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ODA

IWRSM
INTEGRATED WATER RESOURCE SIMULATION MODEL

PROGRESS REPORT 1994/95

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Executive summary

As the demands on limited water resources throughout the world continue to grow, the management of these resources, and the planning and operation of other water-related projects, is becoming increasingly complex. An integrated, basin-wide approach to both the planning of new developments and the improved operation of existing schemes is becoming accepted as the only effective way forward. In this context, the Institute of Hydrology, under ODA funding, has assessed the feasibility of developing an Integrated Water Resource Simulation Model (IWRSM), a user-friendly, multi-purpose, multi-scale model, which engineers, planners and decision-makers can apply to any river basin in the world, enabling them to study the full extent of water resources, environmental and economic problems, and to tackle a wide range of complex planning and operational projects.

Although any IWRSM will have world-wide application, the idea was conceived with developing countries specifically in mind. Developing countries tend to lack the expertise, hardware and software to carry out even rudimentary assessments of complex water resources problems. The provision of a model such as an IWRSM will provide engineers, planners and decision-makers in developing countries with the ability to carry out their own evaluations of water resources projects, and to effectively appraise and update studies done by consultants.

This report describes the results of a scoping study to define what functionality such a model should have. The report also includes a review of models of a broadly similar nature to the proposed IWRSM that are available world-wide. Finally, a suggested work programme is presented for development of a suitable integrated water resource simulation model for use in, and by, developing countries.

Contents

1 Introduction

1.1 BACKGROUND

Throughout the world, the demands on limited water resources continue to grow, making the management of these resources, and the planning and operation of other water-related projects, increasingly complex. Many river basins now accommodate a multitude of engineering schemes which manipulate both the river and the water within it for a wide range of different purposes. For example, a system might typically include combinations of multi-purpose reservoirs for domestic, industrial and irrigation supply, as well as hydro-electric power generation, flood control measures, groundwater abstractions, works concerned with effluent returns, and possibly inter-basin water transfers. The difficult issue of water resource management is perhaps of greatest concern in developing countries, which tend to lack the expertise to conduct even rudimentary assessments of water resources problems, and usually have to rely on overseas consultants to carry out the work for them. Although powerful microcomputers are now frequently found in developing countries, planning and operational agencies in such countries often lack the expertise necessary for understanding such studies, and certainly lack suitable software to handle their own studies.

For both the planning of new developments and the improved operation of existing schemes, it is necessary to study the effects of each current or proposed system component on the river basin as a whole. This integrated, basin-wide approach is becoming recognised, and accepted, as the only effective way forward (World Bank, 1993), and there is a growing need for powerful, yet easy-to-apply, flexible models which will permit the water resources of a whole river basin to be studied. In light of this, a model is required which may provide engineers, planners and decision-makers, particularly in developing countries with the ability to carry out evaluations of water resources projects themselves, or at least to effectively appraise and update studies done by consultants, and assess new consultancy requirements.

1.2 OBJECTIVE OF PROJECT

The principal objective of this ODA-funded project is to define the required functionality of such an integrated, basin-wide model suitable for use in, and by hydrological staff of, developing countries. In light of this, any existing models, developed with a similar function in mind, will be reviewed in order to assess their suitability for such work. If it appears that suitable software is not currently available, the project will assess the feasibility of developing such a user-friendly, multi-purpose, multi-scale model for the management of water resources, and the planning and operation of other water-related projects, within a river basin. The proposed model should be powerful and flexible, yet easy-to-apply and use. It should permit the surface and groundwater resources of the whole river basin to be studied, and should be able to be applied to any river basin in the world, though it should be designed with developing countries specifically in mind. Such a model will be used by engineers, planners and decision-makers, enabling them to study the full range of water resources, environmental and economic problems, and to tackle a wide range of complex planning and operational projects. The intention is that the model would eventually incorporate water quantity, water quality, hydro-ecology and economics modules, though priority would be given to water quantity modelling in the initial stages of development. The model will be therefore be an Integrated Water Resource Simulation Model (IWRSM).

1.3 CONCEPT OF INTEGRATED WATER RESOURCE SIMULATION MODEL

The proposed IWRSM will have to be a generalised model which can be configured for most river basins and applied to most water resource management problems, within the limits of the data and information available to answer any questions posed by the user. The scale and degree of sophistication of modelling applied to different parts of the basin will be variable so that relatively crude, simple black-box models can be applied to data-scarce regions or to parts of the basin of little significance, whilst more detailed sophisticated, physically-based model algorithms can be applied to the particular regions and problems of interest. Modelling time step will also vary with data availability and the importance of the sub-region outflow to the overall problem. Assessment of the performance of a water resource system now needs to include not only the hydrological outputs from the system, but also the associated economic benefits, and so modules capable of examining the financial implications of alternative development or operation scenarios will have to be incorporated, as will modules concerning water quality and hydro-ecology. The different models will be contained within a library of state-of-the-art algorithms and subroutines, which can be added to as new techniques are developed. A map-based graphical user interface, a powerful information control algorithm structure, and good reporting and graphing facilities, will enable users to quickly change the model configuration and test a range of "what-if?" scenarios. The model will be underpinned by a powerful relational database for storage of data, parameters and results, and supported by extensive user manuals and documentation and an on-line context-sensitive "help" facility.

Such a model will provide a powerful tool which will enable studies to be carried out more rapidly and effectively than at present. In order to ensure that the design of the model fulfils the requirements of developing countries, whilst being sufficiently general for application world-wide, the model will be developed with the cooperation of water departments in developing countries.

1.4 STRUCTURE OF REPORT

This report describes the progress of the project in the financial year 1994/95. The work carried out has comprised a general scoping study in which the required functionality of the model has been designed, and existing models of a similar nature to the proposed IWRSM that are available world-wide have been reviewed. The information available on these existing models has varied from case to case, and whilst it has been possible to undertake a fairly thorough review of some models, it has only been possible to comment on others based on literature reviews.

The report is divided into five sections, plus references. Section 2 contains the model specification formulated by the Institute of Hydrology. Section 3 presents the review of existing models. Section 4 gives proposals for the way forward in terms of model development. The final section summarises the progress of the project, and outlines the proposed work in the next financial year.

2 IWRSM specification

This section considers the attributes of the proposed IWRSM, which were set out briefly in section 1.3. The features to be accommodated by the model are listed, together with the input and output data requirements, and the types of models which might be incorporated.

2.1 FEATURES OF THE PROPOSED IWRSM

In order to fulfil the requirements set out in section 1, the IWRSM aims to include the following key components:

- Modules for modelling all aspects of the hydrology and water resources utilisation of a basin, including water quantity, water quality, hydro-ecology and economics, although in the first instance, the study will concentrate on water quantity.

- Library of state-of-the-art model algorithms and subroutines, which can be added to as new techniques are developed, through which these hydrological and water resource allocation modules will be made available to the model;

- Ability to model sub-catchments at a variety of scales spatially, from coarse, lumped black-box models of a sub-catchment to complex, physically-based distributed models;

- Ability to operate models at a variety of scales temporally, as the available data permit, from sub-daily (e.g. hourly), through daily, weekly and 10-day, to monthly;

- A powerful relational database for storage of data, model parameters, operational constraints of the system and results;

- A map-based graphical user interface through which users may control model configuration and initiate model runs;

- A robust information control algorithm structure, which will enable users to quickly change the model configuration and test a range of "what-if?" scenarios;

- Good reporting and graphing facilities to examine model input data and output results;

- Comprehensive user manuals and documentation as well as context-sensitive on-line help system.

- System / database administration and management facilities e.g. system back-up / recovery, database back-up / recovery, system monitoring, granting / revoking user access to database / application modules.

