A REVIEW OF CATCHMENT SCALE HYDROLOGIC MODELLING APPROACHES

A report as part of Project A1: Runoff and solute processes in high water table areas; measurement, modelling and management

C. Jayatilaka
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Report 95/5
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PREFACE

The material in this report is a contribution to one of the core research projects in the Cooperative Research Centre for Catchment Hydrology (CRCCH). The project, led by Dr Luke Connell, is entitled "Runoff and solute processes in high water table areas: measurement, modelling and management" (CRCCH Project A1). It is concerned with water and salt transport processes and how these are affected by land management. The CRCCH has undertaken this work because of the grave environmental problems posed by land and water salinisation in Australia.

This report reviews the broad spectrum of hydrologic modelling approaches described in the literature, emphasising the virtues and problems associated with physically-based, lumped-conceptual and hybrid catchment models. It was prepared by Dr Chandrika Jayatilaka (and her supervisor Dr Luke Connell), a Research Fellow at Monash University. The conduct of this review was a critical step in CRCCH Project A1 because a key objective of this project is to build a model capable of simulating water and salt transport processes in irrigation areas.

Dr Rob Vertessy
Deputy Director
Cooperative Research Centre for Catchment Hydrology

ABSTRACT

Catchment scale hydrologic models are generally based on two alternative modelling approaches. One methodology is the physically-based, distributed approach. With this, in general, each process impacting catchment hydrologic behaviour is described using the principles of physics. In contrast, lumped-conceptual models are based on simplifications introduced through a conceptualisation of the physical process.

This document reviews a number of models based on the two main approaches, and looks at their internal organisation with the aim of identifying their advantages and limitations with respect to application at the catchment scale for the problem of predicting catchment responses to change. In particular, the widely-known physically-based models, such as SHE, TOPOG and IHDM, are considered in detail. It is noted that lumped-conceptual catchment models have been useful for applications in areas such as water resource planning and management, and flood forecasting, but, as yet, lack a clear framework for applications in catchments undergoing natural and man-made changes. The physically-based, distributed catchment models are better suited to predicting the effects of land use change on catchment hydrology. However, the general application of these models at the catchment scale is compromised by their substantial data requirements, complexity and a number of other limitations.

The identified deficiencies of the lumped-conceptual models and the constraints associated with the detailed physically-based models point to the need for a pragmatic catchment modelling approach. An intermediate approach that allows for an appropriate combination of the characteristics of the two alternative approaches could provide the basis for formulating catchment models with greater potential for field application. A concept which could have implications for the development of such an approach is suggested in this study. Several models that have utilised intermediate approaches, and useful practical aspects of the models reviewed are also highlighted.

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SUMMARY

The use of mathematical models has a long tradition among hydrologists. As a result, we have inherited a wide variety of hydrological models that can be categorised according to several criteria. The hydrologic models that attempt to simulate hydrologic processes at the catchment scale are generally based on two main approaches. The early generation of catchment hydrologic models treat the catchment as a spatially averaged system, and use simplified methods to represent hydrologic processes. Over many years, these lumped-conceptual hydrologic models satisfactorily served the needs of engineering designs where the major concern was prediction of total flows and peak discharge rates. However, in recent years, with the recognition of the limitations of the conventional models, there has been a growing emphasis, and a demand for, a new generation of hydrologic models with the ability to predict the effects of man-made and natural changes on catchment hydrology. This has led to the development of physically-based, distributed catchment models.

This report reviews a number of models based on these two approaches. It includes descriptions on model structure, field applications, and provides discussions on strengths and weaknesses of models in simulating catchment hydrologic processes. In particular, the study focuses on the advantages and limitations of the models with respect to application at the catchment scale. The widely-known physically-based, distributed catchment models such as SHE, TOPOG, IHDM and SWAGSIM are considered in some detail. Several other models in this category (THALES, TOPMODEL and the WSHS) are also reviewed. Several rainfall-runoff models, SDI, CATPRO and MIDASS are among the lumped-conceptual models included in the review. The computational method called SALTMOD and a conceptual model developed for salinity modelling in Western Australia are also reviewed.

This study evaluates the suitability of various modelling approaches for hydrologic simulations in catchments. The two alternative modelling approaches reviewed indicate varying degrees of potential for application in different hydrologic simulations. Lumped-conceptual type catchment models can be used to predict spatially averaged catchment responses, and would be suitable in the absence of

spatially distributed model input. Models in this category have been successfully applied both for real-time flood forecasting, and in the extension of short streamflow records using longer rainfall records. When compared with the physically-based, distributed models, these models are structurally simple, and usually provide predictions with an accuracy that is commensurate with the measurements available in the field. However, models in this category utilise a large number of parameters and require long hydrometric records for calibration. The lumped-conceptual models are not applicable for predictions under land use change in catchments that can introduce conditions not represented in the calibration process.

Physically-based, distributed models can represent spatially-variable catchment properties and hydrologic processes, and provide multiple outputs on hydrologic response of the catchment. In theory, these models have the capability to evaluate catchment response under different management practices. Despite the purported abilities of the physically-based distributed models, their application is severely undermined by several disadvantages associated with them. Generally, models in this category have been designed to utilise parameters that have physical meaning. This implies that the model parameters can be estimated through independent measurement. Unfortunately, since this is not practical for most applications, calibration of parameters against observations is routinely performed in order to apply physically-based models. For accurate calibration, considerable care is required to ensure that a unique optimal parameter set is obtained and that the physical basis of the process representations is not obscured.

In order to apply physically-based models, the catchment is discretised into elements based on a grid network. A complication associated with this griding is ensuring that the grid element scale and geometry is compatible with the basis of the process descriptions.

The substantial computing requirements, complexity of the models and the requirement of special training for users are other constraints associated with the models in this category. The effect of such constraints on the applications of physically-based models to simulate catchment response to land-use change is clearly demonstrated by the few field applications reported so far, limited mainly to ideal circumstances.

The constraints associated with physically-based, distributed models and the inadequacies of the lumped-conceptual catchment models raise the need for a pragmatic approach for catchment hydrologic modelling. An intermediate approach that appropriately utilises characteristics of the detailed physically-based models and the useful features of the lumped-conceptual models could provide a basis for models with greater potential for field application. This principle could be implemented in representing catchment properties and hydrologic processes within catchments both in space and time.

Aspects of the existing models that could be useful in the development of such an approach are highlighted in this review. In addition, this study suggested a concept that could provide a useful basis for formulating an intermediate approach. It implies that sensitive areas of catchments (eg. near-channel areas) need detailed representation in catchment models, as the variations of catchment properties through land use change in such areas can have significant influence on output hydrologic quantities. Therefore, the catchment properties and hydrologic processes in these areas would have to be represented in a detailed, distributed manner. In contrast, less influential far-stream areas, where man-made or natural changes would have lesser effects on the hydrologic response of catchments, can be accounted for through the use of simplified, weighted-average or spatially-averaged methods. Such an approach would lead to more economical and efficient models by preserving the detail and accuracy in more sensitive parts of catchments, while rationally accounting for the processes in less effective areas. Several studies describing hydrologic models that have implemented such measures are included in this review.

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1. INTRODUCTION

The use of mathematical models to depict relationships between hydrologic processes and to estimate various hydrologic quantities has been common among hydrologists for more than a century. Over many years, conventional hydrologic models have satisfactorily served the needs of engineering designs where the major concern was prediction of total flows and peak discharge rates. In recent years, however, the increasing cost of water resources development and the emphasis on the quality of water resources, led to the recognition of deficiencies in the conventional models, and spurred the development of new hydrological modelling approaches. This new generation of models has focussed on simulating the effects of natural and man-made changes on catchment hydrologic behaviour.

Generally, catchment models attempt to simulate dynamic hydrologic processes that describe water balance at the catchment scale. The wide range of currently available catchment hydrologic models can be categorised according to several criteria (Mein 1977; Haan *et al.* 1982; Wheater and Jakeman, 1993). The most widely used criteria involve: (1) the character of the results obtained, and (2) the cognitive value of a model. According to the former criterion, the models are generally based on 'deterministic' and 'stochastic' approaches, or on various combinations of the two. In stochastic catchment models, one or more model variables are regarded as random variables having distributions in probability, and therefore, the output produced has certain statistical properties. On the other hand, variables used in deterministic models are considered to be free from random variability (Haan *et al.* 1982).

In general, stochastic models seek to reproduce statistical behaviour of a hydrologic time series without particular attention to an actual event or to the actual processes. Consequently, the stochastic approach is widely used for time periods which average out the transient responses (Dawdy 1969). Stochastic models generally provide estimates of statistical rather than historical sequences of hydrologic quantities (Mein 1977). A major constraint associated with this approach is the requirement of long records of data for model calibration.

The deterministic catchment models utilise a series of mathematical equations to represent effective physical processes. According to the type of equations and the solutions utilised, the models in this category can be of the numerical, empirical or analytical type, or combinations of these types. The deterministic approach, which is also referred to as parametric modelling, usually requires input data of considerable detail. However, unlike the stochastic type models, models based on the deterministic approach can be utilised to model transient systems (Dawdy 1969).

According to the second criterion considered here, based on the cognitive value, a model can be physically-based or of conceptual type. In physically-based models, the governing physical laws and the model structure are well-known, and catchment hydrologic processes are modelled with the use of mathematical equations and physically-based catchment parameters. In physically-based distributed parameter models, the catchment is treated as a spatially variable system: catchment parameters, hydrometeorological input and hydrological response are dependent on their location. Generally, variations of these elements are represented via a grid network over the area considered. A sub-category of physically-based distributed parameter models is based on topographic analysis of catchments, also known as terrain based models. Models in this category are based on a widely accepted concept that emphasises the role of catchment morphology in controlling flow processes (Bonell 1993).

In contrast to the distributed parameter models, lumped parameter catchment models spatially average the hydrometeorological parameters and hydrologic processes effective at the hillslope scale, and are typically applicable to problems requiring prediction of a spatially integrated hydrologic response (Kuczera *et al.* 1993).

Although the physically-based distributed parameter models are theoretically more satisfying, their general applicability is limited by their elaborate input data requirements, and the human expertise and computer resources requirements associated with field applications. Nevertheless, such models provide a useful means for simulating the spatially variable complex catchment hydrologic processes in detail. As a consequence, in recent years, there has been significant activity aimed at development of physically-based distributed parameter catchment hydrologic models.

The majority of the catchment hydrologic models described in the literature can be classified according to the above categories, or into combinations of them. In addition to the approach used in a model, it is important to note the capacity of the model to account for various catchment hydrologic processes. More comprehensive models include the known land-phase processes of the hydrologic cycle of water movement, and can predict solute and particulate movement within catchments. On the other hand, case specific models are designed to accommodate processes that are characteristic of the problem concerned.

1.1 Objective of the Study

The Cooperative Research Centre for Catchment Hydrology project, "Runoff and solute processes in high water table areas", has the objective of developing a model to explain salt export via the stream system from irrigated catchments.

In order to select the modelling procedure appropriate to this objective, a literature review was undertaken, which this report presents. The main objective of this review is to consider, in some detail, some of the existing approaches to catchment modelling. However, this review is not intended to be a comprehensive catalogue of different models, instead, considers published applications for several key examples from the main categories of modelling methodology.

This report;

a) presents a review of catchment modelling approaches and considers in detail the **internal structure** that results and the implications this has for modelling flow and transport.

b) attempts to identify the advantages and limitations of different modelling approaches with respect to application at the catchment scale for predicting catchment response to change.

A subset of models that enables the objective of this review to be addressed was selected from the literature. In particular, the models were chosen due to the emphasis on the model structure and their implications in modelling flow and/or solute transport processes in catchments. This study provides more detail on well-known physically-based distributed models. Several other physically-based and lumped-conceptual models are also reviewed. It should be noted however, the level of detail presented in the discussion of models is a result of the availability of information on each model.

This study also attempts to evaluate strengths and weaknesses of different modelling approaches. The strength of a model is determined by its apparent ability to account for the dominant hydrologic processes that become effective due to the interaction of topographic, climatic, geologic factors, and vegetation characteristics associated with catchments.

In applications for prediction of water quality, the capability of a model to adequately account for the mechanisms of runoff generation is considered as a vital feature, as that determines source components of the flow hydrograph and hence different sources and paths of solutes.
Therefore, the ability of a model to allow for the major flow processes (subsurface flow, saturation excess overland flow and infiltration excess overland flow) to occur under the appropriate conditions is essential. In particular, the ability to represent expansion and contraction of source-areas, and the capability to account for the dynamics of the near-stream area flow system are treated as indicators of suitability of a catchment model.

2. PHYSICALLY-BASED DISTRIBUTED PARAMETER MODELS

During the last decade, there has been growing attention focussed on the development of models in this category which treat the catchment as a spatially variable system. In such models, input required and the output produced are dependent on the location within the catchment. The most widely known models in this category, the SHE (European Hydrologic System) model (Abbott *et al.* 1986a, b), IHDM (Institute of Hydrology Distributed Model, Beven *et al.* 1987), TOPOG (O'Loughlin 1986; Vertessy *et al.* 1993) and a few other models are included in this review.

