WATER QUALITY DECISION-MAKING FACILITATED THROUGH THE DEVELOPMENT OF AN INTERFACE BETWEEN A GEOGRAPHIC INFORMATION SYSTEM AND A WATER QUALITY DATABASE

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ABSTRACT

Decision-making in the field of water quality management requires access to comprehensive data stores of relevant information. Such databases are becoming increasingly available due to the efforts of several agencies engaged in monitoring environmental conditions. On its own, this store of information is not sufficient for adequate understanding and interpretation of real-world problems, as objective decisions rely on a transformation of information into knowledge. This transformation is all too often accomplished within the reference framework of the individual manager, based on intuitive understanding and past experience. This paper outlines development currently being undertaken with the aim to provide an objective knowledge base synthesised from a wide range of water related variables, through the platform of a Geographic Information System (GIS). A GIS provides the potential for powerful geographical analyses and interpretation of hydrological data in a spatial context. A customised menu-driven system is being developed to facilitate access to and interrogation of a water quality database. The system allows on-screen display and analysis of data at a range of scales and detail, with a selection of methods of analysis and presentation of results.

INTRODUCTION

Geographic Information Systems (GIS) are computer-based tools that store, analyse and manage spatial data (Burrough, 1986; Lanfear, 1989; Openshaw, 1987). Initially, development of GIS arose out of the need for computerised cartography. With further enhancement the GIS took on a greater capability, with the ability to store and manipulate large volumes of spatial and associated data, and to present the data in summarised and analysed forms in a useable and accessible way. Currently, available GIS are far advanced beyond the simple cartographic origins, and are powerful tools capable of combining spatial database management, statistical analysis and cartographic modelling techniques (Star and Estes, 1990). GIS can be defined as an enhanced information system that aids decision-making by referencing data to spatial or geographic coordinates (Schoolmaster and Marr, 1992).

Water quality cannot be considered independently of the spatial context within which it occurs. Water quality indices are generally measured at monitoring point stations but reflect the influence of the wider environment, possibly events taking place several hundred kilometers from the site of sampling. Effective management of water quality must therefore take diverse factors into account, and depends on information from a variety of sources and a range of scales. Such diverse information must be assimilated and presented in as concise and accurate a form as possible, and as rapidly as possible so as to support real-time management of water quality problems as and where they may occur. Traditionally, the water quality manager has had to rely on experience and intuition, and to synthesise the relevant data within the scope of this experience. As most water resources data can be referenced geographically, GIS is ideally suited as a management tool (Lanfear, 1989).

A GIS has the capacity to integrate large volumes of information from a wide variety of sources, and to present the data in a summarised and timely way in the environmental context within which they occur (Schoolmaster and Marr, 1992). The ability of the GIS to store and manipulate large amounts of data allows an historical perspective, where long-term data records exist to show the emergence of trends. This perspective can support predictive and anticipatory management decisions, especially where changes in water quality are linked to concomitant changes in landuse activity. Data in a GIS can be accessed, transformed and manipulated interactively, and therefore the GIS acts as a test bed for studying environmental processes, or for analysing the results of trends and anticipating the results of planning decisions (Burrough, 1992). Collection, analysis and reporting of water use data is time-consuming, and the resultant large and diverse database presents a number of logistical problems that contribute to the lag-time between when the information is gathered and when it can be used in the planning process. The database management capabilities of GIS can facilitate the collation of information from diverse sources, expedite automated data collection, and thus accelerate the reporting of spatial and temporal water quality trends (Schoolmaster and Marr, 1992; Shih, 1989).

The accessibility of the data in a useful form, however, depends on the structure and organisation of the GIS, which in this study was tailored to the specific needs of the water quality manager. Further, the integration of a water quality database, incorporating historical data as well as rapidly updated recent data required development of a system beyond that provided in the GIS software. For this purpose a series of programmes was developed to produce a set of menus allowing the water quality manager to step through the relevant data, at relevant scales, in combination with any information that may be pertinent.

As a management tool this system forms part of the development towards a long term water quality management information system within the Department of Water Affairs and Forestry, consisting of an initial demonstration testing ground on which further detail may be added. During the course of its development, a number of directions in which the system should be expanded have been identified to increase its capacity.

AIMS AND OBJECTIVES

The primary objective of this research was to develop a generic set of programmes allowing rapid access, presentation and analysis of water quality related data, to support management of water resources. The development was modularised to allowed the incremental development of different phases without impairing the functionality of completed modules.

