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Application of a GIS for simulating hydrological responses in developing regions

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Abstract Geographical Information Systems (GIS) and Hydrological Modelling Systems (HMS) are separate entities that require coupling to enable communication between both systems for improving hydrological simulation by a more effective use of relevant geographical information. Present capturing, processing and manipulation of spatial data and information as well as coupling processes between the ARC/INFO GIS and the *ACRU* HMS (Agricultural Catchment Research Unit) is demonstrated for the Mgeni basin in Natal, South Africa. Decision support systems facilitate the "translation" of spatial features into meaningful hydrological variables for hydrological simulation. The link between GIS and HMSs will facilitate improved water resources planning and land management decisions to be made in regard to minimizing non-point source pollution originating from agricultural land and informal settlements. The loading of hydrological results back into the GIS for display, map production and the assessment of cause-effect relationships is considered an important aspect of coupling GISs and HMSs.

INTRODUCTION

The physical environment in southern Africa is characterized by a wide range of soils, vegetation types and a particularly variable rainfall pattern. In terms of water resources management, this high risk, natural environment is aggravated by a rapid population growth in the Pietermaritzburg and Durban regions of Natal, South Africa, which produce 20% of South Africa's Gross National Product (Breen *et al.*, 1985). Projected population increases in the region, from 3.6 million people in 1985 to between 9 and 12 million by the year 2025 (Horne Glasson Partners, 1989), and the associated rapidly accelerating water demand due to rural, urban and industrial development will exceed local raw water resources of the 4387 km^2 large Mgeni basin in the near future (Breen *et al.*, 1985). Concommitant with the exhaustive utilization of the Mgeni's water production is the expected deterioration of water quality with associated increased purification costs and health risks in areas where untreated water is widely used for domestic or recreational purposes.

In order to evaluate consequences of possible future scenarios of land utilization on the basin's water resources and to provide an aid to managers, regional planners and water boards, the *ACRU* (Agricultural Catchment Research Unit) agro-hydrological modelling system is being used and is under further development to simulate the quantity and quality of Mgeni's surface water resources. *ACRU*, which has been developed over the past decade in the Department of Agricultural Engineering at the University of Natal, is a

physical-conceptual and multi-purpose modelling system (Fig. 1) revolving around multi-layer soil water budgeting (Schulze, 1989) and containing decision support systems (DSS). The model has been designed for small catchments up to approximately 50 km^2, uses a daily time step and is structured to be sensitive to land cover and drainage basin management changes. Output from *ACRU* has been verified successfully for a range of hydrological regimes (Schulze & George, 1987; Schmidt & Schulze, 1987; Smithers & Caldecott, 1991; Kienzle & Schulze, 1992), and streamflow and other variables can be simulated for a large basin such as the 4387 km^2 large Mgeni basin by using the distributed version of the model, whereby a large number of sub-basins, each relalively homogeneous i.t.o. hydrological response, can be interlinked (Tarboton & Schulze, 1991).

As is the case with most integrated Hydrological Modelling System (HMS) which are applied to large and heterogeneous basin areas, *ACRU* requires considerable spatial information on, *inter alia*, topography, climatic parameters, soils, land cover, reservoirs, population distribution and density, streams, weirs, sampling points and sub-basins. This information can be captured and stored in a Geographical Information System (GIS). In recent years, GISs have emerged as major spatial data handling tools and have been applied in the hydrological field worldwide (Jenson, 1991; Vieux, 1991) as well as in South Africa (e.g., Goulter & Forrest, 1987; Arnold *et al.*, 1989; Conley, 1989; Lynch, 1989; Herald, 1991; Myburgh, 1991). A GIS, which facilitates the capturing, storage, manipulation and display of geographical information, can be used to communicate more or less directly, via an interface, with a HMS (Tarboton, 1991). This paper:

(a) introduces the more important input variables required by *ACRU*;
(b) portrays the capturing of data and storing of spatial information on ARC/INFO, using the established Mgeni GIS as an example;
(c) describes the preparation of hydrological input parameters on the GIS;
(d) outlines the concept of coupling the HMS with the GIS i.t.o. information input;
(e) discusses the coupling between the HMS and the GIS i.t.o. information output.

