Interfacing GIS and hydrological modelling : Mgeni case study[+]

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Abstract

Although geographical information systems (GISs) enhance hydrologists' ability to access and extract relevant spatial information quickly and efficiently, interfacing GISs and hydrological modelling are essential for meaningful hydrological simulation that transforms geographical information into hydrological knowledge. In this paper the Mgeni catchment is used as a case study to illustrate interfacing between a GIS and a hydrological modelling system for simulation of the catchment's water resources.

Creation of the GIS interfacing processes and an example of a hydrological simulation are presented. A possible future development scenario illustrates the routing of GIS derived spatial information through the interface to obtain a realistic hydrological response from the modelling system. Future requirements for interfacing between GIS and hydrological modelling are discussed.

Introduction

Geographical information has been used in hydrological modelling for many years but recent developments in the capabilities and speed of computer hardware together with appropriate software applications have greatly facilitated the manipulation, processing and display of spatial information using geographical information systems (GISs). While many institutions, universities and state departments in South Africa are collecting data and creating GISs (Conley, 1989), it is not always clear for what purpose and how this information will be used. GISs are very adequate for the transformation of data into information, but it is the transformation of information into knowledge that requires greater attention. Hydrological modelling, which makes use of geographical information, including catchment physiography and climatic data, can be greatly enhanced when coupled to a GIS because of the associated ease of data access and extraction and increased speed and efficiency of data manipulation. The accuracy of hydrological simulation, however, remains limited by the quality of input variables. Consequently the usefulness of a GIS for hydrological modelling is dependent on the accuracy of the original data contained in the GIS and the hydrological variables generated at the GIS/hydrological model interface. In this paper the interfacing between a GIS and a hydrological modelling system for the simulation of the Mgeni catchment's water resources is used to illustrate the progress made towards filling the gap between geographical information and hydrological knowledge.

Simulation of the water resources of the 4 387 km^2 Mgeni catchment is necessary because water from the catchment is presently supplied to 3,6 m people and industry and agriculture producing 20 % of South Africa's Gross National Product. It has been predicted that the population in the area presently supplied could increase to between 9 and 12 m by the year 2025 (Horne Glasson Partners, 1989) and that the water resources of the Mgeni catchment will be utilised fully by the year 2005. Concomitant with complete utilisation of the Mgeni's water production, is the envisaged decrease in water quality associated with poor quality return flows from industrial and agricultural wastes, treated sewage effluents and increased informal settlements. Hydrological simulation of water quantity and quality in the Mgeni catchment will enhance the ability of decision-makers to manage effectively the water resources of the Mgeni catchment.

The ACRU agrohydrological modelling system (Schulze, 1989) was chosen to simulate the water resources of the Mgeni catchment and evaluate consequences of possible future development on the catchment's water resources. Geographical information for the entire Mgeni catchment was collected and stored in a GIS. The highly variable physiography and climate of the region necessitated the subdivision of the catchment into 123 subcatchments for hydrological simulation. Since input variables based on the physical features and climate of each subcatchment were required by the ACRU modelling system, the interfacing of the Mgeni catchment GIS with ACRU to generate meaningful inputs from the spatial data formed an important part of the modelling process.

This paper describes the composition of the Mgeni catchment GIS and the processes used to interface the GIS with the ACRU modelling system. Transformation of spatial information into hydrological input variables is illustrated for a selected subcatchment of the Mgeni. A possible future development scenario applied to an area of the Mgeni catchment is used to show how a change in the geographical information is routed through the interface to be realized in a realistic hydrological response from the modelling system. Future requirements for interfacing between GISs and hydrological modelling are outlined with particular reference to the need for simulating water quality aspects of the Mgeni catchment.

