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Development of a GIS-Based Information System for Watershed Monitoring in Mato Grosso, Central Brazil

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Abstract - This paper describes the conceptual framework and implementation of a prototype for a GIS-based Information System for Watershed Monitoring and Planning in the state of Mato Grosso, Central Brazil. The system was developed to support the implementation of water resources management policies passed by Brazilian federal and state legislatures in 1997. The first phase of the information system development was focused on database design, to create modules for the storage and pre-processing of diverse environmental data sets and for georeferenced registration and control of water users. The GIS environment includes tools for data mining and integrating the NGFlow and QUAL2E models for river runoff and water quality simulation; these tools were successfully validated in the Cuiabá River basin. To guarantee acceptance and continuity of system maintenance in regions under development, GIS applications for watershed management should be component-based. They should also integrate models with robustness for input data that are poor in consistency and quality. Finally, they should be implemented with development tools already used by local technical staff and have a high degree of user friendliness.

Keywords - Watershed monitoring, Geographical Information System (GIS), Database System, Brazil

INTRODUCTION

One of the main goals of water resources legislation passed in 1997 by the Brazilian federal and Mato Grosso state legislatures is the creation of information systems as a basic instrument for the management and control of water quantity and quality, supporting sustainable river administration and watershed planning. The implementation of additional instruments ratified by Brazilian law, which should guarantee equitable water resource allocation and sustainable utilization (e.g., the emission of water permits and taxation of water uses), depends directly on the development of an efficient information system, to help establish objective and replicable procedures in decision-making. In addition to the aforementioned instruments, other procedures linked to state environmental legislation are of

concern for watershed management. In the administrative practice of the Mato Grosso state environmental agency, SEMA, digital registration of administrative Environmental Licensing processes has been limited, to the acquisition of cadastral data without quantitative information on water uses, consumption or produced effluents.

Because Mato Grosso's territory includes three of the main South American biomes - Tropical Rainforest, Cerrado Savanna and Pantanal Floodplain - remarkable funding of environmental monitoring programs has taken place during the last three decades. However, multidimensional data sets of water quality, as well as basic hydrological and climatologic data sets, have never been digitally systematized to guarantee efficient update, retrieval, pre-processing and analysis.

In Brazil, despite promising proposals for

the development of watershed management systems (Cirilo *et al.*, 1997a, 1997b; Rodrigues, 2005), the definition of a conceptual and technical framework of operational Information Systems to be applied at the various governmental administration levels and accessible to watershed citizen groups, has not yet been consolidated on either a state or national level. Therefore, as a consequence of the lack of systemized input data and the availability of user-friendly, integrated tools, water allocation in Mato Grosso is still conducted as an administrative procedure; decision making is little influenced by the environmental characteristics of affected areas or specific impacts caused by the respective economic activities.

In this context, this paper discusses the architecture and the implementation of a GIS-based Information System in its political and institutional framework. This system has been designed to systematize environmental data and information on water users in Mato Grosso state, to subsidize the processing and analysis of spatial and non-spatial data, and provide tools for hydrologic modeling, adapted to data availability in the region. To ensure acceptance by projected user groups, such as environmental protection agencies or watershed committees, the Information System uses conventional data structures and is meant to have a high degree of automatization in data pre-processing and analysis procedures. Our contribution is to offer practice-oriented suggestions for the implementation of a component-based watershed monitoring system in a region in development, and to present results of its validation in the Cuiabá River basin, considered to have strategic importance in the State of Mato Grosso.

REVIEW

Ideally, an Information System of Water Resource Management should be thoroughly capable of storing, processing and analyzing both spatial and non-spatial data (Lyon, 2002). These requisites are well addressed by Geographical Information Systems, which possess the proper tools for spatial data processing, interfacing with common database systems and programming environments for the integration, or even implementation, of hydrologic models, and developing personalized applications (Sudheer & Jacobs, 2004). In the framework of water resource assessment, GIS is rarely a stand-alone tool. Large and complex non-spatial data sets (e.g., time series) can be more efficiently processed by database management systems (Leone & Chen,

2007; Aravanitis *et al.*, 2000). Runoff and water quality simulations with high temporal resolution are better performed by lumped models, using the GIS environment only for pre- and post-processing and visualization (Fernandez *et al.*, 2006; Clark, 1998).

