

Catchment hydrology management using GIS: case study of the Modder River Basin, South Africa

E. Pretorius, O. J. Gericke, S. W. Slabbert & M. Dent
*School of Civil Engineering and Built Environment,
Central University of Technology, South Africa*

Abstract

Water is constantly flowing through the landscape in response to weather events and most often, in the form of streams and rivers. This water flow carries micro-organisms, dissolved chemicals and sediment, which define water quality. We need to understand these flow- and quality-patterns and how they change in order to properly manage the water resources of river basins. Hydrological analysis and modelling of water flow and quality are provided by hydrological simulation models, whilst GIS describes the physical environment through which the water flows. Integrating hydrological modelling and GIS involves connecting geospatial data, which describe the physical environment, with hydrological process models, which explains how water moves through the environment. Even though there is a significant synergy between geospatial and temporal water resources information, it is difficult to capture because, up to now, the data (geospatial and temporal) have been held in different formats and archiving environments. One of the aims of this project was therefore to create a geodatabase (GBase) where geospatial and temporal data are captured and stored in one environment. Another aim was to achieve communication and data exchange between GBase, HYDSTRA, a hydrological database and BASINS, an environmental analysis system. The overall purpose, however, was to create an integrated platform, including the above programmes, to provide tools to pre-process data for different independent models, which can then be used to investigate the impact of changes or developments in the river basin. The Modder River Basin, which forms part of the Upper Orange Water Management Area in South Africa, was used as study area.

Keywords: river basin management, information systems, geodatabase, hydrological modelling, GIS.



1 Introduction

Twenty-five years ago, in South Africa, most of the water resources science and management knowledge resided in state departments. Such a knowledge power setting was adequate to cope with the *get more water* and the *use water more efficiently* eras.

Today a significant intellect resides with stakeholder groupings that are in contention for water resources. This shift in the balance of knowledge power, and the enormous changes in the external business forces operating in the water industry and organisational structures governing water, as well as the National Water Law (NWA) [6] led to the establishment of Catchment Management Agencies (CMAs). The objective of this establishment is that the CMAs are to share the responsibility for managing water resources with the state. The exact nature of representation on CMAs as well as their structure, functions and responsibilities are currently being finalised, and are sure signs of the transformation process in South Africa [2].

CMAs already had significant impact on the manner in which water is managed and its influence are reflected in the NWA, 1998, where interdependent problems are no longer simplified to a uni-disciplinary dimension by bounding them in the terms of reference for the job, but are addressed through integrating water science, engineering products and services appropriate to national needs. Thus, the core of integration is to understand and manage the dynamics of all these interdependencies [5, 7], and this can be accomplished through Integrated Water Resources Management (IWRM).

However, the subject of IWRM is so broad and complex that hydrologists and engineers are unanimous in their opinion that no single simulation model can be used for Integrated Catchment Management (ICM), to the exclusion of others. IWRM demands that we take our thinking a step further since each CMA will have a plethora of conditions/aspects which are required to be managed simultaneously and in an integrated fashion. Part of our present predicament is due to the fact that in the past we have attempted to manage only that aspect of the water resource, which happened to be the issue at the time. Hence in the past it was easier to disintegrate the problem and work independently on the problematic condition [2, 4].

As discussed above, the NWA, 1998 demands that this limited and often damaging paradigm must change. The new Water Law places a demand for an integrated team to work on the full range of aspects/problems simultaneously and in an integrated fashion [6].

A vital component in the search for a modelling system for ICM, therefore must be that the system can facilitate inter-operability between time dependent data and the information produced by the different teams. In other words an overall operating system or nested sequence of systems must be created, which will enable reasonably flexible linking of the components of individual models in terms of the processes being modelled.

Through the United States Environmental Protection Agency's (USEPA) Better Assessment Science Integrating Point and Non-point Sources (BASINS)



development [1, 9], the water modelling world is starting to display signs of creating its own equivalent of the open source revolution. According to Maidment (2000) BASINS is the most advanced system presently available for linking Geographical Information Systems (GIS), water quality and -quantity modelling and data for the purposes of ICM.

The set-up costs of installed systems are naturally higher than those for models, which only deal with one aspect at a time. However, experience in the USA, Europe, Australia, South Africa and elsewhere has shown that these costs are recovered through reduced transaction costs over the life of the installed system. It is this cost structure, which inter alia is driving the development of BASINS [3].

Advances in GIS technology have now made it practical to consider far more spatial detail than has hitherto been the case. The market is demanding finer and finer spatial resolution. However, the allied need to link the outputs from the smaller spatial units means that there is also a demand for finer time scales to be employed. The latter demand brings new challenges to model developers and users [11].