Mgeni catchment GIS

Details of the geographical information contained in each layer or coverage for the Mgeni catchment GIS and the sources from which this information was obtained are shown in Table 1. Two commercially available GIS packages in addition to "in-house" software were used to capture, process and store the geographical information. The catchment physiographic information is embodied in the altitude, soils, land-cover, reservoir and river coverages, while the climatic information is contained in the rainfall, temperature and evaporation layers. A distinct

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TABLE 1
COVERAGES OF GEOGRAPHICL INFORMATION COLLECTED FOR THE MGENI CATCHMENT

Coverage	Geographic information	Information sources	References
Altitude grid	Gridded altitudes at 250 x 250 m interval	Chief Directorate Surveys and Mapping, Private Bag, Mowbray	
Point rainfall	Location of 186 daily rainfall stations in and around catchment	CCWR rainfall data base	Dent et al., 1987
Rainfall grid	Gridded median monthly totals of daily rainfall at 1' x 1' of a degree interval	CCWR rainfall data base Natal Univ., Dept. Agric. Engineering database	Dent et al., 1987
Point temperature	Location of stations with measurements of maximum and minimum daily temperature	CCWR temperature data base	
Temperature grid	Gridded means of daily maximum and minimum temperatures for each month at 1' x 1' of a degree interval	Univ. Natal, Dept. Agric. Engineering data base	Schulze and Maharaj, 1991
Evaporation grid	Gridded A-pan equivalent daily potential evaporation for each month at 1' x 1' of a degree interval	CCWR temperature data base	Schulze and Maharaj, 1991
Rivers	Digitised river courses for Mgeni and main tributaries	1:250 000 topographic map (1980)	
Weirs	Point measurements of quantity (gauging weirs) and quality (grab or continuous samples)	Department of Water Affairs data base	
Soils	Digitised land types	SIRI 1:50 000 field maps SIRI Land Type memoirs data base	Smith-Baillie, 1991
Land cover	27 land-cover classes	SPOT satellite images (FCC) (1987) Supplementary aerial photography 1:50 000 topographic maps (1973-1982) 1:10 000 orthophotos (1973-1982)	Bromley, 1989
Reservoirs	Location, surface area, capacity and critical dimensions	LANDSAT multispectral images (1987) 1:50 000 topographic maps (1973-1982) 1:10 000 orthophotos (1973-1982) Field verification	Howman, 1991 Tarboton, 1990
Subcatchments	Subcatchment delimitation according to physiographic boundaries	1:50 000 topographic maps Quaternary subcatchment boundaries	Pitman et al., 1981

