfall-runoff and hydrograph analysis and gauge measurements. Rainfall and streamflow time series data need to have, at least, 20-30 years of historical data. Then, several efforts have been developed looking for more simple methods for delineating flood hazard zones. An interesting example was given by Suryanta et al. (2010), for delineating map flood hazard. These authors used indicators such as geomorphological, land use and isohyets maps and a record of inundation. Dewan et

al. (2007), show a simple and cost effective way to use GIS and remote sensing, for creating flooding hazard map from a available dataset including land use, elevation and geomorphic units.

Therefore, this paper presents a case study, where a limited amount of spatial and temporal data is available. The study area corresponds to the upper section of the Paraíba do Sul basin (São Paulo State portion), comprising nearly 15,300 km<sup>2</sup> and situated in the Southeast of Brazil (Figure 5).

Paraíba do Sul basin has a large importance in the history, culture and economy of Southeast Brazil with high urbanization and industrial activities along a part of the main river. The basin is characterized by heterogeneous geomorphology, hydrology and soils with elevations varying from about 400 m in extental-luvial plains up to more than 2400 m in the Mantiqueira and Serra do Mar mountain ridge. Historically, human activity imposed dramatic transformations of the regional landscape with a reduction in forested areas from nearly 81% to 8.0% over the last 300 years (Fujieda et al., 1997). Currently, the landscape is a complex mosaic of grazing, forest, and urban areas. The population in the Paraíba valley increased 300 per cent in the last thirty years, from approximately 518,000 in 1960 to approximately 1,690,000 in 2000. Cities continue to expand near, or on alluvial plains contributing to the reduction and elimination of wetland ecosystems and occupying a significant part of the floodplain.

Because of its strategic geographical position, multi-purpose reservoirs (electricity generation, flood control and flow regulation) were built first in the 1950s, and later in the 1970s. Since 1952, water is diverted from the Paraíba do Sul River into the Guandu River water treatment plan in the Rio de Janeiro state.

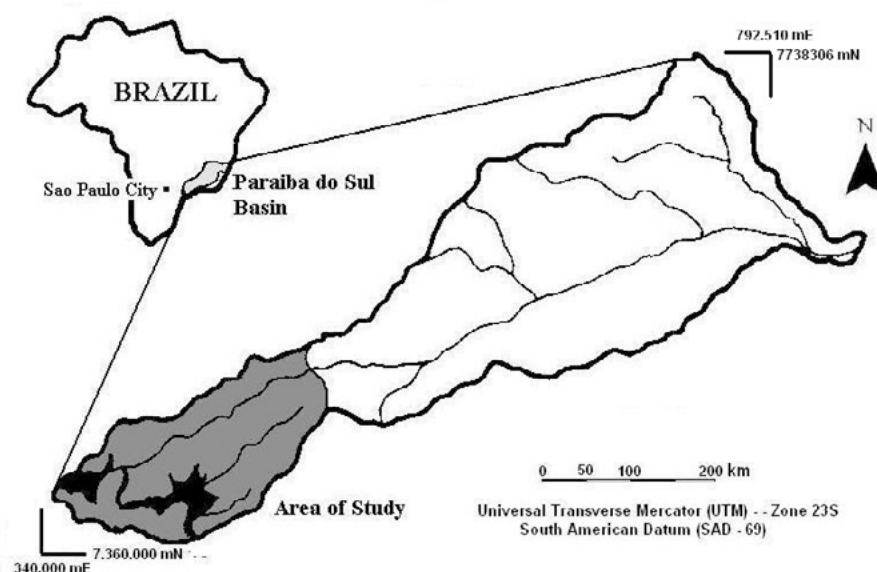


Figure 5 – Study area (Paraíba do Sul basin – São Paulo State)



About 8.7 million people living outside of the basin (in Rio de Janeiro Metropolitan Region) depend on its resources for water supply. In the study area, mean river discharge is 217 m<sup>3</sup>/s; the largest withdrawals of water are made for agricultural irrigation 10.4 m<sup>3</sup>/s, followed by industrial use, 6.5 m<sup>3</sup>/s and domestic use, 3.4 m<sup>3</sup>/s (Sao Paulo State Government, 2002). Therefore, the Paraíba do Sul River is an example of a complex multipurpose water resources management that links hydropower production to agricultural, industrial and domestic water use.

