ECOMAG: An Evaluation for Use in South Africa

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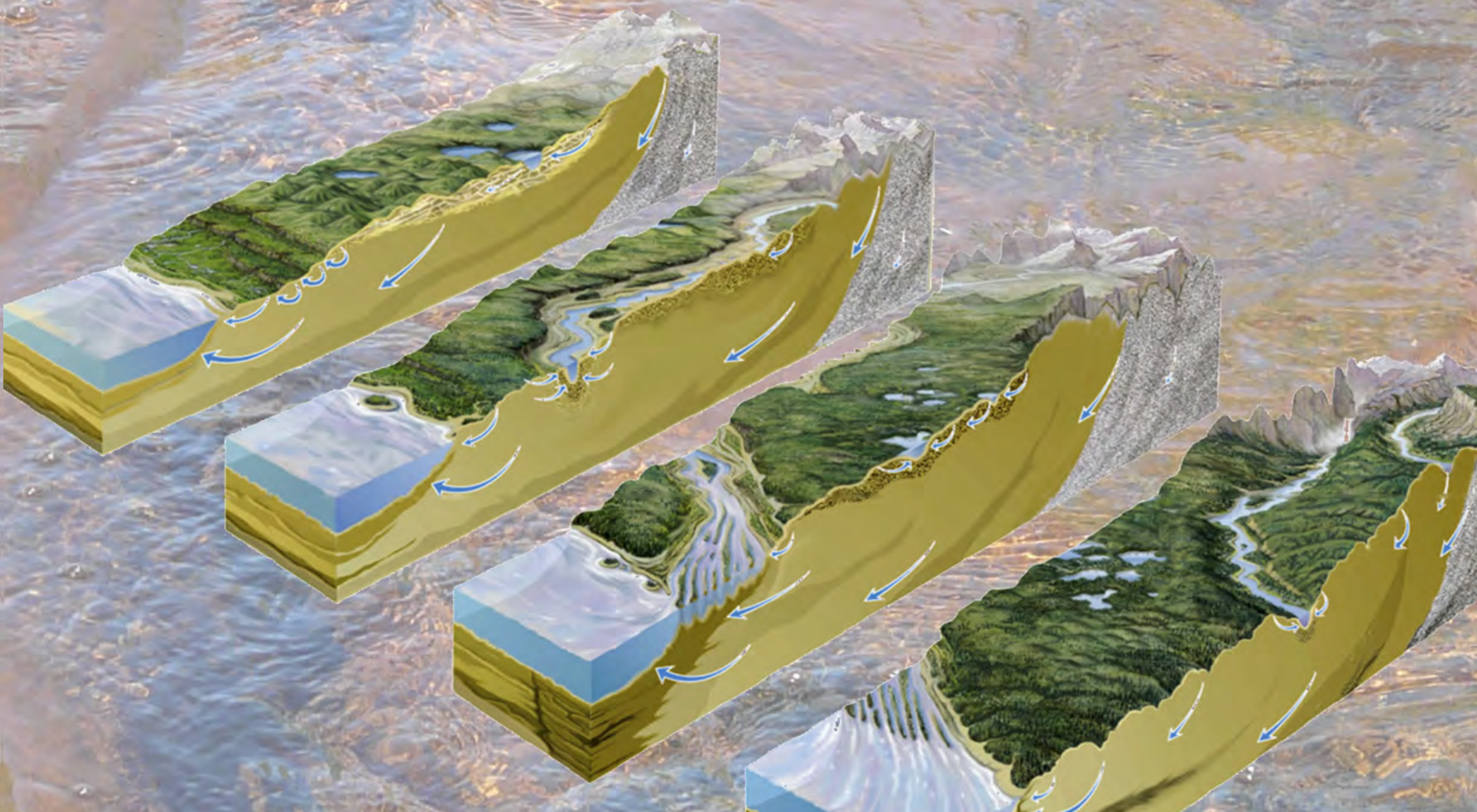

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1 Introduction

1.1 Water resources management: an overview

The complexity of current approaches to water resource management poses many challenges. Water managers need to solve a range of interrelated water dilemmas, such as balancing water quantity and quality, flooding, drought, maintaining biodiversity and ecological functions and the supply of water services to people.

It is a sad fact in southern Africa that water availability is highly variable both spatially and temporally with low runoff coefficients of less than 9% conversion of mean annual precipitation (MAP) to mean annual runoff (MAR) known to be prevalent across large parts of the region (FAO, 2003). With predictions of water scarcity conditions, caused by rapid population growth, expanding urbanisation, increased economic development and climate change, (Rosegrant and Perez, 1997), water looks set to become a limiting resource in Southern Africa. The dynamics of demand and supply will have a large impact on the future socio-economic development of the region (Basson *et al*., 1997).

A mismatch also exists between resource availability and demand with some of the greatest demand located in semi-arid areas, posing challenges for resource allocation. Thus, the reliable quantification of hydrological variables such as rainfall and streamflow is a prerequisite for mutually beneficial, cooperative and sustainable water resource management, planning and development within basins.

Over the past few decades, hydrological simulation models have become standard tools for the generation of data and have been used extensively in South Africa, and as a result, water resource management, decision and policy making have been heavily dependent on model-generated information. Computer based hydrological models, of varying complexity, for simulating the complex physical relationships that exist within a catchment during the rainfall-runoff phase of the hydrological cycle have been developed and applied at an ever increasing rate during the past four decades. The key reasons for that are twofold: (a) improved models and methodologies are continuously emerging from the research community, and (b) the demand for improved tools increases with the increasing pressure on water resources (Wheater, 2005). It has therefore not been easy for the hydrologist or the water resources engineer, especially in this country, to choose the right model for their particular problem.

Models are required partly because it is impractical to measure streamflow or groundwater at a sufficiently representative number of points to provide water resource management authorities with the information needed to quantify the availability of natural resources. They are also required because human activities constantly modify the natural environment and it is essential to be able to obtain estimates of the impacts these modifications may have on the availability of water resources. In a region such as southern Africa, where the natural availability of water is highly variable both in time and space and where the financial and human resources available to sustain long-term monitoring programmes are limited, practical hydrological estimation tools assume great importance. Models have therefore a great deal more to offer society than simply interesting scientific exercises and have the potential (often realised) to contribute to the social and economic development of a country (Hughes, 2004a).

1.2 What is a model?

In general a model is a simplified representation of a real world system, and consists of a set of simultaneous equations or a logical set of operations contained within a computer program; Wheater, 2005). Hydrologic models are simplified, conceptual representations of the different parts of the hydrologic cycle using mathematical representations of the processes involved in the transformation of climate inputs – precipitation, solar energy and wind – through surface and subsurface transfers of water and energy into hydrological outputs (typically, flow in rivers, soil moisture content or water levels in groundwater aquifers, Hughes, 2004b).

A casual search of the literature on hydrological modelling reveals a huge collection of journal articles covering a wide variety of approaches. There are those that focus on hydrological understanding where physical hydrology principles drive the modelling process. Physical concepts are studied and understood before a decision on their adequate representation in a model is taken. Some deal exclusively with the mathematics of modelling where the emphasis is on such issues as the best solutions to differential equations, optimisation methods, objective functions, etc. and the hydrological content is often very small (Hughes, 2004b; 2010; Kapangaziwiri, 2011). There are those that deal essentially with 'modelling' issues where attention has been on the improvement of model efficiency, issues of uncertainty and equifinality (Beven and Binley, 1992) and the type of equations that models can use. Over the past few decades of model development a large number of hydrological models have been proposed and an equally large number of methods for applying them (Hughes, 2004b). Consequently, it is a daunting task in the early 21st century to make a decision on the choice of model to use for a given problem or that should be recommended for use by a government department as the basis for water resources management, planning and development (Kapangaziwiri, 2011).

Two major types of hydrologic models can be distinguished (Clarke, 1973):

- Stochastic Models – These models are black box systems, based on data and using mathematical and statistical concepts to link a certain input (for instance rainfall) to the model output (for instance runoff). Commonly used techniques are regression, transfer functions, neural networks and system identification. These models are known as stochastic hydrology models. A model is stochastic if a set of input values need not produce the same output values because of random components.

- Process-Based Models – These models try to represent the physical processes observed in the real world. Typically, such models contain representations of surface runoff, subsurface flow, evapotranspiration, and channel flow, but they can be far more complicated. These models are known as deterministic hydrology models. A model is deterministic if a set of input values will always produce exactly the same output values. Deterministic hydrology models can be subdivided into single-event models and continuous simulation models. An event-based model produces output only for specific time periods, whereas a continuous model produces continuous output (Wheater, 2005). A lumped model is one in which the parameters, inputs and outputs are spatially averaged and take a single value for the entire catchment. A distributed model is one in which parameters, inputs and outputs vary spatially. A semi-distributed model may adopt a lumped representation for individual sub-catchments (Wheater, 2005).

The distinction between purely stochastic and deterministic models has become blurred in recent years with the inclusion of uncertainty approaches within what are essentially deterministic models. These are based on using different sets of input values (often generated randomly from all likely sets) to generate multiple deterministic outputs (ensembles).

Parameters

In spite of variations in complexity and structure, nearly all models have parameters for which values must be somehow quantified. A parameter is a quantity that characterises a component of a hydrological system in a particular basin and would normally be assumed to remain constant in time, while the basin characteristics remain stationary. Parameters are distinct from variables in a hydrological system which are measurable characteristics of the system that assume different numerical values at different times e.g. rainfall, soil moisture, runoff (Clarke, 1973). The number of parameters in a model has often been used to determine its level of parsimony as there is usually a positive correspondence between model complexity and the number of parameters. Parameters are an inherent component of all models and are sub-basin specific (Nathan and McMahom, 1990; Sivapalan *et al*., 2005).

A model structure, through its parameters, needs to be established in order to adequately simulate the hydrologic response of a specific sub-basin to meteorological inputs. Where there are observed data available to assess the model outputs, the parameters are continuously adjusted until the simulated time series is a reasonable match to observed response. The process of adjusting parameters to get an optimal parameter set is known as calibration. Calibration is a necessary step for many hydrological models, regardless of the number of parameters and the complexity of the model structure because most model parameters cannot be measured, frequently a consequence of the ambiguous physical meaning of the parameters (Ao et al., 2006). An objective function is a statistical function associated with an optimisation problem and determines the success of a solution. It measures the match between simulated and observed time series. The interdependence between model parameters has led to problems of parameter identifiability, over-parameterisation and equifinality (Beven, 1993; 2001). A parameter is said to be unidentifiable if it cannot be uniquely estimated from a given data set, no matter how extensive the data set is. Equifinality defines the existence of a number of different equally good parameter sets within a given model structure that may be acceptable in the reproduction of the observed behaviour of that system (Beven and Freer, 2001). The usually unknown interactions of the parameters make the parameter estimation procedure and the regionalisation of parameters very difficult.

There are some models (especially the family of physically-based distributed models) that are designed to use physical catchment property data (topography, soils, vegetation, geology, etc.) to directly estimate the values of the parameters and therefore avoid, at least in theory, the need for calibration. The question that usually needs to be answered is whether this can be realistically achieved, especially at the scale of typical model applications and given the type, accuracy and resolution of the available physical catchment property data.

Many models of varying complexity have been used in South(ern) Africa with little examination of their suitability. This has chiefly been a consequence of the many different funding agencies almost always prescribing their preferred model structures. In many cases with respect to the “imported” models developed for different conditions, the practice has almost exclusively resulted in some manipulation of the model structure to get acceptable simulations, albeit with dubious hydrological interpretation at times. Experience has shown that there are sustainability issues with using such imported models as most have ceased to be used as soon as the projects that brought them in were finalised. Apparently, there is a problem of ‘after sale’ service! The problem has thus been the fragmented and inconsistent manner (with models rarely ‘talking’ to each other) of approaches to resource estimation to the extent that uncertainties in the generated information are quite significant and disagreements are bound to increase caused by a lack of shared trust and communities of practice, especially where river basins cross national boundaries as is often the case in southern Africa. Evaluation of the suitability and applicability of a model before it can be adopted for use in a region or country should be a pre-requisite and ought to undertaken thoroughly but with an open mind to guard against either discarding a valuable model that will significantly improve resource management or taking up an unsuitable one, application of which may be difficult or may produce results not different from ones currently in use.