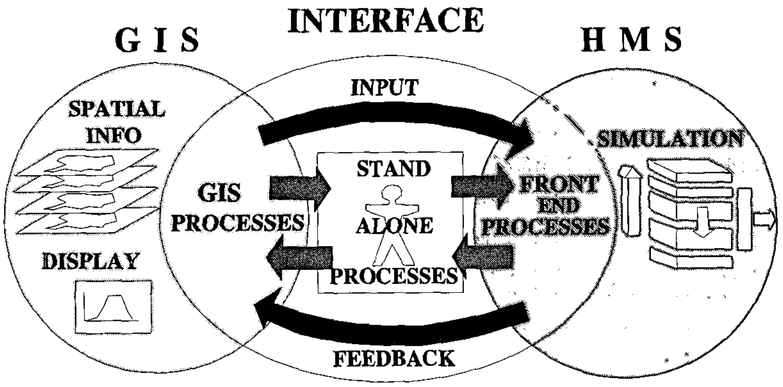

Figure 1
GIS - Hydrological modelling system (HMS) interface concept

advantage of having information stored in layers is that when interfacing a GIS with a hydrological modelling system the information from each layer can be accessed individually or combined selectively with information from other layers to provide meaningful input to the hydrological modelling system. For distributed hydrological modelling one needs to extract physiographic and climatic information from the GIS for each distributed subcatchment element, hence subcatchment delimitation and the creation of the subcatchment coverage is important, since this coverage interacts with all the other layers in the GIS. Ideally, subcatchment delimitation should have been carried out by overlaying all physiographic and climatic coverages, to obtain hydrologically homogeneous subcatchments. Because rainfall is the predominant force driving hydrological models and the rainfall gauging network in the Mgeni catchment is relatively sparse, it would have been futile to disaggregate the catchment into subcatchments at a finer scale than that at which daily rainfall could be estimated accurately. The use of interpolation methods to generate spatial rainfall surfaces was investigated by Tarboton (1991) but found to be unacceptable for the Mgeni catchment. Consequently subcatchments were delimited according to physiographic boundaries with consideration of altitude and land-cover. Subcatchment delimitation was at a considerably finer scale than the "quaternary" subcatchments described by Pitman, et al. (1981) but definition and enumeration of subcatchments was such that they can be easily combined in the GIS to form the quaternary subcatchments.

Information extracted from the Mgeni GIS through combination of the subcatchment coverage with the physiographic and climatic layers was not in a form that could be used directly in the ACRU hydrological modelling system. Consequently interfacing between the GIS and the hydrological modelling system was required.

GIS - Hydrological model interface

Interfacing between two different systems is the means by which the systems can communicate and interact. Essentially the GIS - hydrological modelling system (HMS) interface conceptualised in Fig. 1 consists of the derivation of meaningful hydrological input variables for the HMS from the geographical information and the feedback of hydrological output to the GIS for display purposes. Interfacing processes can take place either within the GIS package or as stand-alone interfacing programs or as front-end processing which forms part of the HMS. One or more or different combinations of these interfacing processes may be used to derive particular input variables or to display output. When the interfacing processes are not completely automated, the human element forms part of the interfacing process and output from one process may be input manually to another process. In the case study for the Mgeni catchment, the interfacing process was not fully automated and output files from the GIS process, already in the correct format, were edited into the ACRU *Menubuilder* (Schulze, et al., 1989) which served as the front end for the HMS. This was primarily because the interfacing processes were still undergoing development. It is envisaged that manual interfacing processes would be minimised in future. Processes to interface the GIS containing the Mgeni catchment coverages (Table 1) and the ACRU modelling system are described in greater detail to illustrate interfacing between a GIS and a HMS.

GIS processing

GIS processing included combining the Mgeni subcatchment coverage with the altitude, temperature and evaporation coverages using an area weighted averaging technique. Representative altitudes, average monthly means of daily maximum and minimum temperatures, average monthly means of daily A-pan equivalent potential evaporation and location of the centroid were determined for each of the 123 subcatchments. Variables obtained in this manner were input into the ACRU *Menubuilder* for front-end processing before they were used in simulation by the ACRU HMS. Reservoir coverage information contained in the GIS included the location, surface area, capacity, wall length, wall height, shape and valley slope for each reservoir (Tarboton, 1990). GIS processing involved the calculation of combined total surface areas and capacities for all the reservoirs in each subcatchment. The fraction of each subcatchment that contributed direct runoff into the reservoirs was estimated manually and entered into the *Menubuilder* together with the combined reservoir surface areas, capacities and a representative reservoir area/capacity relationship.

GIS processing of spatial soils and land-cover information involved obtaining their relative representation within each subcatchment. Table 2 shows the result of the GIS processing of land-cover information for Subcatchment 12 (Fig. 2). Similar processing of the soils coverage results in the percentage representation of each land type within each subcatchment.

Further processing of the percentage representations of soils and land-cover information to obtain hydrological variables for each subcatchment was performed in the stand-alone and front-end processing sections of the interface.