Previous studies have documented the bimodal character of the annual cycle of precipitation in southeast Brazil (Braga and Molion, 1999), with dry and wet seasons consistent with the transition from tropical to mid-latitude climate regimes. In the Paraíba do Sul basin, the average annual precipitation is in the order of 1,400 mm, but exhibits large interannual variability ranging between 800 mm and 2000 mm. Severe droughts occurred in 1943/1944, 1953-1957, 1963, 1968, 1984, 1994, 1997 and 2001; whereas 1947, 1976, 1983 and 2000, 2008-2010 were exceptionally wet years. Dry and wet spells (1 - 2 years) alternate ubiquitously in the observations. Therefore, the region presents a high uncertainty in the long-term assessment of water resources.

In 2001, a severe drought was blamed by the severe reduction in water levels in the reservoirs of many Brazilian hydroelectric power plants (Simoes and Barros, 2007). By September, 2001, the reservoirs were working at minimum capacity (about 20% of the total volume), evidence of the failure of existing energy and water resources management plans to meet unexpected shortages. The shortage period remained until 2004 (Figure 6); by 2007, a wet period starts,

which remains until today (January/2011). Reservoirs were now almost full and several flood events have occurred in the latest years affecting thousands of people. In 2010, São Luis do Paraitinga, a small town located about 200 km from São Paulo, was devastated by a flood, where many historical buildings were collapsed. In the last three years, other towns of different sizes have been affected along the Paraíba do Sul River.

Then, this case study intends to present the first phases of a project, which intends to understand the hydrological response of a large river, as Paraíba do Sul, to the extreme events and its impacts for an extent floodplain. Therefore, this research intends to explore the possibilities of synthesis of geospatial and temporal hydrologic database. In this first stage, we use the ArcHydro framework, which is a simplified version of the ArcHydro storing information about river network, watersheds, and monitoring points.

## 7.2. Database

Several topographic and thematic maps and database are available in the study area (ArcGIS® and AutoCAD® formats). Digital topographic maps include surveys undertaken at 1:250,000 and 1:50,000 scales covering the total basin. For the basin size (13,500 km<sup>2</sup>), this level of topographic scale is suitable and represents a better situation than those found in other Brazilian regions. Digitalized topographic maps at a larger scale (1:10,000) are available for only a very small fraction in the basin. Thematic maps include geology, geomorphology, pedology, and land use/land cover. The Digital Elevation Model (DEM) was derived from a topographic map at