GEOGRAPHICAL INFORMATION REQUIRED BY *ACRU*

ACRU requires variables and estimates characterizing the physical features of the basin rather than using optimizing parameters. As is depicted in Fig. 1, a number of input variables are needed for the *ACRU* model. Many of these variables, such as soil type, are heterogeneous within a basin or sub-basin and variables such as land cover or population distribution vary both in space and in time. These variables need to be defined both spatially within a basin and i.t.o. their respective hydrological and water quality properties. The specialized database management system provided in a GIS offers an environment which

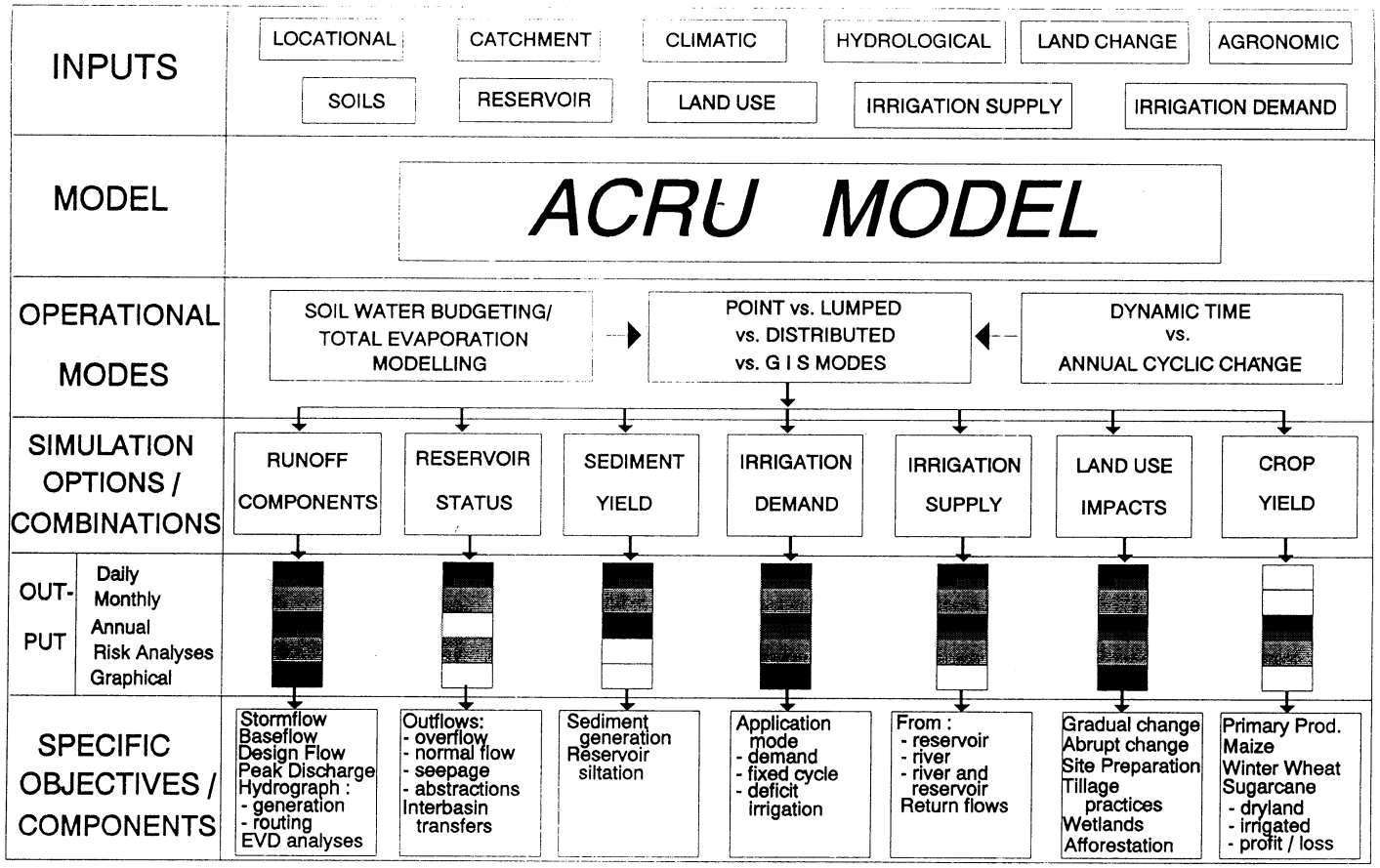

Fig. 1 Concepts of the *ACRU* agro-hydrological modelling system (after Schulze, 1989).

lends itself to not only capture, store and display spatial information, but also to attach non-spatial attributes to a spatial feature.