Assessing model performance

Regardless of the method of parameter estimation used, there is always a need to assess the performance of the model in any particular basin where it is applied. This is achieved by measuring the extent to which the simulated runoff matches the observed runoff time series when these are available. Besides a visual inspection of the simulated and observed time series hydrographs, usually associated with manual calibration, more objective statistical measures are also used. Statistical measures, referred to as 'objective functions', are normally used to objectively assess the correspondence between the two time series. There is a wide variety of objective functions cited in the literature and a specific modelling application usually determines the ones to use. Given that there is so much information that can be obtained from an observed flow time series, it is not possible for all the different flow components (e.g. peaks, low flows, and recessions) of the data to be sufficiently evaluated by a single performance criterion (Vrugt et al., 2003). For a complete assessment, a number of objective criteria should be used. While a more comprehensive list of objective functions can be found in Görgens (1983), a small sample of common objective functions is listed here:

i. Nash and Sutcliffe (1970) Coefficient of Efficiency (CE): The model efficiency has become one of the most widely used measures of goodness-of-fit in hydrological modelling. CE is a dimensionless relative index of correspondence between the simulated and observed time series and is given mathematically as:

$$\mathrm{CE} = 1 - \left[\frac{\sum(\mathrm{Q_{obs}} - \mathrm{Q_{sim}})^2}{\sum(\mathrm{Q_{obs}} - \overline{\mathrm{Q}}_{\mathrm{obs}})^2}\right] \qquad \text{Equation 1}$$

Where: Q_{obs}= observed time series; Q_{sim} = simulated time series and $\bar{Q}_{obs}$ = mean of the observed series. CE can assume any values between -∞ and 1 with the latter indicating a perfect fit between the observed and the simulated flows.

ii. Coefficient of determination, R^2: relates to the proportion of variability within an observed time series data set that is explained by the simulated one and is written as:

$$\mathrm{R}^2 = \frac{\sum[(\mathrm{Q_{obs}} - \overline{\mathrm{Q}}_{\mathrm{obs}}) \cdot (\mathrm{Q_{sim}} - \overline{\mathrm{Q}}_{\mathrm{sim}})]^2}{\sum[(\mathrm{Q_{obs}} - \overline{\mathrm{Q}}_{\mathrm{obs}})^2 \cdot (\mathrm{Q_{sim}} - \overline{\mathrm{Q}}_{\mathrm{sim}})^2]} \qquad \text{Equation 2}$$

Where: Q_{obs}= observed time series; Q_{sim} = simulated time series; $\bar{Q}_{obs}$ = mean of the observed series and $\bar{Q}_{sim}$ = mean of the simulated time series.

R^2 varies between 0 and 1 inclusive and R^2 = 1 indicates that the simulated time series explains all variability in the observed time series, while R^2 = 0 indicates a poor correspondence between the two time series. While the CE is sensitive to systematic errors (general over- or under-estimation), R^2 is not similarly affected and a value close to 1 does not necessarily imply a good simulation. Where both the CE and R^2 are used as assessment criteria, large differences between them indicate systematic errors.

iii. Percentage error of the total discharge volume (%V) or peak discharge (%P): these measure the percentage deviation in the total volume and peak discharge of the simulated from the observed. A perfect correspondence between the hydrographs of simulated and observed flows is shown by a value of zero with poor simulations being shown by an increasing divergence (in both directions) from zero. High values of %P and %V are an indication of systematic error. Low values of %P and %V can indicate low CE or R^2 values. The percentage error of total discharge volume is written as:

$$\%V = 100\frac{(VQ_{obs} - VQ_{sim})}{VQ_{obs}} \qquad \text{Equation 3}$$

Where: VQ_{obs} and VQ_{sim} relate to volume of observed and simulated time series respectively.

A percentage error of the mean annual runoff (MAR) can also be used and is given by:

$$\%Mean = 100\frac{(MAR_{obs} - MAR_{sim})}{MAR_{obs}} \qquad \text{Equation 4}$$

Where: MAR_{obs} = Observed MAR; MAR_{sim} = simulated MAR.

iv. Comparison of flow duration curves: A streamflow duration curve illustrates the relationship between the frequency and magnitude of streamflow and is a cumulative frequency curve that shows the percentage of time that specified discharges are equalled or exceeded. The flow duration curves of the simulated can be compared to that of the observed flow to judge the ability of the model to reproduce the flow pattern. Duration curves reflect the flow regime of the basin, with ranges from the low to the high flows being shown. This is a more reliable method for water resource assessments for the design of reservoirs or establishment of abstraction works.

All the objective functions can be calculated using untransformed (natural) streamflow data or using natural logarithm-transformed data. The logarithmic transformation of data removes the bias towards the high flow values and gives greater prominence to the moderate to low flows.

Modelling Uncertainties

In spite of their undeniable importance, models are imperfect abstractions of complex reality and therefore produce uncertain outputs. Current international practice is towards the estimation, incorporation, analysis and reduction of uncertainty related to input data used to drive the models, the internal structural construction of the model and the model parameters that are used to condition the application of the model in a given basin. While there has been general acknowledgement of uncertainty associated with water resources estimation in the South African (e.g. Ashton *et al.*, 1999; Alexander, 2002), there have been few attempts to quantify the sources of uncertainty and how they propagate through the estimation process. Model outcomes, and the decisions based on them, remain vulnerable if the uncertainties associated with the modelling chain are not analysed and documented (Beven, 2000). Important decisions have been made in this country based on modelling results that have used limited databases of historical observations without incorporation (or even cursory mention) of the uncertainties and risk associated with the model results. While the risks associated with this approach are unknown, there are real chances of sub-optimal use of resources based on conservatism in planning. Only in recent years has the issue of uncertainty been directly addressed through projects supported by the Water Research Commission (e.g. WRC Project K5/1838 & K5/2056) and targeted specifically at assessing the sources of uncertainty and developing approaches to propagate the uncertainties through the modelling chain to determine the impact on model outputs and decision making. Uncertainties related to the input climate data (Sawunyama, 2010) and model parameterisation (Kapangaziwiri *et al.*, 2009; 2012; Hughes *et al.*, 2009; Kapangaziwiri, 2010) have been considered.

The issues of uncertainty become extremely important when models are applied to ungauged basins where it is not possible to directly assess the model outputs against local observations. In these situations it is necessary to make use of direct parameter estimation using physical catchment property information or to use parameter regionalisation approaches that are guided by parameter sets established (and validated) for the relatively small sample of gauged catchments. As already discussed there are uncertainties in the model calibration process as well as in the process of transferring (by whatever method is used) the parameters to ungauged basins.

1.3 Purpose/use of modelling

Models are primarily used for hydrologic prediction and for understanding hydrologic processes, and the frequently stated purpose of developing models is to solve practical water resource problems (Maidment, 1993; Hughes, 2004b). However, the tasks for which rainfall-runoff models are used are many and diverse, and the scale of applications ranges from small catchments, of the order of a few hectares, to that of global models (Beven, 2001). Each model type can be considered to have a range of applications which depend upon the available information, the required accuracy and resolution of the output and the time resources that can be directed at the modelling exercise. From a water resource assessment point of view, the primary objective of modelling is frequently to generate a long representative time series of streamflow volumes from which water supply schemes can be designed (Hughes, 1995). Typical tasks for hydrological simulation models include (Wheater, 2005; Ao *et al.*, 2006):

- Modelling existing catchments for which input-output data exist;
    - e.g. extension of data series for flood design of water resource evaluation,
    - operational flood forecasting or water resource management
- Runoff estimation on ungauged basins;
- Prediction of effects of catchment change;
    - e.g. Land use change, climate change;
- Coupled hydrology and geochemistry, and;
    - e.g. Nutrients, Acid rain
- Coupled hydrology and meteorology.
    - e.g. Global Climate Models

Clearly, the modelling approach adopted will in general depend on the required spatial and temporal scale of the problem, the type of catchment, and the modelling task.

1.4 Model development and use in South Africa

Internationally, a great deal of the work on process hydrology was undertaken during the 1960s and 1970s by various prominent hydrologists, focusing on such as runoff generation processes (Hewlett and Hibbert, 1967) and infiltration (Childs and Bybordi, 1969). A large amount of this work focussed on relatively small scale processes and the results are not always easy to use in the design of catchment scale hydrological models (Beven, 1989). The late 1970s saw the start of a programme of process studies within small experimental catchments in South Africa, largely funded by the Water Research Commission (WRC) and many of these investigations provided much-needed data that could be used to develop and test a range of hydrological model structures (e.g. Hughes, 1984; Schulze, 1986; Hughes and Sami, 1994; Görgens, 1983) and provided the impetus for a large proportion of the South African research into the application of hydrological models.

South African developed models have tended to be of the more complex type, with a relatively large number of parameters, even for monthly time-step models (Hughes, 2004a). This is because of the drive towards the representation of most of the processes of runoff generation within models (the conceptual approach) rather than opting for simpler transformation functions (the mathematical approach) with fewer parameters (Perrin *et al.*, 2003). The overriding motivation for the South African approach has always been that model parameters should be easier to evaluate for ungauged situations because they are more meaningful in terms of real hydrological processes and can be related to measurable catchment characteristics (see Kapangaziwiri, 2011).

It has now been nearly four decades since a model designed for use in climatic conditions prevalent in most South African countries was developed through the pioneer work of

Pitman in 1973 at the University of the Witwatersrand, South Africa. Through different versions (see e.g. Pitman, 1973; Hughes, 1997; Hughes, 2004a) this model has been the most widely used model in the in the country, culminating in the national water resource assessments of the 1980s, 1990s (Midgley *et al.*, 1994), 2005 (Middleton and Bailey, 2009) and the current update project that started in 2012. The Pitman model has found favour for water resource assessment, development and planning purposes in the country because of its relatively simple, yet comprehensive and flexible, structure that can describe hydrological conditions in the region with some reasonable degree of accuracy, producing outputs in which the community of water practitioners in the country have high regard and confidence. The data demands can generally be met in the country and region that are haunted by problems of data scarcity.

Besides the Pitman model there have been other models that have been developed and used in the country. The Variable Time Interval (VTI) model (Hughes and Sami, 1994) is one such model. It was also used quite extensively in basins of the region during the FRIEND project. Outside the FRIEND project applications, where it recorded mixed results, the VTI has only been applied in South Africa.

The fully distributed, physically-based ACRU model, developed at the University of KwaZulu-Natal (Schulze, 1986), has been applied mostly in the humid and temperate parts of the country. It is based on the idea of moisture accounting and uses multiple soil layers to simulate water balances. Its application outside South Africa has been limited. The heavy data demands of the ACRU model impacts on its general use in the general southern Africa region in spite of the success it has enjoyed in the basins of South Africa where it has been used quite extensively.

The national water resources assessment projects, in which the Pitman model played a prominent role in setting the hydrological baseline for the country, have managed to make models, model outputs and model development visible in the country. The development of models has often been driven by the need to address emerging issues in water resources estimation and management. For example, more explicit surface water and groundwater interaction routines were added to the Pitman model (Hughes, 2004a, Sami, 2006) in response to the need for improved integration of these two components of the total water resource. In addition, the Water Research Commission has been sponsoring research on the development of uncertainty approaches to modelling (Hughes et al., 2011) based on the recognition that we can no longer neglect the effects of uncertainty on decision making risk.

1.5 The objective of this review

Whilst a vast array of hydrological models is available, the choice of which one to use for a given basin is not easy. Each model works within specific spatial (field to basin) and temporal (event based to annual water balances) boundaries and can only simulate specific hydrological processes. It is important to select the 'right' model for the 'right' kind of modelling exercise. Numerous criteria are used for informing the choice a hydrological model, or a suite of models, to use for an individual exercise or as part of a suite of models use for data generation, analysis, assessment and decision making with respect to national water resources. Some criteria are rather subjective and depend on the user such as the personal preference for graphical user interface, computer operation system, input-output management and structure, familiarity with a particular model, an explicit non-debatable requirement from the client, even the lack of sufficient funds or user's add-on flexibility (Cunderlik, 2003). However, such factors should not be the most important in influencing the selection process (Koch and Grünewald, 2009). Despite a lack of universal rules, there are common considerations that can be used as a guide in the selection of an existing model (After Maidment (1993) and Loucks and Van Beek (2005)):

- The modelling purpose and intended outputs (e.g. peak flows, long-term flow sequences, flow volumes, event hydrograph, etc.). The problem to be solved by the model or suite of models needs to be well understood and presented, the information required and the questions to be answered all need to be determined. A model that fits the problem, rather than trying to fit the problem to a model, should be selected. It is always best to use the simplest method that will yield adequate accuracy and provide the answer to questions being asked in the problem. It is at least in theory possible to reach a high level of understanding of catchment hydrology using a fully distributed model, which separately describes each small sub-area of the catchment through physically consistent formulations and parameters related to measured catchment properties. However, as pointed out by Beven and Kirkby (1993), this goal has so far been unattainable. Practical difficulties appear in the implementation of the system and the data availability. An adequate database is costly to assemble and may be unavailable for large catchments.
- The catchment processes that need to be modelled in order to meet the purpose or desired outputs. Do not forget the assumptions underlying the model used and do not read more significance into the simulation results than is actually there.
- Availability and quality of input data (are all the requisite input data available at the relevant spatial and temporal scales?). The question that this point raises is whether increased accuracy is worth the increased effort and increased cost of data collection?