Thus, taking all above-mentioned factors into consideration, it becomes evident that the conventional approach of river basin management as illustrated in Figure 1, must be revised in order to address the far more complex yet necessary job of managing the myriad networks of time series which are generated by the fine spatial scale application of our models. This can be accomplished by integrating ArcGIS, HYDSTRA and BASINS as our main platform to work from (Figure 2).

If we wish to succeed with integrated systems we cannot avoid addressing time series challenges such as time dependent estimates of water quantity and quality which connects the various interests of the stakeholders in the catchment, externality conflicts, the developed basin conditions and the actions by contenders for the water resource. Addressing spatial and temporal scales means mastering time series management within our modelling systems.

2 Integrated framework

To address the problem mentioned above one of the first aims of this project was to create a geodatabase (GBase), which operates within ArcGIS and stores captured geospatial and temporal data. Secondly it was important to achieve communication and data exchange between GBase, HYDSTRA, a hydrological database and BASINS, an environmental analysis system to, thirdly, create an integrated platform (Figure 2), in order to provide tools to pre-process data for different independent models. These models can then be used to investigate the impact of changes or developments in the river basin.

ArcGIS is a combination of multiple integrated GIS software products which was developed for building a complete GIS. ArcGIS, released in 2001, is a synthesis of the powerful Arc/Info system with the easy-to-use interface of ArcView, updated to use the latest advances in desktop computing and database technology. The geodatabase model arrived with the release of ArcGIS 8. It



contains three basic programs, ArcMap™, ArcCatalog™, ArcToolbox™, collectively referred to as ArcGIS Desktop. ArcCatalog with the ArcSDE interface was the main program used to create the GBase.

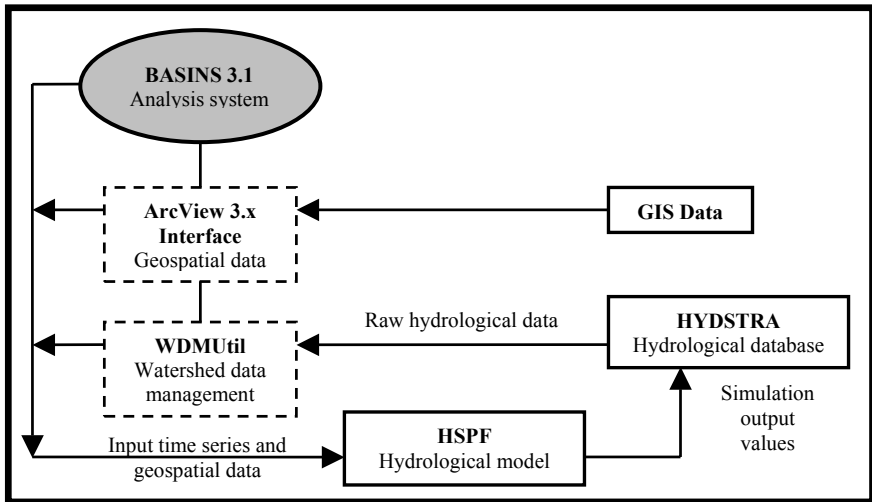


Figure 1: Conventional workflow for river basin management.

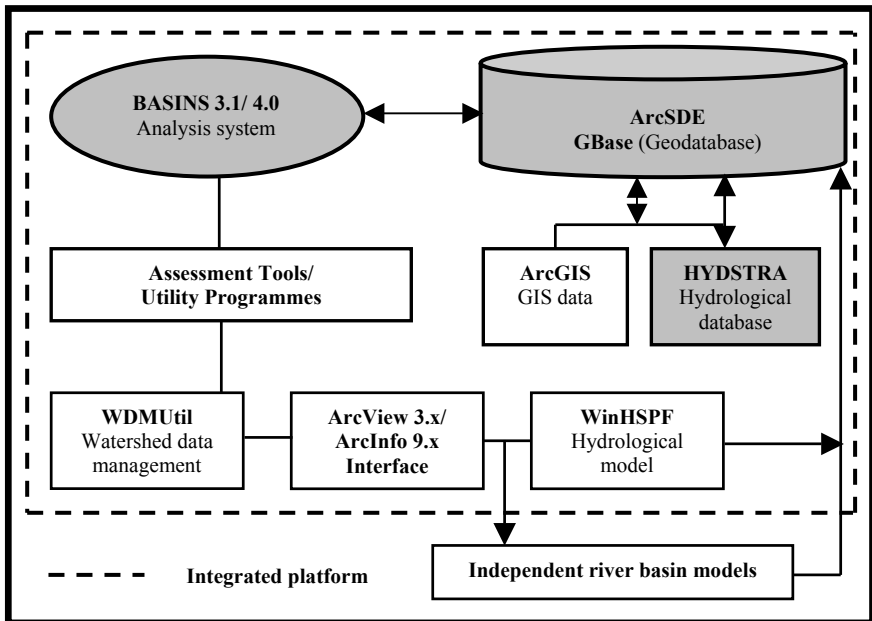


Figure 2: Integrated workflow for river basin management.