Many of these elements already exist in some shape or form, both within the Institute of Hydrology and within other organisations. A large range of hydrological software is available, from rainfall-runoff models, through multi-purpose reservoir operation schemes and general planning and management tools, to groundwater models of an aquifer source and water quality models and the increasingly important river ecology models. However, these existing dedicated models tend to be free-standing, and do not easily interact with each other, or with other general software, such as spreadsheets. Where forms of integrated water resources models have been developed, they have often been specific to the basins being studied, and have included only those elements which are necessary for each particular case. Hence, they have not been sufficiently flexible to allow them to be easily reconfigured to a new river basin.

However, advancements in database management systems, digital mapping and information technology within the computer industry have generated tools, such as windowed environments and graphical user interfaces, which enable development of more flexible, generic software which can more simply be configured to new problems, and also more easily interact with other software.

2.2 INPUTS TO THE PROPOSED IWRSM

Inputs to the proposed IWRSM fall into four categories. The first of these covers the physical and climatic descriptions of the river basin and component sub-catchments. The second and third categories include the measurement sites within the basin and the standard hydrological and meteorological input data requirements, and basic data on allocation of water resources within the basin, respectively. Finally, economic, water quality and hydro-ecology data will be grouped together as additional inputs intended to be fully incorporated in later stages of the study.

2.2.1 Catchment / station characteristics

- Catchment characteristics: location, area, altitude, mean annual rainfall
- Soil and land use data: type, location and areal extent e.g. soil type, crops, forestry, urban areas;
- River network information: digitised river network, locations of significant lakes, major wetlands or swamps, reservoirs and balancing ponds;
- Hydraulic structures: details of artificial structures which could affect the flow in the river e.g. weirs, culverts, barrages, reservoir controls.

2.2.2 Hydrological / meteorological data

- Hydrological network information: station names, types, frequency of measurement, locations, altitude, mean annual rainfall;
- Precipitation: Most countries have long rainfall records, usually daily, sometimes monthly and annual, and less often sub-daily. However, raingauge density in remote areas, such as catchment headwaters, is often poor;
- Stage / flow / rating equations: Length and quality of stage and flow records tend to be poorer than for rainfall records. Ratings also tend to be poor, if they exist at all, particularly for extremes flows;

- Evapotranspiration: Potential evapotranspiration and open water evaporation, measured directly, or estimated indirectly through measurement of various meteorological data, such as temperature, sunshine, windspeed, humidity;

- Groundwater / sub-surface flow: Information on groundwater quantity and quality are needed together with data on pumping tests, spring flows and aquifer properties;

- Snowmelt / glacial melt data: Potentially an important factor influencing the flow in the river in some countries, and requiring various information for estimation, such as pack depth, density, temperature, typical melt rate.

2.2.3 Water resources data

- Reservoir / service reservoir / balancing pond characteristics e.g. type of reservoir, area-stage, storage-stage, discharge-stage, operating rules, water levels, release records, spill records, sedimentation rates, seepage rates, downstream compensation flows;

- Abstraction from / discharge to rivers and reservoirs, together with priority order e.g. water supply might take precedence over hydropower, which might in turn take precedence over irrigation;

- Hydropower data e.g. turbine capacities, turbine efficiencies, firm / secondary energy, power figures, tail water ratings, plus operating strategies and demand patterns;

- Irrigation data for all major schemes within the basin e.g. cropping patterns, cropped areas, water requirements;

- Pipe / canal / aqueduct network e.g. pumping and network details for water distribution within a basin, details of inter-basin transfers.

2.2.4 Other data

- Water quality / river ecology data: These could include physical habitat, chemical and bacteriological data, though measurement of these factors is generally poor in most developing countries. In particular, sediment concentrations could be important in the context of reservoirs;

- Economics / financial data e.g. quantification of tangible / intangible factors

- Reliability information e.g. confidence limits, results of sensitivity analyses.

2.3 MODULES WITHIN / OUTPUTS FROM THE PROPOSED IWRSM

Like the inputs, the outputs from, and therefore modules to be included within, the proposed IWRSM fall into several categories. The first of these includes some general modules, which may operate automatically, concerning data quality control, processing and manipulation. The second category includes the specialised hydrological models and outputs; derived hydrological and meteorological data can be either final outputs or intermediate outputs i.e.

they may themselves become new inputs. The third category comprises models and outputs relating to water resources management. The final category covers modules and outputs concerned with economics, water quality and hydro-ecology, which are not scheduled to be included until the later stages of the study.

2.3.1 General modules

- Quality control of raw and processed data: Module which will automatically display if any of the input or output data exceed pre-set user-determined limits e.g. to indicate whether data are of poor quality, or whether flood flow is likely to occur;

- Aggregation / disaggregation modules e.g. to convert mean daily flow to mean monthly flow, to convert mean daily flow to volume of runoff, or to give monthly accumulations of daily rainfalls;

- Modules for calibration of models: Features may include interactive front-end, optimisation algorithms, a variety of different objective functions, efficiency criterion, ability to perform sensitivity analyses and produce confidence limits;

- Statistical analysis e.g. simple statistics of data series, such as maximum, mean, minimum, median, standard deviation, skewness, rank.

2.3.2 Hydrological / meteorological modules / outputs

- Modules for deriving precipitation e.g. isohyetal maps, catchment average rainfall. The rainfall may be a final output, but will most likely be used as input to other models e.g. rainfall-runoff models;

- Modules for deriving snowmelt / glacial melt;

- Modules for deriving evapotranspiration from meteorological data;

- Rainfall-runoff models;

- Derived flow output e.g. flow from stage and rating equations, flow generated by rainfall-runoff models, flow derived from snowmelt and glacial melt. The flow may be a final output or may be used as input to other models;

- Modules for converting stage to flow, performing low flow frequency analysis and flood frequency analysis, deriving flow duration curves, and performing flow routing;

- Modules for deriving groundwater / sub-surface flow e.g. groundwater level contour maps. This is likely to be a final output;

- Simple stochastic models to generate long data series;

- Water balance models.

2.3.3 Water resources modules / outputs

- Flow: River yield estimates derived by low flow frequency analysis for various durations;
- Reservoir routing models and reservoir / balancing pond design models;
- Reservoir operation / yield models: Several different methods will be available for this e.g. counting years of failure, deficient volumes, Gould, simulation;
- Hydropower generation models and outputs e.g. firm / secondary energy, power figures, shortfalls;
- Irrigation: Sustainable irrigable area of various crops, information on frequencies and durations of shortfalls;
- Reliability indicators e.g. reliability of reservoir yield, reliability of irrigation schemes.

2.3.4 Other modules / outputs

- Water quality / river ecology models and outputs: Again these could include physical, habitat, chemical and bacteriological indicators;
- Economic / financial models and outputs e.g. results of cost-benefit analysis, cost comparisons of alternative schemes.

3 Model review

Previous work by the Institute of Hydrology includes a number of studies in which models of an integrated water resource simulation-type have been developed for specific situations. For example, Gibb *et al.* (1988) and Piper *et al.* (1989) describe a water master plan for the Chi Basin in Thailand which involved development of a model to simulate the network of reservoirs, abstractions and irrigation schemes. The model was used to assess the optimum development options, and determine operating rules for the reservoirs and cropping intensities and scheduling for the irrigation schemes. As part of another study in Botswana, Gibb *et al.* (1992) and Meigh (1995) examined networks of large numbers of small farm reservoirs which were lying in the catchments of major water supply reservoirs and developed a user-friendly model of the systems. The model is used as a planning tool to assess the impact of both existing and proposed farm reservoirs on the water resources of the major water supply reservoirs. There have been other similar models specific to particular situations which have been developed by consulting engineers and by other researchers. For instance, a model for Adelaide, Australia where linear programming was used to optimise operating properties for pumping into reservoirs supplying the city (Crawley & Dandy, 1993).