2.1 European Hydrologic System (SHE)

2.1.1 Description of the model

SHE is an advanced, comprehensive modelling system, capable of accounting for major hydrological processes of the landphase of the hydrological cycle. It is a deterministic, distributed and physically-based model, and was originally developed jointly by the British Institute of Hydrology, the Danish Hydraulic Institute (DHI) and SOGREAH (France). Further developments based on the original SHE modelling concept introduced by DHI are incorporated into a modelling package known as MIKE-SHE.

In SHE, spatial variation of catchment parameters, hydrometeorological input and hydrologic response is facilitated by an orthogonal grid network in the horizontal dimension, and a column comprising several nodes in the vertical dimension at each grid cell. The vertical columns, which represent the unsaturated zone, provides the link between the two identical horizontal grid networks representing overland flow and groundwater flow. The channel/river systems are represented along the boundaries of grid elements. The horizontal grid spacing is considered to be fixed, whereas the vertical node spacing is allowed to vary according to the vegetation type in a grid cell. In addition, the vertical spacing in the root zone can be different from that in the soil layer below the root zone.

Hydrological processes of water movement within catchments are modelled using either numerical solutions (finite difference) of partial differential equations or experimentally derived empirical equations representing the flow processes, the different components of the model being executed simultaneously. Detailed descriptions of SHE are given in Abbott *et al.* (1986a, b), Refsgaard *et al.*, (1992), Lohani *et al.* (1993) and in user guides. A brief description of the basic model components is presented here.

Interception and Evapotranspiration Component:

Two alternative formulations of modelling rainfall interception and evapotranspiration processes are available in MIKE-SHE:

(a) Interception is modelled by a modified Rutter model (Rutter *et al.* 1975). This estimates evaporation, the actual storage on the canopy, and the net rainfall reaching the ground surface as canopy drainage and throughfall. The actual evapotranspiration calculations are performed using the Penman-Monteith equation (Monteith, 1965). Potential evapotranspiration is read in as a time series, which could be calculated either from Penman method or simply from pan evaporation data (Pers. com. Storm, 1994).

(b) A method described in Kristensen and Jensen (1975) is used for interception and evapotranspiration calculations. Interception storage is estimated considering actual leaf area index and an interception capacity coefficient. Net rainfall is then calculated by a simple water balance approach. Potential evapotranspiration data is supplied as part of the model input. The actual evapotranspiration is calculated based on the potential rates and the soil moisture status in the root zone and the leaf area index.

Overland and Channel Flow Component:

When the net rainfall rate reaching the ground surface is in excess of the infiltration rate, surface ponding occurs, and this causes generation of overland flow when the detention storage is filled. The model accounts for the generation of overland from rainfall excess, and from rainfall on to saturated areas where the ground water table has risen to the ground surface. Overland flow in each grid cell is simulated by the two-dimensional form of diffusive wave approximation of the Saint Venant equation (Danish Hydraulic Institute, 1993). Channel flow is simulated using the one-dimensional form of the Saint Venant equation, based on a separate node system located along boundaries of the grid squares.

Unsaturated Zone Component:

Soil moisture distribution in the unsaturated zone is modelled via the solution of the one-dimensional form of Richard's equation. Soil moisture extraction through transpiration and soil evaporation is accounted for through sink terms at node points in the root zone. The infiltration rates at the upper boundary are calculated based either on flux controlled (prior to ponding) or head controlled (during ponding) condition. The lowest nodal point in a soil column is determined by the phreatic surface level. For each soil type, a relationship between the unsaturated hydraulic conductivity and the moisture content, and information on the soil moisture retention curve are required. Using these non-linear functional relationships, Richard's equation is solved numerically by an implicit finite-difference technique. The model allows for the disappearance of the unsaturated zone when the phreatic surface reaches the ground surface.

Saturated Zone Component:

In the original SHE, the groundwater flow is modelled via an implicit finite-difference solution of the two-dimensional partial differential equation of groundwater flow applicable for a single-layered aquifer. Recent developments include a multi-aquifer saturated flow component, which calculates temporal and spatial variations in the hydraulic head by solving the groundwater flow equation in three dimensions.

Aquifer-River Exchange Component:

Rivers are represented via the use of a separate node system running along the boundaries of grid squares, acting as a line source/sink. Flow exchange between the aquifer and the river is provided via three options using Darcy's law. Two of the options take the additional head loss around the river bottom into account in an approximate manner. In the third option, the exchange flow is determined based on the vertical head difference between the water level in the river and that in the adjacent grid square node.

Snowmelt Component:

This component includes two options. A simple option considers the snowmelt as a function of temperature using a degree-day factor. A more complex option models energy and mass flux within a snow pack considering changes in the snowpack structure. It is used when changes in temperature and structure can significantly affect the water flow within the pack.

Other processes/components:

Further developments of the model have also incorporated solute transport and chemical modelling (ion exchange, complexation, precipitation or dissolution) in unsaturated and saturated zones, soil erosion and irrigation modelling. The transport module, SHE-AD, includes three-dimensional and one-dimensional equations for advection and dispersion of solutes for the groundwater and the unsaturated zones, and two-dimensional and one-dimensional form of the equation for the overland and channel flow, respectively.

The present model can account for subsurface pipe drainage flow, surface retention, and macropore flow as bypass to porous media flow. SHE is equipped with comprehensive pre- and post-processors including digitising, grid averaging, contouring and graphical presentations.

General Discussion:

Within the SHE model, simultaneous operation of hydrologic processes represented by each component is controlled by a central frame component. The model offers the flexibility to ignore processes which are not relevant to a given application. It also allows for different time steps for each component, and changes in time steps during a simulation depending on the rate of hydrological change. However, a common time step is used in the closely connected evapotranspiration, unsaturated zone and snowmelt components. The model makes several simplifying assumptions to reduce the computing requirement and can be treated as a quasi three-dimensional catchment hydrologic modelling system. As a distributed parameter model, it requires input data in considerable detail, quantified for each grid node for the components in use.

2.1.2 Model applications

Several applications of the SHE model have been reported at spatial scales ranging from a rainfall simulator (30 m^2) to a catchment of 5000 km^2 and simulation periods ranging from days to several years (Bathurst and O'Connell 1992).

Application in mid-Wales:

Bathurst (1986a) described the first application of the model to the headwaters catchment (with an area of 10.55 km^2) of the Wye river in mid-Wales. The catchment area was represented with a grid consisting of a 17 × 20 array of squares elements with a grid spacing of 250 m (for a discussion of the effects of the spatial scale on hydrologic simulations - see Section 4.1). In the process of calibration, a simulated flow hydrograph was qualitatively compared with the observed flow hydrograph and a match was obtained by changing only a few parameters, mainly the initial phreatic water level. The model was then tested against four different hydrographs using different initial phreatic levels. The differences observed were mainly attributed to the inadequacy of the model (at the time) to account for the subsurface flow through the natural pipe network and along the interface between soil layers.

Sensitivity studies of the model on this catchment (Bathurst 1986b) indicated that simulations can be equally sensitive to structural parameters (such as grid spacing and time step) and catchment parameters (soil and flow resistance coefficients). It was recommended that these structural parameters should be small by comparison with the scales of the spatial and temporal variations which they are used to represent. Also, the study highlighted the need for measuring the catchment parameters to which the simulations are most sensitive (at several representative field locations), and the possibility of evaluating less important parameters using data from the literature.

In addition, Bathurst (1986b) pointed out that the danger of obtaining equally satisfactory calibrations with different combinations of parameter values can be reduced by considering several different events in a catchment.

Applications in India:

In India, SHE was applied to six sub-catchments totalling approximately 15000 km^2 of the Narmada Basin in Madhya Pradesh (Refsgaard *et al.* 1992). The model developed was based on a coarse grid network with 2 × 2 km square elements (the effects of the spatial scale of elements on hydrologic simulations will be discussed in Section 4.1). It was necessary to carry out field measurements of the required input (mainly soil parameters) to supplement the already existing field information scattered among different professional agencies. The calibration procedure used for all six basins was based on a split sample test where the available time series records were divided into two parts. The first part covering a few monsoon periods with intervening dry periods was used for calibration, and the second part of similar length, was used for model validation. The calibration was based on the comparisons between simulated and observed monthly outflow hydrograph flows, outlet peak discharges and outlet baseflow rates. Phreatic waterlevel elevations were also used in a qualitative sense for calibration.

The simulated results indicated that SHE was able to reproduce rainfall-runoff processes in the monsoon environment of the Narmada basin. However, the results highlighted the inadequacy of the 2 × 2 km grid network to provide a complete physically-based, fully distributed description of the hydrologic system. In particular, this discretisation was not fine enough to represent the river channel systems with sufficient accuracy, and this had a considerable effect on the physical meaning of certain parameters. For instance, surface runoff, which generally runs overland for relatively short distances before joining a river channel, was routed over the land for relatively long distances in the model representation. Thus, the overland flow resistance coefficient had to be adjusted in the process of calibration to be more representative of the effects of channel routing (Refsgaard *et al.* 1992).

The less dense channel network in the model required groundwater to travel longer distances before contributing to the river as baseflow, and this influenced the simulated phreatic surface elevations. The calibrated hydraulic conductivity values were considered to account for that. However, this limit the use of hydraulic conductivity values based on field measurements and also the accuracy of simulated water table levels.

In general, the outcome of this study agrees with the suggestions made by Beven (1989) regarding the application of physically-based catchment models. Although SHE is a physically-based model, a certain degree of lumping and abstraction was required in the Indian application. This study highlighted the point that although the SHE model is generally applicable, it cannot be recommended for problems concerned only with prediction of discharges from a catchment. Such problems can be more economically, and simply handled by stochastic and conceptual modelling approaches. However, in dealing with problems concerned with land use changes, where traditional models are known be inadequate, SHE-type models are better suited.

Simulation studies with the SHE on the Kolar subcatchment (study area of 820 km^2) of the Narmada River were reported in Jain *et al.* (1992). The upper areas of the catchment were generally hilly, covered mainly by forest consisting mostly of skeletal soils with shallow depths. In the lower part of the catchment, where the soils are generally deep, hydrological response is known to be slower than in the upstream areas.

Information required for model parameter evaluation was not available directly from the study area. Therefore, evaluation was based on information available outside the catchment and the data obtained from a brief field measurement program and laboratory analysis. Again, a 2 × 2 km grid was used, and the model was calibrated and verified based on data available over three and two years, respectively. The model runs were performed initially over a three-year period using assumed initial soil moisture conditions.

The calibration process indicated that soil depth was an important parameter. It was observed that, in the upland regions of the catchment, tree roots penetrated into deep fissures in rocks, drawing water from greater depths than the soil zone. This necessitated use of a larger effective soil depth than that measured in the field. In the other areas, soil depths finally used in the model were shallower than those originally assumed.

Both in calibration and in verification, simulated hydrograph and runoff volumes were compared with observed values, and a reasonable reproduction of the hydrographs was obtained. Further, analyses of simulations at the Kolar catchment indicated that model output had a greater sensitivity to rainfall magnitude and its spatial distribution than to the soil and aquifer parameters.

Significantly, results from a preliminary simulation based on less realistic parameters were as good as those obtained with true field and laboratory data. This highlighted the fact that a good match between observed and simulated flows at the catchment outlet is not a sufficient test of model accuracy or realism. In addition, the results pointed out the importance of performing sufficient checks on internal process descriptions, in order to avoid a model such as the SHE being used as a traditional lumped-conceptual rainfall-runoff model (Jain *et al.* 1992). Field measurements of model parameters, time series of calibration data from observation wells, information on internal channel networks and flow measurements at several points within the catchment are useful for internal validation of such models.

Lohani *et al.* (1993) described an application of the SHE to an irrigation scheme in central India. Data required for this study were rainfall, potential evaporation, soil data, vegetation data, topography, geometry of canal systems, groundwater extractions, irrigation practices and water requirements. Simulations were performed at three scales; plot scale (single soil profile), field scale (typical length of 100 - 200 m) and command scale (hundreds of sq. km), using meteorological data over a two year period. Two irrigation application criteria were considered; pre-specified irrigation and automatic irrigation.

On the plot scale, the model was used to study the temporal variation in irrigation water requirements for various crops and to predict soil moisture status. On the field scale, simulations demonstrated the problems of non-uniform distribution of water across the field. The model was also used to illustrate soil moisture advancement with the propagation of irrigation from the top end of the field. On the command area scale, simulations included shortage in water supply and priority of supply to individual fields. In this study there were no comparisons with field data.