Several well-conceptualised hydrological models are already in use in South Africa, the most common of which are the Pitman (Pitman, 1973) and the ACRU (Schulze, 1986). These two models have served very well the many diverse requirements of the water sector in the country. However, once in a while some models come to the attention of the modelling society and it is prudent that before these can be recommended for widespread use they be evaluated for their ability to assist planners in assessing different land-use scenarios. Indeed, they could be valuable. Such an evaluation would ordinarily involve the setting up of the model in a few sub-basins and have the results assessed independently and also against those obtained from the current suite of models.

South Africa is a relatively dry country, and limited water resources are set to become increasingly valuable as demand for water by agricultural, industrial and urban sectors increases. Supply in rivers fluctuates widely because of large variation in the amount and distribution of rainfall, both within and between years. Periodic droughts, especially when associated with consecutive years of below average rainfall, have a major detrimental effect on the national economy. In planning optimum water use strategies for the country, it is of paramount importance to adequately quantify the water resources, usually achieved through the use of hydrological and water resources systems models.

In addition to the suite of models currently in use in the country, the Russian developed ECOMAG model (Motovilov et al., 1999a) has been suggested as a possible candidate for use in South Africa. It is thus necessary to evaluate the suitability of the use of this model under South African conditions. This review assesses the applicability of the model in the country and compares it with models currently used for the same purpose in order to make recommendations about adopting the model for local use.

The most significant reason for embarking on a review of this nature is to ensure that the most relevant scientifically constructed and defensible tools are used to generate information upon which important and far-reaching management and policy decisions with respect to the nation's water resources are based. While this may not be loudly proclaimed, it is a fact that such a review may also be aimed at protecting growth of the science of hydrological modelling and the development of suitable software locally. Such protections may be necessary especially when considered against the numerous bilateral national agreements which could be used to flood the local space with imported scientific and technological developments which may suffocate local initiatives. However, it is also prudent to highlight that fair competition could spur the local scientific community to improve their models.

Science questions

For a successful and unbiased review, a number of science questions need to be answered truthfully. The following science questions were chosen to streamline this review. While some questions are explicitly addressed in the review through deliberate targeting by the team, it is hoped that, for others, inferences could be drawn from the broad discussions of the participating models in this review.

i. What are the dominant natural hydrological processes influencing the rainfall-runoff transition process within the South African physical landscape and how are these represented in hydrological models in the country?

ii. Are there alternative process conceptualisations to available local models (at the appropriate model spatial and temporal scales) of the natural hydrologic processes that will provide improved simulation accuracy and facilitate better water resource assessment?

iii. What level of model complexity is required to realise improvements in basin outlet simulations? Is the level of complexity of current South African models sufficient and appropriate? Given the participating models (with a range of structures and complexity) it was hoped that inferences could be made about appropriate model complexity and scale under local physical conditions and given the constraints of data availability.

iv. What level of effort is required for appropriate ways of quantifying parameter values of all the models in both gauged and ungauged basins?

These questions are obviously interlinked and answers to them should provide a reasonable direction with regard to the applicability of the ECOMAG model. In the absence of the software it is indeed difficult to answer some of these questions and the answers provided from a mere literature review may be inadequate to support a decision. Improving simulations at the outlet of basins is the focus of this effort. This review is qualitative, without the model being set up in any catchment. This was necessary given that the team's efforts at acquiring the software through the client (who liaised with DWA on this) were not successful. The main objective of this study is to comprehensively evaluate the ECOMAG Model against equivalent models used in South Africa and, especially, by the Department of Water Affairs.

Specific objectives of the work include:

- Compare the main structure of the ECOMAG model with other local models
- Identify the data requirements of the ECOMAG Model;
- ECOMAG's potential value to the Department of Water Affairs and South African water resources sector;

2 The South African physical environment

The aim of this section is to briefly describe the South African physical landscape and how this influences the hydrology and the hydrological processes that models try to simulate.

The prevailing precipitation mechanisms differ between the humid and the more semi-arid parts of the country. Whereas the arid and semi-arid central and western areas experience generally high intensity, short duration storms in the summer, the winter rainfall region in the south west experiences longer duration frontal type, low intensity storms and the higher altitude east and north experience relatively shorter duration, convective and orographic type storms. The prevalence of relatively thin vegetative cover and high evaporation rates in the semi-arid areas implies that infiltration excess overland flow is a dominant runoff generation process in some areas. This rainfall, and consequently runoff generation, is frequently localised implying that while runoff may be generated on some of the slopes and first order catchments it is short-lived and rarely survives to contribute to runoff at the outlet of catchments (Hughes, 1995). This runoff generated may be absorbed in deeper valley bottom soils, infiltrate into the bed and banks of alluvial rivers (Hughes and Sami, 1993; Hughes, 1995) or be decreased by channel evaporative losses (McKenzie et al., 1993). There is also evidence in some areas to suggest that quite high rates of upstream runoff can be lost through infiltration into fractured bedrock channels and contribute to groundwater recharge (Sami, 1992). The implication is that while the relatively small scale processes of runoff generation are strongly related to rainfall intensity and the infiltration capacity of the soil (following a classic Hortonian type model), the "survival" of runoff on a larger catchment scale may be related to antecedent storages in the catchment (Hughes, 2004a). It seems important that even in a relatively simple model such a concept should be included (Hughes, 1995).

In the more humid areas of the country, the high rainfall implies that antecedent soil moisture is usually quite high during the wet season and that vegetation cover is relatively thick. Three dominant streamflow generation mechanisms, (overland flow, near surface macro-pore flow and groundwater flow), are assumed to contribute to the stream and local seepage zones linked to the stream during an event (Lorentz *et al.*, 2004). Indeed, runoff generation mechanisms in such cases are dominated by saturation-excess flow processes (Hewlett and Hibbert, 1967) and small, low intensity rainfall totals may lead to stream flows observed at the catchment outlet. The effect of cascading increments in moisture downstream leading to saturation towards the valley bottom is important (Hughes and Sami, 1994) in these areas.

The impact of vegetation on the catchment processes is also important and needs to be understood properly and incorporated in models. Different types of vegetation have different influences in the hydrology of a basin (Yang *et al.*, 2011). It is not only the type and density of vegetation that is important but also the stage of growth and growth patterns that exert an influence on catchment processes and models need to be able to capture this dynamism for a proper accounting of moisture in the catchment (Hughes, 1995). Substantial and comprehensive work in the area of forestry hydrology related to growth pattern effects on evapotranspiration and streamflow has been carried out using the ACRU model (e.g. Summerton, 1995; Savage et al., 1997; Lorentz and Esprey, 1998; Schulze, 2004; Gush et al., 2002). The resulting increase in understanding is important given the economic significance of plantation forestry in some areas and the effects of forest management practices on downstream reduction of streamflow.

The subsurface processes of percolation, aquifer recharge, ground water movement, aquifer storativity and transmissivity, ground water outflow to downstream catchments and baseflow contributions to stream flow need to be included in catchment models for them to be integrated. While most of these processes may be difficult to conceptualise, measure and model, it is prudent to incorporate these (or some of them) so as to achieve a holistic approach to catchment modelling. Modelling them separately in surface and ground water models has often led to problems of uptake of results from one approach to another. The often cited problem of different scales and non-contiguous catchment boundaries can easily be overcome with concerted effort from both sets of scientists (e.g. Sivapalan, 2005; Gupta *et al.*, 2008)).

Besides the representation of the physical surface and subsurface processes, catchment models need to be able to represent the rainfall input properly. Catchments often integrate different altitudes and it is common knowledge that higher areas experience more rainfall than low-lying ground. As such there is need to adequately capture these variations in models. For instance, in Swedish catchments, studies have shown that rainfall increases by 10% for each 1000 m rise in altitude (Lindstrom et al., 1997) and this has been incorporated into the HBV model (Bergstrom and Forsman, 1973). While not every model will be so elaborate, the estimation of the input rainfall is very important, as rainfall measurements are usually sparse in the mountainous regions (Smithers and Schulze, 2001).

Research into the effects of wetland impacts on downstream flow regimes is a relatively new field in South Africa. However, over the past few decades wetlands research has grown, especially in relation to hydrological modelling in the context of water resources management (Davies *et al.*, 1993). Wetlands are complex hydrological phenomena that occur in a wide variety of environments, often under differing climatic and topographical conditions. Wetlands form the interfaces between aquatic and terrestrial ecosystems, and a number of streams and rivers originate as a collection of shallow headwater wetlands (e.g. Von der Heyden and New, 2003). Owing to their close association with the drainage network and to their diverse and specialised environment, wetlands are of great significance in the general water resources management of any catchment where they occur. While not a huge component in many catchments in South Africa, there are some significant wetlands in some parts of the country and models would do well to appropriately represent these processes. The Pitman and the ACRU models both have comprehensive algorithms that simulate wetland processes and impacts on riverflows (see Schulze, 1995; Middleton and Bailey, 2009; DWA, 2008; Hughes *et al.*, 2013).

Human activities affect the land surface and therefore physical surface hydrology processes through agricultural activities, freshwater harvesting, economic activities (mining, industrial activities, etc.), urban developments, etc. These activities have varying degrees of influence on how rainfall is partitioned into streamflow. Ncube (2006) identified a distinct correlation between land use, land cover and the hydrologic response in which substantial streamflow reduction was observed in response to an increase in land cover. Ncube (2006) states that land use and its management may affect the hydrology through either enhancing or retarding infiltration and effectively increasing or reducing streamflow generation and its temporal distribution. Schulze (2000) suggests that different land uses are usually associated with particular mechanisms of water use and runoff generation, which hydrological models ought to be able to simulate:

- Commercial plantations (afforestation) – reduces stormflow and groundwater recharge as well as affecting streamflow generation. These effects however vary as it is influenced by the drainage mechanism as well as the age of the trees.
- Human settlements – results in higher stormflows, peak discharges and changes the timing of hydrograph peaks.
- Irrigation – reduces streamflow where abstractions occur. This consequence is however reduced downstream.
- Agricultural activities – cultivation activities like ploughing may reduce stormflow by increasing infiltration and the soil's water retaining capacity.
- Livestock farming – grazing, if managed poorly, increases stormflow, whereas well managed grazing lands may reduce stormflow.
- Riparian vegetation – alien vegetation growing on the banks of rivers reduce streamflow. This is however dependant on the physiological characteristics of the alien growth.

It is therefore evident that water resources cannot be assumed as stationery in time where land use changes are expected.

Lastly, aridity, which covers a huge part of the country, is an important climatic condition in the country and models developed here are designed to try to simulate the hydrology of such areas including an allowance for varying, non-seasonal vegetation cover conditions and transmission losses to alluvial aquifers. Hughes and Meltzer (1998) added a dynamic vegetation cover to the Pitman model and achieved an improvement over the original model in arid basins of Namibia.

3 Models commonly used in South Africa

The following sections provide an overview of existing hydrological models that have enjoyed practical popular use in South Africa for the solution of practical engineering and management problems. The most popular models by far have been the Pitman (Pitman, 1973; Hughes et al., 2006) and the ACRU (Schulze, 1995). A number of other models have also been used sparingly mainly on individual projects.

3.1 The Pitman Model

The Pitman model was borne out of the pioneer work of V.W. Pitman working in the Hydrological Research Unit at the Witwatersrand University. The development of the model was principally aimed at simulating "runoff in a form suitable for water resources appraisal" (Pitman, 1973; pp 1.7). The model is thus essentially a water resource assessment tool though some of its applications have often deviated somewhat from the original plan for the model. The Pitman model was originally designed as a conceptual lumped monthly rainfall-runoff model but in more recent versions the model is semi-distributed (e.g. Hughes et al., 2006). While the basic structure and form of the model has remained intact over the years, it has undergone a number of modifications (e.g. Hughes, 1997; Gan et al., 1997; Hughes and Metzler, 1998; Hughes, 2004a; Hughes et al., 2006). Two approaches have been evident with the later versions – the first being the use of nodes in order to better incorporate a broader spectrum of human influence in managed basins (Middleton and Bailey, 2009). The other route has been to use sub-basins in a distributed modelling approach, with the most recent version being the one in which explicit ground water routines have been added (Hughes, 2004a). The greatest strength of all these changes is that the model outputs from the different formulations of the model are almost always identical. Recent modifications of the model versions include the development of more concise routines for simulating wetland processes (see DWA, 2008; Hughes et al., 2013).

The WRSM2005 (DWA, 2008) is the official tool for water resources assessment used by the South African Department of Water Affairs (DWA). Additional changes to the official version of the model have included model formulations to improve the simulation of highly developed South African catchments including the hydrology of (Middleton and Bailey, 2009):

i. surface water-ground water interactions,
ii. afforestation,
iii. alien vegetation,
iv. dryland crops,

v. off channel wetlands, and
vi. mine and irrigation water including quality aspects.