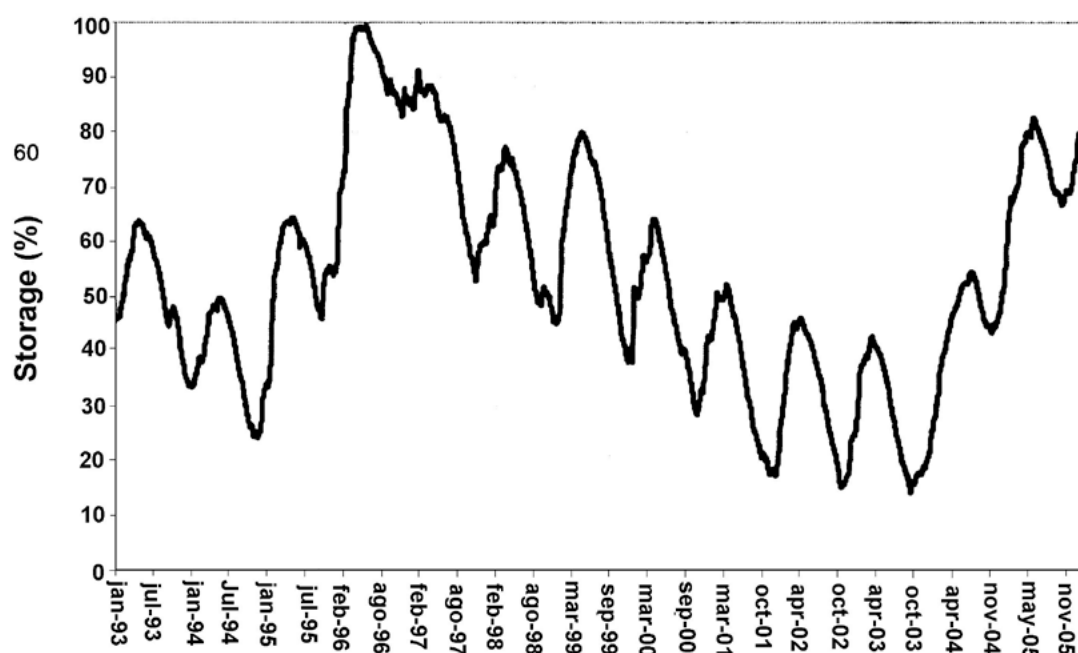


Figure 6 -Variation of water levels in Paraíba do Sul basin reservoirs expressed as percentage (%) of total reservoir water storage capacity between 1993 and 2005.

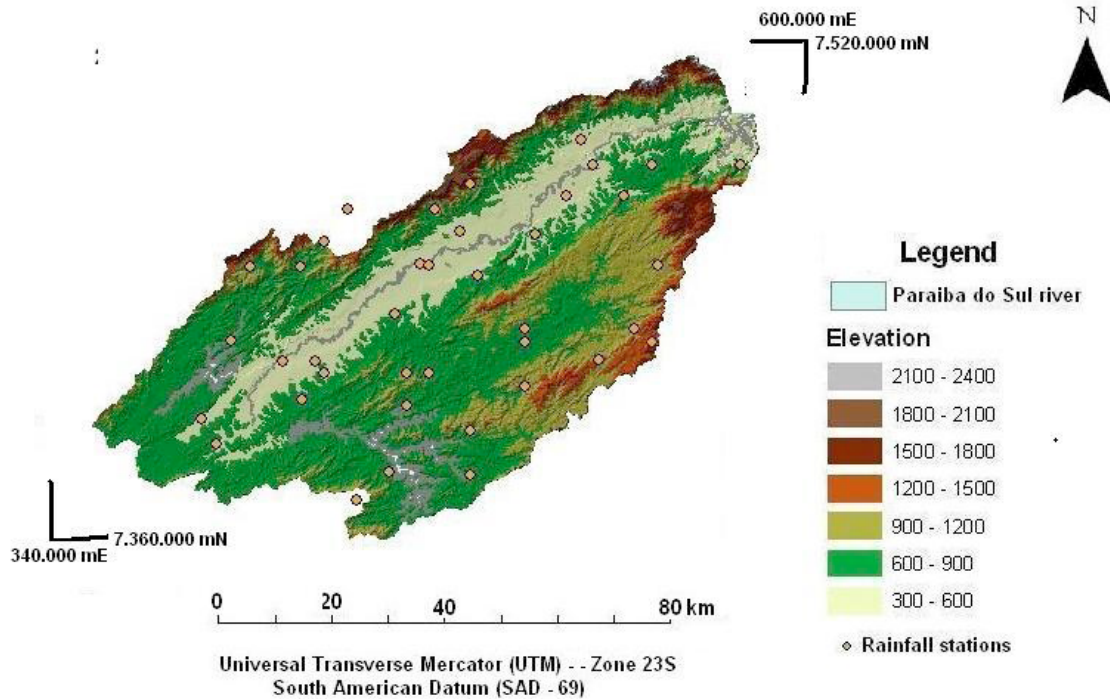


Figure7 – TIN model and select rainfall stations

1:250,000 scale, 30-by-30 minute quadrangle IBGE maps. A hydrographic geodatabase including stream watershed has been compiled using the ArcGIS® 9.2 software and extensions (Spatial Analyst® and ArcHydro). The hydrological data include a network of 107 raingauges (Figure 7) installed at a variety of altitudes (450 m – 1700 m), some of which have been in place since the 1930's, and streamflow gage data maintained by the DAEE (Water and Electric Energy Department, Sao Paulo State).