Specific aims include:

* To allow any combination of a variety of data layers to be viewed on screen for inspection by the manager. Background information includes vegetation types, geology, soils, climatic variables, altitude and landuse activities obtained from satellite imagery. Composite satellite images and scanned topographic maps are also provided for selection as background information.

* To allow the manager to zoom into and out of selected areas of interest, once problems are identified at a coarse scale.

* To allow the manager to view water quality variables within their spatial context for selected sites, selected time periods and selected water quality variables.

* To allow the manager to manipulate and interrogate all spatial data. Information to be readily supplied includes:

- all characteristics of a selected homogeneous unit,
- the surface areas of selected landuses or water bodies,

- relative distances between points or areas of significance,
- highlight zones where a combination of specified factors occur.

* To allow interrogation of spatial water quality data through the use of summary diagrams, time series, statistical summaries and simple linear regression analyses.
  - Water quality indices must be assessed against recognised guidelines, namely for domestic, agricultural, industrial, recreational and environmental user groups.
  - Exceedance diagrams should immediately indicate which monitoring points exceed a certain concentration level, and where a potentially toxic combination of factors occurs the affected points should be flagged.
  - Different concentration levels can then be manipulated to ascertain what the potential effect of effluent discharges or landuse changes in an area would have on different user groups.

METHODOLOGY

A number of water quality managers within the Department of Water Affairs and Forestry was consulted during a series of meetings and interviews to assess the perceived information needs underlying decision-making. A literature survey was carried out to support the findings of the consultations. A geographic database was then assembled on the GIS ARC/INFO v 6.0.1 consisting of spatial information and associated attribute information. Spatial data comprise areal, linear and point type data. Sources of data are primarily topographic maps, which are converted into digital form through digitising or scanning of color separates and subsequent vectorising. Areal data is based on homogeneous units within which a certain factor is assumed constant, similar to a choropleth map. This type of data includes political boundaries, catchment boundaries, altitude, vegetation, geology, soils and climatic variables such as mean annual rainfall and evaporation. Areal data such as dams and urban areas may be seen as point data with change in scale. Linear data includes the river network and lines of communication. Monitoring points are the only true "point" data, and are located according to latitude and longitude. Satellite imagery providing evidence of land cover conditions can be used as a backdrop to the areal, linear and point data. Scanned 1:250 000 topographic maps are also included, over which other data can be overlain.

The spatial database was then linked to the water quality laboratory chemical database which is used to store results of water samples analysed by the Hydrological Research Institute (HRI). This link was possible because the database language ORACLE and ARC/INFO v 6.0.1 are both UNIX based and the data can be directly transferred without the necessity for conversion or alteration of data type and intermediate preprocessing. A monthly batch process updates all chemical data on the GIS, and if more recent data is required there are additional menus provided to automate the import process. Rapid access to the water quality data with reference to previously identified aspects of immediate relevance to water quality management was then initiated.

A set of programmes was developed on a UNIX workstation using ARC/INFO macro language AML. This system consists of a series of user-friendly menus and associated programmes to facilitate the access to and interpretation of water quality information within the spatial context. The initial query development was based on the spatial database, to allow the user to investigate the prevailing conditions, such as geology, mean annual rainfall or soil type, in a particular area of interest. The surface area of each homogeneous unit could also be found, such as the surface area of dams, irrigated lands and urban settlements. An important precursor to all further development was the option allowing the user to zoom in and out of selected areas. Once the spatial interrogation and presentation aspect was complete, the water quality data associated with the national monitoring network was integrated into the system, allowing analysis and presentation of variables chosen by the user for a selected time period, within the spatial context.

APPLICATIONS

The application of the system can be viewed in two complementary ways, namely near real time presentation of water quality data, and long term analysis of water quality trends.

Near Real Time Presentation

Near real time presentation implies an instantaneous "snapshot" picture of the status of water quality throughout the country at the most recent point in time. The instantaneous spatial variability in water quality throughout the country can be viewed in this way. Concentrations of each water quality variable analysed can be rapidly viewed and assessed against the management guidelines for specific water user groups. Those monitoring points at which the concentration of a particular variable is approaching or exceeding the guideline can be identified and remedial action can then be directed towards these river reaches (Figure 1).