The model thus includes explicit routines to simulate interception, infiltration excess surface runoff, soil moisture (or unsaturated zone) runoff, groundwater recharge and drainage to stream flow, as well evaporative losses from the unsaturated zone as well as the groundwater storage (in the vicinity of the river channel). Consequently, the model therefore has a relatively large number of parameters and it is typically impossible to establish parameter sets that generate unique results through conventional calibration approaches. However, the potential advantage of the model is that the different contributions to stream flow can be determined and should be sensitive to changes that occur within sub-basins. These changes may involve climate, land use and land cover or different types of abstractions and water use. Table 1 contains a list of the main model parameters that influence volumes of runoff generation as well as a brief summary of the estimation approaches and Figure 1 shows the flow diagram of the Pitman model formulation.

Currently the Pitman model is used within the Spatial and Time Series Information Modelling (SPATSIM) framework which was developed at the Institute for Water Research (IWR) at Rhodes University as an improvement over its predecessor (HYMAS, Hughes et al., 1994) which lacked GIS functionality and was basically used for managing data for use with several different hydrological models. SPATSIM is a database management and modelling framework specifically designed for hydrological and water resource system applications (Hughes, 2002; Hughes and Forsyth, 2006). SPATSIM uses some GIS functions and allows access to database tables for use with models through data dictionaries which allow SPATSIM to be used as a data platform by different, even older, versions of models (Hughes and Forsyth, 2006). All spatial data loaded into the software through shapefiles whose associated attributes are stored in database tables. SPATSIM has a suite of internal facilities designed to allow the manipulation of data linked with the spatial elements. These facilities include routines for the import/export of data, addition/deletion of spatial features and/or attributes, data exchange protocols between SPATSIM users and a host of common hydrological data processing facilities. Examples of the last group include the generation of duration curves from time series and the generation of spatially averaged (over defined polygons) data using an inverse distance weighting method (. Besides these internal facilities SPATSIM also links with external models and data analysis programs that are individual entities developed outside the software. These include a generic time series data display and analysis program (called TSOFT, Hughes et al., 2000) and a collection of models of which the Pitman and ACRU models are examples (Clark et al., 2009). WRSM2005 uses the Dashboard as the interface from which a number of models can be accessed. A daily version of the Pitman model is also being currently tested for re-introduction, and a trial version is already available. A previous version, developed in the 1970s was never really used as the monthly version was considered more appropriate for the majority of uses. However, there have been frequent calls to add more temporal detail into the outputs from hydrological models.

Table 1. Parameters of surface (A) and sub-surface (B) process descriptions of the Pitman model (Hughes et al., 2006).

Parameter name	Units	Description of parameter
A. Surface processes		
RDF	-	Rainfall Distribution Factor – influences the evenness of rainfall distribution into the four iterations of the model.
AI	%	Percentage of the area covered by impervious area which is contiguous to the river channel
PI	mm	Interception capacity of the vegetation in the basin. This parameter is specified for 2 dominant vegetation types for both summer and winter seasons.
AFOR	%	Percentage area of sub-basin under the second vegetation type
FF	-	Ratio of potential evaporation rate for vegetation type 2 relative to vegetation type 1
ZMIN	mm/month	Minimum sub-basin absorption rate
ZAVE	mm/month	Mean sub-basin absorption rate
ZMAX	mm/month	Maximum sub-basin absorption rate
TL	months	Lag of surface and soil moisture runoff
CL	months	Channel routing coefficient
B. Subsurface process		
R	-	Evaporation-moisture storage relationship parameter
ST	mm	Maximum moisture storage capacity
FT	mm/month	Runoff from moisture storage at full capacity (ST)
POW	-	Power of the moisture storage- runoff equation
SL	mm	Minimum moisture storage below which no GW recharge occurs
GW	mm/month	Maximum ground water recharge at full capacity, ST
GPOW	-	Power of the moisture storage-GW recharge equation
S	-	Ground water storativity
T	$m^2 d^{-1}$	Ground water transmissivity
DDENS	$km\ km^{-2}$	Drainage density
GWSlope	%	Initial regional ground water gradient for ground water movement
RSF	%	The riparian strip factor which controls riparian evaporation losses from groundwater store.

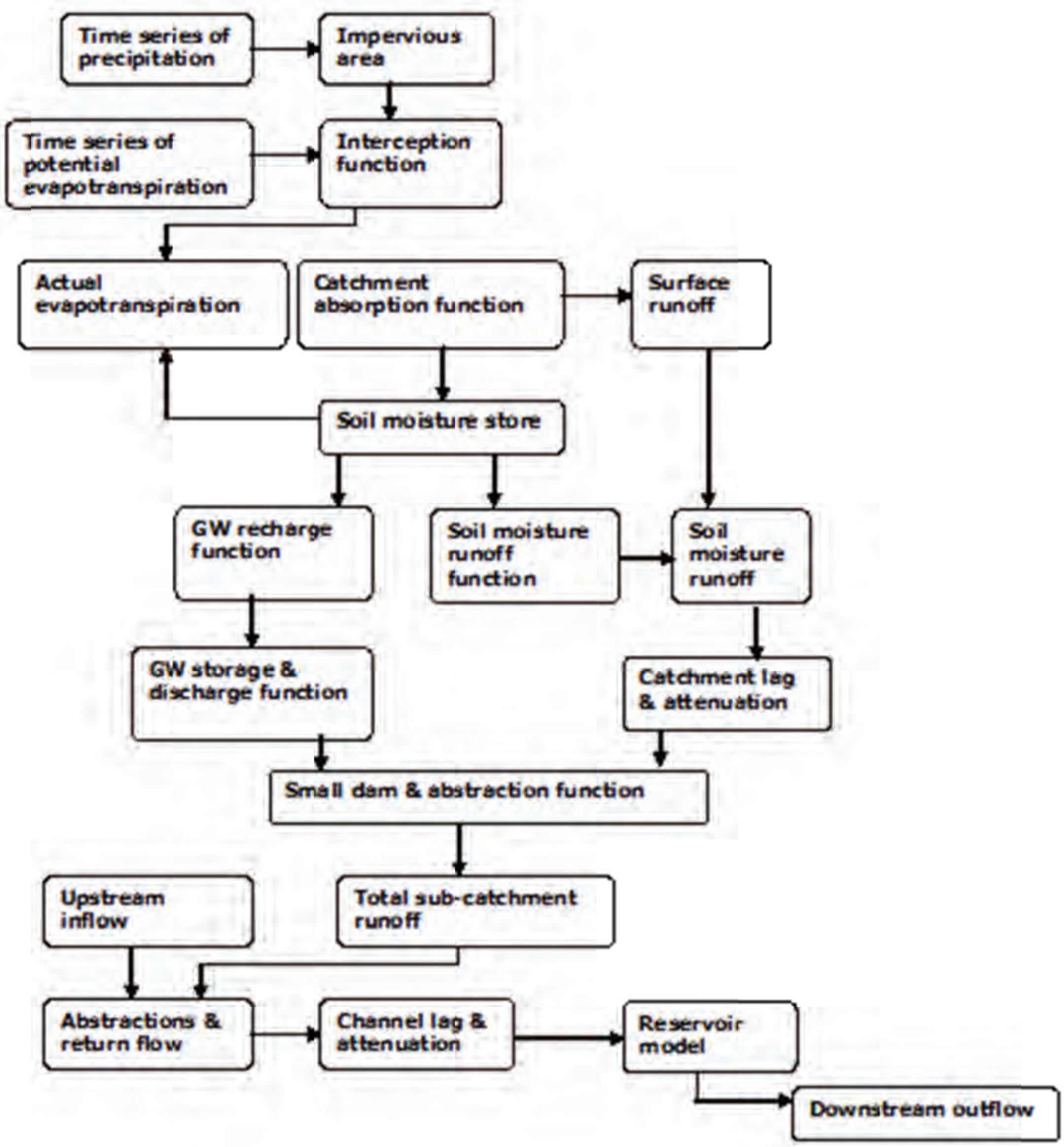

Figure 1. Flow diagram of the main components of the Pitman model (Hughes et al., 2006).

The WRSM2005 interface includes water quality models. While the Pitman model versions do not currently directly include water quality modules, work on this aspect is currently underway at various institutions including the Institute for Water Research (IWR), Rhodes University where a simple water quality model linked to Pitman model was developed and tested in a number of catchments (Slaughter et al., 2012). Hughes (2009) also attempted to model TDS within the Pitman model. Current work now includes the modelling of nitrites and phosphates. A simple monthly time step, quaternary scale, TDS mass balance model was also developed and operates as part of the WRSM2005 system (DWA, 2008). Its purpose is to provide WR2005 with a means of simulating monthly time series of present day incremental or cumulative TDS concentrations at the quaternary outlet. The model, SALMOD, is capable of modelling system networks the same as those used in the Pitman (WRSM2005) hydrological model. SALMOD uses the flow time series generated by the Pitman, but is not an internal Pitman (WRSM2005) process. It is clear from this short discourse that the Pitman model does not directly simulate water quality, and research into this is on-going.

Calibration of the Pitman model.

The Pitman model is typically calibrated manually with some of the parameters often set to constant values based on experience and the literature. Guidelines for the calibration of the parameters have evolved with the use (e.g. Middleton et al., 1981, Hughes et al., 2006) of the model from the initial parameter estimation guidelines given by Pitman (1973). In the water resources assessment study (WR90, Midgley et al., 1994) that included South Africa, Swaziland and Lesotho, regionalised parameter sets were developed for a total of 1946 so-called quaternary basins. These parameter values have provided pre-calibration initial estimates in the gauged basins and provide parameter value estimates for ungauged basins whose sizes are equal to the ones used to develop the regionalisation. The regionalization of the parameters was premised on somewhat subjective parameter mapping based on some measure of similarity. While Pitman (1973) provides some initial parameter values for calibration and Midgley et al. (1994) provide preliminary parameter values for the Pitman model for the whole of South Africa, physically-based parameter estimation routines have recently been developed (see Kapangaziwiri, 2010; 2011; Kapangaziwiri and Hughes, 2008; Hughes et al., 2010) and can be applied within the uncertainty framework proposed by Kapangaziwiri et al. (2009) for use with the Hughes et al. (2006) version of the model. Discussions are underway to apply the same principles to the other versions of the model. This will greatly improve the use of the model in ungauged basins. Attempts at automatic calibration of the model have been made by Gan et al. (1997) and Ndiritu (2001; 2009) with reasonable success. The incorporation of uncertainty and the generation of ensembles using Monte Carlo parameter sampling (Kapangaziwiri et al., 2009; Kapangaziwiri, 2010) can be viewed as an alternative to formal automatic calibration. The ensemble outputs allow a large number of possible parameter sets to be explored and only those that produce behavioural (Beven, 2001) results accepted for further evaluation or use (Kapangaziwiri, 2010).

In addition to the use of graphs (flow time series, duration curves etc.), the model performance is usually quantified using six statistical objective functions measures. These are the Nash coefficient of efficiency (CE, Nash and Sutcliffe, 1970) and the coefficient of determination (R2) and the percentage difference of mean monthly flows for both the untransformed values and natural logarithm transformed values. Zero flows are ignored when using the natural logarithmic transformation. The SPATSIM interface also offers a number of visual options, including flow duration curves, as additional approaches for assessing model performance. The calibration of the Pitman model is therefore typically viewed as a multi-objective problem as six statistical performance measures (as well as visual comparisons) are used to determine the match between the historic and the simulated flows (Ndiritu, 2009).

3.2 ACRU Model

The development of the Agricultural Catchment Research Unit (ACRU) model first commenced in 1981 at the University of Natal in Pietermaritzburg, South Africa. The first version of the model was released five years later based on a report by Schulze (1984). Research, model development, testing and refinement efforts have been ongoing since then. This process has been funded largely by the Water Research Commission (WRC) of South Africa. The model provides a sound basis for quantifying the impacts of land cover and land-use changes on runoff.

ACRU is a distributed, conceptual, physically-based, multipurpose agro-hydrological daily time step model outputting, among others, daily runoff elements (stormflow, baseflow), soil moisture, seasonal crop yields, sediment loads, impacts of climate change and impacts of changes in land cover (Schulze, 1995). The conceptualisation of the model is premised on multi-layer soil water budgeting and is structured to be hydrologically sensitive to catchment characteristics, and there is explicit representation of physical catchment processes (Eagleson, 1983; Schulze and Smithers, 2003; Schulze, 2005). The model inputs comprise measurable information describing climatic, pedological, land use, hydrological and spatial characteristics, which are used to represent and simulate the dominant physical processes affecting rainfall-runoff relationships. At least in theory, this ability enables the model to provide reasonable answers for ungauged catchments and predictive capabilities for flow-related changes due to changes in land and water use within a catchment. Although other models such as the Pitman monthly model are also capable of predicting some land-use change impacts (e.g. irrigation), the "predictive capability of the ACRU model to deal with issues such as overgrazing, afforestation, eradication of alien vegetation, and others, is superior" and it has "the advantage of also modelling sediment loads" (Ndiritu, 2009).