The development of a functional IS in a watershed scale is necessarily influenced by the specific legislation as well as by regional economic development and environmental problems (Belkhouche *et al.*, 1999). Various Brazilian studies of the development of watershed Information Systems have been conducted in the dry northeastern region, characterized by a chronic lack of water resources (Cirilo *et al.*, 1997a), or in highly industrialized southeastern states such as São Paulo or Rio de Janeiro, which have serious water quality problems (Azevedo *et al.*, 2000; Ferraz & Braga, 1998; Neto *et al.*, 2006). Both of these water problems are of concern in Mato Grosso state. While considered a region rich in water resources, parts of the upper Paraguay River watershed face first water supply problems during the dry season (June - October). Particularly in the urbanized areas of the Cuiabá watershed, water quality is seriously affected by point source pollution, mainly untreated domestic wastewater. Watersheds in the Central Brazilian Highlands, which are under intensive agricultural use (soybeans, cotton), are believed to have serious problems of non-point pollution (Libos *et al.*, 2003).

Argent & Grayson (2001) stress the importance of considering the human and financial resources of the user community, its organizational structure, and the specific demands at the different functional levels when developing a GIS application. For simple access and effective democratization of the database, Cirilo *et al.* (1997b) implemented a user-oriented module of the Information System of Water Resources of Pernambuco state without the use of commercial GIS products. They emphasize that such a solution reduces functionality for applications needing tools for spatial data analysis, such as DEM processing or distributed modeling. On the other hand, in order to reduce development and programming efforts, pre- and post processors for hydrological models, such as those developed for HMS (Oliveira & Maidment, 1999) or SWAT (Arnold *et al.*, 1998; Di Luzio *et al.*, 2002; Oliveira *et al.*, 2006), as well as complete watershed management tools such as BASINS (US Environmental Protection Agency, 2006), are frequently based on commercial GIS software or used as integrative environments.

Nowadays, a considerable number of models for runoff and water quality simulation are available to support decision making in a watershed scale,

some of them integrated in GIS environments (Becker & Jiang 2007; Reddy *et al.*, 2006; Schumann *et al.*, 2000; De Roo, 1998; Yang *et al.*, 2000). Generally, complex model designs, which describe more precisely underlying physical processes, tend to need a higher amount of exacter input variables (Tong & Chen, 2002). As mentioned by Maidment (1993), the factor that most limits hydrologic modeling is not the ability to characterize hydrologic processes mathematically, but rather the ability to accurately specify values of the model parameters representing the flow environment. Limited data availability can be overcome by the application of GIS, thus justifying the application of this technique in the studied region.

For Central Brazil, no comprehensive comparative studies on the performance of precipitation-runoff or water quality models are available. Therefore, when selecting a model the authors looked for one with a robust mathematical approach, taking into consideration reduced data availability and proven applicability in similar climatic conditions.

WATER RESOURCES IN MATO GROSSO AND THE CUIABÁ WATERSHED

Mato Grosso, with an area of about 906,800 square kilometers, is one of the four states that make up the Central West of Brazil. The territory contains three biomes: the Amazon rain forest, the Cerrado scrubland and, in the south, the Pantanal of Mato Grosso, the world's largest floodplain. Characterized by continuous economic and demographic development - between 1985 and 2004, Mato Grosso state GNP grew about 315% (local currency), while in the same period state population increased about 68% (IBGE, 2006) - demand on water resources is expected to increase in the future.

Situated in the southern part of Mato Grosso, with an extension of about 55,000 square kilometers, the Cuiabá River watershed plays an important strategic role for the state, considering both socio-economic and environmental aspects (Fig. 1). The metropolitan agglomeration of Cuiabá and Várzea Grande is the most densely populated and economically developed region of Mato Grosso. More than 80% of its water supply depends on the Cuiabá River (Teixeira, 1997). At the same time, water quality is diminished, with a confirmed trend of deterioration (Lima, 2001). In 2001, when treatment plants were equipped to remove only organic loads, less than 30% of domestic and industrial wastewater of the metropolitan region was being treated.

The Cuiabá watershed, the test area for implementation of the Information System, includes areas employing the two most important forms of land use in Mato Grosso. Extensive cattle farming dominates great parts of the mid-Cuiabá River basin, the best-adapted land use for the shallow soils of the Precambrian basement in the so-called "Cuiabá Lowlands." The headwater sandstone regions of the Manso River watershed are under intensive agricultural use, with soybeans and cotton as the dominant cultures; these cultures have already been shown to have significant impacts on water quality (Libos *et al.*, 2003). Since it is a declared objective of state government to intensify agricultural production by expanding irrigation techniques, an increasing water demand can be expected in the upper watershed.

Figure 1 - The Cuiabá River watershed inside Mato Grosso state.