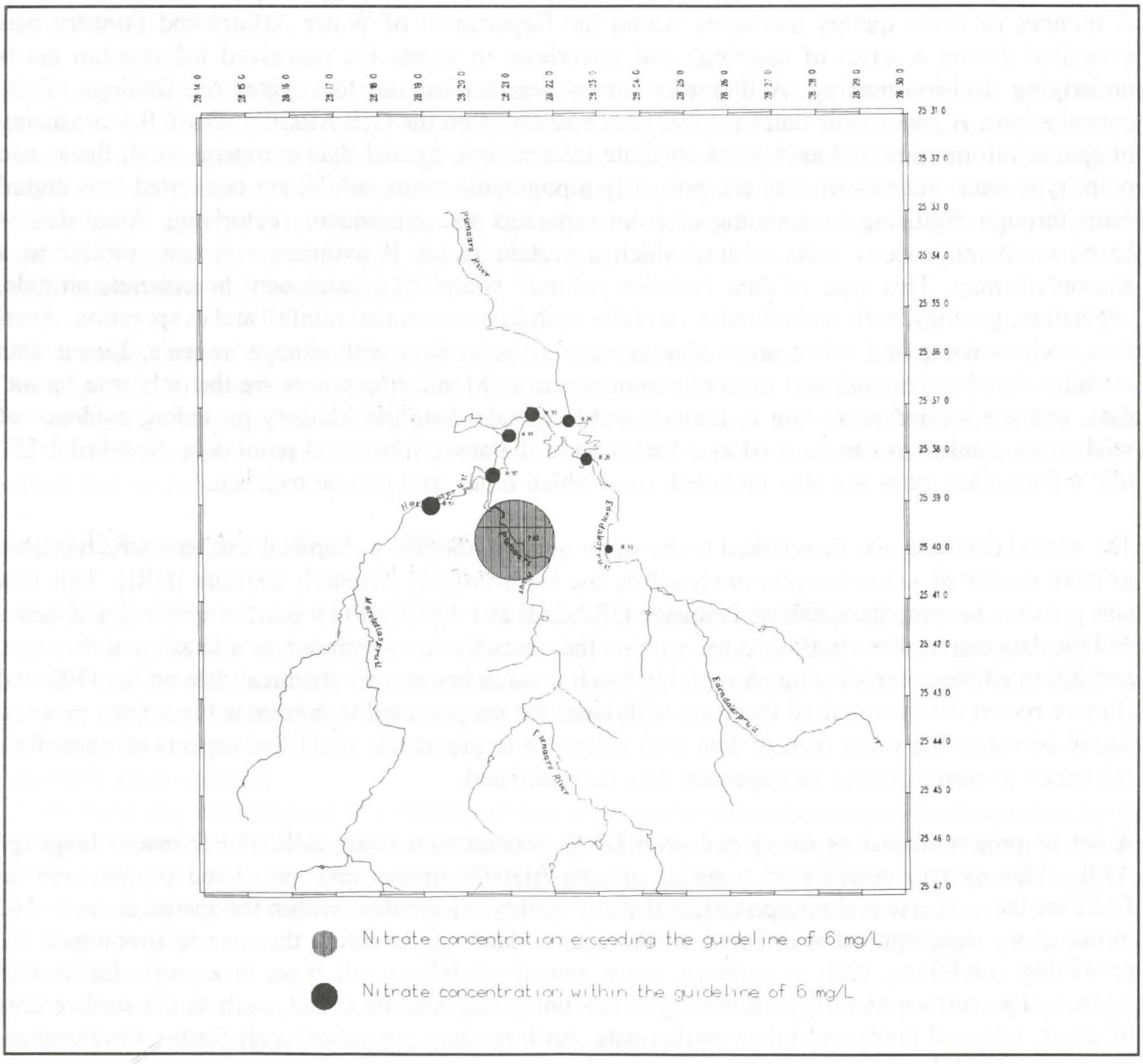

Figure 1: Monitoring points within the Roodeplaat Dam Catchment which exceed the 6mg/ Nitrate guideline for domestic use (Water Quality Guide for Domestic use, 1993), as at 11 May 1993

Trend Analysis

Water quality varies temporally as well as spatially and the system also allows the changes over time to be highlighted. This is an application particularly well suited to the GIS, as spatial changes in the catchment can be represented on screen alongside changes in water quality. The period of time to be reselected from the database is specified and represented in a number of different ways. The most easily interpreted application of temporal change is to plot a time series of the water quality variable of interest (Figure 2), which can be combined with the recommended guideline for the variable against which the actual values can be compared. Seasonal and other cyclic trends are immediately identified in this way. Other summary diagrams available include box plots, star diagrams and maucha plots, although these do not give an indication of changes with time.