Application in the Tragowel Plains, Victoria:

Mudgway and Nathan (1993) used SHE to model flow and salt transport processes between shallow groundwater and surface drainage in an 8.9 ha set of irrigation bays in the Tragowel Plains in north-central Victoria, Australia. The study area was covered with clay-rich soils with swelling and cracking properties that strongly affected soil hydraulic conductivity. Particularly during early periods in winter, when large cracks were present, infiltration mainly occurred through the soil cracks, bypassing the soil matrix, and causing rapid rises in the water table. With saturation of the soil, cracks gradually closed, reducing infiltration and increasing surface runoff.

The calibration of the model against observed overland flows, water table levels and soil moisture was reported to be difficult due to the behaviour of the soil in response to changing soil moisture levels. However, results indicated that exfiltration of groundwater into overland flow, and transfer of soil salt to overland runoff, were more effective mechanisms in transporting salt to surface drainage than the base flow component. The simulations were used to study the effect of deepening drains on discharge of salt loads. It should be noted, however, that the results obtained depended on the ability of the SHE model to account for the effective runoff mechanisms in high groundwater situations (see discussion), which is a major factor in determining its applicability to similar field conditions.

2.1.3 Discussion

The SHE modelling system uses a quasi three-dimensional approach for modelling flow and solute transport processes in a catchment. It can predict outflow hydrographs, concentration of solutes, spatial distribution of soil moisture and phreatic surface levels. As a distributed-parameter catchment model, it provides a way to study the impact of land-use changes on flow and quality of water within catchments.

Although the model accounts for the hydrologic processes in a comprehensive manner, it does not account for certain processes. It cannot handle lateral flow in the unsaturated zone, and does not have flexibility to model near-stream flow processes (explained below). The ability of the model to account for these processes appears to be limited by the structure of the model.

In the applications noted so far, spatial variations of catchment parameters and runoff components within catchments (in the horizontal) are accounted for by square grid networks. The linkage between the soil surface and the groundwater zone is provided through the use of vertical columns (representing the unsaturated zone), spacing of which is determined by the horizontal (square) grid. This has implications for both the computing and data requirements of the model, and for its ability to model processes within more active areas of catchments.

Runoff mechanisms affecting channel/drain flow are mainly contained within the more dynamic, shallow water table, near-stream areas of catchments. Such areas require finer grid spacing than the less dynamic, deep-water table areas further away from the channel. When applied to catchments with high groundwater levels, lack of resolution in the near-stream area can significantly affect the accuracy of model predictions. In such situations, during rainfall or irrigation events, a highly transient flow system can occur in the near-stream area of catchments (Gillham

1984; Abdul and Gillham 1984, 1989). The rapid response of the water table in such situations (resulting from the low available storage capacity in the unsaturated zone in the area adjacent to the stream) can cause gradual build up of water table mounds on either side of the stream/channel. The development of seepage faces and the increased hydraulic gradient towards the channel caused by the water table mounds result in increasing overland flow and subsurface flow contributions to channels.

The processes highlighted above are of particular importance in relation to the ability of the model to predict the quality of stream/channel flows. As also noted by Beven *et al.* (1987), the use of a fixed grid for spatial discretisation limits the resolution with which model can represent near-stream processes. As such areas warrant a finer grid-spacing, the required resolution cannot be provided unless a grid comprised entirely of fine elements is adopted. In addition, options provided to account for the channel (river) aquifer interactions in SHE are not adequate to accommodate the two-dimensional flow system caused by the rapid response of the near-stream shallow water table areas in catchments. Incorporation of a more detailed representation of the near-stream flow processes may enhance the capacity of SHE, and may improve its predictive accuracy.

The computer resource requirement of SHE can be substantial, particularly with respect to application at the catchment scale. Presently, the model attempts to minimise computations by avoiding repetitive calculations among cells with similar characteristics. Also, it uses time scales appropriate to simulate different hydrologic processes. These reduce the computational requirements of the model. With an improved flexibility in spatial-discretisation, it would be possible to further reduce computations in the less dynamic (far-stream, deep water table) areas of catchments.

Another major constraint associated with SHE with respect to application at the catchment scale is its substantial input data requirement. Bathurst and O'Connell (1992) discussed the approaches available for parameter evaluation accounting for the between-grid and within-grid spatial variation. A coarser representation of the far-stream areas of catchments can also have a significant impact on the data requirement of the model, and could improve the efficiency of the model.

The field studies reported so far included testing of the components associated with the early versions of SHE. It would be useful to obtain comparisons between field observations and simulations utilising recently added components of the model. Further, comparison of simulations of the model not only with total observed hydrographs at catchment outlets, but also with flow hydrographs and solute concentrations measured in the field at several points within a catchment would be useful.

General application of SHE is further limited by the long familiarisation times and special training required for the users. It should also be noted that the model is equipped with powerful pre- and post-processing facilities. These are quite helpful in setting up the model under various configurations making the best use of the available data, and also, in analysing the output. However, in order to exploit its capacity as a physically-based, distributed model, applications of SHE would have to be limited to situations with sufficient information to define the required input.

SHE provides a comprehensive means for hydrologic investigations at the scale that allows the required inputs to be obtained with a reasonable accuracy. However, the potential for widespread application of the model at the catchment scale, involving practical use of its capacity is questionable. At larger scales, its use increasingly resembles that of a lumped catchment model. Nevertheless, in many situations where the effective hydrologic processes can be sufficiently represented by the SHE model, it could provide a guiding tool in the process of development of simpler catchment hydrologic models.

2.2 Institute of Hydrology Distributed Model (IHDM)

2.2.1 Description of the model

The Institute of Hydrology Distributed Model is based on a cascading modular structure and utilises a sequential solution of a series of hillslope planes and channel reaches. The model has undergone several stages of improvement, and Beven *et al.* (1987) provide a detailed description of the current version, IHDM4.

The catchment is divided into hillslope planes running orthogonal to the contours, and no-flow boundaries are assumed between adjacent hillslope planes. Each hillslope plane can have a number of input zones classified with respect to vegetation type and microclimate. The model represents each hillslope plane as a vertical slice (with variable width), based on a two-dimensional finite-element representation. It can account for varying slope widths and slope angles resulting from convexity or concavity, and convergence or divergence.

The net rainfall reaching the ground is estimated via a sub-program that accounts for interception, snowmelt and evapotranspiration losses. IHDM simulates saturated and unsaturated subsurface flows that occur in hillslope sections, hillslope overland flow (either from infiltration excess or from saturation excess) and channel flow. Both the channel flow and any overland flow on hillslopes are represented by a one-dimensional downslope kinematic wave equation, solved using an implicit finite-difference scheme. Unsaturated and saturated subsurface flow in a vertical slice is modelled by using a two-dimensional form of Richards equation. It is solved by a finite-element scheme based on the Galerkin method of weighted residuals for the space dimension, and an implicit finite-difference method for the time dimension. The model estimates lateral flow contributions to channels, accounting for the overland flow over the hillslope, and the net subsurface outflow through the seepage face and the fixed-head boundary segments at the end of the hillslope.

Another sub-program interpolates meteorological data for each zone in a catchment from the measured data from meteorological stations, and calculates interception, snowmelt and evaporation for that zone. The snowmelt is calculated using either an energy budget method, or a temperature index method. When there is no snow cover, potential evaporation is calculated using the Penman-Monteith equation (Beven *et al.* 1987). Evaporation of the intercepted water from a wet canopy is allowed according to vegetation cover characteristics, while changes in canopy storage is modelled by a modified form of the Rutter model. Finally, the sub-program produces net rainfall or melt-water at ground level in each zone as input to the main IHDM program.

Negative ground surface flux output from the sub-program indicates that there is some potential evapotranspiration remaining after losses from the interception storage have been accounted for. The residual potential evaporation is fulfilled by considering the surface flow, soil surface, and transpiration from the root zone, respectively. When applicable, evapotranspiration loss is calculated based on the remaining potential, a root density distribution for the vegetation type, and the soil water potential. The actual evapotranspiration is estimated using a two parameter function relating potential evapotranspiration and soil moisture potential as used by Feddes *et al.* (1976a and b).

The main groups of data required by the IHDM model are topographic and surface characteristics of the catchment, meteorologic input, and physical properties of channel sections, and of the soil(s) and aquifer(s) of each hillslope section (Calver 1988). Each channel section requires information on slope, width, roughness and initial upstream and downstream discharges. The hillslope sections require data on: surface roughness and soil properties including porosity, saturated hydraulic conductivity in the vertical and horizontal directions, the relationships between moisture content and moisture potential, and unsaturated hydraulic conductivity and soil moisture potential. The initial conditions are supplied through the saturated zones, and soil moisture potential at the nodes in the unsaturated zone.

The current version of the model uses four levels of time step; the highest used in the sub-program for providing input to the main program is generally one hour. The next level, which is used for exchanging fluxes between hillslope and channel components, can be equal to or smaller than this time step. This determines the resolution of the final discharges predicted for the catchment. The third level of time step used for subsurface flow and channel flow calculations can be less than or equal to the exchange time step. The fourth level of time step is used in overland flow calculations in the hillslope, and there is a fixed integer number of these in each subsurface flow time step.

2.2.2 Model applications

Applications at the Tanllwyth catchment:

Rogers *et al.* (1985) applied an earlier version of the IHDM model to the Tanllwyth forested catchment (0.92 km^2) in the headwaters of the River Servern in central Wales, to study the sensitivity of the model output to its parameters. The catchment was represented in the model by one headwater and two sideslope hillslope elements, contributing to a single channel element. Five storm events, representing a range of meteorological and antecedent conditions, were considered. Two summary measures of model output, the sum of the squared errors between observed and predicted discharge and the estimated hydrograph peaks, were used for comparisons. The results indicated that the model predictions were most sensitive to the surface roughness parameter and to the saturated hydraulic conductivity of the soil. In addition, the effect of uncertainty in the effective parameter values on the predicted discharges was assessed using the Rosenblueth (1975) method for two other storms.

Calver (1988) described calibration of IHDM4 on the Tanllwyth experimental catchment, instrumented by the Institute of Hydrology. At the time, the catchment was mainly (90%) covered by coniferous forest, and the remaining area was covered by moorland grass. In the model, the catchment was represented by three hillslope sections and one channel section. The response of the catchment during a rainfall event was simulated. The model output included discharges from each hillslope section and at the catchment outlet. Although an improvement in the model predictions can be expected with smaller spatial and temporal discretisation, initial attempts in running the model did not show any significant changes in the predicted discharge rates with finer discretisations. The best fit obtained through the calibration showed a reasonably good agreement between the simulated and the measured flow hydrographs. The model also provided estimates of subsurface and overland flow components in hillslope runoff; however, no measured data was available for these.

Using the best fit simulation as a baseline, sensitivity analysis of the model simulations was carried out in the Tanllwyth catchment (Calver 1988). The key physical variables assessed were hydraulic conductivity, porosity, initial moisture potential and surface roughness coefficient. As expected, drier initial conditions required more rainfall to satisfy the soil moisture deficit, resulting in lower peaks of the hydrograph. Under relatively wet initial moisture levels, higher and earlier peaks of hydrographs were predicted. The hydraulic conductivity of the subsurface soil showed an important effect on the relative activity of the various flow components, and also on infiltration rates. With higher hydraulic conductivities, subsurface flow dominated the hydrograph; lower conductivities tended to promote generation of overland flow due to reduced infiltration. The changes to porosity mainly influenced the peaks of the hydrograph, causing a lower and a later peak under the higher porosity as a result of increased buffering. The overland flow resistance coefficient became increasingly important as the event progressed generating surface flow. When the resistance to flow was higher, the hydrograph peak was later and lower.

In order to verify the model, the best fit set of physical parameters obtained through calibration was used to simulate different storm events in the same catchment. The satisfactory results of the test increased confidence in the parameters used. Later, the same set of calibrated parameters was used to simulate rainfall events in a physiographically similar catchment with some success.

Applications at the Gwy catchment

Beven and Binley (1992) applied the IHDM model to the Gwy catchment at the head of the River Wye in central Wales, which has drainage area of 3.9 km^2. This upland catchment area was covered with grassland vegetation, and consisted predominantly of shallow soils with an impermeable bedrock. The catchment was divided into five hillslope sections and three channel reaches. The model was calibrated using five rainfall events and was verified using five more events.

This study illustrated a methodology for calibration and uncertainty estimation of distributed models called the Generalised Likelihood Uncertainty Estimation (GLUE) procedure. This procedure works with multiple sets of parameter values, and allows that, within the limitations of a given model structure and errors in boundary conditions and field observations, different sets of values may be equally likely as simulators of a catchment (Beven and Binley, 1992).

A study on the predictive uncertainty of the IHDM model was investigated by Binley *et al.* (1991) using the Wye catchment. Out of the two methods considered, the Rosenblueth method and the Monte Carlo method, the former allowed a reasonable first estimation of uncertainty limits based on few simulation runs. The Monte Carlo method appeared to be more suitable when a detailed response was required. The results also indicated that the predictive uncertainty bounds for physically-based parameters were quite wide, even when parameter values were constrained by calibration. The study also highlighted the importance of the conjunctive use of modelling and field measurements when considering significant land use changes in catchments.