The tropical, semi-humid climate of southern Mato Grosso, with mean annual temperatures between 22 and 25°C and annual precipitation between 800 and 1600 mm, is characterized by an expressive seasonality of precipitation with strong response in river discharge. The Cuiabá River in the city of Cuiabá has shown a mean monthly runoff between 100 m³/s in August and 828 m³/s in February (1948-98). In November 1999, the dams of the Manso hydropower plant were closed, followed by a filling phase of the reservoir lasting three years. As the Manso River contributes up to 56% of the discharge of the lower Cuiabá (Shirashi 2003), operation modalities of the power plant strongly influence downstream water availability. Despite the local problems in the Cuiabá metropolitan region, with impacts on uses such as public water supply and fishing - the latter an important economic activity for the low-income population - both water

pollution and modification of hydrological regime are supra-regional concerns since the lower Cuiabá River crosses and inundates periodically about 15,000 square kilometers of the northern Pantanal floodplain. Preservation of this biome, with a unique flora and fauna, is a declared environmental protection objective both nationally and internationally.

ARCHITECTURE OF THE INFORMATION SYSTEM

Overview

The Information System (IS) on Water Resources consists of three main elements: Database System (DBS), Geographical Information System (GIS), and two models which were integrated into the host GIS application. The NGFlow precipitation-runoff model (Ye *et al.*, 1996) was developed using a map-centric approach, where model equations, maps which define the study area, and the data tables

which describe the study area and model parameters are integrated in the GIS. The integration of the QUAL2E model for stream water quality simulation (US Environmental Protection Agency, 2001) is tightly coupled, where the GIS environment provides an interface for pre-processing, model viewing and application control.

An external database (DB) application called APLICA, which has recently begun to be distributed to water users to provide data related to water utilization, should simplify and improve control of environmental licensing as well as automate actualization of the central DBS at the state Environmental Agency (Fig. 2). Sub-components, which are already being implemented or are in an advanced phase of development, are marked separately from those which are projected or in an initial phase of development; the latter are a distributed model for simulation of non-point pollution, a Decision Support System for the emission of water permits and taxation, and a coupled WWW-application for online water availability simulations.

Figure 2 - Main components and functionality of the Information System (+: available functionality; -: in development).

The DBS client was developed in MS Access (Microsoft Inc.), widely used software for environmental applications in Brazil (Cirilo *et al.*, 1997). Tables are stored in a MS SQL Server DBS (Microsoft Inc.). Two modular blocks can be distinguished in the DBS: one for the storage and pre-processing of environmental data sets such as water quality and time series of hydrological and climatologic data, called SIBAC, and another for registration of water users, called LICA. The external APLICA DB application, developed in Visual Basic (Microsoft Inc.), provides water users

with a tool to generate digital files containing the obligatory information demanded for the approval of a business' Environmental License. Both components of the central DBS can be used as stand-alone tools for operational tasks, including time series processing and the emission of reports about water users and the status of licensing processes. To carry out analytical tasks in watershed monitoring and decision making, summarized data tables of the DBS can be accessed through the GIS Interface.

At present, spatial data sets are stored in the ArcInfo and ArcView (ESRI) data models. ArcView

3.x was selected for GIS Interface development, considering its user friendliness (Rybaczuk, 2001), its extended tools for GUI programming, and its wide dissemination, particularly for applications in hydrology and watershed management (US Environmental Protection Agency, 2001).

Database system

Since datasets of environmental parameters and water users are of fundamental importance for all consecutive analyses and modeling procedures, most attention in the first phase of IS development was focused on data acquisition and database design (Staudenrauch & Flügel, 2001). Functionality of both DBS components can be controlled through user interfaces. Data tables can be filled in using

forms with control mechanisms programmed in VBA to avoid incorrect data entry. Other forms have been developed for interactive database queries.

Database component for environmental data (SIBAC)

Environmental data sets from more than 200 sampling points in the Cuiabá watershed, collected from 10 different public and governmental institutions, have been joined in the database (Tab. 1). To systematize environmental data available from different data sources, and to facilitate the application of the developed tools in other watersheds, a complete and consistent coding scheme for data tables and geographic features (sampling points, river reaches, sub-basins) was developed.

Table 1 - Sampling points and time series maintained in the environmental DB component.

Data set	Sampling points	Time series (max.)	Origin*
Water quality (effluents, river monitoring, withdrawals)	122	1985 – 2006	DESA, FEMA, Furnas, CPRM, SANEMAT, AMSC
Runoff (daily / monthly)	40	1966 – 2006	DESA, Furnas, Defesa Civil – MT, CPRM
Precipitation (daily / monthly)	63	1922 – 2006	ANEEL/ANA, Furnas, INMET
Climatology (daily / monthly)	12	1972 – 2006	DESA, INMET, Dep. Agro, Sec. Agr.