In general for the ACRU model:

- Parameters are typically estimated from physically based characteristics of the catchment. Hence the assertion that the ACRU is not a parameter fitting model by Schulze (1995). However, experience has shown that the model also requires to be calibrated as not all parameters can be satisfactorily estimated from the basin physical input information.
- The model integrates the various runoff production and water budgeting components of the surface water hydrological system (Schulze and Smithers, 2003).
    - the model is based on the daily multi-layer soil water budget. This water budgeting can be applied as a versatile model for applications in hydrology

(e.g. climate change impacts, land use impacts, ecological requirements and water resource assessments) as it is sensitive to both climatic and land use changes (Schulze, 1995).

- ACRU uses Fourier analysis to internally transform variables such as crop coefficients from monthly inputs to the required daily level. If more sensitive intra-daily climate variables are required, ACRU synthetically disaggregates daily values into shorter time steps; for instance, when sub daily rainfall distributions are required for flow routing (Schulze and Smithers, 2003).

The ACRU model was developed as a simple decision making tool for agrohydrological problems. The model may be applied in ungauged catchments as certain parameters, given the physical basis of the model, are capable of being estimated through default relationships with measurable catchment properties, i.e. soils, vegetation, management practices, etc. (Schulze, 2000). ACRU has dominantly been applied in the temperate and humid regions of South Africa, frequently investigating the impacts of various land use changes, e.g. commercial afforestation (Hughes, 2004a) as well as being used for water resource assessments (Everson, 2001) and irrigation supply (Dent, 1988). However, evidence documenting successful semi-arid applications is not easily obtainable (Hughes and Meltzer, 1998).

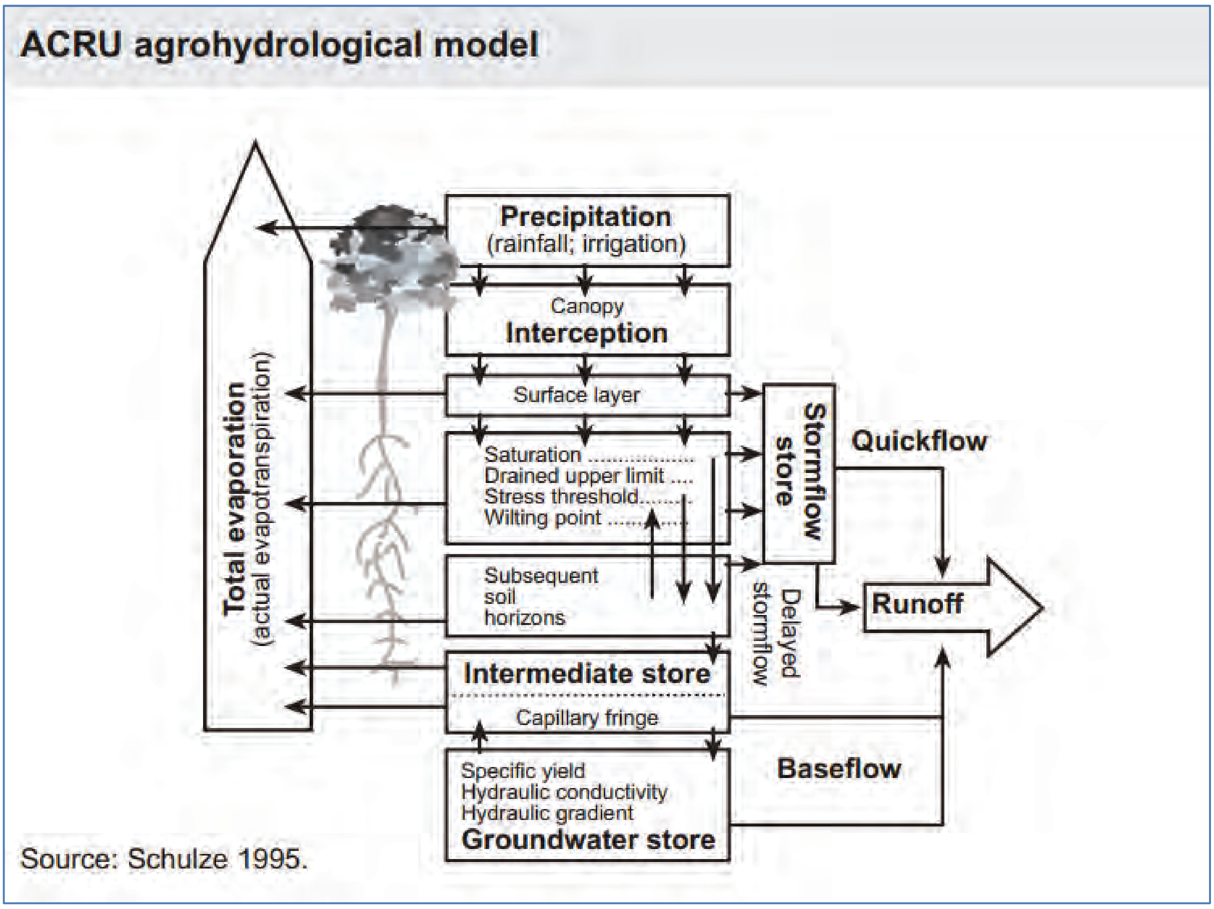

Figure 2. The main processes of the ACRU model (Schulze, 1995).

ACRU is a physical conceptual hydrological model that conceives a one-dimensional system in which processes are included in discrete time units. The model represents the soil's ability to store and transmit water, while vegetation water use is modelled using parameters related to the stage of development of vegetation. The generation of stormflow is based on the assumption that, after initial abstractions, runoff is a function of the rainfall amount and the soil water deficit from a critical depth of soil. The soil water deficit antecedent to a rainfall event is simulated by ACRU's multi-layer water budgeting routines on a daily time scale. Stormflow is divided into quickflow and delayed flow, resulting in varying temporal responses at the catchment outlet.

Flow attenuation is achieved by use of a 'lag' which depends on soil properties, basin size, slope and the density of the drainage network. The model requires input data of rainfall, maximum temperature, minimum temperature, A-pan, leaf area index, incoming radiation flux density (MJ m-2 day-1), relative humidity (%) and wind run (km day-1). The model operates on a daily time step and has numerous parameters which require quantification (Everson, 2001; Hughes, 2004b; 2005). Schulze (1995) provides a detailed description of the algorithms and theoretical background of the original model structure.

The continued development and modification of the ACRU model has resulted in the inclusion of a comprehensive module for simulating water quality – ACRU-NPS. The water quality routines of ACRU-NPS are based on the Groundwater Loading Effects on Agricultural Management Systems (GLEAMS), a root zone model that describes the movements of nutrients across surface boundaries (Leonard et al., 1987; Knisel and Davis, 1999). The ACRU-NPS model describes the impacts that land use and land management interventions have on the translocation of non-point source water quality constituents of sediment, nitrogen and phosphorus (Ngcobo et al., 2012). Lorentz et al. (2011) entreat that this ACRU sub-model is designed to simulate:

- Nitrogen (N) and Phosphorus (P) losses in surface runoff, sediment and leaching
- N and P cycling in the soil-water-plant-animal system
- N and P mass balances in the catchment

The model links hydrological components (e.g. rainfall, runoff) with nutrient sources (e.g. fertilisation, irrigation, industrial and animal waste) to describe impacts on N and P movements within the catchment. Nutrients generated upstream are routed through the various control structures in the model (such as wetlands and dams) to evaluate the effect of these controls on the downstream movement of these variables (Ngcobo et al., 2012).

4 The ECOMAG model

4.1 Introduction/Overview of the model

ECOMAG (ECOlogical Model for Applied Geophysics, Motovilov *et al.* 1999a; 1999b), was developed by Professor Yuri Motovilov at the State Institute for Applied Ecology (SIAE, Moscow, Russia) from a physically-based model designed by Kuchment *et al.* (1986). Primarily the model was constructed for solution of applied tasks of regional ecological monitoring. It is a fully distributed, physically-based catchment model that works at the regional (or macro) scale. Sokrut *et al.* (2002) contend that ECOMAG can be considered as an attempt at an integration of a "physically-based representation of hydrological processes into a conceptual model" framework developed to work in data sparse regions.

The current version of ECOMAG consists of a hydrological and a geochemical module. The hydrological module is a representation and description of the main catchment hydrological processes (such as infiltration, evaporation, thermal and water regime of soils, snow cover formation and melting, formation of surface, subsurface, ground, and river flow), while the geochemical module dwells on surface accumulation of pollutants, their precipitation, dissolution and penetration into the soil, interaction with soil solution and solid body, transfer of pollutants by surface, subsurface, ground and river flow (Gottschalk *et al.*, 1998; Motovilov, 1995). The model's flexibility allows it to represent a drainage basin by either irregular elements or a regular grid network, which has, over the years, enabled relatively easier integration with groundwater models. Each element is considered as an individual hydrologic landscape unit characterised by specific topography, land use and soil types (Motovilov, 1995). In general ECOMAG describes the processes of infiltration and evapotranspiration, soil heat and moisture properties, overland and subsurface flow, groundwater and river flow, snow accumulation and snowmelt at a daily time scale.

The model consists of a geographic information system (GIS) interface, databases of hydro-meteorological data in real-time, and landscape description. The GIS interface is used in the 'model dimensional patterning of the river basin' using ArcView (Sokrut, 2001). The databases contain information on soil properties, land use, vegetation, pollutants, and hydro-meteorology.

General assumptions of the ECOMAG model.

The assumptions listed below have been extracted verbatim from Sokrut (2001) and are:

- Processes in the soil and snow cover have an important role in terrestrial water. In distributed physically based models Richard's equation is often used to describe water movement in the unsaturated soil and snow. This approach needs detailed spatially distributed information about relationships between capillary-sorption potential, hydraulic conductivity and moisture. In principle, Richard's equation is based on a micro-scale concept of the "representative elementary volume" (REV). This approach makes it difficult to account for the effects of soil non-homogeneity and macro-porosity, important for generation of preferential flow in the boreal regions.

- A more simplified approach based on the concept of so-called “water constants” may be useful for the description of a water regime in the soil and snow at the meso-scale. According to this approach water is divided into several classes depending on the nature of the soil-water or snow-water interactions. Water in the porous medium, for example, could be classified into three kinds (Baver, 1965):
    - Hygroscopic water, which is adsorbed from water vapour of atmosphere as a result of attractive forces in the surface of the solid particles.
    - Capillary water, which is held by surface tension forces as a continuous film around the particles and in the capillary spaces.
    - Gravitational water, which is not held by the soil and drains under the influence of gravity. In the soil and snow hydrology there are several so-called soil-water and snow-water constants that are used to express water interactions under the action of different challenged forces.
    - Wilting point (WP) refers to the soil moisture content at which soil cannot supply water at a sufficient rate to maintain turgor, and the plant permanently wilts. The tension of the soil water at WP is about 15 atmospheres. Water in the soil is held as a thin film around the particles. The movement of water within the soil takes place mainly in the vapour phase since the capillary conductivity is assumed zero.
    - Field capacity (FC) of the soil is defined as the amount of water held by surface tension on the soil particles after the excess gravitational water has drained. The mean tension of the soil water at FC is about 0.3 atmospheres. The hydraulic conductivity at FC approaches zero at least decreases by several orders relatively saturated hydraulic conductivity. Water movement is very slow at moisture content below FC. This constant seems to be similar for water holding capacity (WHC) in the snow.
    - Saturated soil (snow) represents the amount of water that is necessary to fill the whole pore space. The moisture content is equal the total porosity (P). The capillary tension is nearly to zero. The hydraulic conductivity is equal the saturated one. The water moves due to the gravitational force. The soil and snow water constants might be considered as boundaries which separate different parts of the water concerning to the ability to move and change. The soil loses the water by rapid drainage due to gravitational force until the moisture content decreases from saturated state to field capacity (gravitational water). For the snow, such behaviour proceeds until the

moisture of snow decreases to the snow water holding capacity. The movement of water takes place trough large non-capillary pores that do not hold water tightly by capillary forces. The non-capillary porosity (D) is equal the difference between total porosity and soil field capacity (water holding capacity for the snow).