Therefore, a GIS is perceived as being an essential component, together with a series of DSS and the *ACRU* modelling system itself, to synthesize and manage spatial information and to integrate it into a unified system (Fig. 2).

PREPARATION OF THE GIS

Data and information were compiled and captured (digitized) in the form of point, arc and polygon coverages to form the foundations of the so-called Mgeni GIS. Maps at a scale of 1 : 50 000 formed the basis for most spatial information, and digitizing accuracy was kept to 1 mm (= 50 m in the field). Because of the size of the Mgeni basin and the unfortunate situation that certain areas in the Mgeni basin are inaccessible due to periodical unrest, information on land cover and in particular rural population distribution can only be acquired by remote sensing, which, in the case of satellite imagery, is in immediate GIS format. For land cover information, a multispectral SPOT image was geo-corrected and registered using control points digitized from 1:50 000 topographical sheets. Selected areas of the basin were displayed on the screen for visual classification and on-screen digitizing, with subsequent field verification of the land cover classification thus obtained (Kienzle *et al.*, 1992). Other GIS information, such as gridded values of rainfall and reference evapotranspiration, were generated using multiple regression functions (Dent *et al.*, 1987; Schulze & Maharaj, 1991). Additional GIS data were obtained from a number of co-operating organizations by directly importing already existing coverages. Table 1 gives a list of the different coverages which were obtained for the Mgeni basin. The attached information is either integrated directly into the GIS or can be accessed through a DSS.

A distinct advantage of having information stored in layers (i.e. separate coverages) is that, when coupling the GIS with *ACRU*, the information from each layer can be accessed individually or combined selectively with information from other layers to provide essential input to *ACRU*. For distributed hydrological modelling one needs, for example, to extract physiographic and climatic information from the GIS for each distributed sub-basin element. Hence, sub-basin delimitation and the creation of the sub-basin coverage is important, since this coverage interacts with all other layers in the GIS.

Initially, information extracted from the Mgeni GIS, through a combination of the sub-basin coverages with the physiographic and climatic layers, was not in a form that could be used directly in the HMS. Consequently, the coupling of the GIS and the HMS was required.