In accordance with data availability, six basic time series data tables were designed, one for daily climatologic data, two for daily and monthly precipitation data, two for daily and monthly hydrological data, and one for water quality monitoring data. Time series are related to tables of sampling and station points and other complementary tables, storing information on data origin, parameter description and units.

Through the main interface of the DBS component, three main procedures can be executed: one for table *Update*, one to *Undo* erroneous data updates, and one for the *Export* of data tables, which are used for spatial visualizations in the GIS environment and as inputs in runoff and water quality models. All update sub-procedures create or actualize new filtered and consolidated tables, using some intermediate temporary tables and queries not visualized in the flow diagram of figure 3.

Sub-procedures (*UpdateTab_MonthlyRunoff*, *Create_Mean_Climate*) consolidate daily runoff and climatologic data in tables with average / accumulated monthly data. To create a table of all available monthly precipitation data, a sub-procedure called *UpdateTab_Precipitation* joins registries of the climatologic stations operated by INMET with data acquired at precipitation stations under the responsibility of ANA (see Tab. 1). Water

level values, some of them available through the Internet (ANA, 2007), can be transformed by sub-procedure *UpdateTab_DailyRunoff* execution in stream runoff, using a table with the coefficients of time-specific station-rating curves. Another sub-procedure called *Estimate_Precipitation* can be used to estimate and fulfill data gaps in the original precipitation table through linear regression models, which are dynamically calculated from available data sets. Control functions in the *UpdateTab_WaterQuality* sub-procedure check original water quality data for digitizing errors and data inconsistencies and update a table of filtered data. All kinds of alterations done by these *Update* sub-procedures can be reverted using the *Undo* procedure. *Export* sub-procedures were programmed to create pre-formatted GIS and model input tables of climatologic, precipitation, runoff and water quality data. The *Export* sub-procedures *Create_Mean_Climate* / *ExportArcView_Climate*, *ExportArcView_Precipitation*, *ExportArcView_DailyRunoff* and *ExportArcView_MonthlyRunoff* create reformatted tables used for input and optimization of the NGFlow precipitation-runoff model. The *ExportArcView_WaterQuality* sub-procedure prepares tables for input in the QUAL2E water quality model, and for interactive visualization tools available through the GIS interface.

Figure 3 - First level data flow diagram of the DBS component for management of environmental data sets (SIBAC), according to Yourdan (1990).

Database component for information on water users (LICA)

Since the homologation of legislation on water resources in 1997, all commercial water users in Mato Grosso are obligated to inform the government, in the context of an environmental licensing procedure, about the water uses of their commercial activities, such as industry, agro-business or mining. To automate registration, storage and analysis of related data sets, a DBS component has been developed. Three basic procedures are available: the manual inclusion of new administrative processes, the query of data sets, and an import routine to update the DBS with new data sets, digitally generated by water users employing an independent database application called APLICIA (Fig. 4). Another procedure permits the creation of queries and reports summarizing water uses differentiated in districts or watersheds.

In accordance with the legislation, tubular wells, cored to attend the water demand of an economic activity, must be licensed independently from the proper business. To avoid erroneous data duplication on water runoff and consumption - these data are being collected in the administrative licensing procedures of the proper business project and of eventual associated wells - the procedure to register licensing applications permits the association of general business activity and tubular well procedures. The Query procedure can be used to

locate specific processes.

Figure 4 - First level data flow diagram of the DBS component for management of cadastral information on water users (LICA), according to Yourdan (1990).

Successive interfaces support the import of data on licensing processes created by the APLICIA application, permitting the association of a new process to existing processes / businesses. During the execution of import routines, internal indexes are transformed, guaranteeing the integrity of the central database system at SEMA. Information on wells, withdrawals of surface water, and discharges is geo-referenced, permitting the analysis of spatial distribution of consumption, runoff and water quality data as well as the automated model calibration through the GIS environment.

Spatial database

During the last decade a socio-economic and environmental zoning of the complete state of Mato Grosso was conducted, resulting in digital thematic cartography on a scale of 1:250.000, including vector layers of geological units, soil units and land use (SEPLAN, 2006). Digital elevation models, the main input for the pre-processor of the NGFlow runoff model, have been interpolated for the Cuiabá watershed from digitized isolines and a digitized hydrographic network of 19 1:100.000 topographic maps covering the watershed (Zeilhofer, 2001). Sub-division of hydrologic response units and the main river network, both with associated attribute tables of physiographic characteristics and automatically corrected topology, have been generated by the NGFlow pre-processor. Most spatial data sets are still stored in ESRI vector and grid formats. These datasets are previewed to be migrated to DBS tables, as are point features of water quality, hydrological and meteorological stations, as well as licensed wells and withdrawals.