### 7.3. Results

#### Preparing the data

The first step in creating an Arc Hydro dataset is to collect GIS data, commonly represented as feature classes, which are collections of geometric objects (points, lines, or polygons) that share common themes and attribute types. A typical resource for hydrological data is the National Hydrography Dataset (NHD) for the United States. The NHD includes everything necessary for a simple Arc Hydro model. However, in many regions worldwide, a considerable preparation is needed before the database can be loaded into the ArcHydro database.

After preparing the data, a personal geodatabase is created, in which all of the Arc Hydro objects (feature classes, tables) will be stored. During this process, it is important to select a correct projection system and spatial reference frame, which should be one that will accurately represent different geographic areas of the watershed of interest. Geodatabase works best when the feature classes have the correct class names. For that, an Arc Hydro schema is applied, which

mainly consists of objects such as feature datasets, feature classes and tables, and relationships among them (for more details, see Maidment, 2000). Figure 8 shows a typical geodatabase where *HydroPoint*, represents point features such as gauge station, *HydroEdge* represents line shapefile such as drainage, and *Watershed* represents a polygon feature class, which contains any subdivision of the landscape into drainage areas.

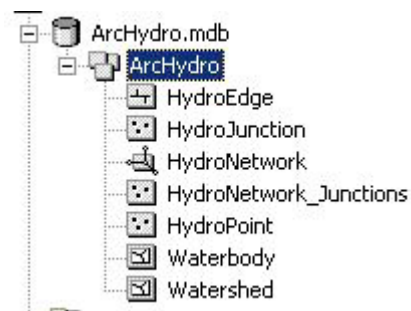


Figure 8 - A geodatabase with typical Arc Hydro feature classes

One of the important characteristics of the ArcHydro principles is to construct water flow network. The final Arc Hydro Network creates a well-defined topology among polygon features (watershed boundary), lines (drainage system) and points (monitoring points). Therefore, *HydroEdge* and *HydroJunction* form a geometric network called *HydroNetwork* (Figure 8). This way, ArcGIS can now be used to trace paths between any two network locations. Figure 9 shows the

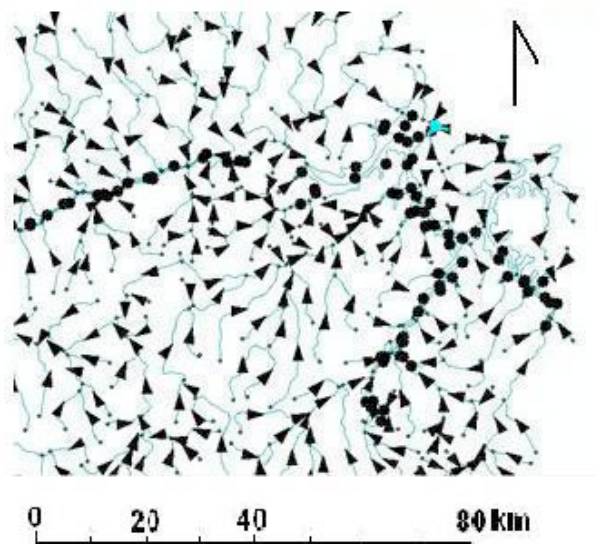


Figure 9 – Drainage network connectivity determined by the flow direction grid

topological connectivity of drainage network of the study area near the river outlet.