However, in recent years, there has been an increasing tendency for models to be developed which are more generally applicable, and ten of these models, commercially available and of a broadly similar nature to the proposed IWRSM, or having at least some of the necessary functionality, have been reviewed. This section presents the findings of the review, which examined the models and assessed their applicability according to the specification outlined in section 2. The aim of the review was to investigate whether any of the existing models had enough of the required attributes to be considered as a possible baseline model for an IWRSM, which could then be developed in collaboration with another organisation.

3.1 MODELS

The ten models considered are listed below in alphabetical order. A more detailed description of each of the models is given in Appendix A.

- EUREKA (Jamieson, 1994). A comprehensive decision-support system for integrated river-basin planning developed from a combination of GIS, database technology, modelling capability, optimisation techniques and expert systems.

- FLOAT (Perceptive Systems & Software Ltd, 1994). A modular flow analysis tool with mouse-driven user interface and a range of data visualisation capabilities overlying a DBMS, which was developed to aid the water industry worldwide.

- HEC-5 (HEC, various dates; Eichert, 1994a). A well-established model which has developed from the original simple flood control system to a highly complex, multifarious tool that provides capabilities in flood control, hydropower and water supply simulations.

- HYMAS (Hughes *et al.*, 1994). A model suite covering many of the hydrological estimation requirements that are essential to the development of river basin planning and management strategies.

- IGSM (Montgomery Watson, 1995). A comprehensive catchment planning tool, combining groundwater, surface water, water quality and reservoir simulation routines, developed to aid water resource planning and management.

- IRAS (Loucks *et al.*, 1995). A generalised model with a graphical user interface for simulating the quantity and quality of surface water and groundwater, which was developed to provide a tool for evaluating the performance of water resource systems.

- ISIS (Halcrow / HR Wallingford Ltd, 1995). A system for simulating flow, water quality and sediment transport in canals, rivers and estuaries, which was developed to assist in the design of engineering schemes and the development of river basin management plans.

- MOSPA (Ringham *et al.*, 1994; WSC, undated). An integrated suite of programs for simulating the operational performance of water supply systems, and for deriving medium-term policies which minimise operating costs while satisfying reliability constraints.

- SWRRB (Arnold *et al.*, 1993). A simple groundwater flow and level model added to an existing basin-scale surface water model to provide a tool for water resource development and planning.

- WATHNET (Kuczera, 1992). A generalised reservoir simulation package using linear programming and a mouse-driven user interface, which was developed to assist in the planning and operation of reservoir systems.

3.2 REVIEW

Table 3.1 summarises how each of the ten models performed in terms of the IWRSM specification. For the majority of the models this assessment was done through a survey of recent documentation, and therefore incorporated a degree of subjectivity on the part of the authors as to the interpretation of particular model components or features. The main points of the review are discussed below.

3.2.1 General features

Common general features include the ability to add in newly-developed model algorithms and subroutines (not in WATHNET), ability to model catchments and component sub-catchments at a variety of spatial scales, good reporting and graphing facilities, comprehensive user manuals and documentation (although ISIS is weak in this respect), and system / database administration and management facilities. The majority of models also have the ability to operate at a variety of temporal scales, with the exception of the basically monthly IGSM, the daily SWRRB and the monthly WATHNET. Similarly, the majority of models can be easily reconfigured to test alternative scenarios, with the exception of EUREKA, FLOAT and HEC-5, the former and latter putting some emphasis on potential problems. However, in reality, no model as complex as these will be "easily reconfigured", but the process should be made as problem free as possible for the user. All the models claim to be user-friendly, and operate on the microcomputer and/or Unix workstation platforms now commonly found in offices in the UK and, for the former, increasingly in developing countries.

There are essentially only two general features where models vary significantly, and these are the presence, or absence, of a database for storing input data and results, and a map-based graphical user interface to help users set up and operate the model. Only two of the models have an underlying database i.e. EUREKA and FLOAT; the other rely on input and output data files and pre- and post-processing programs to set up and analyse these files. Half of the models have a map-based front end i.e. again EUREKA and FLOAT, but also IRAS, ISIS and WATHNET; the others tend to use shell programs which display menus of the available options, with schematic representations of the model configuration sometimes available.

In summary, in terms of general features, all ten models displayed much of the functionality sought, and the superficial differences between the models are small. The presence of a database and/or the standard of the front-end are the key factors which discriminate between different models.

3.2.2 Hydrological and water resource features

By definition, all of the models have some water quantity components. Just over half also model water quality to a greater or lesser extent, whilst just under half include some sort of economics component. EUREKA is the only model to include both quality and economics, whilst WATHNET is the only model to exclude both.

Table 3.1 *Summary of model performance*

Feature	EUREKA	FLOAT	HEC-5	HYMAS	IGSM	IRAS	ISIS	MOSPA	SWRRB	WATHNET
General features										
Ability to add new model algorithms	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Modelling at variety of spatial scales	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Modelling at variety of temporal scales	✓	✓	✓	✓		✓	✓	✓		
Relational database management system	✓	✓								
Map-based graphical user interface	✓	✓				✓	✓			✓
Ease of reconfiguration				✓	✓	✓	✓	✓	✓	✓
Good reporting and graphing facilities	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Good user manuals and documentation	✓	✓	✓	✓	✓	✓		✓	✓	✓
System / database administration facilities	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
User friendly system	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Platform (Unix, Pc, Vax, Macintosh)?	U	U P	P	P	P	U P V	U P	U P	U P M	U P
Hydrological / water resources features										
Rainfall analysis / modelling				✓					✓	
Rainfall-runoff modelling	✓			✓	✓		✓		✓	
Flow analysis / modelling		✓	✓	✓						
Flow routing	✓		✓	✓	✓	✓	✓		✓	✓
Stage - flow conversion										
Snowmelt / glacial melt modelling									✓	
Evapotranspiration modelling				✓					✓	✓
Groundwater / sub-surface flow modelling	✓			✓	✓	✓			✓	
Reservoir simulation module	✓		✓	✓	✓	✓		✓	✓	✓
Hydropower module			✓			✓		✓		
Irrigation module	✓		✓		✓					
Water quality / river ecology	✓			✓	✓	✓	✓		✓	
Economics / financial	✓	✓	✓					✓		
Rating										
General features / 10	9	9	7	8	7	9	8	8	7	7
Hydrological / water resources features / 13	7	2	6	8	6	5	3	3	8	3
Total rating / 23	16	11	13	16	13	14	11	11	15	10
Potential in developing countries?		✓	✓	✓		✓			✓	

Considering the water quantity components in more detail, the number of components included, and the degree of modelling within each component vary considerably between models. The two most common components are flow routing (except in FLOAT and MOSPA) and reservoir simulation (except in FLOAT and ISIS), whilst none of the models appear to include stage-to-flow conversion, and only SWRRB has a snowmelt component. Most of the models are concerned with water once it is in the river, and so rainfall, evapotranspiration and flow (surface and groundwater) analysis modules are rarely included (only really in HYMAS and SWRRB). However, given adequate input data, half the models incorporate some level of rainfall-runoff modelling and groundwater modelling, with EUREKA, HYMAS, IGSM and SWRRB including both. Of the eight models which include reservoir simulation, only three extend this explicitly to hydropower, namely HEC-5, IRAS and MOSPA. Similarly, only three of the models include an irrigation component, which is particularly important in developing countries.

In summary, in terms of hydrological features, there are some great differences between the models. Some models include more of the basic components of the hydrological cycle e.g. HYMAS, whilst other models deal only with components directly relating to water resources. Out of a total of twelve features considered, the number included varies from as few as two, to as many as eight.

3.3 SUMMARY

The models descriptions given in Appendix A and the summary given in Table 3.1 show that all of the ten models considered already have some of the necessary functionality of the proposed IWRSM, to a greater or lesser extent. The models tend to incorporate the same general features, except for the presence of a database and/or the standard of the front-end. The differences between the models are better defined by the hydrological and water resources features, with the components which are included dependent primarily upon the origins of the models, as discussed below.