2.2.3 Discussion

The cascading modular structure and several other features associated with the IHDM model offer several advantages with respect to reducing computer requirements and improving model efficiency. For example, the model represents hillslope sections using vertical slices, thus reducing the number of computational nodes required to represent it in three-dimensions. The model accounts for the variations in surface characteristics through the use of input zones, allowing a degree of lumping, while still preserving the distributed modelling capability.

IHDM provides the flexibility to account for the near-stream processes through the use of a finer discretisation in such areas. Allowing for dynamic flow processes to occur in the near-channel area during rainfall events, the model calculates total lateral flow to channels from hillslope sections. Further, it can provide estimates of proportions of overland flow and subsurface flow components in the hillslope hydrograph.

The flexibility to simulate the rapid near-stream response, facilitated via a finer discretisation towards the channel, is a useful feature of the model. However, IHDM does not model solute transport. In addition, its applicability to situations with multi-aquifer systems at the catchment scale appears to be limited.

It should be noted that the field applications of the model reported so far are limited to small experimental catchments where the required information is available in considerable detail. Further studies are required to assess general applicability of the model to catchments with limited information and also at the regional scale. However, the detail required and the demand on computer resources imposed by the use of numerical schemes such as the finite element method, limit its application to large catchments over long simulation times.

2.3 TOPOG - A Terrain Based Model

2.3.1 Description of the model

The TOPOG catchment modelling framework, developed at the CSIRO Division of Water Resources in Canberra, Australia, contains a family of physically-based models designed to simulate water, solute and particulate movement (Vertessy *et al.* 1994). TOPOG is based on a sophisticated digital terrain analysis model, which is used to generate a network of catchment elements. This is the primary strength of the model, which is designed to simulate the effects of different land management practices on moisture status and water movement within catchments. Several application modules designed to simulate catchment processes under steady state and transient conditions, sit on the kernel, and these can be called upon according to the problem concerned.

An overview of the TOPOG model and its applications is given in Vertessy *et al.* (1994), and details of earlier steady-state versions can be obtained from O'Loughlin (1986; 1988). Vertessy *et al.* (1993), Hatton *et al.* (1992) and several CSIRO Technical Memorandums provide details on different transient modules. Based on these, a brief description of the model is provided here.

Using a contour map as input, the fully automated terrain analysis procedure embedded in the model calculates a computational element network for the catchment and key topographic quantities required to describe water movement down the hillslope. This provides the basis for water balance calculations done by the application modules. Each element in the computational network is bound by a pair of flow trajectories, and an upper and lower contour. The user can specify the contour interval or the trajectory spacing to obtain the required size and the number of elements in the network. The elements form bundles of interconnecting flow strips providing a convenient means to solve flux equations in a single dimension in the downslope direction. Spatial variation of other variables are accounted through overlay routines similar to those found in Geographic Information Systems.

The steady-state water balance modules in TOPOG are based on a simple model of soil moisture redistribution by saturated subsurface flow according to the topographic gradients, as described in O'Loughlin (1986; 1988). A steady state 'wetness index' is defined combining the local slope, soil transmissivity, the upslope catchment area per unit width of contour, point source or sink terms and the residual rainfall rate. The residual rainfall rate is calculated by deducting evaporation and deep percolation of water to groundwater from the rainfall rate. The dimensionless wetness index is an indicator of the relative ability of the element to drain under a given net steady rainfall rate. A wetness index of unity or more represents soil saturation.

Two application modules attached to the model, TOPOG_Yield and TOPOG_IRM perform transient water balance computations. Both models account for unsaturated zone flow in the vertical dimension, and saturated flow in the vertical and the lateral dimension. The soil water module within the transient modules handles infiltration, vertical percolation of water, and lateral movement of water in the saturated zone. Vertical fluxes are modelled using a fully implicit, finite difference solution of the Richards equation. Lateral subsurface flow, which is considered to occur when a watertable develops, is allowed to move downslope along the flow strips; this is calculated according to Darcy's law, utilising local topographic gradient. Overland flow is permitted to occur on any element under conditions of saturation excess or infiltration excess, and due to the incoming flux from upslope (exceeding the transmissive capacity of the element considered). Allowing for re-infiltration on unsaturated elements encountered, overland flow is routed downslope along the flow strips.

The evapotranspiration module within the transient modules calculates daily rates of evaporation from intercepted water, transpiration and soil evaporation. The amount of incoming radiation is considered to be dependent on the slope and aspect of each element, and the radiant energy is divided between the canopy and groundlevel based on light extinction logic. Soil evaporation and transpiration are computed via the use of variants of the Penman-Monteith equation (Vertessy *et al.* 1994). Soil evaporation, transpiration and interception are linked with leaf area index (LAI) of the vegetation. TOPOG_Yield can account for the spatial and temporal variation of LAI. TOPOG_IRM includes a dynamic vegetation growth module, which simulates LAI dynamics, according to the availability of light, water and nutrients.

The model input includes time series data such as rainfall, maximum and minimum temperature, and solar radiation. In addition, soil hydraulic property data for each soil type represented in the catchment, and properties of different vegetation types are also required. The model outputs include discharge, evapotranspiration, soil moisture levels and watertable elevation. Both models are designed to run on daily time-steps, although TOPOG_Yield can accommodate time steps of less than a day.

TOPOG_Yield is linked to a deep groundwater flow model which solves for two-dimensional isotropic, saturated flow based on a finite element network. Co-registration routines in the model overlay the two different computational networks.

Recent developments of TOPOG have incorporated alternative numerical schemes that can be implemented for modelling saturated/unsaturated flow in the shallow zone, and several coupling algorithms for linking the deep groundwater system (Beverly 1992b). The computations are performed simultaneously in the finite element mesh representing the deep groundwater zone and in the soil columns based on the surface element network representing the shallow soil zone. The soil columns and the groundwater zone are dynamically linked, ensuring correct coupling and mass balance (O'Loughlin and Beverly 1993). The linked model can estimate recharge/discharge components between the deep groundwater zone and the shallow zone, and the resulting water levels in the aquifer.

TOPOG_Yield models solute transport based on the traditional convection-dispersion equation. In the shallow model, the one-dimensional form of the equation is solved using a finite-difference scheme, whereas the deep groundwater model adopts a two-dimensional finite-element formulation (Beverly in prep., c).

Further details on TOPOG_Yield are given by Beverly (1992; in prep., a,b,c,d) and Vertessy et al. (1993). Descriptions of TOPOG_IRM and example applications are reported by Hatton *et al.* (1992), Dawes and Hatton (1993), Hatton and Dawes (1993) and Vertessy *et al.* (1995).

2.3.2 Model applications

TOPOG has been applied to small (<10 km^2) upland catchments to study several problems including waterlogging, erosion, slope stability, salinity, effluent loading and water yield, as summarised in Vertessy *et al.* (1994).

Design of an effluent disposal scheme using TOPOG, in an area outside the city of Canberra, Australia, based on the trench absorption method is described by Short *et al.* (1990). The objective of the project was to transmit up to 45 Kl/day of sewage effluent on a steep hillside through subsurface trenches, without producing surface saturation. Using the steady-state wetness index, TOPOG was used to determine the length and optimal location of the absorption trenches in the hillside and the rate of trench loading under different climatic and antecedent soil moisture conditions. Effluent inflow was represented by a steady-state percolation rate, distributed uniformly along absorption trenches sited on hillside contours. Two different layouts of trenches were considered. Based on the predicted saturated areas, a suitable design was selected, and that has been operating satisfactorily over three years. This site has also been further instrumented, and the data collected has allowed further testing of TOPOG.

The transient TOPOG_Yield module was applied to a small (0.32 km^2) headwater catchment in the forested water supply area for the city of Melbourne in Australia (Vertessy *et al.* 1993). Simulated daily runoff volumes were compared with observations over a continuous twelve year period, during which the catchment vegetation was in an undisturbed climax condition. The input used was based on published and measured data. However, some variables were adjusted (within known ranges) to obtain a best fit in the process of calibration, which was based on the first year of the simulation. All variables, except climatic inputs, remained unchanged for the following eleven years, in which the predictions of the model indicated a good agreement with the measured flows.

Sensitivity studies indicated that only a few of the 21 input parameters used in Topog_Yield, had significant effects on the predicted yield. The most significant parameters were: leaf area index, saturated hydraulic conductivity, the interception coefficient and maximum canopy conductance. Simulations under four different element networks, with an order of magnitude difference between the finest and the coarsest mesh, indicated only a minor variation in the predicted terrain attributes and in water balance statistics. In the conclusion of this study, the authors highlighted the need for collecting distributed hydrologic data, and the importance of comparing model predictions with such information in the development of physically-based models.

Hatton *et al.* (1992) used Topog_IRM to predict water balance changes resulting from climatic change. Simulations were performed for current and 2 ´ current ambient CO_2 levels, and the results indicated only a slight increase in the water yield, due to compensating interactions between stomatal resistance, plant growth, rainfall interception and soil evaporation.

Vertessy *et al.* (1995) described an application of TOPOG_IRM to predict the water balance and growth response of a mountain ash (*Eucalyptus regnans*) forest catchment to clearfelling and regeneration. The model was applied to a 0.53 km^2 Picaninny catchment for a 3 year pre-treatment period, and a 20 year period following clearfelling and re-seeding of 78% of the catchment area. Simulations were evaluated by comparing observed and predicted streamflows, rainfall interception and soil moisture values. The model satisfactorily simulated observed temporal patterns of overstorey live stem carbon gain and produced a leaf area trajectory consistent with field observations. Model predictions of cumulative throughfall, soil moisture storage, streamflows, were in good agreement with field observations. This study demonstrated that physically-based, distributed models such as TOPOG_IRM can play a useful role in the management of forest catchments where the required information is available.

O'Loughlin and Beverly (1993) used TOPOG_Yield to predict groundwater recharge rates in a small upland catchment in Western Australia. In the experimental catchment considered, the land surface was modified by removing overburden and vegetation in areas which were to be mined. The effects of vegetation removal were represented in the model by changing the leaf area index. However, changes in topography and soils were not represented, although the model has the capability to represent such changes. The model provided estimates of pre-and post-clearing recharge rates to groundwater, and simulated the changes in watertable levels according to the spatial and temporal variations in recharge rates.

2.3.3 Discussion

The element network generated through the digital terrain analysis component of TOPOG allows computations of lateral water movement to be performed in a single dimension with no loss of accuracy compared to traditional two-dimensional methods (Band *et al.* 1995). Although the topographically based element network is a strength of the TOPOG model when applied to natural catchments, it can have adverse effects in situations where the man-made conditions influence flow processes. For example, in irrigation areas, the layout of farms and irrigation bays may not follow the boundaries of topographically based elements. In such areas, surface runoff is dictated by the artificially constructed boundaries, although the subsurface flow would follow the natural flow path. This could impose constraints on the application of TOPOG operating on the naturally formed interconnecting flow strips, which may not conform to the artificial boundaries.

In natural catchments, however, the TOPOG model offers a useful means for evaluating soil saturation, erosion hazard, slope stability, water yield and surface water groundwater interactions. In particular, it is well suited to study the effects of land-use changes on hydrological processes within catchments. The steady-state version of TOPOG can predict areas most susceptible to waterlogging, based on topographic information, without the need for detailed data bases. Considering data deficiencies usually encountered in the field, this can be recognised as an important practical aspect of the model.

Nevertheless, the application of the transient TOPOG modules in larger catchments is impractical given the substantial computing and data requirements of the model. The numerical schemes used for solving flux equations demand considerable computing resources. However, TOPOG provides the option to model saturated/unsaturated flow in the shallow zone via less sophisticated methods, facilitated by the alternate numerical schemes as documented in (Beverly, in prep., a). Two options are provided for solution of the Richards equation. The first option adopts Kirchoff transformation and permits a solution to be obtained using a Newton-Raphson method (Beverly, in prep., a). The second option provides a solution using an nth order Runge-Kutta numerical scheme, and this can reduce the solution time by 50% compared with the first option. TOPOG provides a third option for simulating saturated/unsaturated flow with the use of a simplified bucket model, which could reduce the solution times by two orders of magnitude when compared to that of the first option (Beverly, in prep., a). These options therefore increase the potential for application of the model to large catchments.

TOPOG has the ability to lower its data and computing requirements in far-stream areas of catchments. The use of natural flow paths down hillslopes provides a convenient means to implement this measure, in comparison with grid-based models such as SHE. The use of a larger contour spacing in the upslope areas and a gradually decreasing contour spacing in the near-stream areas could increase the accuracy of predictions and the model efficiency.