#### *Implementing a drainage system*

The first step in hydrological modeling is to define a model area by defining the outline of the watershed boundary. Since the model is distributed (e.g. is supposed to describe flow processes in each and every point inside a catchment) and more topographic information is needed, it is normally used a digital elevation model (DEM), for drainage delineation and for the estimation of topographically related parameters. DEM better represents the land surface and drainage flow, as compared to TIN, because of its regular cell structure. In this particular case of this study, this gridded data is derived from a TIN surface using ArcGIS® geoprocessing tools.

All ArcGIS® raster operation involved in the watershed delineation are derived from the premise that water flows downhill according the eight-direction pour point model (for more detail see, for instance, Oliveira et al., 2000).

This first important grid derived from the digital elevation model grid (DEM) is the flow direction grid (Figure 10a). A flow direction grid consists of values that indicate which neighboring cell the water will flow from. The cell values are the flow directions, which can only have eight possible directions for the water to flow (eight-direction pour point model). It is important to note that the DEM must have enough precision of elevation measurement to support correct flow direction determination. Large extents of flat areas might produce a natural drainage pattern. The Paraíba do Sul basin could be an example of such situation, where floodplain associated with the

Paraíba do Sul River occupies an expressive area (Figure 10b).

Flow accumulation is calculated from the flow direction grid. As highlighted by Oliveira et al. (2000) from the physical point of view, flow accumulation grid is the drainage area measured in units of grid cells. Therefore, it indicates how many cells are upstream or upslope of the current cell. Flow accumulation has been used along with the flow direction, flow length and slope for flood forecasting (Chen et al., 2003). The flow accumulation grid for the Paraíba do Sul basin clearly shows how drainage areas are accumulated in the downstream sector of the study area (Figure 11a). With a flow accumulation grid, streams may be defined through the use of a threshold drainage area or the flow accumulation value (Oliveira et al., 2000). The cell values are assigned as 1, where there is a stream and NODATA elsewhere. Therefore, all the stream cells are labeled identically with a value of 1, as showed in figure 11b.

To define catchments for each stream link, the flow direction grid is used to define the zone of cells whose drainage flows through each stream link (Oliveira et al., 2000). The results of the delineation are stored in a catchment grid. Figure 12 shows catchments and hydrographic reaches for the study area. Note each hydrographic reach has only one catchment. This raster grid may be converted into a set of catchment polygons using ArcHydro (or ArcGIS) raster-vector conversion functions. This is useful for finding out what geographic features are in the each catchment.

#### **PARTIAL CONCLUSION**

In recent years, the attention of hydrologist and watershed professionals has been turning to the problem of providing a spatial view of the hazard. Then, the potential for the use of GIS technologies in floodplain management and flood mapping are huge.

The methodology of mapping flood hazard is still being developed involving a large amount of techniques and approaches. On the other hand, it is a challenge to keep up floodplain maps updated due to the advance of the urbanization or others expressive land use change.

Particularly in developing countries, the use of prone-flood maps is still limited by lack of appropriate scale of data and GIS-hydrology experts. The demand for GIS-based analysis systems in flood plain analysis will increase in the future, as more detailed digital environmental sets become available. Meanwhile, an alternative could be the development of methodologies based on more simple approaches, which considers a limited number of inputs such as rainfall, slope contours, geomorphologic features, and land use. Besides, the selected approach should facilitate the integration between spatial and temporal data. An example is the combination of the ArcGIS and the HEC-HMS to produce detailed terrain models and floodplain analysis. However, other GIS software and