MOSPA and WATHNET are integrated systems for modelling water resources in the context of water supply, hence they really have only the hydrological features necessary for their current purpose. Other integrated systems have developed as different components are added to a base model. For instance, ISIS started off as a hydrodynamic model to which hydrology and water quality modules have been added, HEC-5 began as a flood control system to which water resources modules have been added, and HYMAS originated as a set of hydrological process models which has expanded to include water resources and water quality modules. Similarly, three of the models i.e. IGSM, IRAS and SWRRB, appear to have been developed from the combination of existing surface water and groundwater models, to which water resources and water quality modules have again been added. Only two of the ten models considered have been conceived from their beginning as integrated water resource simulation-type models i.e. EUREKA and FLOAT, though the latter is basically a front-end awaiting an underlying model suite.

The potential for application of each model in developing countries must also be considered, and Table 3.1 summarises the results of this assessment. The appraisal was based on the data requirements of the models and their ease of use, though previous documented applications in developing countries were also taken into account.

Table 3.1 shows that half the models are regarded as having potential for application in developing countries i.e. FLOAT which was evolved to aid the water industry worldwide; HEC-5 which, though possibly difficult to set up initially, has been applied in numerous countries worldwide, including some in Africa; HYMAS which has been developed in South Africa and is therefore to some extent aware of the problems that might be encountered in developing countries; IRAS which has again been produced with developing countries, as well as developed countries, in mind and has been used in India; and SWRRB which has been designed to accept readily-available inputs of data, though it has only been tested in the USA. The front-runners must be those with both high ratings and potential for application in developing countries, namely HYMAS, IRAS and SWRRB.

The reasons for rejecting the other five models, as far as application in developing countries goes, rest mainly with their data requirements and functionality. MOSPA and WATHNET have been developed to solve specific problems, so are limited in their functionality, though WATHNET in particular could probably be used elsewhere fairly easily. EUREKA, IGSM and ISIS are clearly extremely powerful tools, but the documentation implies that this strength is at the cost of highly extravagant data needs. In addition, these models generally require powerful workstation computing platforms, thereby putting them beyond the reach of most developing countries. EUREKA is still under development, but is acknowledged as possibly difficult to set up initially, and prototypes have only been tested in the UK and Mexico, whilst IGSM has only been applied in the USA, and ISIS is also still under development.

4 Options for IWRSM development

The model review has shown that several of the existing integrated water resource simulation type models have many of the attributes of the proposed IWRSM. When considering whether or not to develop another model, whether is it either necessary and/or desirable to repeat much of the work that has already been undertaken by other organisations must be taken into account. In addition, the priority must be to complete the IWRSM as soon as possible so that it can start to be applied to critical water resources problems. At least five of the ten models examined in the review can be considered as possible baseline models for the IWRSM, which could possibly be developed in collaboration with other organisations. This section seeks to outline the various options available for the way forward, and identify the preferred option.

4.1 OPTION 1 : IWRSM DEVELOPMENT BY INSTITUTE OF HYDROLOGY

This option entails the Institute of Hydrology developing the IWRSM alone from first principles, and according to the specification outlined in section 2

The advantages of this approach are that model development would not have to take into account any existing model components other than those regarded as particularly useful, and that the model would be tailored to meet a specific objective, namely for use primarily in developing countries. However, the corresponding disadvantages are that model development would be at least two to three years behind that of some of the existing models (by which time they would be some years further ahead), and the limited resources and time scale would be spent repeating some of the valuable work already done by other organisations which seems neither desirable nor necessary.

Although this approach does have its advantages, this option cannot be regarded as viable, unless other paths of investigation fail, for the reasons described above.

4.2 OPTION 2 : ADOPTION OF EXISTING IWRSM-TYPE MODEL FOR USE BY DEVELOPING COUNTRIES

Under this approach, the Institute of Hydrology would essentially adopt one or more of the suitable existing integrated water resource simulation-type models, and exhaustively test and evaluate it. The model(s) would be included under the Institute of Hydrology's software umbrella, and the Institute of Hydrology would undertake promotion, sales and training of the model(s) in developing countries, but would not be involved in upgrading and refining the model(s).

The advantages of this approach is that model development would be fully undertaken by other organisations, and that the Institute of Hydrology could concentrate on application of the model(s) and technology transfer. However, the former advantage is also a disadvantage in that the Institute of Hydrology could have no say in current and future model development i.e. should the model(s) fail to include an important feature, it might therefore become necessary to develop a piece of dedicated supplementary software which goes against the aim of producing a generalised integrated model which can be applied anywhere.

This option also has advantages, but as the model review indicated, none of the existing models currently have the complete functionality of the proposed IWRSM, and so it is unlikely that this option is feasible either.

4.3 OPTION 3 : COLLABORATION TO DEVELOP IWRSM

This option accepts the model development work by other organisations and seeks collaboration between the Institute of Hydrology and one of those organisations to refine their existing model to the IWRSM specification, so that it can be applied to water resource problems as soon as possible.

The advantage of this approach is that, as well as providing a potentially valuable link between the Institute of Hydrology and another organisation which could be mutually beneficial, the work already done can be consolidated and areas requiring further development prioritised so that the resources available to the Institute of Hydrology and partner organisation can be used as effectively as possible, concentrating on the strengths of both organisations. The obvious disadvantage is that the potential collaborators may not wish to collaborate as they might have their own vision of future model development and application.

Given that collaboration is possible, then this is clearly a sensible option. The Institute of Hydrology would be able to contribute in the areas where it is best placed to, and would be able to exploit its record of overseas experience to apply the model and train local staff in its use. The baseline model could in reality be any five or six of the ten considered in the earlier review, but only those with high ratings and potential for application in developing countries are mentioned further. The Institute could help add a database to IRAS, HYMAS and SWRRB, as well as assist in improving the user interface to the latter two, refining other general features as necessary, and particularly providing models for hydrological processes, water resources, water quality and economics where required. Indeed the Institute of Hydrology already has other research links with some of these organisations and model developers which would enhance the prospects for collaboration.

4.4 OPTION 4 : JOINT COLLABORATION TO DEVELOP IWRSM

This option is a variation of option 3, in which the Institute of Hydrology seeks collaboration with more than one of the organisations who have already developed integrated water resource simulation-type models. This option could increase the benefits to each participating organisation, though would probably have greater logistical problems. Table 3.1 indicates that potential gains are likely from any combination of the models regarded as suitable, though the most beneficial would probably be to combine a strong water resources model with an existing map-based graphical user interface e.g. IRAS, and a more process-dominated model e.g. HYMAS or SWRRB, and add on a database. Like option 3, this option clearly has some potential, but would be more difficult to organise and administer than option 3.

5 Summary

This report has identified the need for an IWRSM and provided a provisional model specification. The review of ten existing models of a similar nature to the proposed IWRSM was a useful exercise, identifying several models with many of the general and hydrological features required, and with potential for application in developing countries. Various options for the development of the IWRSM have been considered, and preferred options identified. This section summarises the findings and conclusions presented in this report, and describes the next steps to be carried out.

The proposed IWRSM should be a generalised model which can be configured for most river basins and applied to most water resources problems, and section 2 itemises the large number of features, both general and hydrological, that will need to be incorporated into the model in order for it to fulfil its objectives. Many of these elements already exist in some shape or form, some already combined together to produce integrated water resource simulation-type models, and ten of these models were reviewed.