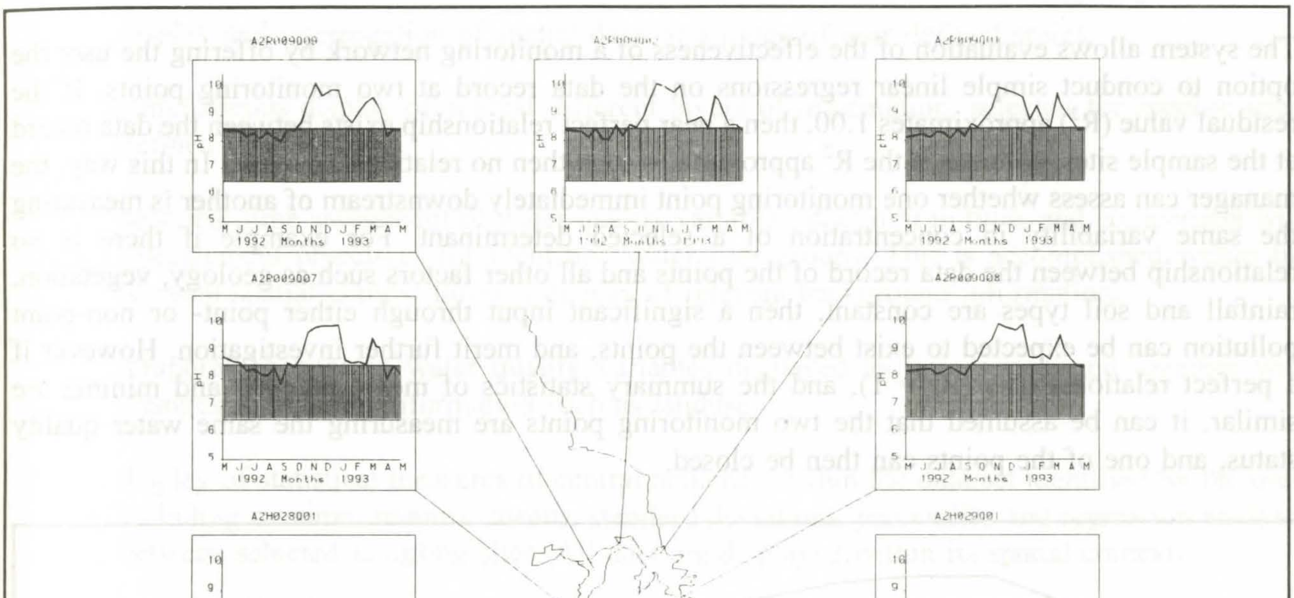

Figure 2: Time series plots for pH at monitoring points within the Roodeplaat Dam catchment, showing the recommended recreational guideline range of 6.5 - 8.5 (Water Quality Guide for Recreational use, 1993)

Statistical Analysis

Summary statistics available through the system include maxima, minima, means, standard deviations and percentiles for any data record specified by the user. These statistics can be represented in tabular form at the base of a map of the area or alongside each monitoring point. The user may choose an option to draw pie diagrams showing a slice of one color to indicate the percentage of time the criteria was exceeded during the period selected, and a slice of another color for the proportion of time the concentrations were within the guideline set for the specific variable. In this way it can clearly be seen which monitoring points are seldom above a management objective, and which points continuously exceed a specified level.

Regression Analyses

The system allows evaluation of the effectiveness of a monitoring network by offering the user the option to conduct simple linear regressions on the data record at two monitoring points. If the residual value (R^2) approximates 1.00, then a near perfect relationship exists between the data record at the sample sites, whereas if the R^2 approximates 0.00 then no relationship exists. In this way, the manager can assess whether one monitoring point immediately downstream of another is measuring the same variability in concentration of a selected determinant. For example if there is no relationship between the data record of the points and all other factors such as geology, vegetation, rainfall and soil types are constant, then a significant input through either point- or non-point pollution can be expected to exist between the points, and merit further investigation. However if a perfect relation exists ($R^2 = 1$), and the summary statistics of mean, maxima and minima are similar, it can be assumed that the two monitoring points are measuring the same water quality status, and one of the points can then be closed.