Personalized GIS tools for visualization and data assessment

The US Environmental Protection Agency (2001) presented, in its BASINS watershed assessment system, comprehensive tools for spatial data visualization and assessment of water quality data.

The BASINS “Target” and “Assess” modules for the classification of sampling points and sub-watersheds were adapted and modified in the presented Information System. As BASINS does not incorporate a proper DBS, database query modules were developed to provide for the GIS component synthesized water quality data. To facilitate interaction, users can select through a unique GUI observation period (year/s), season (dry, rainy) and water quality parameter to obtain a classification in accordance with monitoring values of sub-basin specific sampling points. Other modifications of the original Avenue scripts were necessary to make the code compatible with table structure and naming conventions in the DBS. To support the control of environmental licensing, modules for the classification of sub-watersheds according to the number of registered users of superficial and subterranean water resources were added. Developed modules update georeferenced water users during the initialization of the GIS environment. As no conclusive hierarchy of Mato Grosso watersheds has yet been established, the selection of point features in the classification process can be done dynamically through spatial queries, which allows the application of the modules in freely defined polygonal subdivisions and different hierarchical levels of watersheds. Figure 5 shows the execution result of the visualization tool representing the number of licensed wells in the watershed of the São Lourenço River, a main affluent of the Cuiabá River.

Figure 5 - ArcView layout, dynamically created by the data mining tool for classification of sub-watersheds according to number of licensed wells (“poços tubulares”).

Model Integration

To support watershed monitoring and future decision-making for the granting of water permits and taxation, two main requirements for modeling capabilities of the information system were initially identified: simulation of mean monthly runoff in the main river reaches should permit estimates of low water availability during the dry season, when a water quality model should address point pollution problems, particularly caused by precarious waste water treatment in the regional agglomeration centers such as the cities of Cuiabá and Várzea Grande. Model integration was guaranteed through the development of DBS and GIS modules. The integrated water quality model needs only a basic ArcView license (version 3.0 or later). The semi-distributed runoff model needs, in addition, an installation of the Spatial Analyst extension for raster processing.

A. Implementation of the NGFlow stream flow model for operational use

Ye *et al.* (1996) presented a map-based surface flow simulation model called NGFlow, constructed under an ArcView GIS-environment, which was successfully applied in the Niger Basin,

Africa, a “data poor” region like Mato Grosso state. All elements - the equations that govern the hydrologic processes, the spatial data and the database tables - are integrated in a unique environment, guaranteeing portability and user-friendliness. Modeling can include information on reservoirs, which allows the influence of operation routines of the Manso power plant on the study area to be considered. Local runoff at a river section is estimated by soil water surplus in the corresponding sub-watershed. Soil water balance and surplus can be estimated by a simple bucket model, with given inputs of precipitation time-series and information on soil-water holding capacity and potential evaporation. Estimates of local runoff are the sum of an overland flow component, based on a response function of local runoff on surplus and a sub-surface water flow component, which can be simulated by a linear-reservoir-model. In NGFlow, flow routing on a river section can be simulated using the Muskingum or Muskingum-Cunge method.

The presented implementation of NGFlow includes a complete interactive and automated pre-processor based on Digital Elevation Models (DEM) to extract data layers of sub-watersheds and hydrographical network and perform their vectorization, overcoming the necessity in the original version of NGFlow to utilize ArcInfo (ESRI) for DEM processing (Fig. 6).

Figure 6 - Dataflow in the SIBAC-integration of NGFlow (adapted from Zeilhofer & Santos 2005).

Most original NGFlow modules suffered extensive modifications in the GIS-integration. New components such as those for importing precipitation stations, spatial interpolation of precipitation, parameterization of river reaches and sub-watersheds, as well as for estimating soil-water surplus were developed to improve modularization and user-friendliness, and to add functionality. All processing steps, such as model setup, run and

optimization, can be executed through a sequence of ArcView menu items. Figure 7 shows a comparison of observed and simulated monthly runoff for the Cuiabá city river gauge using the NGFlow implementation for a six year time series (1994-99). To evaluate model applicability in non-gauged watersheds, no model calibration has been conducted.

Figure 7 - Un-calibrated NGFlow simulation run and observed monthly discharge of the Cuiabá River, city of Cuiabá, Porto between May 1994 and April 1999 (RMSE: 0.086, COE: 0.764).

Overestimates in the first months of the simulated time series can be explained by the defaults in a new model run, assuming complete saturation of soils. The simulations without calibration show some systematic errors: anticipation of discharge increase at the beginning of the rainy season and a time lag in reproducing runoff decrease after the rainy season. In the mass balance, discharge is overestimated. Obtained RMSE error under 0.10 and a COE value higher than 0.75, however, can be considered satisfactory (ASCE, 1993).