All of the models already have some of the necessary functionality of the proposed IWRSM, tending to incorporate the same general features, except for the presence / absence of a database and graphical user interface, but differing considerably in the hydrological features which they include, and their potential for application to water resource problems in developing countries. Section 3 describes the model review, and the reasons for selecting and discarding some of those models at this early stage. The three models most worthy of further consideration are: HYMAS (Hughes *et al.*, 1994) which is a model suite designed specifically for South African catchments, where data availability is highly variable; IRAS (Loucks *et al.*, 1995) which is a generalised model with a powerful graphical user interface developed to operate on the microcomputers increasingly found in developing countries; and SWRRB (Arnold *et al.*, 1993) which is a daily model designed to accept readily-available inputs in order to allow general use over large regions. Two other models, regarded as suitable for application in developing countries but otherwise not rating as high, are FLOAT (Perceptive Systems & Software Ltd, 1994) which is basically an impressive front-end and database awaiting an underlying model suite, and the well-established HEC-5 (HEC, various dates; Eichert, 1994a) which has transformed from a simple flood control system to a much more complex and powerful multifaceted package. Other models were discarded because of their large data requirements and/or lesser functionality.

Section 4 outlined the options for the way forward regarding development of the IWRSM. For the Institute of Hydrology to develop an IWRSM alone from first principles would discount the valuable work that has already been done by other organisations over the past five or so years. The Institute of Hydrology should aim to utilise this work to the best effect. To simply adopt one or more of these models for future application, but have no part in the further development of it, is one option, but as the review has shown, none of the models considered already have the complete functionality of the proposed IWRSM. The preferred option at this stage must be to try and collaborate with one or two of the organisations responsible for the best of the existing models, namely HYMAS, IRAS and SWRRB.

Demonstration versions of two of these models, HYMAS and IRAS, have already been obtained, and one for SWRRB is currently being sought. This will enable these three models to be studied in more detail, and the best model(s) selected. It may be useful to set up a register of water resources projects conducted by the Institute of Hydrology over the past ten years, for instance, so that it is possible to assess if any of the models would have been suitable for use, and what, if any, further model developments are needed. Once the best baseline model has been selected, collaboration will be sought with the appropriate organisation in order to complete model development and start applying the model to real problems.

In addition, cooperation with water departments in developing countries will be sought to ensure that the design of the model fulfils their requirements. Ideally one basin from each of two different countries will be selected, with the approval of their water departments, and visits to these countries will be made to collect the necessary information.

6 References

Arnold, J.G., Williams, J.R., Nicks, A.D. & Sammons, N.B. 1990. *SWRRB - A basin-scale simulation model for soil and water resources management.* Texas A&M University Press, College Station, 255pp.

Arnold, J.G., Williams, J.R., Griggs, R.H. & Sammons, N.B. 1992. *SWRRBWQ - A basin-scale model for assessing management impacts on water quality: Model Documentation and User Manual - Draft.* USDA-ARS, Temple, 195pp.

Arnold, J.G., Allen, P.M. & Bernhardt, G. 1993. A comprehensive surface-groundwater flow model. *J. Hydrol.*, 142, 47-69.

Crawley, P.D. & Dandy, G.C. 1993. Optimal operation of multi-reservoir system. *Journal of Water Resources Planning & Management*, **119**, 1-17.

Eichert, W.S. 1993. *Summary of capabilities for HEC-5.* Eichert Engineering, El Macero, California, 10pp.

Eichert, W.S. 1994a. *Capabilities description for HEC-5.* Eichert Engineering, El Macero, California, 23pp.

Eichert, W.S. 1994b. *Eichert Engineering changes to the HEC-5 package.* Eichert Engineering, El Macero, California, 8pp.

Futter, M. 1995. Integrated water resources management. *World Water and Environmental Engineering*, May, 24.

Sir A. Gibb & Partners, Institute of Hydrology, Minster Agriculture Ltd, TEAM Consulting Engineers. 1988. Chi Basin Water Use Study - Final Report. *Confidential report to Royal Irrigation Department, Bangkok, Thailand.*

Sir A. Gibb & Partners, Institute of Hydrology. 1992. A study of the impact of small dam construction on downstream water resources. *Confidential report to Department of water affairs, Gaborone, Botswana.*

Halcrow. undated. *ONDA User Manual.* Sir William Halcrow & Partners Ltd.

Halcrow / HR Wallingford Ltd. 1995. *ISIS publicity brochure.* Sir William Halcrow & partners Ltd / HR Wallingford Ltd, 4pp.

HEC. various dates. *HEC-5 User Manuals & various training documents.* US Army Corps of Engineers, Davis, California.

Hughes, D.A. 1992. A monthly time step, multiple reservoir water balance simulation model. *Water S.A.*, **18**, 279-286.

Hughes, D.A. 1994. Soil moisture and runoff simulations using four catchment rainfall-runoff models. *J. Hydrol.*, 158, 381-404.

Hughes, D.A., Murdoch, K.A. & Sami, K. 1994. A hydrological model application system - A tool for integrated river basin management. In Kirby, C. & White, W.R. *Integrated River Basin Development*, 397-406.

Hughes, D.A. & Sami, K. 1994. A semi-distributed, variable time interval model of catchment hydrology - Structure and parameter estimation procedures. *J. Hydrol.*, **155**, 265-291.

Hughes, D.A. & van Ginkel, C. 1993. Nutrient loads in runoff from developing urban areas - A modelling approach. *Proc. Sixth South African National Hydrology Symposium*, Sept. 1993, Pietermaritzburg, South Africa.

Jamieson, D.G. 1994. Eureka EU 487 : A decision-support system for integrated river-basin planning. *BHS Occasional Paper No. 4.*

Kuczera, G. 1992. Water supply headworks simulation using network linear programming. *Advances in Engineering Software*, **14**, 55-60.

Loucks, D.P., French, P.N. & Taylor, M.R. 1995. *IRAS - Interactive River - Aquifer Simulation : Program Description and Operation*. Cornell University & Resource Planning Associates, Inc., Ithaca, New York.

Meigh, J.R. 1995. The impact of small farm reservoirs on urban water supplies in Botswana. *Natural Resources Forum*, **19**, 71-83.

Montgomery Watson. 1995. *Integrated Groundwater and Surface Water Model (IGSM) - Reference Information*. Montgomery Watson, High Wycombe, UK.

Natural Environment Research Council (NERC). 1975. *Flood Studies Report*. Institute of Hydrology, Wallingford, UK, 5 volumes.

Perceptive Tools & Software Ltd. 1994. *FLOAT - The FLow Optimisation and Analysis Tool*. Perceptive Tools & Software Ltd, Farncombe, UK, 10pp.

Piper, B.S., Sukhsri, C., Thanopanuwat, S. & Knott, D.G. 1989. A simulation model for planning water resource developments in the Chi river basin. *Water Resources Management*, 3, 141-153.

Pitman, W.V. 1973. *A mathematical model for generating monthly river flows from meteorological data in South Africa*. Report No. 2/73, Hydrological Research Unit, University of Witwatersrand, Johannesburg, South Africa.

Ringham, J., Howard, K. & Wyatt, T. 1994. An integrated approach to modelling water resource and supply systems. *BHS Occasional Paper No. 4*.

Smithers, H. & Wyatt, T. 1994. Modelling the possible redeployment of Lake Vyrnwy. *BHS Occasional Paper No. 4*.

US Soil Conservation Service (USSCS). 1972. *National Engineering Handbook*. USSCS.

Walker, S., Walsh, P.D. & Wyatt, T. 1989. Derivation and application of medium-term operating policies for the Northern Command Zone system of North West Water (UK). In IAHS *Closing the gap between theory and practice*, IAHS Publ. No. **180**, 53-62.

Wallingford Software Ltd. undated-a. *SALMON User Manual*. HR Wallingford Ltd.

Wallingford Software Ltd. undated-b. *Hydroworks User Manual*. HR Wallingford Ltd.

Water Systems Consultants Ltd (WSC). undated. *The MOSPA computer program suite*. WSC, Henley, UK, 3pp.

World Bank. 1993. *Water Resources Management - A World Bank Policy Paper*.