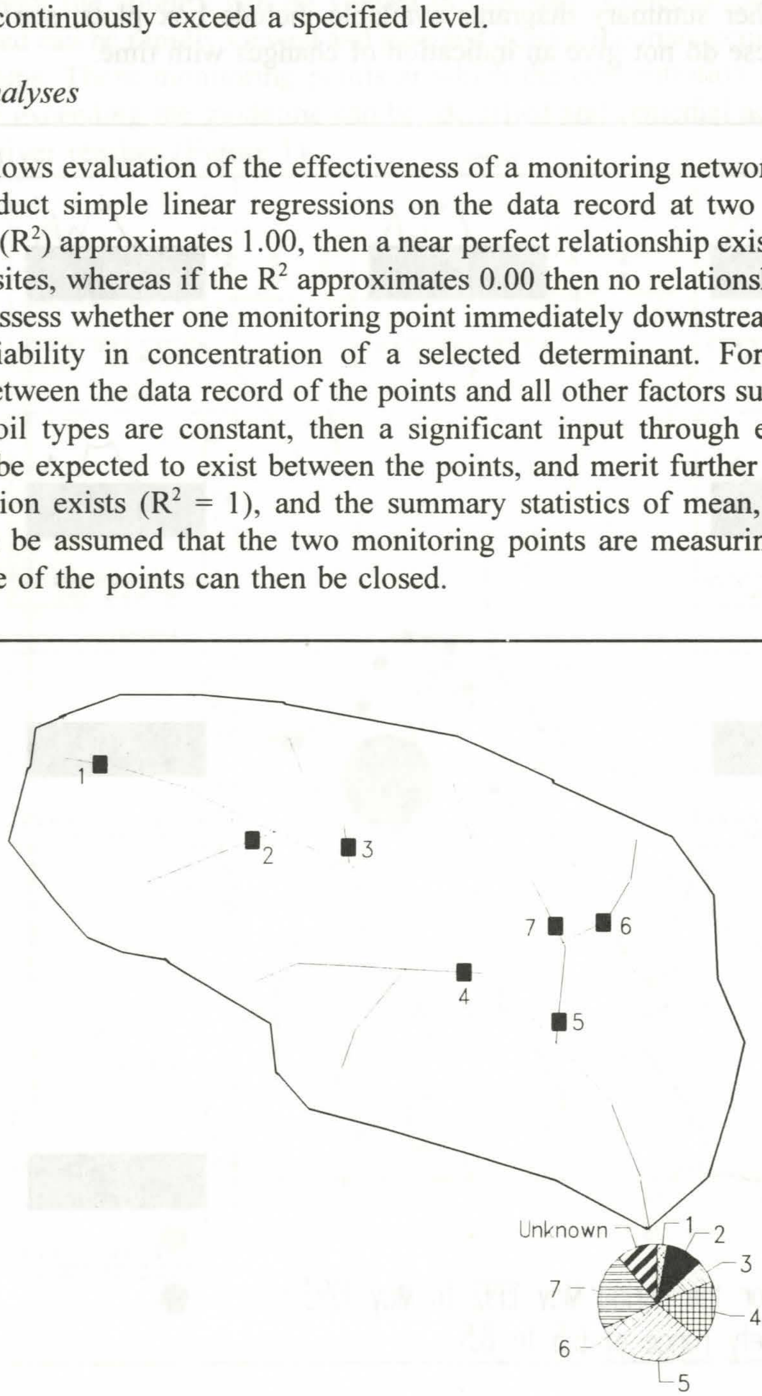

Figure 3: An example catchment where a multivariate analysis indicates the proportionate contribution of each tributary to the total load

Further development of this application is taking place, with the aim to allow multivariate analyses of the water quality variables at several monitoring points within a catchment (Figure 3). It is intended that the outcome of this development will be to determine the proportionate contribution of each section of the catchment to the overall load leaving the catchment. Changes in contribution can then be monitored with change in landuse such as growth in industrial, urban or agricultural areas.