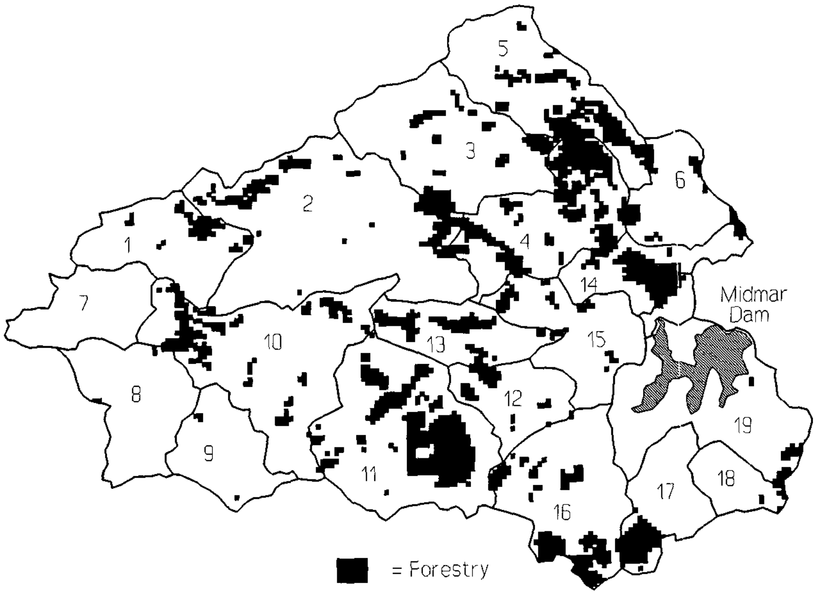

Figure 2
Spatial distribution of forestry upstream of Midmar Dam under present land cover

TABLE 2
LAND COVER FOR SUBCATCHMENT 12

Land cover	% Area
Pines	7,01
Eucalypts	0,42
Indigenous forest	0,29
Grassland	66,73
Mixed forest	1,43
Wattle	1,03
Dams	0,23
Undifferentiated cropping	5,96
Irrigated pastures	4,80
Maize	12,11

TABLE 3
CROP COEFFICIENTS FOR SUBCATCHMENT 12

Month	Crop coefficients	
	Original cover	After afforestation
Jan	0,72	1,05
Feb	0,71	1,05
Mar	0,64	1,05
Apr	0,57	1,05
May	0,40	1,05
Jun	0,33	1,05
Jul	0,33	1,05
Aug	0,33	1,05
Sep	0,40	1,05
Oct	0,52	1,05
Nov	0,60	1,05
Dec	0,70	1 05

Stand-alone processing

Stand-alone processing at the GIS / HMS interface for the Mgeni catchment involved the use of a soils interpretation program, a rainfall estimation program and manual inputs to the *Menubuilder*. Soils information consisting of percentages of each land type for each subcatchment output from GIS processing were input into a stand-alone soils interpretation program described by Angus and Schulze (1990) and refined by Schulze et al. (1991) to obtain average soil horizon depths, hydrological soil water retention constants and redistribution response rates for each subcatchment. Median monthly totals of daily rainfall obtained by GIS processing for each subcatchment, were used with selected driver stations (Tarboton, 1991) and a stand-alone program to generate daily rainfall files for each subcatchment with a format that could be read directly by the ACRU modelling system.

Although the ACRU *Menubuilder* (Schulze et al., 1989) can stand alone it is used as a front-end program to the ACRU modelling system to prepare input information in a format that can be read directly by the modelling system. Further discussion of the *Menubuilder* as a front-end process follows.

Front-end processing

Interfacing at the front end of the hydrological modelling system is carried out predominantly by the ACRU *Menubuilder*, which is a user-friendly interactive program (involving human input) that creates an input data file for the ACRU agrohydrological modelling system (Schulze et al., 1989). The *Menubuilder* contains a HELP facility and performs internal checks for realistic input values, issuing warning or error messages if input beyond a physically acceptable range is keyed in. It contains a decision support system with pre-programmed values for soils and land-cover information.