B. Integration of the QUAL2e stream water quality model

QUAL2E, a one-dimensional stream water quality model, was chosen for integration in the Information System. A complete model description can be found in US Environmental Protection Agency (1985). QUAL2E has already been applied successfully under semi-humid climates in Brazil (Cunha *et al.*, 2004; Milanezi *et al.*, 2001; Kotlhar & Luca, 1999), including for simulations in the Cuiabá watershed (Lima, 2001). The US Environmental Protection Agency (2001) presented an integration of the QUAL2E model in the BASINS 2.0 environment, where model inputs are generated from static ArcView data tables. To improve operational applicability of the QUAL2E integration with access to

actualized time series, a pre-processing scheme for alphanumeric data was developed in the SIBAC database environment. Water quality and hydrological parameters associated to effluents, withdrawals and monitoring points are the principal functional data sets used in QUAL2E. Data sets of effluents and withdrawals are used as modeling input when measurements at monitoring points are applied to define the initial conditions at the first river reach to be modeled. To prepare automated model input, a new database (SIBAC_AV) can be dynamically created from export modules of the main SIBAC database component (Fig. 8). The tables of water quality parameters include fields for runoff, water temperature and meteorological data to facilitate the generation of QUAL2E input files. Due to poor temporal resolution of water quality sampling, mean values for the two main regional hydrological periods - the dry season between May and October and the rainy season between November and April - are used for the QUAL2E simulations. Before seasonal averaging, threshold algorithms are applied to filter unrealistic values of water quality parameters caused by errors of digitizing or laboratorial analysis. In the current integration, global climatology variables such as average temperatures, wind speed, etc., needed as QUAL2E inputs, must still be entered manually.

Figure 8 - Data flow of alphanumeric data in the Information System for water quality simulations with QUAL2E (table names translated). In the scheme of database components (SIBAC, SIBAC_AV), only tables with relevance for the QUAL2E integration are represented.

For validation purposes, the model was applied in a Cuiabá River reach with a total length of 26 km, passing the urban perimeter of Cuiabá and Varzea Grande. Data input included water quality parameters and runoff of thirteen effluents, monitored during the dry seasons of the years 1999 and 2000, the period with the most consistent monitoring data. Figure 9 compares the model outputs for a Dissolved Oxygen (DO) simulation between the monitoring points Rc5, upstream from the urban agglomeration, and Rc12, downstream from the urban perimeter. Figure 10 shows the simulation result generated and visualized dynamically in the programmed ArcView GUI.

Figure 9 - QUAL2E-simulation of Dissolved Oxygen concentrations along a 26 km Cuiabá River reach (Rc05-Rc12), passing the urban agglomeration of Cuiabá. Average values of the dry seasons for the years 1999 and 2000.

Figure 10 - Layout of an OD simulation in the urban reach of the Cuiabá River, dynamically created from the SIBAC-QUAL2E GIS-integration.

Model run predicts a DO decrease from 7.5 at Rc5 to 7.0 mg/l at Rc12. The overall RMS error under 15% indicates a good applicability of the model for DO predictions, one of the most important indicators for organic pollution. With exception of sampling point Rc09, simulations slightly overestimate observed average values. Temporary increase of DO concentrations at point Rc09 may be explained by the surging of rock cascades in the streambed during the low water season. Since QUAL2E was developed for steady flow conditions, these alterations are not reflected in the simulation.

DISCUSSION

Validation of the Information System

The most crucial point for initiating systematic watershed analysis was found to be the lack of a consistent DBS to centralize and process environmental data and information on water users. Initial concerns about data consistency, particularly with respect to water quality data, which are being collected by different institutions, could be partially dispelled by Lima (2001), who showed in a homogeneity analysis that measurements of most origins can be joined. Runoff data must pass a critical evaluation process, as discrepancies between measurements performed by different institutions at identical stations were noted. Incoherence is believed to originate from the use of different rating curves to transform water levels in runoff. Inclusion of analogous environmental license processes in the LICA database component is ongoing. Distribution of the APLICA software to water users, initiated in 2004, is expected to accelerate data acquisition significantly. Poor data consistency of older licensing procedures will hopefully be improved by the utilization of the APLICA DB application, which only permits the generation of files to be delivered to SEMA if all obligatory fields are completed.