- Due to evapotranspiration the moisture content of the soil can decrease from the field capacity until it reaches the wilting point. The difference between field capacity and wilting point represents the amount of water available to plants. This is actual capillary porosity(C). The movement of water in capillary zone during rain less period is slightly expressed and is carried out mainly from the thin films around soil particles to the nearest root tissue of plants.
- The decrease in soil moisture below wilting point may be caused by physical evaporation from the surface during long dry periods. Main process & their representation

4.1.1 INTRODUCTION AND MODEL INPUTS

Irrespective of the number of hydrologic units, the same process formulations are applied within each unit independently. The ECOMAG model calculates streamflow on a daily time scale as a function of defined model parameters and input data. The inputs necessary to run this model are daily time series data for precipitation, air temperature and vapour pressure deficit. Also required as input are data to describe the catchment related to land physiographic characteristics, soil hydraulic properties (porosity and conductivity) and land use (Engeland and Gottschalk, 2002). Observations of river runoff, snow cover, soil moisture, groundwater levels, soil temperature, soil frost depth, evapotranspiration etc. can be used for calibration of parameters and validation of the model. This point observed input data is interpolated to each grid cell by the inverse distance weighting method (Motovilov *et al.*, 1999a).

The type of precipitation is determined by a threshold temperature and snowmelt is estimated by a degree-day-factor equation, evapotranspiration by Thornthwaite-Budyko, surface runoff by a kinematic wave formulation, horizontal subsurface flow by Darcy's law and vertical movement is controlled by the infiltration capacity (Engeland and Gottschalk, 2002).

ECOMAG represents and has routines to model the wide range of processes listed below:

- Hydrological processes – Infiltration; Interception; Evaporation; Soil moisture; Snow cover; Surface water; Ground water and River flow.
- Geochemical processes (of contamination by pollutants) – Accumulation; Dissolution; Penetration; Degradation; Sorption and Transformation
- Biological processes (of plants) – Photosynthesis; Transpiration; Growth of plants and yield

4.1.2 VERTICAL STRUCTURE OF THE ECOMAG MODEL

To achieve vertical structuring in the model, each hydrologic landscape unit is divided into several layers, which are a snow cover layer in the cold period, a surface layer and three soil layers (a top layer, horizon A, a transition layer, horizon B, and a bottom layer called groundwater-zone, Fig. 3). Horizon A soil layer is characterised by high porosity and conductivity, while horizon B is a deeper more compact layer of lower porosity and conductivity.

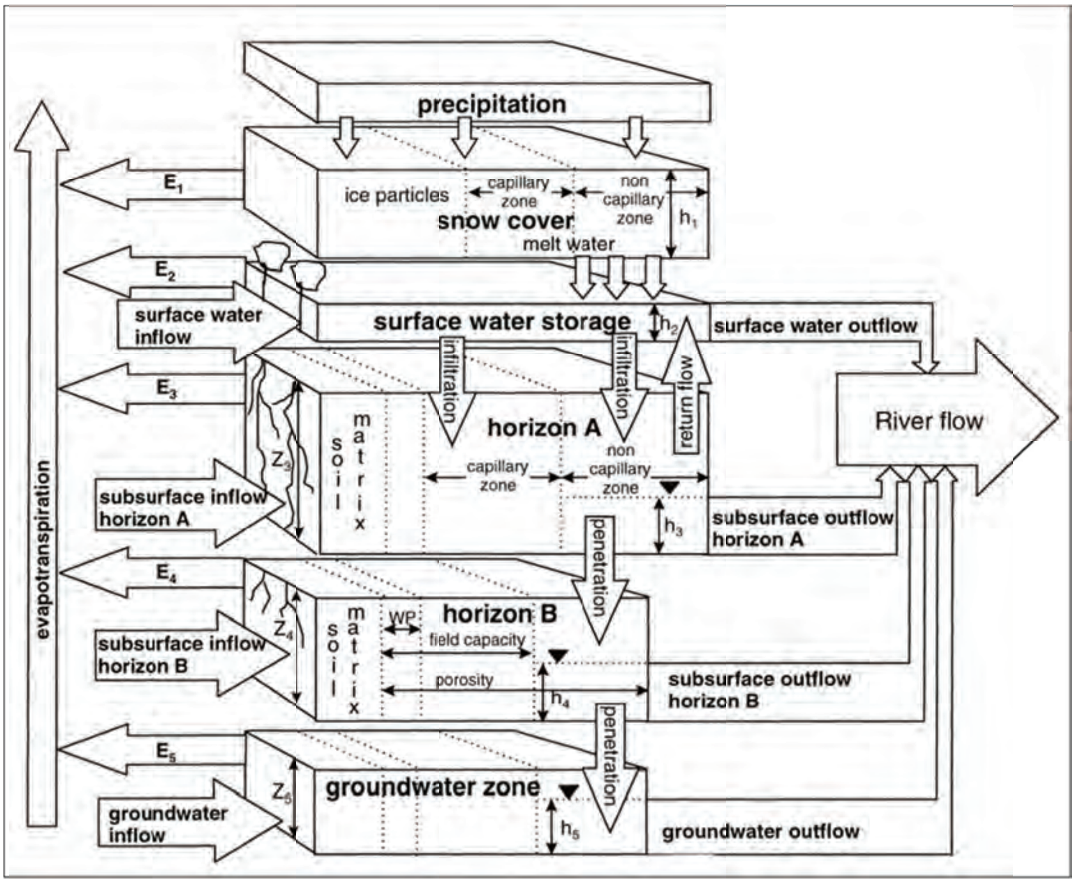

Figure 3. Block-scheme of the vertical structuring of the ECOMAG model for a single hydrologic model element (Sokrut, 2001).

Depending on a threshold temperature and the daily mean temperature, precipitation can be either rainfall which would fall during the warm season or snow during the colder season. Rainfall directly activates surface processes (infiltration, storage, surface runoff, etc.), whereas snow will first initiate snow cover processes (freezing and thawing of the soil, formation of snow cover and snow melting) before the surface processes can commence. The mean air temperature in conjunction with vapour pressure deficit is used to estimate evaporation of the solid and liquid phases of the snow. One of the important assumptions used in the vertical structure of the model is that the vertical temperature profiles in the snow, as well as in the frozen and thawed soil, differ only slightly from linear ones, and that the migration of moisture to the freezing front is negligible (Motovilov, 1995). Consequently, a set of ordinary differential equations can adequately be used to describe the soil-frost and soil-thawing depth dynamics within the model (Motovilov and Nazarov, 1991).

When the excess rain or melt-water reaches the surface, runoff and/or infiltration occur. After the filling of depressions on the surface, the excess of water, not absorbed by the soil, runs off on the sloping land surface (assuming the Hortonian mechanism) to the river network (surface flow). A part of the water, which is infiltrated into the soil, follows a temporary, relatively impermeable, boundary along the slopes as shallow groundwater (subsurface) flow. Another part is transported in the groundwater zone and forms base flow. The subsurface and groundwater flow is modelled as a Darcy flow, while the surface and river runoff are described by a simplified version of the kinematic wave equation (Rose *et al.*, 1983). The influence of the amount of ice in the frozen soil on the soil's hydraulic conductivity is used to determine the rate and amount of infiltration into the frozen soil.

The total porosity of the soil is divided into two parts: a capillary zone (the upper limit of which is the field capacity) and a non-capillary zone (the difference between total porosity and field capacity) (Fig. 4). Infiltrated water penetrates into the capillary zone if the capillary soil moisture is less than field capacity; otherwise it drains into the non-capillary zone. In the capillary zone water is lost by evapotranspiration only. Actual evapotranspiration is simulated using the Thornthwaite-Budyko approach (after Brutsaert, 1982; Feddes *et al.*, 1974 in Motovilov *et al.*, 1999a). The algorithms implemented in the ECOMAG for simulating the evapotranspiration are given in Equation 5. At or near saturation conditions of the soil, actual equals the potential evapotranspiration, and it linearly decreases with the decrease of the soil moisture content to zero at soil moisture content equal to the wilting point (Motovilov *et al.*, 1999a) essentially the same as the Pitman model when parameter R is set to zero.

From the non-capillary zone water seeps into a deeper horizon or can have its vertical migration arrested by an impermeable layer between soil horizons leading to accumulation. If the non-capillary zone is filled up, the excess water is released as return flow on the surface. In the groundwater zone some water can be exchanged with even deeper groundwater horizons. The subsurface and groundwater flow is modelled as a Darcy flow (Motovilov *et al.*, 1999a).

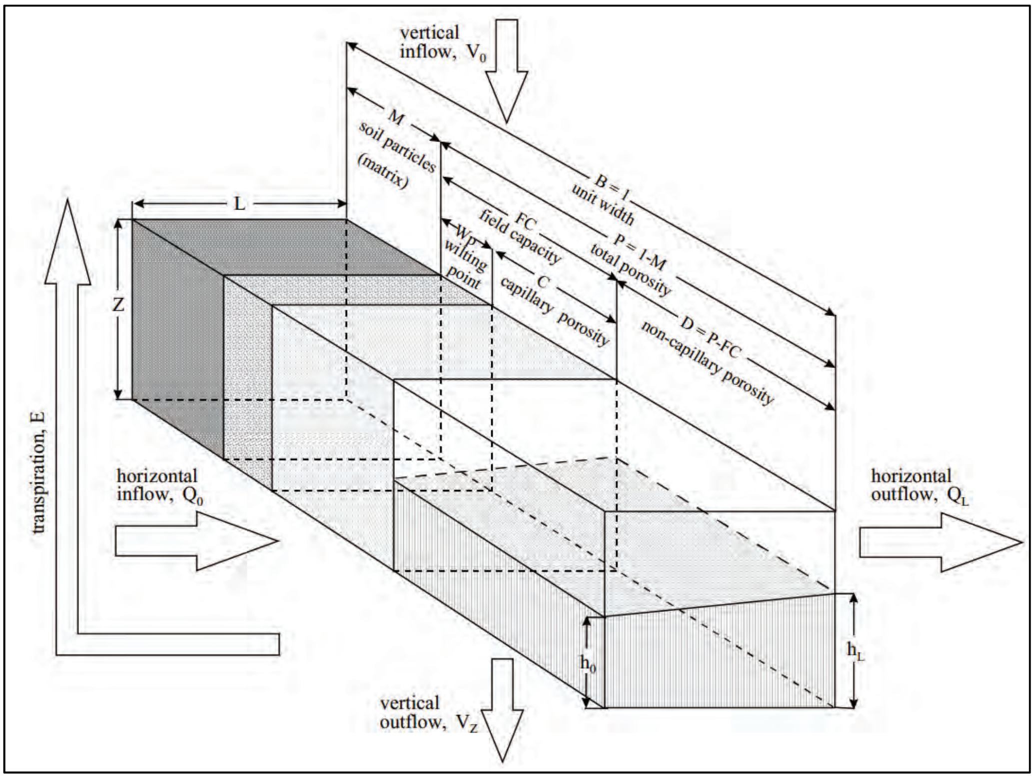

Figure 4. Structure of soil sample and soil water constants (Motovilov et al., 1999a).

$$E_j = \begin{cases} E_{pot,j} & for\ W_j > WE_j \\ E_{pot,j}\left(\dfrac{W_j - WP_j}{WE_j - WP_j}\right) & for\ W_j \leq WE_j \end{cases}$$

Equation 5

Where: $E_{pot,j} = E_{pot}k_{w,j}$ is the potential evapotranspiration from the soil layer j; $WE_j=(FC_j\ WP_j)*0.5$ is the critical moisture content for evapotranspiration; k_{wj} is a weighting factor, disturbing the potential evapotranspiration between soil layers influenced by the distribution of the root system.

Finally, the processes in the river network are simulated using kinematic wave equations. The landscape information extracted from the GIS only relates to large-scale features. Small-scale fluctuations in landscape characteristics, however, are important for the runoff formation processes. Thus, the variability within a single hydrological unit is solved by using spatial distribution functions (Kuchment *et al.*, 1986; Moore, 1985), e.g. for three parameters – the vertical saturated hydraulic conductivity of soils, surface depression storage and soil field capacity. For the first two parameters an exponential function is applied, while a parabolic function is used for the last one.

The Geochemical component

For the geochemical sub-model of a river basin, the pollutants can penetrate into the soil from the atmosphere (dissolved in rain or snow-melt or impacted at the land surface by dry deposition) or from sources of contamination located on the land surface from human activities such as combustion of fossil fuels, industry, vehicles. Both point and non-point sources of contaminants are considered. According to Sokrut (2001) a number of atmospheric pollutants originate from human activity (combustion of fossil fuels, gas exhausting by industry, etc.). Contaminant sources located on the land surface may be point sources mainly referred to river network (discharge from wastewater treatment plants and industry), or non-point sources distributed over the land, which usually originate in agriculture (fertilisers).

After a fall of rain on the surface the pollutants (e.g. nitrates, phosphates) dissolve partially in the rainwater. Some of dissolved pollutants are removed by surface runoff and the others leach into the soil. The behaviour of dissolved pollutants in the basin depends on intensity of hydro-meteorological processes. The contaminants are carried mainly along with moving water (i.e. surface, subsurface and groundwater flow). Therefore, the amount of pollutants, removed by river runoff from the basin, is defined as a combination of those components of river runoff as well as by load of pollutants in the river basin.