The GBase is a geospatial and temporal data model, which was created to store both, normal text information as well as geographical information of the Modder River Basin (see section 3: Study area). HYDSTRA is a database used by the Department of Water Affairs and Forestry (DWAF) and stores all raw hydrological data (flow, precipitation, evaporation etc.) for South African river basins. An automatic link between the GBase and HYDSTRA ensures that the data in the GBase applicable on the Modder River Basin are updated on a three monthly basis. Data are extracted from the GBase and imported into BASINS. The BASINS programme contains tools and utility programmes for data synthesis and assessment, as well as for preparing input data for different simulation models. BASINS makes it possible to quickly assess large amounts of data in a format that is easy to use and understand. BASINS also allows the user to assess data at selected locations (gauging stations) or throughout an entire river basin. As BASINS is a multipurpose environmental analysis system it is designed for use by regional, state, and local agencies in performing river basin and water quality-based studies. BASINS therefore integrates environmental data, analytical tools, and modelling programmes to support development of cost-effective approaches to river basin management and environmental protection.

3 Study area

The Modder River Basin (Figure 3) is located in the southwestern part of the Free State Province, South Africa, which forms part of the Upper Orange Water Management Area (WMA). The Upper Orange WMA extends further also over parts of the Eastern- and Northern Cape provinces.

The Modder River originates in the vicinity of the town, Dewetsdorp and then flows in a northerly direction after which it turns to the west. After about 340 km the river flows into the Riet River that ends in the Oranje-Vaal River drainage system. The Modder River was traditionally, like most inland rivers in South Africa, a seasonal river but due to the construction of three significant dams e.g. Rustfontein-, Mockes- and Krugersdrift Dam the river now resembles a permanent river. However, the dams' levels can fall to 30% full in the dry season and the water in the lower reaches is basically stagnant in winter.

The natural mean annual runoff (MAR) and ecological reserve (ER) of the Modder River Basin forms 5.8% and 3.3% of the total MAR and ER in the Upper Orange WMA respectively. The available water yield of the Modder River Basin was 3.1% of the total water yield of the Upper Orange WMA in the year 2000. The water requirement, in comparison, was a high of 36.2% of the total water requirement of the Upper Orange WMA in that year. Predictions for the year 2025 indicate that there will be an increase in the water requirements of between 14.4 and 24.2%, depending on whether a base- or high case scenario is being evaluated [8]. The relatively high percentage of water requirement compared to the low percentage of available water yield re-emphasizes the importance of ICM within the Modder River Basin, as well as the relevance of our study.



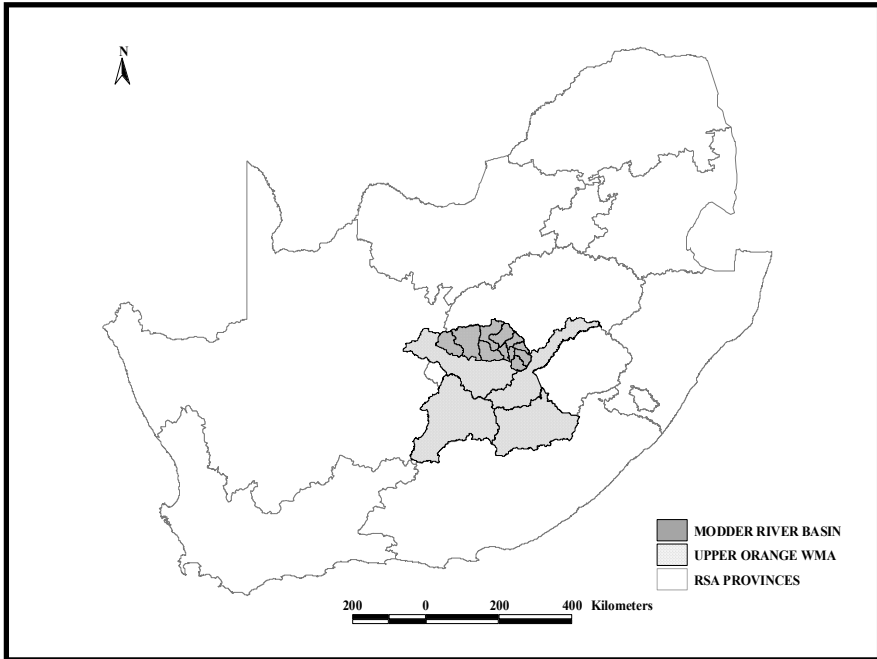


Figure 3: Modder River Basin.