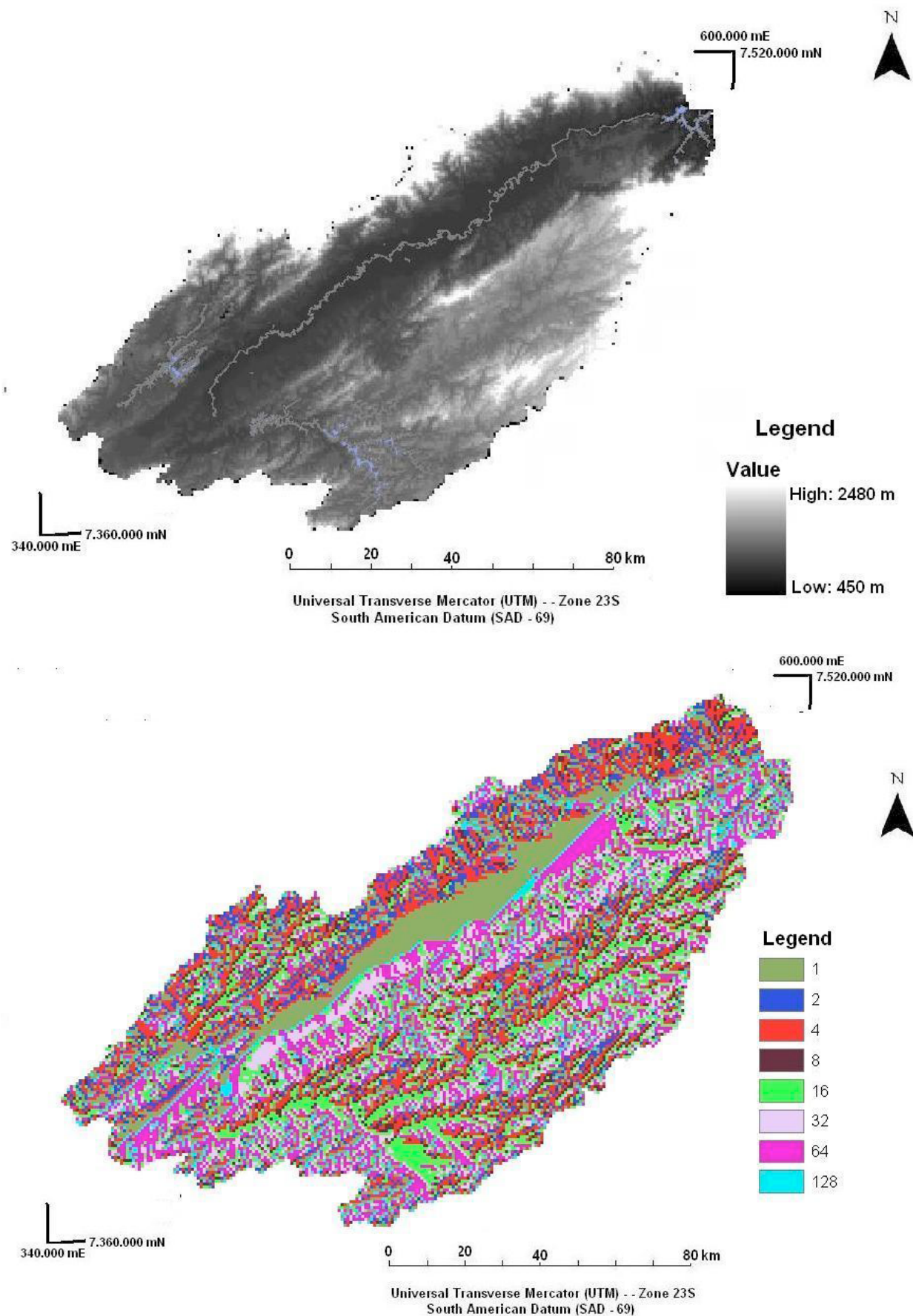


Figure 10 – (a) Digital elevation model of the Paraíba do Sul basin (São Paulo State portion); (b) The flow direction grid of the Paraíba do Sul basin