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Appendix A Model descriptions

A.1 EUREKA

EUREKA is the product of an ongoing, collaborative research project to produce a comprehensive decision-support system for integrated river-basin planning (Jamieson, 1994). Figure A.1 shows the basic system architecture, the components of which are listed below.

- Interactive user interface to access applications and components of system, overlying main program for coordinating tasks.
- GIS for storing, displaying and analysing spatial data e.g. maps, satellite imagery, coupled with DBMS for storing non-spatial data e.g. site information, time series data.
- Analytical tools i.e. simulation, optimisation and expert system models.
- Pre- and post- processors for editing of input data and analysis of model output.

To date, the analytical tools include a water resources planning model which can select the best reservoir site; several hydrological models ranging from the simple RRM daily lumped rainfall-runoff model to the fully distributed, finite difference SHE model for surface and subsurface flows, soil erosion and sediment transport; groundwater / surface water pollution models; and an agricultural water use model. The system will eventually also include water quantity and quality in estuaries and coastal waters.

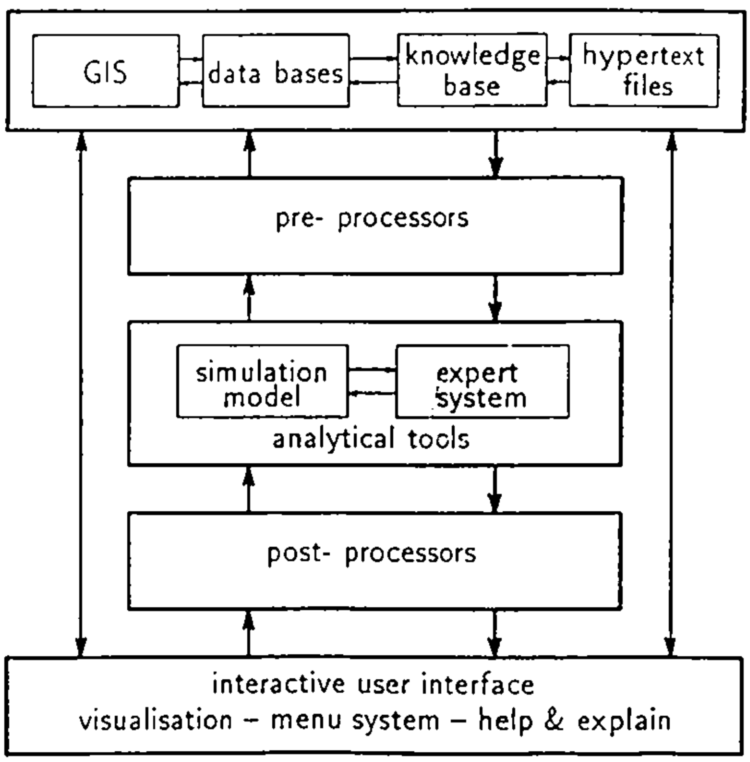

Figure A.1 System architecture (After Jamieson, 1994)

Jamieson (1994) mentions application of the system to the Thames Basin in the UK and to the Rio Lerma / Lake Chapala Masterplan in Mexico. Indeed, the general impression is that the model has been designed primarily for use in Europe and North America, requiring powerful and expensive workstations and demanding data not generally available outside these countries. In all the model appears to be perhaps too complex and sophisticated for widespread general application in developing countries.

A.2 FLOAT

FLOAT (Perceptive Systems & Software Ltd, 1994) consists essentially of a mouse-driven user interface with a range of data visualisation capabilities overlying a DBMS with associated system management facilities. To date this highly flexible system has been used to store and perform simple analyses on flow and related economics data, hence its name FLOAT (FLow Optimisation and Analysis Tool).

The system is modular and ongoing development aims to incorporate scientific modules such as water cost and quality tracking and hydrological modelling, as well as increase the flexibility and graphics. However, at present, the model appears to have no surface water or groundwater modelling capabilities, and all inflow data and groundwater resource data must be presented to the model in the form of input data files.

FLOAT was developed with the aim of aiding the water industry worldwide, and the company has contacts in Botswana, South Africa, Zambia and Zimbabwe. Whilst the model has some of the required functionality, it is still at an early stage of development. There is no doubt that it could, in time, evolve into a suitable model, or that it could provide a base model for collaborative development.

A.3 HEC-5

HEC-5 was developed in 1972 as a simple flood control system, but has since transformed into a highly complex, multifarious tool that provides capabilities in flood control, hydropower and water supply simulations (HEC, various dates; Eichert, 1994a).

HEC-5 simulates single and multiple reservoir systems for flood control, hydropower and water supply for time intervals ranging from 1 minute to 1 month, and optimises reservoir storages and yields for hydropower, water supply and/or irrigation for time intervals ranging from 1 day to 1 month. Seven different flow routing techniques are available for flood control evaluations. Some economic analysis is also available. In addition, several utility programs enhance program user-friendliness. The Eichert Engineering version, which has been developed in the private sector since 1989, has some differences to the version still distributed by HEC, detailed in Eichert (1994b). Eichert (1993) summarises some of the general capabilities of HEC-5, which are described in more detail in Eichert (1994a).

The package was developed to assist in planning new reservoirs or new reservoir operating policies in a system, and in sizing the flood control, hydropower and water supply storage requirements for a system, and has been applied to hundreds of different systems in numerous countries, including some in Africa. However, though this model is powerful and flexible, it admits to perhaps lacking the user-friendliness necessary for it to be widely applicable by staff in developing countries.

A.4 HYMAS

HYMAS (Hughes *et al.*, 1994) is a suite of, currently, seven models covering many of the hydrological estimation requirements that are essential to the development of river basin planning and management strategies. The models have been incorporated into a single package with common procedures which form the four basic components of the system, and which are described briefly below.

- Parameter estimation and editing facilities, both for a set of standard physiographic and climatic characteristics describing the catchment, and for a set of model parameter values.
- Data input and editing options for generating input hydrological time series data files, including routines for converting different data formats to a standard format.
- Model running, either singly or as part of a batch process, the latter option being particularly relevant to applications, such a integrated catchment management, where a change made to one part of the system may affect the whole system.
- Model results display, listing and analysis procedures either for the whole system and/or the complete data series, or for user-specified parts of the system and/or periods of record.

HYMAS (HYdrological Model Application System) currently contains seven models including:

- Variable Time Interval (VTI) model (Hughes & Sami, 1994) for simulating catchment hydrology, including groundwater recharge and surface / groundwater interactions,
- RAFLES model (Hughes, 1994) which is a daily rainfall-runoff model with algorithms for soil erosion, sedimentation and reservoir storage,
- PEXP model (Hughes & van Ginkel, 1993) which is a daily model for estimating stormwater volumes and nutrient loads from developing urban areas,
- Pitman model (Pitman, 1973) which is a monthly rainfall-runoff model, widely used in southern Africa for water resources assessments,
- Multiple reservoir simulation model (Hughes, 1992) which is a monthly single / multiple reservoir water balance model frequently used in conjunction with the Pitman model,
- Design flood estimation model which is an hourly rainfall-runoff model incorporating a simple Muskingham flow routing component,
- Raintank resource model which is a daily roof runoff and raintank water balance model for evaluating the potential of raintanks for water supply in developing communities.

The model was developed specifically for South African catchments where hydrology and development status, and available information, are highly variable, and Hughes *et al.* (1994) demonstrate application of HYMAS to two catchments in South Africa. This model provides the most complete suite of hydrological subprograms of any of the systems reviewed, but currently has no real water resources components. The model could provide a useful base for collaborative development.

A.5 IGSM

IGSM (Montgomery Watson, 1995) is a comprehensive catchment planning tool which represents the surface and groundwater components of the hydrological cycle, quantitatively, qualitatively, and in an integrated manner. IGSM (Integrated Groundwater and Surface water Model) is a 3-dimensional finite element model which includes all the major elements of the hydrological cycle to enable simulation of groundwater, surface water, water quality and reservoir operation.