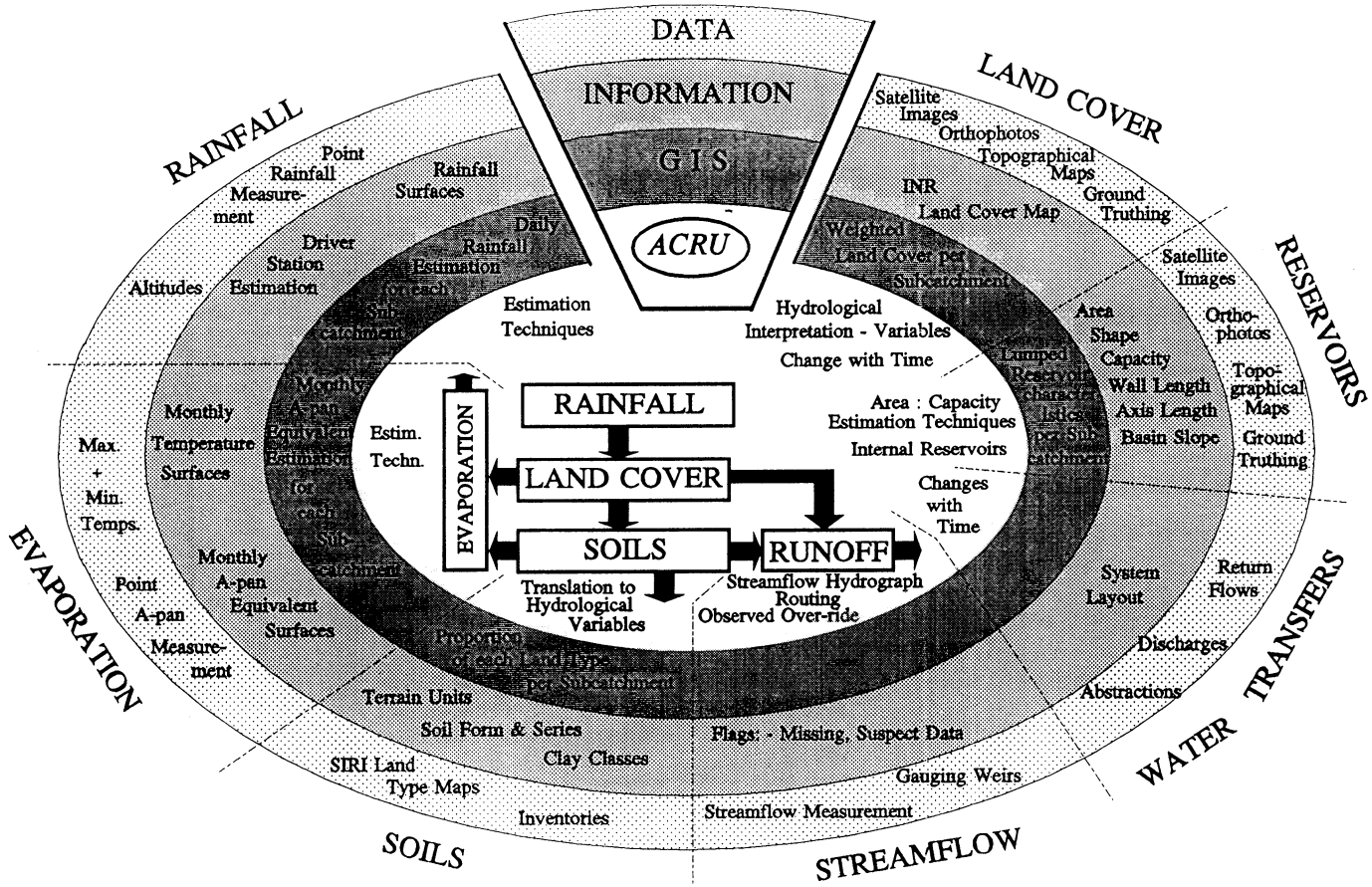

Fig. 2 Concept of integrated distributed *ACRU* hydrological modelling system (after Tarboton, 1991).

COUPLING THE GIS AND *ACRU*

GISs and HMSs are separate entities. Coupling of the Mgeni GIS and the *ACRU* model is the means by which the two systems can communicate and interact. Essentially, the GIS-*ACRU* coupling conceptualized in Fig. 3 consists of:

(a) output of spatial features from the GIS, such as land cover, soil type, reservoirs, settlements without provision of water supply and sewage, and their areal proportions and spatial distribution within a sub-basin;

(b) assignment of hydrological variables to these features via a set of DDSs, e.g., seasonally varying interception values, rooting depth and distributions, crop coefficients or fertilizer rate and application date, as well as non-transient attributes such as soil water retention characteristics, reservoir capacities and their surface areas, faeces production etc.;

(c) area weighting of relevant attributes within a delineated sub-basin or sub-basin in order to derive one representative set of hydrological properties for each sub-basin;

(d) semi-automatic input of the representative properties into the *ACRU* hydrological modelling system;

(e) operation of the model;

(f) loading the results into the GIS and displaying them in form of maps with the option of attaching graphs.

GIS PROCESSING

GIS processing includes combining the different coverages listed in Table 1 to obtain coverages with the desired input information required by *ACRU*. For distributed hydrological modelling in the Mgeni basin it is necessary to combine the sub-basin coverage with each of the coverages containing the input information required by the modelling system. This concept is illustrated in Fig. 4, which has two base coverages, the first containing a delimited sub-basin and the second a coverage with land cover information. In order to create a coverage containing land cover within the delimited sub-basin, the two coverages are "unioned", i.e. combined, resulting in a new coverage with the desired information. At the same time, attributes of the coverages are combined so that a summary of the information in the new coverage can be generated, as given in Table 2.