TOPOG calculates lateral subsurface discharge according to the Darcy's law, using local topographic gradient and the saturated height of each element. This could provide reasonable estimates of lateral subsurface flow when the piezometric gradients can be approximated by local topographical gradients. However, when the gradient of the water table in the surface zone differs considerably from the topographic gradient, the approach used may introduce some error in calculating lateral subsurface flow.

The model estimates lateral flow components to the channel from the surface zone based on the flow components in the element adjacent to the channel. Discharge of deep groundwater into drains is not considered in the present model. In shallow groundwater situations where the water table rises to the ground level in response to rainfall, both overland flow and subsurface flow to the stream would be increased as discussed in section 2.1.3. Although a finer discretisation in the near-channel area would improve the ability of TOPOG to accommodate near-stream processes, it is not clear whether the model has the capacity to adequately handle the dynamic response of the water table in shallow water table areas. In addition, streamflow routing is not represented in the model.

The user interface and the graphical capabilities of TOPOG aid in setting up the model for field applications. These are particularly helpful in obtaining suitable discretisations in the shallow zone and the groundwater zones. The graphical facilities allow the model input and output to be displayed and analysed at various stages. However, users require training in order to become sufficiently familiar with these routines.

TOPOG has been successfully applied in several field studies. Further field applications of the linked model and the recently added solute transport component, and comparisons with field observations would be useful steps in further development of the model. The TOPOG modelling framework offers a refreshing alternative to the traditional grid-based distributed parameter catchment modelling approach.

2.4. The SWAGSIM Model

2.4.1 Description of the model

Prathapar *et al.* (1994) described a soil water and groundwater simulation model (SWAGSIM) that predicts watertable fluctuations in irrigation areas. The area concerned is characterised by nearly flat surfaces and predominantly shallow water tables. The model incorporates processes considered to be relevant to the irrigation area, where the magnitude of the vertical fluxes to/from the watertable are considered to be greater than the horizontal fluxes within the underlying unconfined aquifers.

SWAGSIM performs an above ground water balance computation according to the following steps. Initially, the potential evapotranspiration is estimated from climatic variables based on a locally calibrated Penman model. Subsequently, the actual evaporation is estimated by correcting for the type of evaporative surface and the soil moisture status.

In calculating the actual evaporation, the effects of different evaporative surfaces are accounted for through the use of appropriate crop factors. The crop factors usually range between 0 and 1 and vary depending on whether it is bare soil, pasture or citrus. The crop factors used for rice and wheat are allowed to change according to the stage of the crop.

The rate at which water enters or leaves the soil surface is calculated by deducting the depth of rainfall and/or irrigation from the actual evaporation in a particular day, and this forms the upper boundary condition for modelling soil water flow in the unsaturated zone. (It should be noted that 90% of the total depth of rainfall and irrigation is considered in the above calculation, and the remaining 10% of rainfall and/or irrigation is assumed to be surface runoff.)

Using the actual evaporation as the surface boundary condition and the watertable as the bottom boundary condition, recharge to or capillary rise from the watertable is estimated using a transient analytical solution for Richards' equation. The model assumes the soil profile in the unsaturated zone to be homogeneous. Properties of the most restrictive layer, which is considered to control flow through a layered soil, are used for determining input parameters for the analytical model of the unsaturated zone flow.

The soil moisture content within the root zone is updated by considering the net accumulation or loss of water on a given day. When there is a net water flux entering the soil surface in a given day, infiltration into the soil profile is allowed according to the saturated hydraulic conductivity of the soil. The remaining water is carried over to the next day, and is considered when calculating the available flux at the surface.

The spatial response of the watertable due to recharge or capillary upflow is determined by modelling the groundwater flow system. SWAGSIM simulates groundwater flow using a numerical (finite-difference) solution of the partial-differential equation governing non-steady, two-dimensional groundwater flow in a non-homogeneous, isotropic, unconfined aquifer. It assumes that the change in transmissivity due to changes in the saturated thickness of the aquifer is negligible.

The estimated recharge/discharge amounts are input to the groundwater module via the source/sink terms allowed in every active cell within the modelling area. In the shallow water table regions considered, the magnitude of the horizontal fluxes are generally smaller than vertical fluxes. As such, a relatively larger time step (15 days) is used in solving the groundwater flow equations. Although the deep aquifer systems are not incorporated, the model allows leakage (in or out) across a confining layer at the bottom of the unconfined aquifer.

2.4.2 Model applications

The application of SWAGSIM to Camarooka area near Griffith, New South Wales, Australia is described in Prathapar *et al.* (1994). The project area covers 3750 ha and included 160 paddocks, owned by 25 farmers. The predominant crop (21%) in the area was rice. In addition, pastures, vegetables, and citrus were grown. The study area was generally flat, with a slope of 1:10000. Throughout the year, the watertable was within 2 m of the soil surface of 80% of the study area.

For solution of the groundwater flow equation, the modelled area was discretised into 600 cells, based on a square grid of 250 × 250 m cells. Recharge into the watertable and capillary upflow from the water table was calculated by co-registering the surface grid (based on the paddock boundary map) and the finite difference grid used to represent the groundwater zone.

At the surface, the area was covered by a clay layer with varying thickness from 1 to 5 m, which was underlain by a mixture of moderate clays, loams and fine sands, to a depth of 25 to 30 m. The groundwater flow in the unconfined aquifer was modelled based on the piezometric levels; leakage across a confining layer to the underlying aquifer was estimated. As the general direction of the groundwater flow was from east to the west, constant flux boundary conditions were assumed for the eastern and western boundaries. Along the northern and southern boundaries no flow conditions were assumed.

Initial model runs were aimed at obtaining a suitable set of aquifer and soil parameters, and boundary conditions, based on a coarser model grid (1 × 1 km). In calibration of the model, data collected over a year was compared with the simulated piezometric levels. Differences between the observed and simulated levels were indicated as root mean square error or RMSE values over the project area for each month. A good agreement was obtained between the calibrated and observed results for rice growing areas. However, discrepancies were apparent in bare paddocks, and this was attributed to lack of information regarding farming practices in these areas.

A sensitivity analysis of the model output to variations in model parameters was performed, based on the differences interpreted through RMSE. The simulated results were most sensitive to the saturated hydraulic conductivity of the soil, which determines vertical fluxes to the watertable. This resulted from several characteristics pertaining to the study area that contribute to relatively larger vertical fluxes in comparison with the horizontal fluxes.

The calibrated model was used to predict water levels over a period of one year, following the calibration period. Model predictions also included rates and distribution of recharge and discharge over the study area, and total recharge and discharge volumes for sub regions. The model was then used to evaluate effects of rice area on the extent of shallow watertable, and on the magnitude of vertical fluxes to/from the watertable.

2.4.3 Discussion

SWAGSIM performs water balance and recharge/discharge computations in the zone above the watertable, based on a paddock layout map, and simulates the groundwater flow system based on a finite-difference grid. The paddock boundaries are determined according to the farm layouts and crop types. This approach allows for the incorporation of the effects of land use on shallow zone hydrologic processes. The model utilises time steps appropriate to the dynamics of the zones above and below the water table. The water balances at the soil surface and in the root-zone, and the recharge and discharge (capillary rise) from the water table are determined using daily time intervals. Fluctuation of the water table is determined by considering recharge to or discharge from the groundwater zone over 15-day time periods, using a 15-day time step.

The use of dual-computational grids and variable time-steps are among the most useful features of SWAGSIM, contributing to its computing efficiency. The use of an analytical solution for Richards equation for modelling soil water flow in the unsaturated zone is an important feature, and contributes to lower computing requirements and simplicity of the model. This becomes particularly clear when the requirements associated with the use of numerical solutions are compared with that of the analytical solution. Calculation of vertical fluxes in the unsaturated zone of the model is based on the properties of the restricting (least permeable) layer. This is a clever means of avoiding the requirement for detailed information on the unsaturated zone, which is difficult to measure in the field.

The input requirements of SWAGSIM are modest, and the structure of the model is simple in comparison with other models that include unsaturated-saturated flow processes. These features, and the predictive accuracy shown in the field application in the Camarooka project area, make SWAGSIM a particularly attractive model.

However, several hydrologic processes, which are not regarded to be important in the irrigation areas concerned, are not included in SWAGSIM. For example, with interception losses, it is assumed that the amount of water applied through irrigation is quite large compared to losses due to interception. In addition, the model alots a fixed portion (10%) of water (rain and/or irrigation) applied in a day to be surface runoff.

The model can accommodate surface water bodies such as lakes and swamps through the use of fixed-head cells in the finite-difference grid that represents the groundwater flow system. However, this does not provide sufficient flexibility to account for streams or drain networks along paddock boundaries without using a very fine resolution for the finite-difference grid. The model cannot easily calculate lateral discharge of surface and subsurface flow components into the drain network. Further development of the model to accommodate: (1) drains along active cell boundaries, (2) topographic slopes in the areas contributing to the drains, and (3) components of lateral discharge into drains would be useful.

With respect to applications in rice irrigation areas, such features may not be essential due to the nature of irrigation practices. Nevertheless, in other areas with some topographic gradient, lateral discharge into drains/streams as overland flow and subsurface flow is important. Moreover, the dynamic flow systems that would be created adjacent to such waterways, during rainfall/irrigation events in shallow water table situations (section 2.1.3), could have significant effects on overland flow and subsurface discharge to drains and on water table elevations.
The present version of SWAGSIM has shown significant potential for use as a practical tool for irrigation areas. Incorporation of the above mentioned processes in to the model will enhance its versatility, with respect to application in shallow water table situations. Further development of SWAGSIM is currently under way, aimed at incorporating a capability to simulate surface runoff more accurately.

2.5 Other Models

2.5.1 TOPMODEL - A terrain based model

TOPMODEL (Beven and Kirkby 1979; Beven *et al.* 1984; Beven 1986)is a topographically and physically-based, variable source area hydrological model, originally developed for application to flood runoff studies. It is based primarily on three assumptions (Wolock *et al.* 1990). The first of these implies that surface runoff is generated when precipitation falls on saturated portions of the catchment. Secondly, it is assumed that subsurface flow at a given location of the catchment depends on the saturated hydraulic conductivity, soil depth, surface slope and saturation deficit at that point (the amount of water required to bring the water table to the surface). The third assumption is that saturated hydraulic conductivity decreases exponentially with depth in the upper soil layers. This has been attributed to the greater abundance of macropores in the upper soil horizons, and to greater soil compaction with increasing depth.

Further assumptions are that, saturation deficit at a point is related to its upslope area per unit contour width and the local slope. All points within a catchment with the same value of that function are assumed to respond in a hydrologically similar manner. These assumptions form the basis of the surface and subsurface discharge calculations in the model.

The inputs required by the model include soils and topographic parameters, catchment latitude, and time series of precipitation and air temperature. Potential evapotranspiration is calculated using the time series of temperature and a time series of day length, based on the catchment latitude (Hamon, 1961). Model predictions include stream discharge, estimates of surface and subsurface runoff, and estimates of the depth to the water table.

Durand *et al.* (1992) described an application of a simplified version of TOPMODEL for simulating the hydrological behaviour of two sub-mediterranean catchments. Model input included hourly rainfall data. Outputs were: hourly average soil moisture deficits, hourly discharge separated into surface runoff from saturated areas and the subsurface flow component. Although some discrepancies were noted, a good overall match was obtained between the simulations and the measured flows. As reported by Bonell (1993), observed anomalies could have been partly caused by the inadequacy of the model to account for interactions between the stream and the groundwater system.

2.5.2 THALES - A Terrain based model

THALES (Grayson *et al.* 1992) is a physically-based hydrologic model which uses a contour based method of terrain analysis, as in the TOPOG model discussed before. It divides a catchment into elements, based on the streamlines and equipotential lines, allowing more realistic representation of the surface water flow system. The THALES model accounts for the Hortonian mechanism of surface runoff, variable source area runoff, and exfiltration of subsurface flow. The model allows surface runoff to be modelled either as sheet, rill or channelized flow. As THALES was designed for simulation of storm events, it does not model evaporation.

The model was applied to a 7-ha field site at Wagga Wagga, in New South Wales, Australia, to simulate several storm events (Grayson *et al.* 1992). It was also applied to an arid catchment in the United States, to simulate catchment response during rainfall events (Grayson *et al.* 1992). Although comparisons between the simulated and measured hydrographs were reasonably good, some differences were also evident. Several factors that may have contributed to the apparent differences were identified, including insufficient resolution of the rainfall information, and problems associated with the flow measuring device. These studies also highlighted the effects of model structure on model output, and the scarcity of measured field data, and the lack of a methodology for collection of data at a scale appropriate for models such as THALES.