Figure A.5 shows the interaction between the hydrological components of IGSM. Integration between the groundwater and surface water flows is carried out using a mixture of soil moisture accounting and an unsaturated flow model. The groundwater part of the model operates on a monthly time step, whilst the surface water part can use either a daily or a monthly time step. The input data requirements include aquifer layer dimensions and type, storage capacity, flow rates, hydrogeological parameters, land use, water demand, rainfall, boundary inflows and water demand, and the model input data files can be prepared using pre-processing routines. Both the input and output files can be examined by post-processing routines and can be linked to a variety of GIS software.

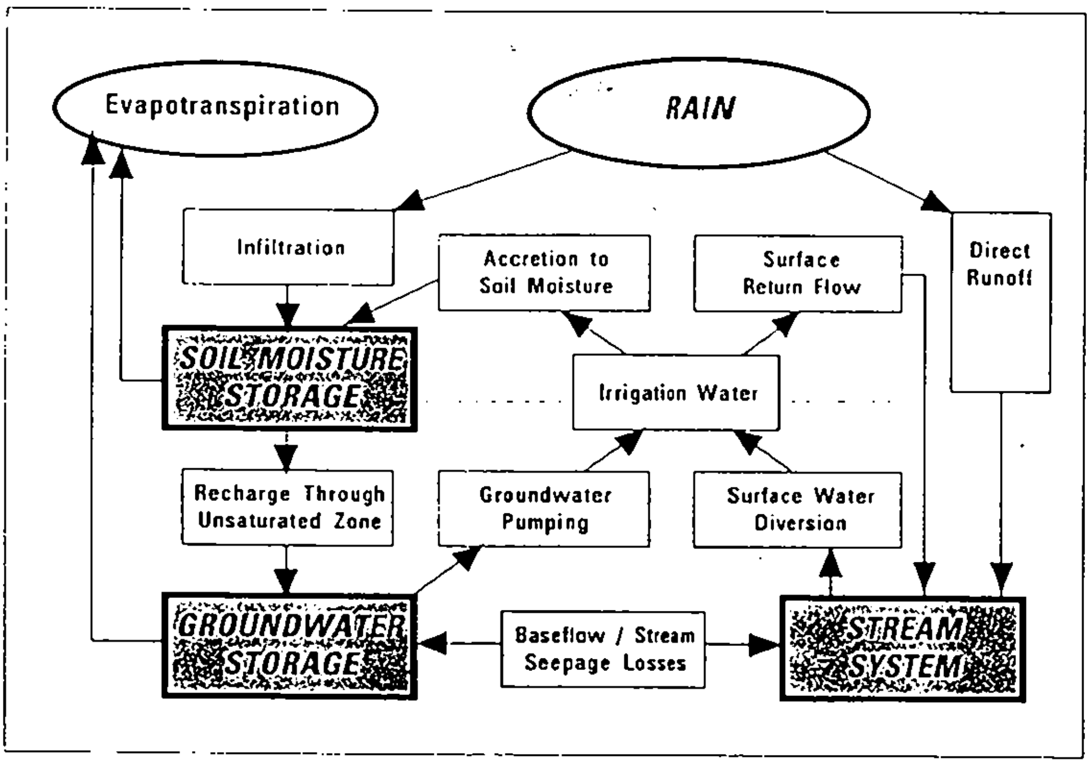

Figure A.5 Interaction between the IGSM's hydrological components

The model was developed to aid water resource planning and management through detailed investigation of many different options to enable identification of the most effective overall solution. The model has been refined over several major water resources projects in the USA, including a basin management plan for the Salinas Valley in California (Futter, 1995). This is basically a powerful combined surface and groundwater model, but one which appears to lack any real water resource systems components.

A.6 IRAS

IRAS (Loucks *et al.*, 1995) is a generic model for simulating the spatial and temporal distributions of flows, storage volumes, water quality, and hydropower production and/or energy consumption. IRAS (Interactive River - Aquifer Simulation) can evaluate the performance of any specific system configuration and set of operating policies, but cannot identify a preferred system design or alternative operating policies as it does not contain a system optimisation capability.

Figure A.6 outlines the IRAS simulation process. The first stages of the process entail identification of the study objectives and data requirements, collection and analysis of those data, generation of the input data files, and construction of the system network schematic. The mouse-driven user interface facilitates creating and editing of a digitised map image of the river basin; inputting, retrieving and editing system files and data files; defining alternative system operating policies; defining a water quality model to user requirements; operating the simulation program; and displaying, editing and printing the simulation inputs and outputs. The simulations are based on mass balances of quantity and quality constituents, taking into account factors such as flow routing, seepage, evaporation and consumption. Following the simulation runs, a variety of data presentation and statistical analysis procedures aid understanding of the model results.

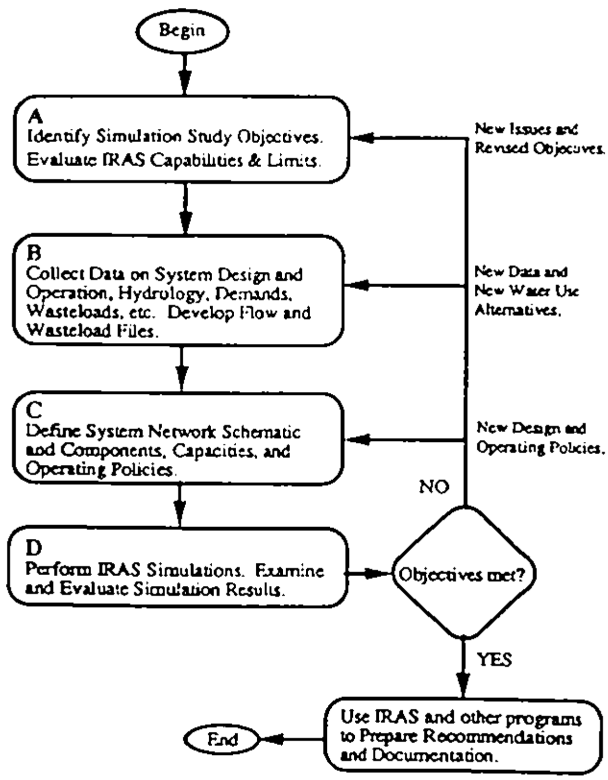

Figure A.6 The interactive river-aquifer simulation (IRAS) process (After Loucks et al.*, 1995)*

The model was developed to provide a tool for evaluating the performance of alternative designs and operating policies of regional water resource systems, and applications of prototype versions include irrigation planning in India and river water quality prediction in Canada, as well as numerous studies in the USA. This model is probably closest to the planned functionality required by the IWRSM model. If collaborative development were possible it may provide a cost-effective means of producing the sort of integrated basin model suitable for use in developing countries.

A.7 ISIS

ISIS is the prototype product of an ongoing joint venture to produce a comprehensive range of tools to assist in the design of engineering schemes and the development of river basin management plans (Halcrow / HR Wallingford Ltd, 1995). ISIS derives from the well-known SALMON (Wallingford Software Ltd, undated-a) and ONDA (Halcrow, undated) packages for hydrological and hydraulic modelling.

ISIS aims to be a modular system for simulating flow, water quality and sediment transport in canals, rivers and estuaries. The functions of the modules are outlined briefly below.

- FLOW module which is a fully hydrodynamic flow and level simulator for open-channel systems, which can model in-bank / out-of-bank flows in branched and looped networks.

- STEADY FLOW module which provides an alternative to the FLOW module, computing backwater profiles for design of channels and structures in branched and looped systems.

- HYDROLOGY module which provides a number of alternative hydrological techniques for modelling catchment and sub-catchment runoff to provide input time series to the FLOW module, including the FSR (NERC, 1975) and SCS (USSCS, 1972) methods.