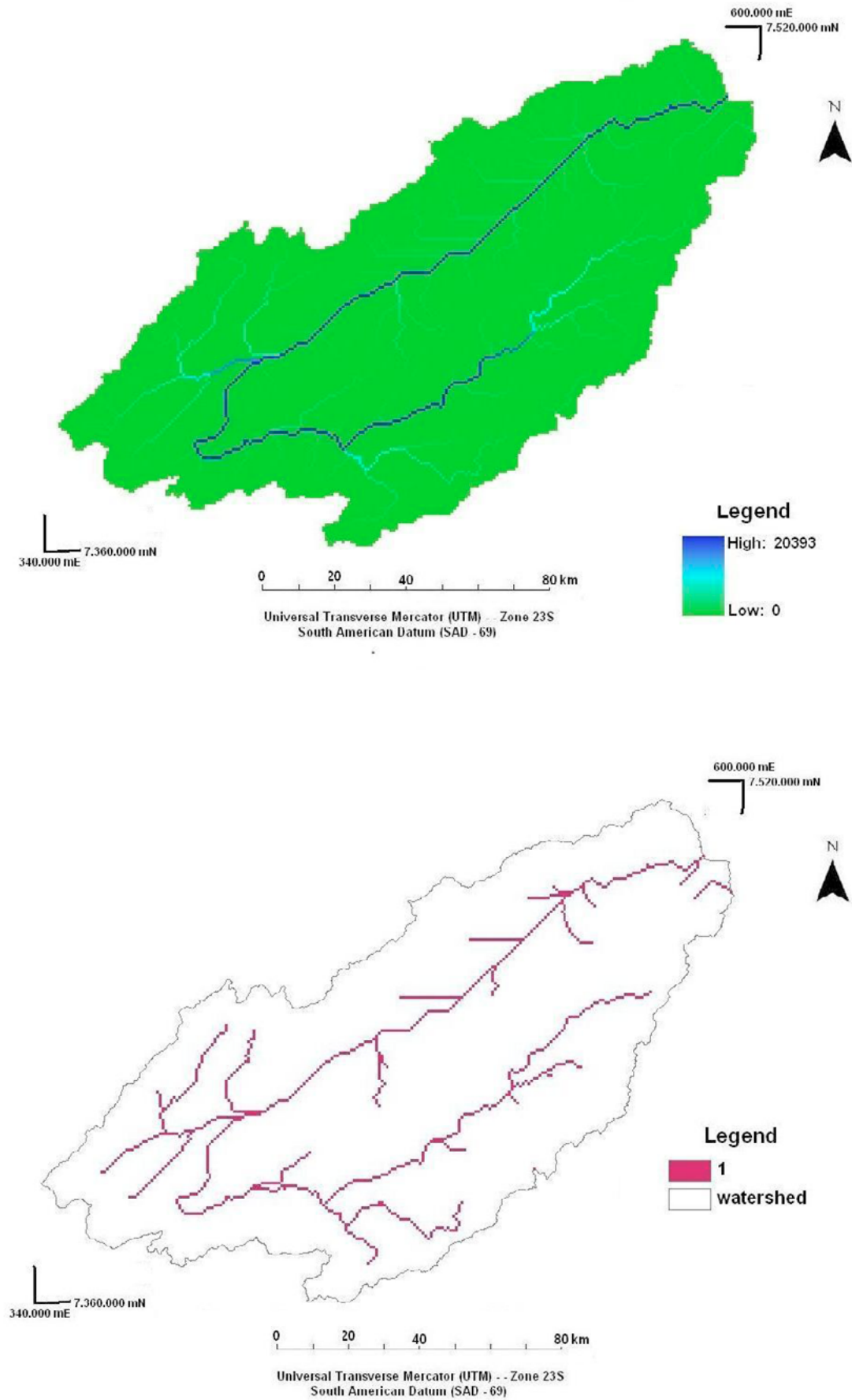


Figura11—(a) Flow accumulation grid of the Paraíba do Sul basin; (b) Streams definition