CONCLUSION

A GIS is an essential tool in the collection, management, analysis and display of water quality data, and the use of GIS in communicating spatial and temporal trends in water quality is demonstrated. The following applications have been successfully identified:

* display and interrogation of spatial data, at a range of user-defined scales,
* simultaneous display of several different layers of information, selected for specific user-defined applications,
* near real-time assessment of water quality variables at a point in time, and comparison with management objectives for identified water user groups. This is accomplished within the relevant spatial context through display of relevant background information,
* temporal changes in water quality variables displayed as time series, and together with changes in relevant information such as landuse,
* display of statistical measures of central tendency within the data set identified by the user, including maxima, minima, means, standard deviations, percentiles and regression analyses between selected sampling sites. All data are displayed within its spatial context.

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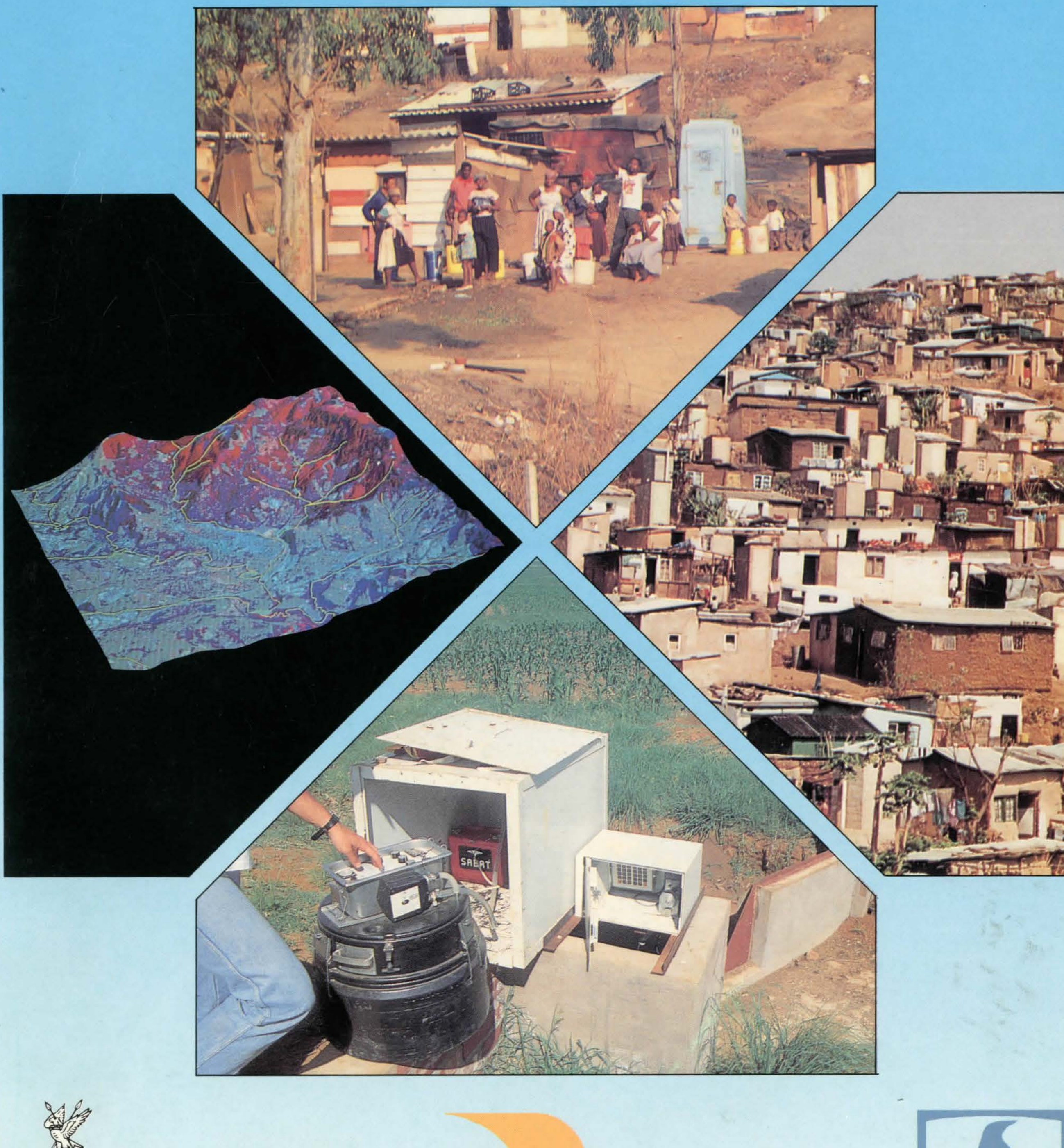

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