- QUALITY module which uses the stored hydrodynamic data from the FLOW module to simulate water quality in river and channel networks.

- SEDIMENT module which simulates sediment transport using results from the FLOW module.

- WORKBENCH module which provides a user interface and tools to assist in building models, editing data and presenting results, as well as facilities for system management.

A future prospect entails combining ISIS with the established HydroWorks system for controlling water in the urban environment (Wallingford Software Ltd, undated-b) to provide a model applicable to both rural and urban environments. However, it seems clear at present that the emphasis in model development is as an engineering design tool for channel improvement / flood control purposes, and not for water resources assessment through the planning of new water resources schemes and the management of existing schemes. The model appears to be intended for rather different end goals to those required by general water resources planners and managers where modelling the whole river basin is the key objective.

A.8 MOSPA

MOSPA (Ringham *et al.*, 1994; WSC, undated) is an integrated suite of programs for simulating the operational performance of water supply systems, and for deriving medium-term policies which minimise operating costs while satisfying reliability constraints.

MOSPA (Modular Optimisation / Simulation Program) comprises six separate modules, described briefly below, which together cover the multifaceted requirements of water supply system management.

- Resource and supply system development planning module to minimise total capital and operating costs over a specified planning horizon.

- Long-term operations planning module for optimising long-term system and component operating policies; investigating relationships between operating costs, supply reliabilities and environmental protection constraints; demonstrating compliance with required levels of service; and determining system yield.

- Medium-term operations planning module for providing daily abstraction and system component throughput schedules; and analysing effects of hydrological and component availability scenarios on supply reliability, environmental conditions and operating costs.

- Medium-term operations planning for linear water supply systems module for providing optimised daily abstraction and system component throughput schedules with ranked alternatives.

- Medium-term operations planning for non-linear water supply systems module for providing optimised daily abstraction and system component throughput schedules with ranked alternatives.

- Pump scheduling and valve setting module for producing least cost pump and valve setting schedules which meet specified levels of service standards; and producing least cost schedules for individual pumping stations, taking account of pump efficiencies, hydraulic interaction and energy costs.

The modules incorporate simulation models of the water resource / supply systems and feature a number of different optimisation techniques including linear, dynamic and non-linear programming methods.

Walker *et al.* (1989) describe application of MOSPA to optimise operating policies in part of the North West Water region, whilst Smithers & Wyatt (1994) illustrate use of MOSPA in modelling the possible redeployment of Lake Vyrnwy in Wales. Again, whilst this model offers much of the required functionality, particularly as far as reservoir operation is concerned, it is not a truly integrated system as all hydrological inputs must be separately modelled externally and data read in from input files.

A.9 SWRRB

A simple groundwater model has been added to the existing SWRRB surface water model to produce a basin-scale, linked model (Arnold *et al.*, 1993) which allows simulation of water resources under various land use management, water resource management and climate change scenarios. Input data are provided in files, and a decision-support system assists users in the development of input data sets. Figure A.9 shows the flow chart for the linked model, which operates on a daily time step.

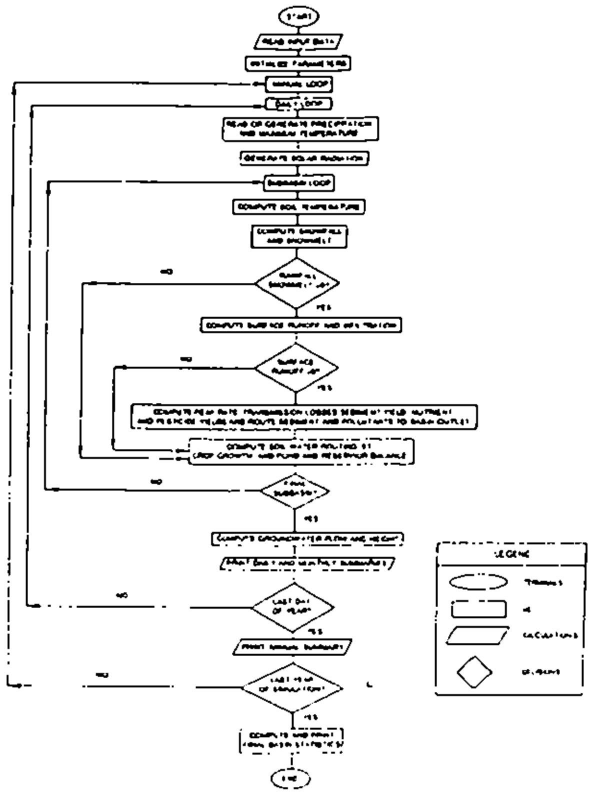

Figure A.9 Model operation flow chart (After Arnold et al.*, 1993)*

SWRRB (Simulator for Water Resources in Rural Basins), was originally developed to predict the effect of management decisions on water quantity in ungauged, rural basins (Arnold *et al.*, 1990), but more recently water quality components have been added (Arnold *et al.*, 1992). SWRRB has eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management, and detailed descriptions of each are given in Arnold *et al.* (1990; 1992). The groundwater model is a simple, yet realistic, flow and height model. Both models accept readily-available inputs in order to allow general use over large regions.

The linked model was designed to provide a tool for water resource development and planning, and Arnold *et al.* (1993) describe validation of the model on a basin near Waco, Texas. The model appears to be aimed primarily at irrigation and the possible effects of land use changes on water resources, and has no facility for reservoir operation modelling and hydropower.

A.10 WATHNET

WATHNET (Kuczera, 1992) is a generalised reservoir simulation package, made up of four modules, described briefly below. Figure A.10 shows the relationships between these modules and the files required to run each module.

- EDNET module is for configuring the system with the dedicated mouse-driven user interface to produce a schematic map which bears close resemblance to reality. Configuration entails either creating a new reservoir system or editing an existing one.

- WATSTRM module is for managing the required streamflow, demand and evaporation data which are held in columns in a single data file. Synthetic streamflow and climate data may be generated, together with summary statistics.

- SIMNET module is for simulating or optimising system operation using network linear programming to make all the operational decisions, based on system information and criteria supplied by the user.

- WATOUT module is for analysing the simulation results. Results may be presented at different levels of detail, depending upon user requirements. In addition, a playback feature provides a detailed snapshot of system operation at any time step.

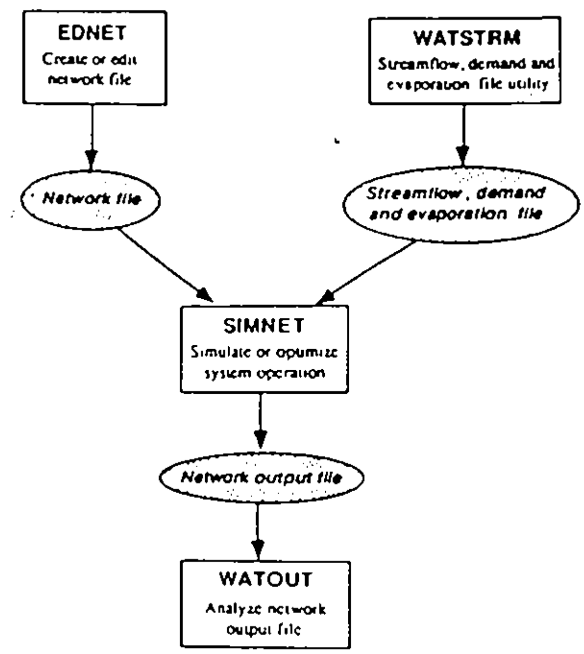

Figure A.10 Schematic of WATHNET programs (After Kuczera, 1992)

The model was developed to assist in the planning and operation of reservoir systems, and Kuczera (1992) demonstrates significant features of the model through reference to the Newcastle water supply reservoir system, Australia. This model also lacks the required integrated functionality in that much of the basic hydrological modelling must be undertaken externally.