The climate of central South Africa is moderate to hot in summer with an average minimum temperature of 12°C and an average maximum of 30°C. In winter the average minimum is 3°C with an average of 18°C as a maximum. This area falls in a summer rainfall region and precipitation ranges from about 300 mm in the west to about 550 mm in the east. The rainy season is from early September to mid April with a dry winter.

The study area is located at an average height of 1200 m above mean sea level (MSL) with the highest point at ± 2100 m and the lowest at 1100 m. Although there is a 1000 m-height difference between the highest point and the lowest point, 99% of the catchment lies between 1200 m and 1400 m above MSL. The catchment is characterised by very shallow slopes and water tends to pool easily, thus influencing the attenuation period of floods and high flow conditions.

Vegetation is mainly grassland. Extensive sheep and cattle farming are characteristic in some parts of the catchment. Some dry land cultivation occurs where the precipitation and soils are favourable, with sizeable areas under irrigation below the main storage dams. The area is geologically very stable and relatively uniform although the geology does dictate the flow to a certain extent.

The city of Bloemfontein, as an administrative and commercial centre, is the only large urban development in the Modder River Basin. Demographic projections show a small decline in rural population, which is balanced by growth in the Bloemfontein area, resulting in little change in the total population of the basin within the period of projection. There are also no strong stimulants for economic growth in the basin [8].

4 Results

The main result which had to be obtained was the creation of the integrated platform, which consists of the GBase, HYDSTRA and BASINS (Figure 2). As indicated in section 2, ArcGIS Desktop consists of ArcView, ArcEditor, ArcInfo and each version of ArcDesktop includes the same applications - ArcMap™, ArcCatalog™, ArcToolbox™. ArcCatalog with the ArcSDE interface was the main program used to build the GBase. This ArcGIS Desktop application is similar to the Windows explorer but enables a preview of geographic data and metadata. Besides the spatial data, which is stored locally, ArcCatalog is capable of displaying and managing the content of connected databases, e.g. an Oracle9i database. The connection was established through the ArcSDE interface. All the information banks that were necessary for the GBase was created out of ArcCatalog, for instance feature classes, tables, relationship classes etc. Existing shape files from the hard drive or from other geodatabases were also imported. Editing of content was done by ArcMap.

Other programmes used in the study include ArcView 3.2a® along with Spatial Analyst and BASINS 3.1 extensions. Digital data were obtained from Mowbray, Cape Town, South Africa in the form of a set of contour maps of the study area. These polylines were converted in Arcview 3.2a to points with the extension Poly conversions to spaced points 1.2 with a point every 50 m. The data were checked and all errors were removed. Kriging, as an interpolation method with quaternary drift was used for the construction of a Digital Elevation Model (DEM) at 50 m-grid size (Interpolation is when the software uses a number of adjacent points to estimate what the surface between the points will look like.) After the creation of the grid the Fill Sink tool was run on the grid in order to eliminate the sinks that develop between two far removed points.

After the creation of the DEM grid (Figure 4) it was converted to a United States Geological Survey (USGS) DEM GRID and added into a BASINS project with a predefined projection. In BASINS the digitised river line was added and the automatic delineation process started. This entails the adding of the DEM into the calculation and setting up its parameters (meters or degrees) where after the river will be defined. For this project it was decided to use the digitised river (the program uses the DEM to burn a stream from surface characteristics) due to the unique characteristics of the Modder River.

The river line and the DEM were used to derive the river basin areas and the slope. The number of cells was defined to justify a runoff line. The stream outlets were then identified (at the confluence of two streams) and selected to calculate the sub-basins. The parameters, which influence land cover in terms of vegetation cover (evapotranspiration, water interception), ground cover (type of soil, rock sheet etc.) and soil characteristics (infiltration, soil type) were then fed into BASINS. All these output parameters were then exported to a Watershed Data Management (WDM) file in WDMUtil. Once this platform had been created a link between BASINS and different simulation models were established (Figure 2). The objective is that the platform must be able to link to any independent river basin model. However, the model, which is used in this



project, is WinHSPF, as it is developed for EPA by AQUA TERRA consultants and distributed with the EPA's BASINS software.