An example of front-end processing is the conversion of the percentage representation of each land-cover output from the GIS, to vegetation variables that can be used directly in the ACRU HMS. Interfacing the percentage cover obtained from the GIS for Subcatchment 12 displayed in Table 2 to the crop coefficient variables under the heading "original cover" in Table 3 involved entering a land-cover code and the percentage land cover into the *Menubuilder*. Area weighting of pre-defined crop coefficients was carried out in the *Menubuilder* to obtain

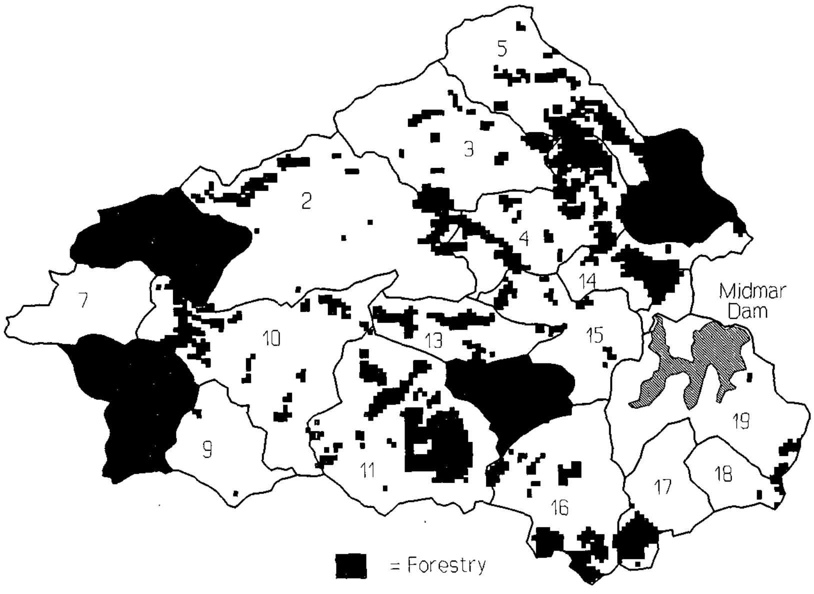

Figure 3
Spatial distribution of forestry for the scenario to double the area under forestry upstream of Midmar Dam

TABLE 4
MEDIAN MONTHLY SIMULATED RUNOFF FOR SUBCATCHMENT 12

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Original cover	18,67	8,15	16,38	5,85	4,75	0,94	1,32	2,03	3,10	2,74	6,80	11,89	124,83
After afforestation	10,10	3,76	7,96	2,03	0,01	0,01	0,01	0,01	0,10	0,30	4,10	9,39	75,28

weighted monthly crop coefficients for each subcatchment. Similarly the leaf area indices, values of rainfall interception by vegetation and proportion of roots in each horizon were calculated automatically by the *Menubuilder*.

Another aspect of front-end processing is the updating of variables that change with time. A dynamic file indicating dates of change and variables that change is read directly by ACRU to account for gradual or sudden physical changes in a subcatchment. Front-end processing can also be considered to include pre-simulation and post-simulation processing within the HMS. In the ACRU modelling system, pre-simulation processing uses harmonic analysis to generate daily values from monthly means for many variables including temperature, evaporation and vegetation variables. Post-simulation processing at the front end of the hydrological modelling system includes writing of hydrological output to selected formats for display with either stand-alone packages or with the GIS.

Afforestation scenario - Interfacing example

To illustrate the value of interfacing a GIS with a HMS the scenario of doubling of the area under forestry upstream of Midmar Dam in the upper reaches of the Mgeni catchment is presented. For details of the inputs, subcatchment layout and results of the application of this scenario the reader is referred to Tarboton and Schulze (1991).

Figure 2 shows the present spatial distribution of forestry in the Mgeni catchment upstream of Midmar Dam. Forestry in the area was subdivided into pines, eucalypts, wattle, indigenous and mixed forest, as indicated for Subcatchment 12 in Table 2. Doubling of the area under forest was achieved by assuming Subcatchments 1, 6, 8 and 12 to be planted to *Eucalyptus grandis*, except for the area covered by reservoirs. This implied that in Subcatchment 12 the area under forest was increased to 99,77% with the remaining 0,23% under dams. Interfacing the GIS spatial representation of the scenario (Fig. 3) to a hydrological simulation in the ACRU HMS and presentation of output involved the following procedures:

- GIS processing produced land-cover representation for each catchment similar to that shown in Table 2 for each subcatchment.
- Front-end processing in the ACRU *Menubuilder* resulted in weighted monthly "after afforestation" crop coefficients (shown in Table 3 for subcatchment 12) and other vegetation variables for each subcatchment.
- Front-end processing in the form of harmonic analysis was used to disaggregate the monthly vegetation variables into daily values for use in ACRU.
- Post-simulation processing produced the requested output, from which the median monthly simulated runoff for both the original cover and the afforestation scenario for Subcatchment 12 has been extracted and is displayed in Table 4.
- The output shown in Table 4 was fed back to a stand-alone package for display as illustrated in Fig. 4.

A dynamic file could have been used to apply the afforestation gradually or to deforest the area rapidly and return to simulation using the vegetation variable values for the original cover. Output could alternatively have been fed back to the GIS for display.

Interfacing of a GIS to the ACRU modelling system can assist water resource managers to make effective decisions based on results and display of output. The transformation of a spatial development scenario represented by Figs. 2 and 3 into a result displayed in a form useful to decision makers such as Fig. 4 was made possible by interfacing a GIS and a HMS and contributes to the hydrological understanding of the implications of possible development scenarios.

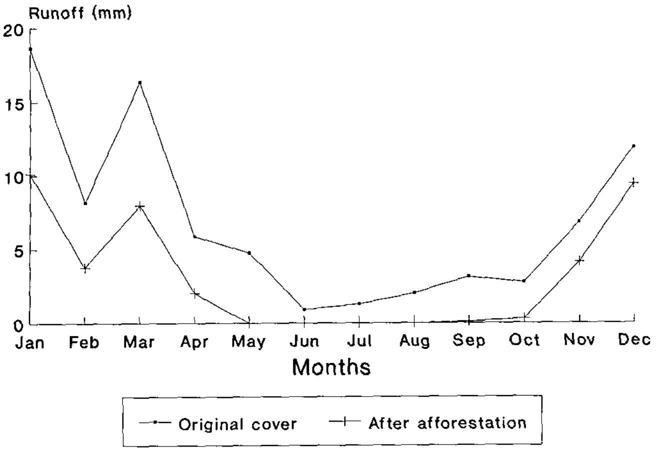

Figure 4
Median monthly simulated runoff for Subcatchment 12

Future envisaged interfacing

Automation and minimising of the human element is perceived as a requirement for future interfacing. It is suggested that stand-alone programs be reduced to a minimum or eliminated completely by incorporation into either the GIS or the hydrological modelling system. Deteriorating water quality in the Mgeni catchment with associated increased purification costs and health risks in areas where untreated water is used for domestic purposes necessitates the future hydrological modelling of water quality in this area. Hydrological model development is required to simulate diffuse and point source impacts on water quality. Diffuse impacts could include the impacts of different crops, agricultural practices and chemical fertilizer or herbicide applications. Point source impacts are likely to be derived from industrial and municipal effluents and concentrated agricultural point sources. Spatial representation of both diffuse and point sources of possible pollution will be required in a future GIS, as will interfacing between the GIS and water quality modelling routines. It is envisaged that this type of interfacing could take the form of the association of quality constituent loadings or coefficients with spatially represented land cover or land use.

Conclusions

Geographical information systems and hydrological modelling systems are separate entities that require interfacing to enable communication between the two systems for meaningful hydrological simulation and effective use of the geographical information. Present interfacing processes between GISs and hydrological modelling, as demonstrated for the Mgeni catchment, have the potential to make effective use of spatial geographic information and transform it into representative variables for hydrological simulation. The transformation of hydrological results back into displays that can be used for making water resources decisions is an important aspect of interfacing GISs and HMSs. Future interfacing requirements were perceived as being the inclusion of interfacing techniques to enhance hydrological water quality simulation and the automation of the interfacing process. Interfacing between GISs and hydrological modelling systems is contributing towards optimising scientific understanding and linkages by helping to bridge the gap between information and knowledge.

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