2.5.3 The WSHS model

The WaterShed Hydrologic System (WSHS) model, described by Al-Soufi (1987; 1989) and reviewed by Al-Soufi (1991), is a physically-based mathematical model that can predict water flow and solute concentrations in non-homogeneous anisotropic porous media. It couples hydrologic subsystems via the use of several modules which simulate: (1) crop transpiration and soil evaporation; (2) interception, evaporation, transpiration and throughfall in forested areas; (3) extraction of water by the root system; (4) depth and discharge of surface runoff soil recharge rates; (5) three dimensional soil water flow; and (6) three dimensional reactive solute transport and contaminant generation.

The processes of plant transpiration and soil evaporation are simulated using the Penman-Monteith equation, incorporating both plant physiology characteristics and canopy properties. The model represents the forest canopy interception as a store of water, and allows its replenishment by rainfall and depletion due to evaporation and dripping.

When the rainfall intensity is less than the infiltration capacity and the soil water potential at the top layer is negative, rainfall is allowed to infiltrate into the soil profile. If the rainfall exceeds the infiltration capacity, Hortonian (infiltration-excess) overland flow is allowed to occur, which is modelled using a finite difference solution of the kinematic wave equation.

The non-steady, saturated and unsaturated subsurface flow is modelled by the varied saturation soil-continuum module (Al-Soufi 1987). The soil water flow equation is solved by using a finite-difference method, dividing the soil continuum into small finite cubic elements called cubic nodes. Solute transport is modelled using a three-dimensional mass balance equation for the advection-dispersion solute flow in soil. The finite difference solutions of both the flow and transport equations are based spatially on a cubic element network.

The model was applied to a subcatchment with an area of 6 km^2, in the middle of Velen Valley in southern Sweden (Al- Soufi 1987). The modelled area was represented via a network of 910 cubic nodes, based on a square mesh of 250 × 250 m elements (for the effects of the spatial scale of grid elements on hydrologic simulations - see Section 4.1). The model was calibrated by simulating catchment response for rainfall events, and comparing measured and simulated water table levels.

Al-Soufi (1989) described a one-dimensional simulation of an irrigation field experiment on a 6.1 × 6.1 m plot, with the use of WSHS model. The initial volumetric water content of the soil was uniform throughout the profile, and was reported to be at 0.2. The soil was initially irrigated with water containing $CaCl_2$, then later with fresh water.

Simulated water content and solute concentration distributions in the soil profile, at different times during infiltration, were compared with the observed. The results were also compared with the simulated concentration profiles from another model (Segol 1977) based on a Galerkin finite element approach. Both numerical schemes adequately predicted the concentration and moisture profiles. However, the results obtained by using the finite element model were more sensitive to variations in longitudinal dispersivity coefficient (Al-Soufi 1989).

Other similar models:

Several models with the capability to predict flow and solute transport in porous media have been reported. Segol (1977), mentioned above, simulated transport of water and nonreactive solutes in the soil zone (Al-Soufi 1991). Warrick *et al.* (1971) described a model for nonreactive solute movement in unsaturated soils. Pickens *et al.* (1979) reported a three-dimensional mass transport model, based on a Galerkin triangular finite-element approach. Numerical models of this nature are generally suited to investigate well defined, areally limited, field situations in detail. Their application as practical catchment models is restricted mainly due to the forbidding size of the data and computer requirements.

3.0 Lumped-conceptual models

Lumped catchment models are usually based on simple, mechanistic structures, and attempt to reproduce catchment response without modelling spatial variations in catchment properties or dynamics. Numerous mathematical models for rainfall-runoff transformation encountered in the hydrologic literature are based on this approach. Such hydrologic models have been successfully applied in various water resources planning and management projects. Several other models that attempt to predict catchment responses to rainfall, with varying degrees of detail in representing flow processes on solute concentrations, have also been reported. It is not feasible, however, to describe all the models in this category within the context of this review. Therefore, only a limited number of models and associated useful studies are included in this section.

3.1 Rainfall-Runoff Transformation Models

The general use of rainfall-runoff transformation models is the estimation of flood hydrographs, a requirement associated with many problems in Engineering Hydrology. A detailed review of the approaches used in flood forecasting is given in Srikanthan *et al.* (1994). The main thrust of these models is to predict runoff volumes and peaks adequately, accounting for losses from rainfall due to various hydrologic processes. However, the way in which the hydrologic processes are represented in these models varies considerably.

Franchini and Pacciani (1991) conducted a comparative analysis of seven conceptual rainfall-runoff models which represented the broad spectrum of models available in this category. The models compared were: STANFORD WATERSHED model IV (Crawford and Linsley 1966), WMO (WMO 1977), SACRAMENTO (Burnash *et al.* 1973), TANK model (Sugawara *et al.* 1983), APIC model (Sittner *et al.* 1969), SSARR model (Rockwood 1958; Rockwood *et al.* 1972), XINANJIANG model (Zhao 1977), and ARNO model (Franchini and Todini 1987).

Two main components were common to all the models: a water balance component, and a transfer function for routing flows to the catchment outlet. The first component is the most important part of the model. Generally, in this component, soil moisture balance is represented by considering several zones (upper, middle, and lower). Based on these, surface runoff resulting from incoming precipitation is estimated allowing for loss due to evapotranspiration. The second component handles flow of water along hillslopes via the drainage network to the outlet of the catchment. The initial transfers generally involve the use of the unit hydrograph method. Transfers along drainage networks are usually based on well known routing methods.

The models considered in the study were applied to a test case at the Sieve watershed of the Arno River, in Italy, where hourly data on precipitation, temperature and flow rates were available for a period of four months. Two calibration procedures were considered; an automatic calibration procedure, and a method based on the successive rational attempt which allowed the model parameters to be assumed or adjusted within a meaningful range. The latter was chosen as the preferable method for calibration of the models, as it enables adjustment of parameter values over meaningful ranges, while the former would have implied significant difficulties in the optimisation phase itself (Franchini and Pacciani, 1991).

Among the models considered, the STANFORD IV and SACRAMENTO models required the greatest effort in calibration. It was also noted that these two models, although classified as the conceptual type, model various processes of runoff generation in considerable detail. The methods used in these models to represent interactions of various components in rainfall-runoff transformation processes result in increasing the number of parameters needed. This increases the difficulty of the calibration procedure.

On the other hand, more simple models such as the TANK model are based on schematised approaches that do not provide sufficient links with the physical processes. In addition, when using such models, there is a less possibility of utilising knowledge about the catchment or watershed response. This is a disadvantage of the approach used.

In general, conceptual models in this category utilise methods that integrate hillslope processes, and attempt to estimate outflow hydrographs from catchments. Usually these models use a large number of parameters, and require long historical records for calibration. The difficulty in calibration increases with the number of parameters used, and this makes it increasingly difficult to visualise interrelations between catchment parameters and physical properties. It is noted that models with significantly different model structure provided similar results, based on calibration times proportional to the degree of complexity of the model structure.

The application of the models in this category for studies in which the runoff sources and paths are important is severely limited by the nature of their structure. Nevertheless, models in this category have frequently been applied for prediction of runoff volumes and peaks from areas ranging from small watersheds to large basins. As these models are not physically-based, their applicability outside the range of the conditions represented in the calibration process is limited.

3.2 The SDI Model

The SDI (soil dryness index) model (Langford *et al.* 1978; Kuczera 1988) is a lumped-conceptual catchment model designed for monthly streamflow prediction, and for forecasting and record extension applications in water supply catchments. It is applicable to catchments in moderate to high rainfall regions, and has provided predictions consistent with observations of monthly streamflow and depth-averaged soil moisture levels in water supply catchments serving Melbourne, Australia.

The SDI model operates on a daily time step using rainfall and pan evaporation as inputs. In the model, hillslope processes are represented based on two stores; a soil store, and a saturated soil (groundwater) store. The soil store represents the top layer of the hillslope, and consists of root and vadose zones. The depth of water in this store is given by the soil dryness index, defined as the deficit of water below the soil field capacity at the end of each day. The saturated soil store introduces a delay in transferring recharge flux to the stream channel. This store can be conceptualised either as a local unconfined aquifer, or as a temporary perched water table in the soil horizon.

The evapotranspiration process is modelled using a simplified form of the Penman-Monteith equation. The model allows for flash runoff, though it does not discriminate between Hortonian flow and overland flow from saturated areas. The flash runoff is meant to be the runoff volume that enters stream network within a day or less after rainfall.

Interflow is modelled as the passage of the infiltrated water through the soil store to the stream network. The soil store causes a delay in transferring the infiltrated water to the channel. When the field capacity of the soil store is exceeded, recharge is allowed to occur to the saturated zone. Base flow from the saturated store is estimated considering a linear reservoir in the saturated zone. The loss of water to deeper systems is allowed, and is interpreted as a seepage loss. Streamflow is estimated as the summation of the flash flow, interflow and the base flow minus the seepage loss.

The SDI model uses up to twelve parameters and this introduces difficulty in the model calibration process. However, depending on the application, less than twelve (usually eight) parameters need to be estimated. Several case studies using the SDI model are reported in Kuczera (1988), and a model validation exercise in a forested catchment is described in Kuczera *et al.* (1993).

3.3 The CATPRO Model

Raper and Kuczera (1991) described a conceptual model that represents the dominant hydrologic processes operating in temperate and semi-arid Australian catchments. It is based on a quasi two-dimensional structure, which incorporates dynamic aspects of subsurface saturation. The model represents hillslope hydrologic processes using three soil stores, and requires daily rainfall and potential evapotranspiration data. At least monthly average streamflows are required for calibration. The amount of rainfall reaching the ground surface (throughfall) is assumed to be linearly dependent on the rainfall rate.

The topmost of the three stores considered, the 'A' horizon store, is conceptualised as an inclined rectangle of unit length. The phreatic surface level within it is assumed to be flat, and allowed to move at a constant inclination to the horizontal. The degree of inclination was considered to be a function of soil properties and the hillslope angle. Though in a simple manner, the model allows for the variations in the subsurface saturation in the 'A' store. This allows for the expansion and contraction of areas producing saturation overland flow. Lateral subsurface flow is modelled according to the Darcy's Law. The vertical flow from the 'A' store is considered to be dominated by the pipe flow through the macro-pores. When a perched watertable exists, evapotranspiration is allowed from this store until either the demand is met, or the store becomes unsaturated. The remaining demand for evapotranspiration will then be satisfied from the two lower stores.

The second soil store, the 'B' horizon, which lies below the 'A' store, is conceptualised as a linear store. Through this water drains under gravity to the groundwater store, which lies below. The 'B' store is recharged by the lateral, radial flow from the macro-pores in which water flows vertically from the overlying 'A' store. The evapotranspirative demand from this store is met at a rate proportional to the relative saturation. Subsequently, gravity drainage is allowed to occur.

The groundwater store is recharged from gravity flow from the 'B' store and the macro-pore flow from the 'A' store. The evapotranspirative loss is allowed at the potential rate, provided there is storage to satisfy the demand. Other outflows from this store are base flow contribution to streamflow and leakage into the deeper aquifers.

Total streamflow is the summation of contributions from the 'A' store (surface runoff and lateral subsurface flow) and the base flow component from the groundwater store. The model estimates groundwater recharge rates from the summation of gravity drainage from the 'B' store and the macro-pore flow from the 'A' store.

The CATPRO model was designed to predict recharge rates in catchments where ephemeral, perched water tables exist. Raper and Kuczera (1991) described an application of the model to predict recharge rates in a 81.6 ha catchment in south-west Western Australia. The model was calibrated using monthly streamflow records over a twelve year period, based on the NLIFT parameter optimisation scheme. The study also demonstrated the effect of parameter uncertainty on predicted recharge and on computed evapotranspiration rates. Kuczera *et al.* (1993) described an application of the CATPRO model for modelling water yield changes due to strip thinning of a forested catchment. The model provided a reasonably good prediction of monthly yields, both before and after the strip thinning treatments.

3.4 The MIDASS Model

Nathan (1993) described a lumped-conceptual model, MIDASS, for prediction of streamflow and salt yield from irrigated catchments with high groundwater levels. The model is designed for applications in medium size catchments; however, when several models are arranged in a cascading order, it can be applied to areas of several hundred square kilometres. Rainfall, irrigation and evaporation are assumed to occur uniformly over the sub-catchments modelled. In addition, soil moisture status, groundwater levels and salinity are also assumed to vary uniformly over the sub-catchment area. The model allows for water and salt outflow from sub-catchments via the surface drainage network.

MIDASS utilises a variable source area concept, and allows rain falling on saturated areas adjacent to drainage channels to contribute directly to streamflow. It represents the expansion and contraction of saturated areas during and after rainfall events. Rainfall outside the saturated areas is considered to enter the soil profile regardless of its intensity. This assumption implies that the rainfall in excess of the infiltration capacity of the soils (outside the saturated area), may pond and would later infiltrate without contributing to surface runoff.