Where an impoundment such as a lake or dam exists on the surface, this is simulated as storage with a recession coefficient defined on the basis of the kinematic wave equation. The review team is not entirely clear what water quality variables are included in this sub-model. If the model deals with non-conservative constituents such as nitrates and phosphates as well as conservative salts then this approach will not work. This is an important point and a search of available literature could not provide the requisite answers.

4.1.3 HORIZONTAL STRUCTURE OF THE ECOMAG MODEL

GIS is used for spatial analysis of the topography, landuse and soil information creating files with coordinates and parameter classes of each hydrological landscape and river element. The catchment is divided into sub-basins using the river network and topography. Water movement takes place in the direction of the prevailing slope towards the river. The sub-basins are divided into prevailing slopes, and the river network into river links. Each river element has two adjacent slopes. Hydrological landscape units shown in Figure 5 are then determined for all the slopes using landuse and slope. The hydrological landscape units are in the polygon shape, whose coordinates are registered, and their area, length, width and slope are calculated, and a soil and land use class is assigned. This set of parameters represents physical characteristics of each landscape element. The river links are characterised by length, width, slope and Manning's roughness coefficient (Sokrut, 2001) based on digital elevation models (DEM). It is not clear what uncertainties would be introduced into the model outputs if relatively low resolution data sets (typically available in southern Africa) are used.

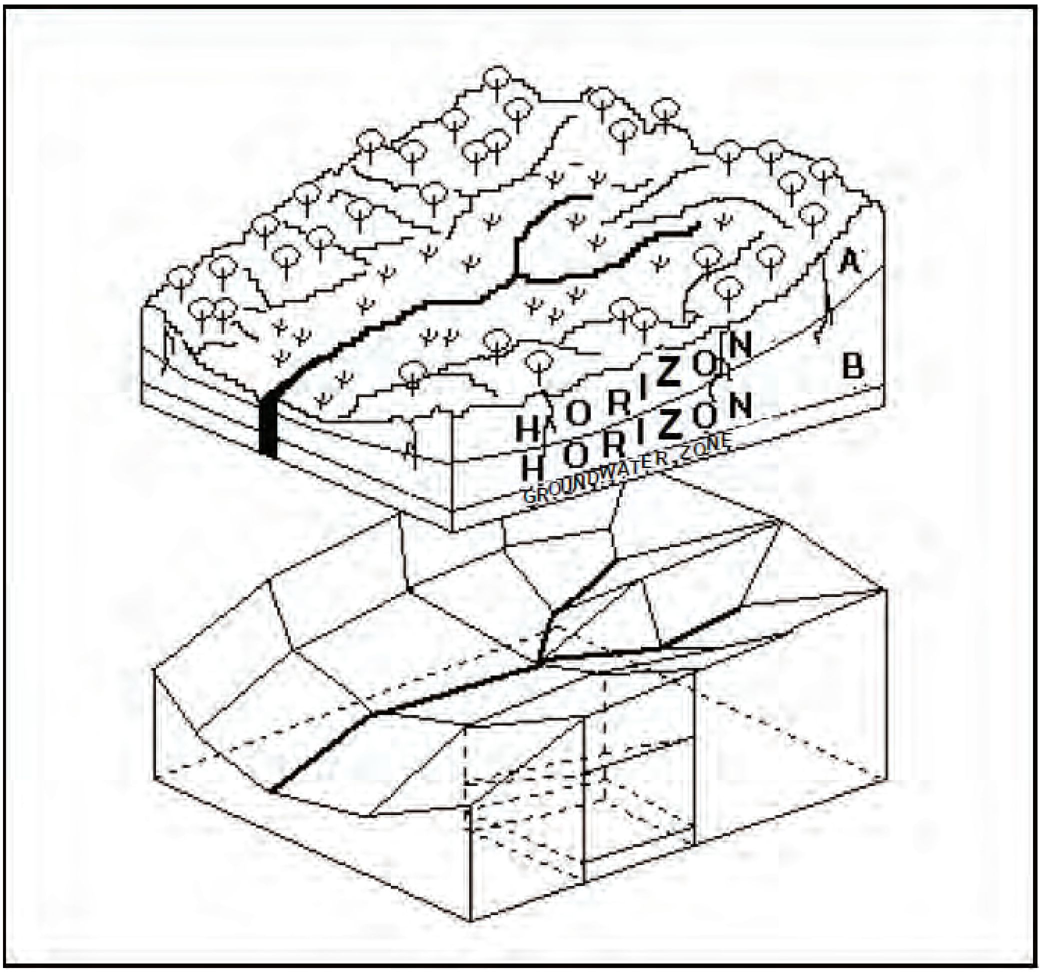

Figure 5. Schematisation of a catchment in the ECOMAG model (Motolinov et al., 1999a)

The hydrological landscape units and the river links form a tree-structure and are numbered following a hierarchical system as illustrated in Figure 6. River links are numbered, starting at the source of the main river to the outlet of the unit, followed by the tributaries based on the size of the tributary. The same approach is used for the hydrological landscape units, beginning with the left side. Such a structure allows easy calculation of both water movements between units and along the river network.

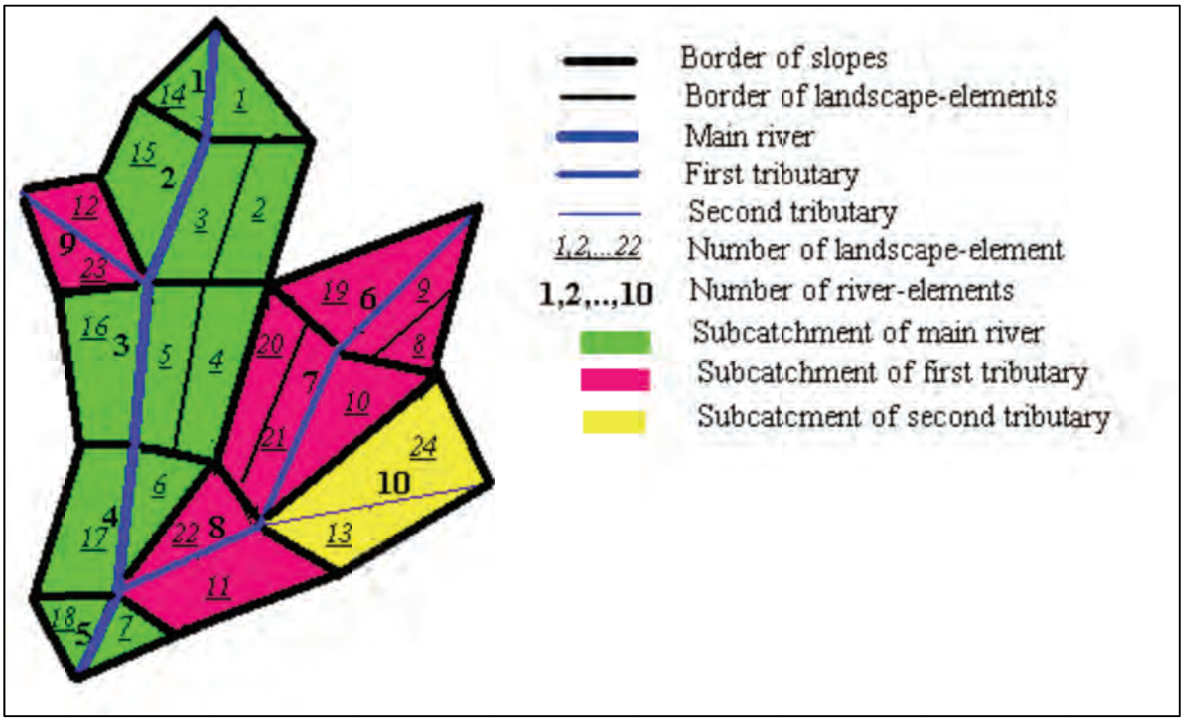

Figure 6. Numbering of landscape elements and river links in ECOMAG (Motolinov et al., 1999a).

The information derived from the process described in the last sections is archived in ASCII format and is used as input files in ECOMAG.

Model parameters and calibration

The original scheme for process parameterisation in the ECOMAG model is of the conceptual type, which implies that input and state variables are interpreted as some type of averages over modelling units.

Soil properties control the main processes of the terrestrial water cycle (e.g. infiltration, evaporation, water exchange between soil horizons, lateral groundwater flow etc.), while surface processes like surface flow, water retention in relief depressions and snowmelt are influence by land use properties. Soil parameters like soil volume density, vertical saturated hydraulic conductivity, thickness of the top soil horizon, which usually are measured at agricultural fields, may be different for other land cover classes (for example, for forested area). This is achieved in the model with references to coefficients of corresponding values from a certain soil class. Table 2 presents parameters of the ECOMAG model.

Table 2. The main parameters of the ECOMAG model (Motolinov et al., 1999a)

Parameter Class	Parameter description	Unit
Parameters of soil classes	Volume density	$m^3\ m^{-3}$
	Porosity	$m^3\ m^{-3}$
	Field Capacity	$m^3\ m^{-3}$
	Wilting point	$m^3\ m^{-3}$
	Vertical saturated hydraulic conductivity	$m\ day^{-1}$
	Horizontal saturated hydraulic conductivity	$m\ day^{-1}$
	Heat conductivity for thawed and frozen/unfrozen water in frozen soil	$w\ m^{-1} day$
	Thickness of soil horizon	mm
	Parameter of distribution of field capacity	
Parameters of land use classes	Maximal retention storage	mm
	Manning's roughness coefficient for slope	$day\ m^{-1}$
	Degree-day factor	$m\ day^{-1}\ {}^{o}C^{-1}$
Parameters for whole catchment	Parameter for potential evapotranspiration	mm
	Critical temperature of the snow/rain	°C
	Density of new snow	$kg\ m^3$
	Snow water holding capacity	mm
	Parameter of snow compaction	$m^2\ kg^{-1} day^{-1}$
	Depth of unchanged ground temperature	m
	Mannings roughness coefficient for river	$day\ m^{-0.33}$

Some of these parameters such as the soil water constants can be measured in the field. The initial values of these parameters for the different soil types can be determined on the basis of regional information about the hydrological properties of the soil and supplemented by data from literature sources. For other parameters, experimental results allow to establish empirical relations (heat conductivity of both soil and snow, unfrozen water content in frozen soil, snow water holding capacity) or indicate reasonable well-defined limits for parameter values (degree-day factor and critical temperature for snowmelt, parameter of snow compaction). In other cases, the limits are not so well defined (for example, horizontal hydraulic conductivity for calculation of shallow groundwater flow) and the parameter values must be determined by calibration to achieve an acceptable model performance. Not all parameters of the model are identifiable and well-defined. This is a consequence of the scale of model application which is different from the scale at which measurements of inputs are taken. The heterogeneity of the landscape often impinges on the representativeness of the data interpolated from the point measurements. Such issues and inadequacies of the model to represent regional processes will have an impact on the parameterisation of the model.

While it is postulated that the different groups of model parameters may be calibrated in separate steps using data related to evapotranspiration, soil moisture, groundwater, snow cover, frozen soil and river runoff (Sokrut, 2001; Motolinov *et al.*, 1999), it is difficult to see how parameters would not interact with each other. Investigation of this could not be done given that the software was not available to the team. Parameters are adjusted by means of a visual comparison of the simulated and observed hydrographs or a numerical performance criterion. The Nash-Sutcliffe efficiency measure (Nash and Sutcliffe, 1970) and an automatic calibration procedure based on the Rosenbrock's optimisation techniques (Rosenbrock, 1960) are used in the model.

4.2 Example applications of the ECOMAG model

The ECOMAG has basically been applied only in the boreal environment of Russia and the Scandinavian landscape. The following are documented applications of the model:

- Regional environmental monitoring – Kurgan district and Siberia
- Regional hydrological modelling
    - NOPEX (Northern hemisphere climate Processes land-surface Experiment, Halldin et al., 1995; 1999) project on prediction in ungauged basins in Sweden and Norway.
    - GAME (GEWEX Asian Monsoon Experiment)-Siberia, Russia
    - Ecological and economic risk assessment – Reconstruction and expansion of the sea oil harbour (Caspian sea)
- Estimation of water resources pollution
    - In catchments in the Baltic Sea basin (HELCOM Convention). HELCOM is an intergovernmental organisation governing the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention). HELCOM works on protection of the marine environment of the Baltic Sea

Table 3 is a summary of the comparative assessment of the main attributes of the ECOMAG, Pitman and ACRU models.

Table 3. A summary of the main attributes of the Pitman, ACRU and ECOMAG models.