GIS processing of spatial information on soils and land cover involves the acquisition of the relative representation within each sub-basin by combining the soils or land cover coverage with the sub-basin coverage as described in Table 3. This table illustrates the result of the GIS's processing of land cover information for a selected sub-basin in the Mgeni basin. Similar processing of the soils coverage results in the percentage representation of each

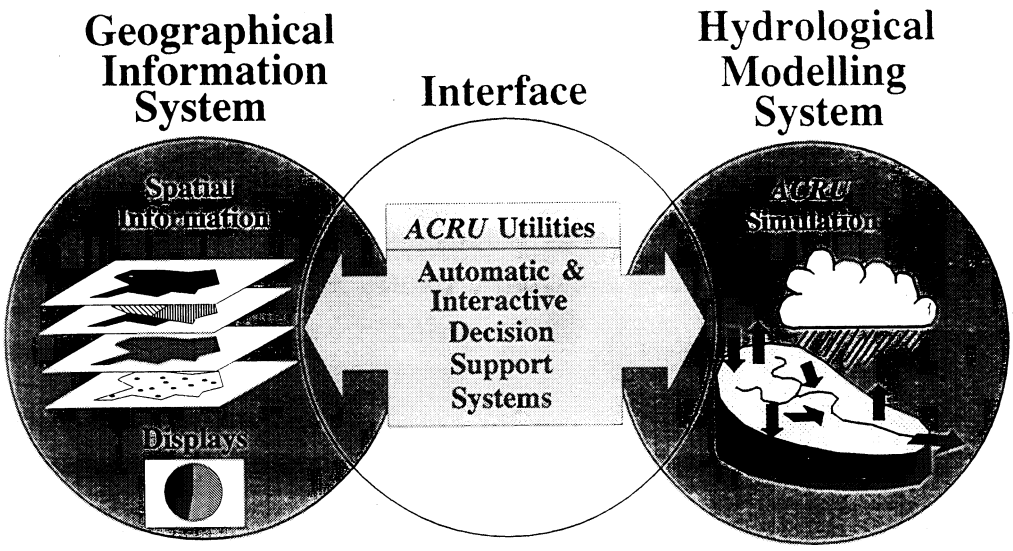

Fig. 3 Concept of the GIS-HMS-interface used for *ACRU*.

Table 1 GIS coverages and their attached attributes for the Mgeni GIS.

Coverage type	Geographical feature	Attributes attached to the feature
Point	Rainfall	S. Afr. Weather Bureau raingauge number, altitude, start year, end year, number of complete years, MAP, raingauge position
	Sampling station	current sampling frequency, first record, last record, median values and 90 percentiles for selected water quality variables
	Weirs	first record, last record, accuracy
Arc	Rivers	name, length, hydraulic properties, e.g. roughness
Polygon	Rainfall grid (1'x 1')	median monthly rainfall
	Temperature grid(1'x 1')	monthly means of daily max. and min. temperature
	Elevation grid(1'x 1')	altitude above sea level
	Evaporation grid(1'x 1')	mean monthly A-pan equivalent reference evaporation
	Soils	area, for A- and B-horizon: soil depth, texture class, wilting point, porosity, field capacity, drainage properties
	Land cover	area, crop coefficient, leaf area index, interception loss, root distribution
	Sub-basins	area
	Population	density, estimation of proportion without water supply or sewage
	Reservoirs	surface area, capacity, wall height, wall length, axis length, basin slope, dam shape