The model assumes a fixed irrigation efficiency, and that only a small fraction of irrigation water directly enters drainage channels. From the water that enters the soil profile, either due to rainfall or due to irrigation, only a small fraction is assumed to enter the soil moisture store, and the major proportion is diverted to groundwater. The daily evapotranspiration from the soil store is estimated according to the available soil moisture level. When the watertable is with in two metres of the ground surface, outflow from the groundwater store via capillary rise is allowed at a rate proportional to the depth to the watertable. The groundwater flow in or out from the channel is estimated based on the head difference between the drain and the groundwater store. The vertical flow (leakage) across a confining layer which separates the unconfined aquifer from the deeper confined layer is estimated according to the Darcy's Law. When the watertable reaches the ground surface, groundwater within the variable source area is allowed to flow directly into the channel, or to pond on the surface until evaporation or reinfiltration occurs.

The depth of water in the channel, which is used for estimating the groundwater flow component, is determined according to the Manning's equation. Depth of channel flow is assumed to decrease exponentially after storm periods.

The model represents salt transport processes by accounting for mass balance, based on the assumption of complete mixing. Rainfall and irrigation inputs are assumed to have fixed salinities. Complete mixing within soil and groundwater zones is assumed over fixed depths of 1.5 m and 8 m, respectively. Further, salinities of the internal process components (for example, capillary rise of groundwater to the soil store) are assumed to be determined by their sources. The salinity of partial area runoff and groundwater exfiltration is evaluated based on a fixed leaching fraction of the current groundwater salinity. The leaching fraction is determined through calibration.

MIDASS requires daily values of rainfall and irrigation deliveries and potential evaporation as inputs, and provides estimates of weekly or monthly yields. As such, streamflow routing is ignored.

MIDASS has been applied to a catchment with an area of 465 km^2, in Tragowel Plains in northern Victoria, Australia (Nathan and Earl 1993). The model was modified to suit the area, introducing a separate soil moisture store capacity, and a variable source area exponent for low and high salinity areas. Model calibration was performed based on nine gauged sub-areas within the catchment, arranged in a cascading order. The calibration was achieved by optimising six parameters, and the rest of the parameters were assigned fixed values in all nine catchments. The simulated weekly flow and salt load hydrograph indicated a good agreement with the measured data. Subsequently, the model was used to evaluate effects of different management options.

The model allows automatic optimisation of a selected subset of parameters, using an objective function based on both streamflow and salt load hydrographs. All the internal fluxes can be examined though the use of extensive interactive graphics, and which is a useful feature in the calibration process.

3.5 Other Models

3.5.1 SALTMOD - A computational method

Oosterbaan (1992) presented a computational method called SALTMOD for predicting the long-term effects of water management options on soil and water salinities, and watertable depths in areas under irrigation. The water management options supported by this package include irrigation, reuse of surface drainage water or subsurface drainage from pipe drains. The model provides estimates of depth to water table, salinity of groundwater, drain water and well water.

The computational method used in SALTMOD is based on the seasonal water balance observed in agricultural areas. The seasons in a year are considered as: dry, wet, cold, hot, irrigation and fallow. Water balance computations are performed using seasonal inputs of rainfall, irrigation, evaporation, reuse of drainage water, surface runoff and extraction rates from wells. Other components involved in the water balance computations such as downward percolation, upward capillary rise and gravity drainage are included in the model output. The drainage output is determined with the use of two drainage intensity factors (specified as input) for drainage above and below the drain level. In addition, a drainage reduction factor is used to simulate the effectiveness of the drainage system. Different drainage options are represented by varying the drainage intensity and drainage reduction factors.

The input data on irrigation, evaporation and surface runoff are specified for each season based on three agricultural practices: rainfed agriculture or fallow, irrigation of "dry foot" crops and irrigation of submerged rice fields (paddy land). Areal fractions of these types and information on seasonal rotation of the different land use types (eg. full rotation, no rotation) need to be provided as input.

SALTMOD performs a number of interactive water balance calculations to obtain an equilibrium condition. The calculations are based on three different reservoirs: an upper (shallow) soil reservoir that represents the root zone, an intermediate reservoir or transient zone and a deep reservoir. When a horizontal subsurface drainage system is present, the intermediate zone is divided into two zones: an upper transition zone, above the water level, and a lower transition zone below the drain. Water balance calculations are performed for each reservoir. The excess water leaving one reservoir is treated as input for the next reservoir.

The upper soil reservoir that represents the evapotranspirative zone and the transition zone below can be unsaturated, saturated or partly saturated. Except for the flow to subsurface drains, water movement within these zones is considered to be totally vertical (either upward or downward). Flow in the deep reservoir, which is mainly horizontal, represents saturated aquifer flow.

Salt balance calculations are performed for each reservoir separately, based on the salt concentration of input and output flow components. Salt concentrations of rainfall, irrigation water, incoming groundwater, and initial salt concentrations of each reservoir need to be provided as input to the model. Output salt concentrations are based on several leaching and salt mixing efficiencies supplied as model input.

The dissolution of soil minerals or chemical precipitation are not represented in SALTMOD. However, effects of these processes can be incorporated to some extent, via the use of modified inputs such as increasing or decreasing salt concentrations of irrigation water or incoming groundwater. The model output includes seasonal average values of: depth to the watertable, salt concentration of different soil reservoirs, drainage and mixed irrigation water, and some indicators of irrigation efficiency and sufficiency.

While the model assumes uniform depth to the watertable, variations in this property can be incorporated by dividing the modelled area into several sub-areas. Within each subarea, the distribution of crops, irrigation and drainage characteristics are similar. It is possible to use a larger area approach initially, and then gradually narrow the area down while using some output obtained in the initial analysis.

SALTMOD uses a large number of model parameters. Some of the parameters initially defined by the user are changed during the modelling process. The final equilibrium water and salt balance is attained through an iterative calculation procedure. Discharge through the subsurface drainage system is calculated utilising depth of the drain below the soil surface, and two reaction factors defined along with the model input. Surface drainage originally provided as input to the model is subsequently adjusted through the iterative calculation procedure.

SALTMOD provides a method for water and salt balance calculations in agricultural areas, when the long term effects of agricultural practices are of interest. However, its application largely depends on the availability of information necessary to define the model parameters and input hydrologic quantities. This is a major constraint faced with the application of SALTMOD.

3.5.2 Salinity modelling - Western Australia

Ruprecht and Sivapalan (1991) described a lumped-conceptual model for prediction of long term salt balance in experimental catchments in south-west Australia. The coupled water and salt balance models are based on three interdependent storages; A, B and F, which represent stream-zone, saturated and unsaturated zones respectively. The water balance model incorporates interception, evaporation, overland flow (both Hortonian and saturated excess), subsurface flow from the stream-zone, and groundwater flow.

The salt balance model assumes complete mixing in the conceptualised A, B and F zones. The salinity of overland flow is assumed to be that of the throughfall. The salt concentration of subsurface and groundwater flow is determined by assuming complete mixing in the stream zone and the groundwater zone, respectively. The model accounts for the addition of salt into the B store due to leaching and mobilisation of salt stored in the unsaturated zone, caused by the increased recharge resulting from the clearing of native vegetation.

The model was applied to two experimental catchments (Salmon and Wights) in Western Australia (Ruprecht and Sivapalan 1991). These catchments were instrumented to monitor fluxes of water and salt as part of a long term study on the impact of native vegetation clearance on catchment hydrology. The predicted salt discharges from both catchments over a ten year period showed a good agreement with the measured salt loads.

4.0 Suitability of Catchment Modelling Approaches

The currently available catchment models offer varying degrees of suitability with respect to modelling hydrologic problems, dependent on the model structure and the type of the approach used. As noted by Vertessy *et al.* (1993), each modelling approach can play a role in some hydrologic simulation. However, in developing a model or when applying an existing model to handle a particular problem, it is important to consider several factors that determine model suitability. Some of these factors are: scale of the problem, (hillslope or regional), type of simulation (event or continuous), predictions required (flow and/or solute concentrations) and the accuracy of the output required. In addition, the availability of the data, both for model parameterisation and for calibration and verification, need to be taken into account. Grayson and Chiew (1994) presented several questions and decision points which may be helpful in establishing the appropriate model for a given problem.

The two alternative modelling approaches reviewed so far indicate varying degrees of potential for their application to different hydrologic simulations and conditions. Lumped-conceptual models have been successfully applied for real-time flood forecasting, and in the extension of short streamflow records using longer rainfall records (Abbott *et al.* 1986a). Generally, lumped catchment models utilise a large number of parameters, and depend on the availability of long meteorological and hydrological records for calibration (Bathurst and O'Connell 1992). Such records may not always be available. Also, due to the curve fitting aspect usually involved in the calibration of such models, physical interpretation of the model parameters is difficult (Abbott *et al.* 1986a). In addition, the models cannot usually be employed for predictions outside the range of conditions included in the calibration process (Bathurst and O'Connell 1992). This implies that lumped-conceptual models are not generally applicable for predictions under various land use changes. However, lumped-conceptual models with suitable structures and conceptualisation of the physical processes can be used to predict hydrologic response under spatially averaged changes in catchments. When compared with the physically-based distributed models, these models are structurally simple, and usually provide predictions with an accuracy that is commensurate with the measurements normally available in the field.

On the other hand, in physically-based distributed models, parameters used have physical meanings, and usually can be measured in the field (Bathurst and O'Connell 1992). The models in this category require spatially distributed, but relatively short meteorological and hydrological records for calibration, and can be applied outside the range of conditions used in the calibration and verification. Prior knowledge about the catchment behaviour can be utilised in testing of physically-based models (Bathurst and O'Connell 1992). These models provide multiple, spatially variable outputs on catchment hydrologic response, and have a greater potential to evaluate different management practices.

The above mentioned points and some other aspects of lumped-conceptual models and physically-based distributed models are discussed in detail by several authors (eg. Abbott *et al.* 1986a; Anderson and Rogers 1987; Bathurst and O'Connell 1992; Beven and Binley 1992). It has been argued that physically-based distributed parameter models offer many advantages, and have the capacity to account for the spatial variability of catchment properties and physical processes. However, to properly exploit the capabilities of the physically-based, distributed models, considerable detail on spatial variability of the model input is essential. In addition, proper calibration and verification of these models require records on the distributed hydrologic response of the catchments. The amount of information required for the proper use of this type of model is not normally available in the field. Usually, it is necessary to carry out extensive field measurements to supplement existing information when applying these models. As a result, despite the purported abilities of the physically-based, distributed models, there have been few published studies on the application of these models to simulate catchment response to land use change. In fact, the reported applications (eg. Vertessy *et al.* 1995) are limited to somewhat ideal circumstances where the required data was available in considerable detail. The following section presents several factors which limit the application of physically-based, distributed models, and discusses some of the concerns and questions raised by several authors with respect to application of these models for practical prediction in hydrology.

4.1 Application of Physically-Based, Distributed Models

In recent years, there has been a growing scepticism concerning the use of physically-based, distributed models at the catchment scale (eg. Beven 1989; Grayson *et al.* 1992; Grayson and Nathan 1993). It has been argued that these models employ physically-based equations, derived for small spatial scales, but are being used at spatial scales several orders of magnitude greater (Hughes and Sami 1994). In addition, as it is not practically possible to estimate the model parameters at the required grid element scale, model applications at the catchment scale are often based on parameter values which can be called as 'best guesses' (Vertessy *et al.* 1993). This enforces models to be used with a degree of empiricism. It has also been pointed out that some factors and/or processes which are not significant at small spatial scales could play important roles in the catchment scale. These points raise questions about validity of the equations used in the models at the catchment scale.

Beven (1989) elaborated the causes for the concerns mentioned above, eg. limitations of the model equations relative to a heterogeneous reality, and the lack of theory of sub-grid scale integration. It was argued that the equations used in the physically-based, distributed models are good descriptors of the processes that occur in well defined, spatially homogeneous, statistically stationary *'model'* catchments and hillslopes in the laboratory. It is not clear how these equations could describe the complex, three-dimensional, spatially heterogeneous and time varying system in the real catchment situations. Also, Beven (1989) pointed out that in the filed applications, these equations which are based on small scale physics of the homogeneous systems, are being extrapolated up to large grid scales, for example 250 × 250 m in the case of the SHE application to the Wye Catchment (Bathurst 1986a,b, discussed in Section 2.1.2). Validity of this process is questionable, as there is no theoretical frame work for carrying out lumping of subgrid processes for spatially heterogeneous grid squares (Beven, 1989). The uncertainty involved increases with larger grid sizes (eg. 2 × 2 km) such as that used in the application of SHE to six

Indian sub-catchments totalling approximately 15000 km^2 (Refsgaard *et al.* 1992, discussed in Section 2.1.2).

Generally, physically-based distributed models have been designed to utilise parameters that have physical meaning, and that these can be estimated through independent measurement. As noted earlier, for most applications, it is not practically possible to obtain such measurements at the required resolution. Due to this, calibration of parameters against observations is routinely performed.