Age, quality and accuracy of available spatial data sets are ambiguous: Mato Grosso state has been thematically mapped in a 1:250.000 scale (SEPLAN, 2006), including an actualization of main infra-structure networks. The 1:100.000 topographic maps used for DEM generation - some of them with 40m equidistance, others with 50m equidistance - were elaborated at the end of the 1960s. As shown by Zeilhofer (2001) for a study area in the Cuiabá region, derived DEM have accuracies slightly below the standard US 1:250.000 DEMs, and are therefore appropriate for delimitation and physiographic parameterization of sub-basins in the watershed scale (Wang & Yin, 1997). Overlay of 1:100.000 and 1:250.000 scales showed spatial discrepancies of river networks of up to two kilometers. Future combined use of both scales, for applications such as distributed simulation of non-point source pollution (Libos *et al.*, 2003), will demand extensive manual corrections of each map sheet.

The two developed database components are working independently, attending both scientific objectives and administrative needs for the monitoring of water quality and related environmental parameters, as well as for control of water users. A common export tool permits the simulta-

neous extraction and normalization of time series, cadastral data and table creation for automated update of point data representing monitoring stations, effluents etc., in the GIS environment. Implemented regression tools for the fulfilling of data gaps were found to be fundamental, particularly for the generation of consistent time series of precipitation data for input into the NGFlow runoff model. The number of usable precipitation stations for spatial interpolation in and around the upper and mid Cuiabá watershed (about 30,000 square kilometers and eight years of monthly data) could be more than doubled from 15 to 32 stations, using a minimum Pearson correlation coefficient of 0.80 between stations as the criteria for filling data gaps through linear regression.

Avenue-programmed visualization tools, which produce standardized output maps and charts, will rarely meet the requirements of detailed analysis in scientific work, which depends on changing visualization procedures and interactive access to different spatial and alphanumeric data sets. On the other hand, operational work at an environmental state agency needs to follow standards in producing objective and comparable products, which should be independent of the system operator at any given time. The tools developed in this study can be understood as a first attempt to demonstrate visualization and analysis capacity of GIS environments in the case of Mato Grosso, which is not well known by the technical staff of the environmental agency. Familiarization with the offered tools will hopefully enrich communication between the GIS user and developer, creating new demands that are in accordance with the particular needs of the agency (Argent & Grayson, 2001).

Model integration

In presented NGFlow integration, a complete surface water runoff modeling can be conducted in an ArcView 3.x (ESRI) environment, needing as minimum data input a DEM and precipitation stations with associated time series. Observed time series of runoff for optimization, as well as location and alphanumeric data of dam reservoirs, can be added through the GIS Interface. Un-calibrated simulations with a six-year monthly time series resulted in slight underestimates of dry season runoff and overestimates in the rainy season. The most critical parameter for model adjustment was found to be the estimates of surplus fraction of overland runoff and which passes underground reservoir.

In the QUAL2E GIS-integration, some spatial data pre-processing must still be done manually, using the common editing tools of ArcView (ESRI). The new Avenue scripts, however, establish river network connectivity and hydraulic characteristics. Sampling points of domestic and industrial effluents, withdrawals and water quality monitoring points are dynamically associated to the river reaches. The Avenue pre-processor script available from the BASINS watershed information system revealed limitations for an operational application. New programming code was added, which now permits the automated definition of initial conditions for a simulation. During execution, this code screens the water quality tables of river monitoring points, identifying appropriate measurements (location, year, period) for its attribution to the first river reach in a chosen subset of the network. It was also noted that the *qualtran* C-subroutine distributed with BASINS, which is called for the creation of the input text file for a QUAL2E run, can create erroneous withdrawal inputs. At river reaches, where various effluents and withdrawals coincide spatially in a unique segment, the withdrawals are either omitted or the sequence of withdrawals and effluents is changed in the complete river reach. Now, after the generation of the input QUAL2E files, a new section in the Avenue integration script accesses the locations of withdrawals and adds them to the input file. If a withdrawal coincides with a computational element already identified as an effluent, the script redistributes the withdrawal to the nearest free computational element (standard), modifying the effluent sequence in the respective cards of the QUAL2E run file.

The presented water quality simulations established for river reaches passing the urban agglomeration of Cuiabá produced some promising results regarding the applicability of QUAL2E in the Cuiabá River basin. Forthcoming model calibration and validation is believed to be viable, as the watershed has a regularly operated network of water quality monitoring (16 stations). Lack of data availability on point sources, however, was identified to be the main problem for an operational use of QUAL2E. Only the major industries are obligated to regularly control and report produced effluents. The wastewater treatment plants treat less than 30% of domestic wastewater produced in the Cuiabá/Varzea Grande agglomeration, and none of them monitors effluents. Most cities in Mato Grosso state do not even have plants for domestic wastewater treatment. For operational watershed monitoring at SEMA, QUAL2E input data of non-systematically sampled water quality of industrial effluents should therefore

be substituted by projected effluents available through environmental licensing. Both the quality and the quantity of domestic waste water should be estimated according to such indicators as number of domiciles, population density etc. (Davis & Cornwell, 1998), corrected by the rates of wastewater treatment. For future application in regions where agricultural use predominates, the PLOAD module of the BASINS watershed analysis tool (US Environmental Protection Agency, 2001) is being integrated in the information system, with additional modules guaranteeing the automated migration of simulation results to the QUAL2E input file.