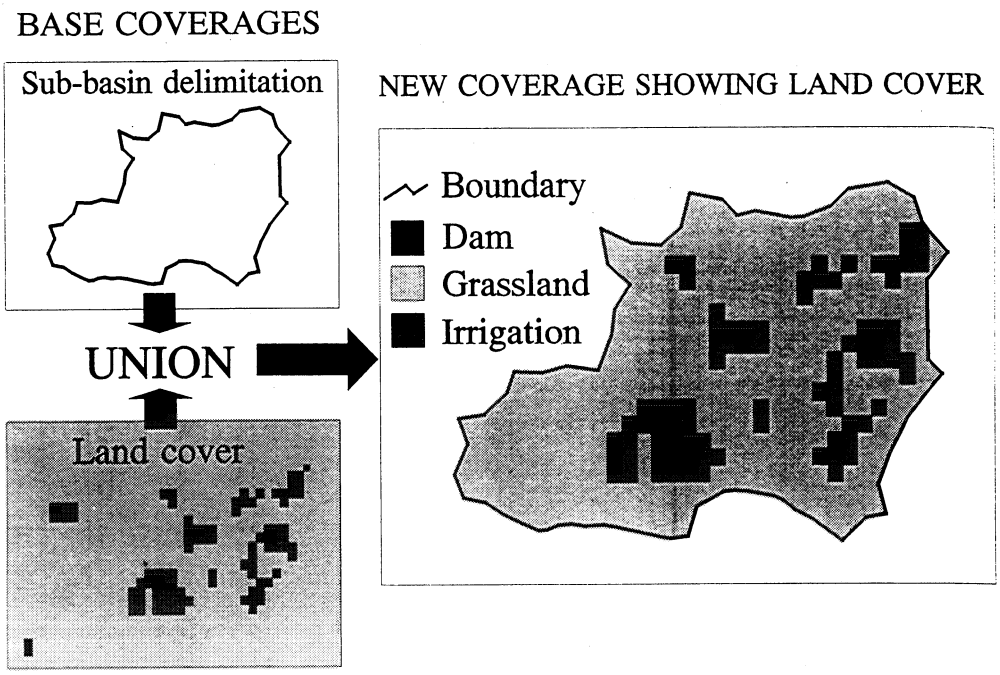

Fig. 4 Concept of combining coverages with a GIS (after Tarboton, 1991).

soil type within each of 123 sub-basins which make up the Mgeni basin. Further processing of the percentage representations of soils and land cover information to obtain hydrological variables for each sub-basin was performed by means of especially developed DSSs incorporated into *ACRU Utilities*, a computer program to guide the user through various applications.

The DSSs contain pre-programmed values of hydrological variables obtained from soils and land cover information. Land cover information from Table 3 serves as an example as to the manner in which spatial information obtained from the GIS is transformed into hydrologically meaningful variables. Table 3 displays the resultant area-weighted monthly values of crop coefficients, vegetation interception and proportions of roots in the topsoil. The table lists information that is obtained from DSSs and which can be attributed to the spatial features in a specific format automatically for direct input into *ACRU*.

Table 2 Example of land cover information within a sub-basin obtained by combining sub-basin and land cover coverages.

Land cover	Area (km^2)	Area (%)
Dams	1.25	4.16
Grassland	24.67	82.51
Irrigation	1.25	13.33
Sub-basin	33.01	100.00

Table 3 Hydrological variables obtained by entering land cover percentages into the *ACRU DSS* for the same sub-basin used in Table 2.

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop coefficient	0.67	0.67	0.67	0.57	0.34	0.24	0.23	0.23	0.31	0.50	0.56	0.66
Interception loss (mm rainday^{-1})	1.12	1.12	1.12	1.03	0.94	0.94	0.94	0.94	1.03	1.12	1.12	1.12
Proportion of roots in topsoil horizon	0.91	0.91	0.91	0.95	0.98	1.00	1.00	1.00	1.00	0.96	0.91	0.91

CONCLUSIONS

With the increasing use of GISs worldwide and in South Africa, spatial information required by hydrologists and modellers become readily available, exchangeable and affordable. As soon as new or updated information on, e.g., land cover or population distribution, becomes available, it can easily be added to an existing GIS. By "translating" spatial information into hydrologically meaningful values as input into hydrological modelling systems, more meaningful results can be obtained.

The power - and the restriction - of integrated distributed modelling systems, such as *ACRU*, lies in the substantial amount of input required, in particular input on spatially distributed variables. If the modelling system has multi-level input options, as *ACRU* does, then with the availability of spatial input information, answers may be obtained more easily and can be portrayed more meaningfully for decision makers and hydrologists alike. The type of application presented in this paper is envisaged to be an initial step leading towards an era where GISs and environmental sciences will become more fully integrated entities.

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