Application of distributed models to real catchments involves a large number of parameter values, and this makes the calibration process very difficult (Wood *et al.* 1990). For example, in the application of SHE to the Wye catchment, it was necessary to specify approximately 2400 parameter values, not including topographic variables or changes in parameter values over time (Beven 1989). The involvement of such a large number of parameter values, and the interaction between the parameters inherent in hydrological systems, make the use of any parameter optimisation procedure to be more complicated than in the use of simpler lumped models.

Furthermore, in the application of physically-based models at the catchment scale, the use of effective parameter values at the grid element scale limits the ability of the model to represent the hydrologic processes within grid cells. For example, it is not possible to predict overland flow occurring over part of the grid square (Beven, 1989). In addition, with the use of large cells, it is not feasible to accurately represent surface flow systems such as river or channel networks, or the response of the water table particularly in the near-channel areas.

As pointed out by Beven (1989), the spatial interpolation and lumping usually involved in the application of physically-based, distributed models implies that the spatial variability of a particular catchment characteristic can be assumed to be a stationary random field within a grid element. Runoff generation within catchments is a multiscale phenomenon with different length scales characterising soil, topography, and rainfall variability, each of which may it self have small- and large-scale components (Wood *et al.* 1988). However, a certain threshold scale at which some average hydrologic response that is invariant or varies slowly with increasing area has been proposed. Wood *et al.* (1988) suggested that this scale represents a 'Representative Elementary Area' (REA) which is thought to be a fundamental building block for catchment modelling, analogous to Representative Elementary Volume (REV) in porous media.

If the REA concept is valid, the grid for physically-based, distributed models needs to designed on spatial scales determined by the REA(s) of a given catchment, for a given hydrologic simulation. However, little work has been published investigating the feasibility of the REA concept. Wood *et al.* (1988) carried out an investigation into the existence of a Representative Elementary Area (REA) based on actual catchment topography as represented in Coweeta River experimental basin with synthetic realisations for rainfall and soils. The hydrologic response of the catchment was modelled by a modified version of TOPMODEL (described in Section 2.5.1). The results suggested that a REA exists in the context of catchment hydrologic response, and is strongly influenced by the topography, through (a) the sizes and shapes of subcatchments and (b) its role in the hydrologic response model. The authors found an REA of the order of 1 km^2 for particular rainfall, soil and topographic fields (Beven *et al.* 1988). Vertessy *et al.* (1993) reported a study carried out in a small forested test catchment (described in Section 2.3.2), adopting a mean element size of 290 m^2. It was suggested that the topographic attributes, soil characteristics and vegetation attributes of the upland forest catchments could be represented meaningfully with the use of discrete values at this scale. The authors believed that the model cell size was close to the upper limit in upland forest systems, and argued that anything coarser would probably undermine the physical basis of model predictions. Although these studies provide some insight in to the use of REA concept, further work is required to investigate the feasibility of using REA as a basis for spatial discretisation for hydrologic simulations in catchments.

The need to use small spatial scales for the proper application of physically-based, distributed models introduces a substantial demand on computing resources, particularly at the catchment scale. The computational burden associated with the application of these models is further increased by the use of numerical solutions to solve equations representing most of the catchment hydrologic processes. In addition, due to the complexity of the models, users need special training and long familiarisation times before using the models for field applications. These constraints undermine the advantages offered through the advanced and comprehensive nature of theses models.

The constraints associated with these models are reflected in the relatively small number of field applications at the catchment scale reported so far. Nevertheless, physically-based distributed models can continue to be used for detailed studies in well instrumented, well monitored sites, providing valuable insight and understanding of the effective physical processes. This would be a vital initial step in the formulation of more simple models applicable as practical tools at the regional scale.

4.2 Intermediate Approaches

Among the numerous hydrologic models based on the two modelling approaches described, a common characteristic which emerges is the scarcity of field application. Indeed, the lack of potential for field application of the existing models could have contributed to the following view: *'Nowadays model building has become a fashionable and generously supported indoor sport'* (von Bertalanffy 1966, cited by Beven 1993). It can be suggested that the models with greater potential for field application need to be based on intermediate approaches which can provide a compromise between the detailed physically-based modelling approach and the lumped-conceptual approach.

Such approaches can adopt useful features associated with both types of models discussed above. For instance, where detail and accuracy is vital to achieve the modelling objective, characteristics of physically-based models can be employed; similarly, where appropriate, simpler, spatially integrated methods used in lumped-conceptual models could be utilised. This philosophy can be applied both in space and time in representing catchment properties, hydrologic processes and their variations within catchments. In the following sections, models cited in the literature which attempt to utilise intermediate approaches are described. Also, useful features of the models reviewed so far that can have implications for such approaches are highlighted.

Hughes and Sami (1994) discussed the need for a compromising hydrologic modelling approach introducing the conceptually-based, HYdrological Model Application System (HYMAS). This semi-distributed, variable time-interval model utilises physically-based and empirical parameters. An important feature of the model is that it uses a probability distribution approach for moisture accounting and runoff generation, based on the properties of soils in each sub area. Variations of saturation within sub areas are accounted for by considering spatial scales below that of the main distribution system. The model accommodates several inter-linked components, including surface water-groundwater interactions, to simulate catchment hydrologic processes. However, field applications of the model have not yet been reported. This study highlights the important effects of temporal resolution in hydrologic modelling. HYMAS utilises a variable time-interval approach and a scheme based on user-defined rainfall thresholds. SWAGSIM and SHE models also adopt multiple time steps in simulating different hydrologic processes. The use of multiple time steps allows simulation of different hydrologic processes in appropriate detail, and can be noted as a useful feature with a favourable impact on simulation times.

Suitable methods of spatial discretisation are equally important in formulating practical catchment models. Such methods could provide efficient means for representing hydrologic processes and catchment properties without undermining the accuracy of the model predictions. Knudsen *et al.* (1986) described a semi-distributed hydrological modelling system (WATBAL) which employs a useful technique for representing detail and processes within catchments. In WATBAL, primary attention is given to the hydrological processes at the root zone level. It accounts for the processes within this zone via the use of a physically-based distributed approach, whereas groundwater processes are represented in less detail by using a lumped-conceptual method. The catchment is divided into several topographic zones and hydrological response units. Within each topographic zone, hydrological processes are modelled with decreasing detail with increasing depth. This provides flexibility for representing spatial variation of hydrologic processes and input in the shallow zones in more detail, and for spatial averaging the processes in deeper zones where the variation is minimal. The model provides estimates of total discharge, though does not discriminate between different components of the hydrograph. Nonetheless, the concept utilised in WATBAL is useful with respect to development of simple, practical models.

The use of dual computational grids, which allows incorporation of varying degrees of detail as appropriate to simulate different flow processes in catchments, is also noted in some models included in the review. For example, SWAGSIM uses a dual grid based approach in representing land use-based shallow zone processes and the groundwater flow in the unconfined aquifer. TOPOG utilises two different computational networks to represent the topographically -based surface flow regime and the deeper groundwater flow system. This is an efficient way to represent catchment properties and hydrologic processes that require varying degree of detail.

HECNAR, a model designed to account for the hydrologic effect of the capillary fringe on near stream-area runoff, is described by Jayatilaka (1986) and Jayatilaka and Gillham (1994). The model simulates the overland flow and subsurface discharge to the stream in near-stream regions with shallow water tables. An important feature of HECNAR is that it treats the watershed in terms of three-zones with differing storage characteristics. Components of the model are formulated considering the hydrologic response of each zone.

The model accounts for the hydrologic processes occurring along a cross-section with an increasing degree of detail with closer proximity to the stream. This approach allows the treatment of the more dynamic response of the watertable in the near-stream zone separately, and accounts for the transient flow system which occurs during rainfall events in that zone in more detail. Simultaneously, it facilitates spatial averaging of hydrologic processes in the far-stream zone which generally covers a vast area of the watershed and has only a relatively minor impact on the output hydrologic quantities. However, in appropriate conditions during rainfall events, the model allows participation of the far- stream zone in the generation of runoff. It accounts for the expansion and contraction of the near-stream saturated zone by simulating the response of the intermediate zone.

The model has a physical basis and uses a semi-distributed method for spatial discretisation. Some empirical equations are used for representing flow processes and the hydrologic response of different zones identified in the watershed. Although HECNAR is designed to account for the highly transient near-stream character of humid watersheds, it introduces a method which is simple, yet capable of accounting for the spatially and temporally varying hydrologic response of the watershed. When suitably adopted in a catchment model, this approach could help reduce the computing and data requirements considerably, and could improve modelling efficiency.

In formulating models with greater potential for field application, the concept used in IHDM offers a useful means of representing the catchment by delineating it into a series of hillslope planes and channel reaches. This approach allows a series of sequential solutions, and could help avoid massive computing resource requirements in applying models to large catchments. Also, the terrain based TOPOG model offers a convenient means for delineating natural flow paths, and can offer a useful basis for identifying representative hillslope sections and channel segments in catchments.

In order to increase the potential for field application, the processes along the hillslopes would have to modelled using simpler, practical approaches than those used in models such as SHE, TOPOG and IHDM. To achieve this, the identified representative hillslopes could be divided into computational zones by combining topographic and depth to watertable information. In the process of formulating and testing suitable methods for representing catchment properties and hydrologic processes in the computational zones, the comprehensive physically-based models (ie. SHE and TOPOG) could provide valuable guiding tools.

5.0 Summary and Conclusions

The traditional catchment models, which are based on the lumped-conceptual approach, utilised simplified, spatially averaged conceptualisations of hydrologic processes. In recent years, the growing concern on the hydrologic impact of land use and climatic changes in catchments has led to the development and testing of models based on the physically-based, distributed approach.

Lumped-conceptual type catchment models can be used to predict spatially averaged catchment responses, and would be suitable in the absence of spatially distributed model input. Both the complexity involved and the computer requirements are low when compared with the distributed parameter physically-based models. However, the model parameters usually have no direct physical meaning, and therefore, cannot be derived from independent measurements within the catchments (Refsgaard *et al.* 1992). In addition, these models are not readily applicable outside the range of data and catchment conditions used in calibration. As a result, the models in this category cannot be used to study the effects of land use change on the hydrologic response of catchments. Lumped-conceptual type models are still useful, providing the necessary estimates in water resource planning and management (Hughes and Sami 1994).

In theory, physically-based distributed models have the capability of predicting hydrological effects of natural and man-made changes in catchments. These models can account for spatial variations of catchment properties in detail in both the lateral and vertical dimensions. They can represent the spatially-variable hydrologic response of the catchment, and provide multiple ouputs at different locations within the catchment. However, widespread practical application of these models is severely constrained due to several disadvantages associated with them.

To represent spatial variability of catchment properties adequately, physically-based distributed models should be based on sufficiently fine grid networks at the required resolution. This, in combination with the requirements of numerical schemes used to solve flux equations, imposes substantial computer resource requirements, particularly with respect to application at the regional scale or for long simulations.

In addition, the detailed information required to define the model input, and the spatially-variable hydrologic data required for calibration are not generally available in the field, and are expensive and difficult to measure. Because of the large number of parameter values generally involved in utilising the distributed aspect of these models, calibration is difficult.

Considering the scale at which the model algorithms are derived, and the scale at which the models are applied, it is being increasingly argued that their application in the field invalidates their physical basis (Beven 1989; Grayson *et al.* 1992; Grayson and Nathan 1993). Rather, according to some, their use has been viewed as similar to that of over-parameterised empirical models, or more like the lumped-conceptual models at the grid scale.

Nevertheless, physically-based, distributed parameter models based can provide a valuable understanding of the physical processes at the scale where the required input can be adequately defined. At the catchment scale however, the need for a pragmatic approach for formulation of hydrologic models with greater potential for field application has become apparent. As also noted in several recent studies, such an approach could be a compromise between the detailed physically-based distributed parameter and the simpler lumped-conceptual approaches, and perhaps, could set the future direction for catchment hydrologic modelling.

This study highlights a useful basis for formulating a pragmatic, compromising catchment modelling approach. It implies that sensitive areas of catchments (eg. near-channel areas) need detailed representation in catchment models, as the variations of catchment properties through land use change in such areas can have significant influence on output hydrologic quantities. Therefore, the catchment properties and hydrologic processes in these areas would have to be represented in a rather detailed, distributed manner. In contrast, far-stream less influential areas, where man-made or natural changes could have relatively subdued effects on the hydrologic response of catchments, can be accounted for through the use of simplified, weighted-average or spatially-averaged methods. This approach could lead to more economical and efficient models by preserving the detail and accuracy in more sensitive parts of catchments, while efficiently accounting for the processes in less effective areas.

It has become clear that through the long tradition of hydrological modelling we have inherited a variety of hydrologic models. A characteristic common to many catchment hydrologic models encountered in the literature is the scarcity of field application, which points to the necessity for a pragmatic approach for catchment hydrologic modelling. The concepts highlighted in this study will be useful in formulating catchment hydrologic models with greater potential for field application.

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