The original integration script of QUAL2E was improved and adapted to the SIBAC database system. Interaction with databases, however, should permit an automated data input of global climatic variables in the future. In its current form, setup and formatting of spatial data sets has to be done manually in the GIS environment, a task which is supposed to be difficult to be done by technicians at SEMA. Recent developments focus, therefore, on a coupling of the NGFlow runoff model with the QUAL2E integration. Network topology and attribute tables generated by the NGFlow pre-processors should be directly used for representation of river connectivity and physiographic parameterization as demanded by QUAL2E; results of runoff simulations should be formatted so as to be automatically migrated as input to QUAL2E runs.

Lessons learned during project development

During project development we dealt with irregular funding due to political and/or administrative changes in the responsible agencies, which is, we suppose, typical for countries in development. This situation makes a straightforward implementation of Information Systems difficult, complicating the correct execution of recommended steps of GIS development as formulated by Pantazis & Donnay (1996). In general, developers should count on an extended awareness phase, as stakeholders in higher administrative levels do not always recognize the need for an IS for water resource management. In our case, increased paperwork coupled with higher demands of national and international funding institutions concerning data management concepts helped to facilitate the acceptance of introducing computation techniques. We agree in principal with the paradigm about the importance of user involvement in GIS development as stressed by various authors (Argent & Grayson, 2001). It was our experience, however, that it is not always

possible or useful to expose all technical details of the IS during the implementation phase. Special attention should instead be given to the development of an illustrative pilot project, capable of exposing IS capabilities to subsidy problem solving in daily routine, instead of theoretical explanations of the importance and applicability of GIS tools for watershed management.

In 1999, at the beginning of project development, the choice of commercial software for GIS development was believed to be the most viable approach: new database modules could be developed more quickly and adapted to continuous modifications in administrative procedures which have to be carried out. In addition, user involvement in technical issues of system development is increased if common applications are utilized. Previous work of public domain for the development of watershed monitoring systems in the ArcView GIS environment (US Environmental Protection Agency, 2001; Ye *et al.*, 1996) has facilitated and accelerated implementation of the IS. We also claim that a strict modular development of watershed management tools should be followed in less-developed regions, mainly for two reasons. First, should development be interrupted due to financial problems or administrative re-orientation, concluded components can be reused / reactivated at a later time. Second, we believe that periodically presenting working solutions, even partial ones, is important to guaranteeing acceptance throughout an ongoing development process.

CONCLUSIONS

This paper reports on the experiences acquired during a five year period of conceiving and implementing a GIS-based Information System for watershed monitoring, including visualization and modeling tools, adapted to specific demands and data availability in Mato Grosso state. Interfaces of developed database applications for storage and retrieval of environmental (SIBAC) and water resource users (LICA-APLICA) are already in use, but should be migrated to architectures which support Internet-embedding. The implemented precipitation-runoff model (NGFlow) was found to adequately simulate monthly discharges in the test area, considering low data density and quality. More efficient water quality simulations with the GIS-integrated QUAL2e model will depend on the consolidation of information on effluents and withdrawals (model inputs) and on monitoring programs to improve model calibration. Applied commercial

GIS-development tools (ArcView-Avenue), which could be considered state-of-the-art technologies at the beginning of the project, were recently reengineered (ArcGIS 9.x -Visual Basic) and were completed with modules for the programming of Web-Applications (ArcGIS IMS, ArcGIS Server). The growing availability of free GIS-clients such as TerraView (INPE, 2007), and WEB-GIS development tools such as MapServer (University of Minnesota, 2008) and Geotools (Geotools Project, 2008), make them low-cost alternatives, particularly if completely new development initiatives are initiated.

We believe that architecture of GIS for watershed monitoring in a developing country should be strictly component based, to overcome phases of interrupted funding and re-organization in governmental agencies. In the selection of hydrologic modeling approaches for GIS integration, special attention should be given to model robustness for sparse, low quality input data. Operational applicability of hydrologic models such as QUAL2E, while considered a simple conception, has shown limitations due to restricted availability of input data. As instruction levels of technical staff in governmental agencies is frequently inferior than in first world countries, the presentation of a pilot project capable of demonstrating applicability of the IS to practical problem solving is essential. The successive presentation of working IS modules and improved user friendliness is crucial to guaranteeing acceptance throughout system development.

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