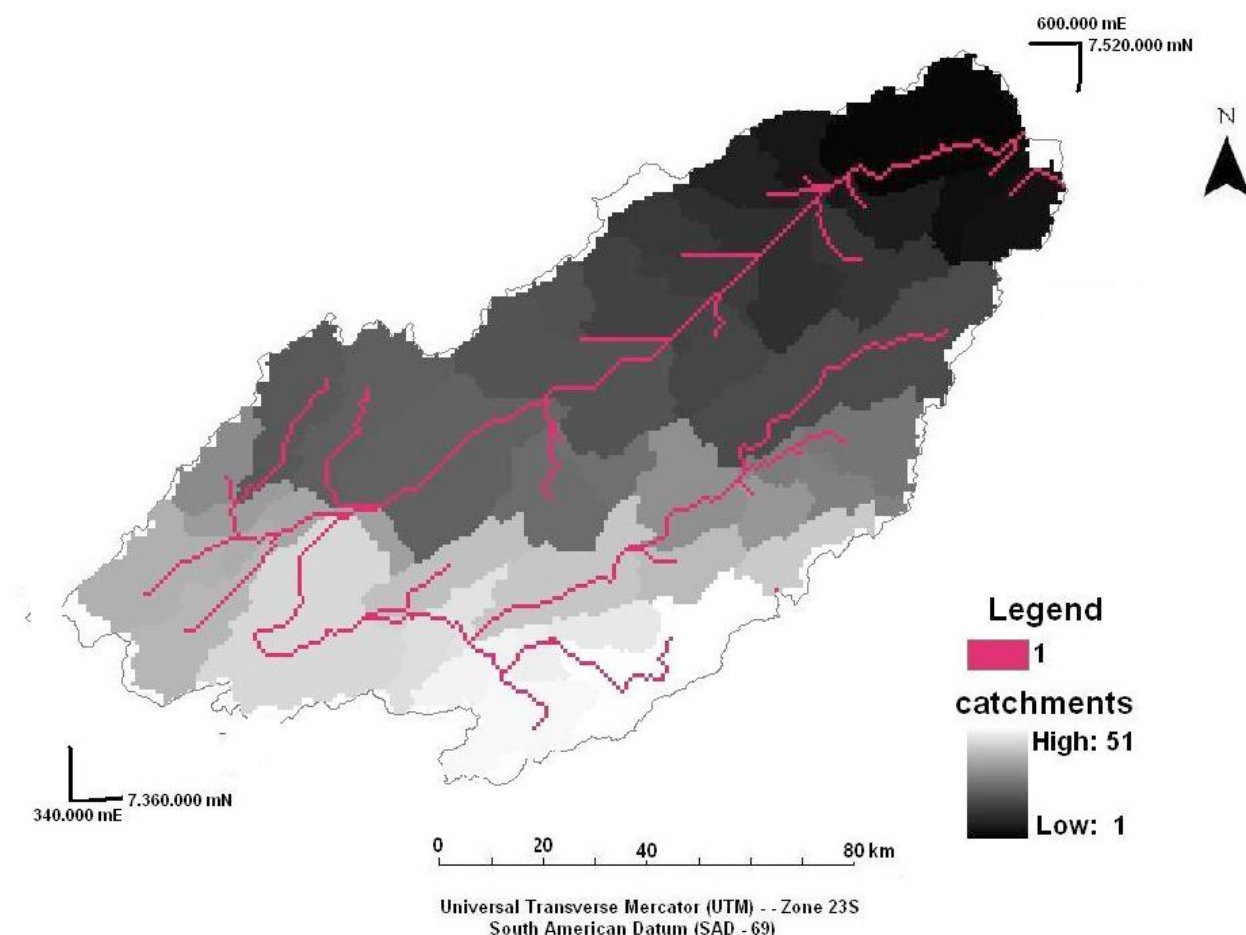


Figure12 – Catchments and drainage lines of the Paraíba do Sul basin

modeling software could be used for the same proposal.

The case study presented in this paper has a database which is suitable for the basin dimension including topographic maps at scales 1:250,000 and 1:50,000, and an expressive rainfall gauges network. Geological and land use maps are available at a regional scale (1:250,000) but an appropriated scale for soil data is not available.

The next steps in this research are: a) to incorporate rainfall time series data from forty-two stations in ArcHydro to build a hydrologic data model within a GIS environment and b), to combine ArcGIS®/ArcHydro and HEC-HMS hydrologic model, in order to produce a spatial-temporal model for floodplain analysis at a regional scale.

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