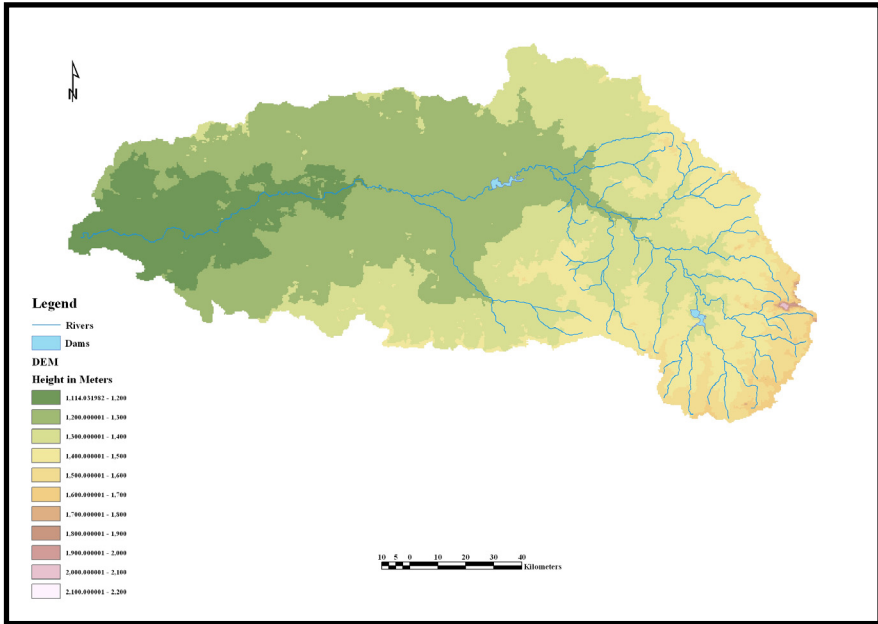


Figure 4: Digital Elevation Model of Modder River Basin.

5 Discussion and conclusion

Currently some of the input data and parameters for the user input file (.uci) must be developed manually since this process is not automated in BASINS 3.1 for South African data sets. This cumbersome process will be addressed in the new version of BASINS 4.0, which is at present being developed by consultants at AQUA TERRA. One of the most significant enhancements in BASINS 4.0 will be support for ArcGIS 8. A custom GIS interface for BASINS will be available in ArcGIS through a toolbar in ArcMap. The BASINS Toolbar will contain menus for accessing the suite of BASINS GIS functions. The software underlying each menu option in the BASINS toolbar will be packaged as a separate DLL, providing flexibility in the structure of the toolbar, as well as expandability as other tools or models are added in the future. Each menu option will invoke a tool developed in Visual Basic, using ESRI's ArcObjects for GIS functions. All of the tools and models will share a common component for interacting with ArcObjects. This design enforces a clear separation between tool components and GIS functions. The HSPF tool, known as 'BASINS HSPF for ArcGIS', is the first of the menu options to be implemented (Figure 5). The user interface for this tool was developed using Visual Basic, making use of a number

of Visual Basic custom controls and utilities developed for other BASINS tools. Through this interface the user specifies the GIS layers and fields within those layers to be used in setting up a new HSPF project.

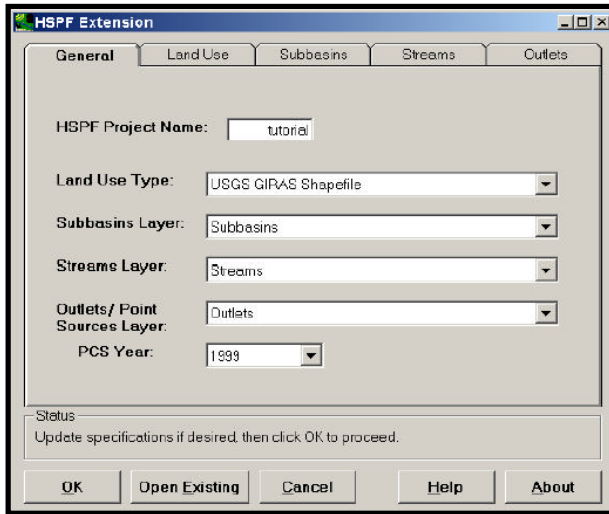


Figure 5: BASINS HSPF for ArcGIS.

As soon as BASINS 4.0 is available, it will be incorporated into the platform in order to enhance the workability/practicality thereof (Figure 2). It will furthermore improve the communication and data exchange between the platform and the independent models. Finally we hope that it will contribute to the open source revolution (section 1; par 7) and will open up new opportunities for more effective analysis of river basin management.

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