Property/Name	Pitman	ACRU	ECOMAG
Type	Conceptual, semi-distributed(or modular), continuous simulation model; (Pitman,1973; Hughes, 2004a)	Conceptual, physical, distributed (Schulze, 1985)	physically based, deterministic, continuous, watershed-scale hydrologic and water quality simulation model (Motolinov *et al.*, 1999a)
Simulation interval	Monthly and daily	Daily	Daily
Data requirements	Rainfall, evaporation demand	Rainfall, temperature, basin characteristics data (soils, slope, etc.)	Rainfall, temperature, basin characteristics data (soils, slope, etc.),
Processes	Simple surface & ground water interactions; Infiltration & saturation excess flow; Wetlands impacts; mining water quality and quantity;	Compartmentalised soil layers, agro-hydrological processes. Surface-groundwater interactions; wetlands impacts	Compartmentalised soil layers, geochemical processes. No groundwater evapotranspiration processes.
Parameters	14 calibration parameters (methods for *a priori* estimation that would by-pass calibration); some fixed from physical basin property data, experience or literature	56 parameters, most quantified *a priori* but calibration is often necessary for some parameters	At least 19 major parameters, some estimated a priori from physical basin property data. Calibration is necessary for some parameters
Criteria for efficiency	Manual; At least 6 Statistical objective functions	Manual, objective functions	Manual; Objective functions – Nash-Sutcliffe Efficiency measure
Application	Water resources estimation/assessment; Mostly SA and southern Africa, with some applications beyond the region	Water resources assessment, climate and land use change assessments, research	Regional water resources and pollution assessment
Major outputs	SPATSIM can produce 26 time series outputs relating to runoff (from surface, subsurface, groundwater flow), evapotranspiration, etc.	daily runoff elements (stormflow, baseflow), soil moisture, crop yields, sediment loads, impacts of climate change and changes in land cover, etc.	Daily runoff elements; pollution loads, etc.

Motovilov *et al.* (1999b) contend that the ECOMAG model could be described and viewed as a "compromise" between model structure complexity and limitation of data availability. Thus, while the ECOMAG possesses characteristics of a lumped hydrological model, characterised by simplicity in their use, and a minimised number of model parameters; it also preserves the main features of the physically-based distributed models, such as simulation of hydrological processes on a fine resolution scale. This is an advantage of the model as it is capable of handling hydrological situations across spatial scales without strain.

However, the ECOMAG model was developed specifically for boreal conditions (Sokrut *et al.*, 2001) which are very different from the semi-arid and arid conditions that are prevalent in South Africa. The boreal climate is characterised by long, cold winters and short cool to mild summers. With 5-7 consecutive months where the average temperature is below freezing, all moisture in the soil and subsoil freezes solidly to depths of many feet. Summer warmth is insufficient to thaw more than a few centimeters from the surface, so permafrost prevails in some parts of this climate regime. It is common knowledge that the frost-free season is very short, varying from about 45 to 100 days at most, and a freeze can occur during any month in many areas. Most boreal climates have little precipitation, about 380 mm per year. Away from the coasts, precipitation occurs mostly in the warmer months, whilst in coastal areas with boreal climates the heaviest precipitation is usually during the autumn months when the warmth of sea relative to the land is greatest. Low precipitation, by the standards of more temperate regions with longer summers and warmer winters, is typically sufficient in view of the very low evapotranspiration to allow a water-logged terrain in many areas of boreal climate and to permit snow cover during winter. Vegetation in regions with boreal climates is generally of low diversity, and trees are mostly limited to conifers, as few broadleaved trees are able to survive the very low temperatures in winter. Even though the diversity may be low, numbers and density are high, and the boreal forest is the largest forest biome on earth, with most of the forests located in Russia and Canada.

Such a climate as described in the last section is very different from the general climatic conditions that prevail in South Africa. The implication is that the geophysical and hydro-climatic conditions that drive the rainfall-runoff relationships and therefore the natural hydrology in the boreal climate would be very different from those in South Africa. It is therefore logical to assume that a model developed for typical boreal conditions would have process conceptualisations and representations that are neither suitable nor easily transferable to a different environment. A search of literature on the ECOMAG reveals that the model has almost exclusively been applied in the Scandinavian countries (e.g. for the NOPEX project (Halldin *et al.*, 1995; 1999; Motovilov *et al.*, 1999a; Engeland and Gottschalk, 2002), and in Russia where the model was developed. While the review team concedes that they may have missed some other applications outside these areas, the limited diversity in the climatic conditions of the areas of application of the model could be a pointer to the specificity of use intended for the model. Notwithstanding the sound scientific and theoretical basis of the model and some advantages it may have over local models, it would thus, at least in theory, be difficult to laterally transfer the model to South Africa without compromising the model integrity in some way or modifying it to suit local conditions. Whether that is necessary or desirable is not for the review team to assess. On the basis of climatic conditions, the models that are likely to succeed in the country would be those conceptualised and developed for conditions in Australia (see for example the evaluation of the IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Stream-flow data) model in South African catchment by Dye and Croke (2003)), given that environmental conditions are almost similar.

Experience of the application of a model, the Hydrologiska Byråns Vattenbalansavdelning (HBV) (Bergstrom and Forsman, 1973), similar to the ECOMAG (with respect to conditions for which it was developed and general conceptualisation) in Zimbabwe and Mozambique (SMHI, 2000; SWECO, 2004; Liden and Harlin, 2000; Liden *et al.*, 2001) where the geophysical and hydro-climatic conditions are similar to those in South Africa, has shown that there are problems of transferability of seemingly excellent model formulations. This was essentially based on the differences in condition. In such cases where the model was challenged by the environment, it was manipulated to produce acceptable results. This in part explains the fact that the model has not been used since the end of the projects.

Hydrological modelling in the region has developed against a background of a high degree of spatial and temporal variability in hydro-meteorological processes, a general lack of available data and limited financial and personnel resources. Despite these limitations there have been models developed that have proved to be invaluable in assessments of the region's water resources and that have been used successfully in the design and management of water resource development schemes (Hughes, 2005). The main limitations are related to the lack of an adequate quantitative understanding of some processes such as channel transmission losses and a lack of spatial and temporal detail in the available rainfall data (Hughes, 2004a). While there are prospects for improving the rainfall input to models through the use of remote sensing, an improvement in the quantitative understanding of transmission loss process seems less likely. A model formulation that adequately addresses this challenge would be most welcome. However, the ECOMAG is not that kind of model. The issue of river transmission losses is not addressed, directly or indirectly, in the model. This makes it less attractive as an alternative to current local models or as part of a suite of models.

South African hydrology is characterised by a high degree of variability with climate zones varying from tropical to extremely arid. Within individual climate zones, and particularly, the semi-arid regions, hydrological (rainfall and streamflow) variability is as high as anywhere in the world (McMahon, 1979). While extremes of floods and droughts, and their social or economic consequences, tend to receive a great deal of publicity, it is often the less dramatic components of hydrological variability that present some of the greatest challenges to sustainable water resource management. There are several basins within the region that have their headwaters in relatively wet and well watered regions but then pass through much drier regions. The need to understand streamflow loss, as well as streamflow generation processes increases the complexity of any modelling study. The fact that many of these rivers also cross national boundaries (Orange, Limpopo, Okavango, Zambezi, etc.) adds to the complexity of managing water resources at the regional scale (Hughes, 2005). Between them, the Pitman and the ACRU models adequately cover the essential hydrologic and anthropogenic processes that are necessary for a successful scientifically sound and defensible simulation of local conditions. This should not, however, be construed to mean that the models are flawless. The Pitman, for instance, cannot be used for short-term forecasting purposes, which is essential for planning. However, it can be used for medium term forecasting if the rainfall forecasts are available. Its outputs have been used as inputs in water resources planning models, which are used in the country for both operational and long-term planning.

Hughes (2005) suggests that the high degree of spatial variability of rainfall patterns, coupled with relatively complex associations between soil characteristics (depths and hydraulic properties) and topography, suggests that developing generalisations about patterns of runoff generation can be extremely difficult, even at the scale of relatively small catchments (up to 10 km^2). At larger scales, additional processes associated with the spatial discontinuity of channel flow, permeable channel beds, high rates of evaporation and a lack of antecedent baseflow contribute to complex spatial variability in streamflow. This is a challenge to local models and with the ECOMAG operating at the regional scale, this may affect its ability to represent these difficult conditions. While it is a fact that the boreal environment poses little challenge with respect to rapid changes and variability in environmental conditions even at small spatial scales, it is not clear how well the model will be able to simulate the processes that are dominant within the semi-arid South African environment without substantial compromises to some of the fundamental model process conceptualisations.

A thorough understanding of the total water resource availability of semi-arid South Africa includes both surface and ground water and implies that they should be modelled together. Understanding surface runoff processes on hillslopes, as well as mechanisms of recharge (Sami and Hughes, 1996) to sub-surface storages, should be the key to the joint modelling of surface and ground water in semi-arid basins. While the ECOMAG does not have detailed and articulate modules for groundwater simulations and groundwater-surface water interactions, it has successfully been used in conjunction with the MODFLOW (McDonald and Harbaugh, 1983; 2003) in Sweden in an integrated form known as ECOFLOW (Sokrut *et al.*, 2002; 2007). In the application of ECOFLOW, one of the main drawbacks reported is the limitations and poor simulations of the surface water (channel) and overland flow which were being handled by the ECOMAG component of the integrated model. However, without adequate information about the results if the study it is difficult to conclude whether there is a problem with the way the ECOMAG model simulates these processes, or if there were other unknown problems. Given the importance of these processes for South African conditions, the ECOMAG model definitely needs to be evaluated in a few example catchments to assess this potential weakness.

It is noted that the surface and groundwater interactions within the ECOMAG model are not well explained. In the Pitman model, for instance, it is possible to experience groundwater recharge but no streamflows. This is an important and real occurrence in the southern African semi-arid environment. The approach used within the Pitman model is that the drainage from the groundwater towards the channel can be intercepted and lost through riparian evapotranspiration (using the riparian strip factor parameter). This is a known process and the team could not identify a similar component in the ECOMAG model. This is important if one wants to model for the right reasons and integrate surface and groundwater where there is need for recharge to supply aquifers and groundwater pumping but not to generate streamflows in arid basins. It is therefore possible that the ECOMAG model would not be able to simulate zero stream flows in the presence of positive values for groundwater recharge. Some other models developed in largely humid or temperate climate regions, where all major rivers are perennial, suffer from similar problems.

It is possible that all the three models will have a similar response to rainfall inputs and soil storage state. The critical issue is therefore establishing parameter values as well as the nature of the non-linearity of the relationship between runoff generation and moisture storage. These need to be examined in more detail in a few example applications and compared with each other and with what might be expected from the available knowledge of physical hydrology.

One of the most important processes is the surface runoff generation process. An examination of the model structure indicates that while in the Pitman it is driven by only rainfall, in the ACRU and ECOMAG both rainfall and soil moisture content are used. This is a problem in that it would be difficult to simulate 'real' infiltration-excess flow as simulated infiltration would be affected by the antecedent moisture content of the soil.

Both the Pitman and the ACRU model structures are more suited to predictive modelling for operational catchments, making them practical and useful tools in operational hydrology, whilst the relatively more complex ECOMAG model's other limitation for application in South Africa could be its input requirements which could not be easily supported by the available data. The model's well developed GIS interface could also provide an efficient means to configure the model, input spatial data and view output data. Whether this may translate into more accurately representing the spatial and temporal variations of input parameters is a different matter and unfortunately could not be ascertained.

For the ECOMAG model to be verified more comprehensively and for its application in operational catchments it will be necessary to improve the representation of spatial and temporal changes in precipitation and vegetation parameters for South African conditions. It is however expected that the grid approach to modelling of the ECOMAG could improve this.

One of the issues that are important in the acquisition of a software package is the cost. While some packages are available for free, others are commercial and are available at a cost. While this could not be ascertained for the ECOMAG model, experience has shown that cost can be steep. For instance, the HBV and the DHI suite of models cost upwards of €10 000. The steep costs have prompted DHI to sign memorandum of understanding with various potential users who would get licences for free. While this cost may not be that high for government departments, this is substantial for private individuals or institutional users. Local models have been developed essentially from Water Research Commission (WRC) funding and are available to the public free of charge.

Besides the cost implications one has to also look at the product support. This is essential given that to use and maintain a product requires a sufficient level of skill and support, and it is a lot easier if this support is resident in the country. It is not known what level of support one would get from the ECOMAG development team as there was no interaction with them during this review period. Be that as it may, the development teams for local models are available in the country and therefore support, when needed, is available. Related to this support issue, one also has to be conversant with licence issues of the imported software product. Some are so restrictive that it may stifle chances of widespread distribution within an organisation.

5 Conclusion and recommendation

This review has qualitatively assessed the applicability of the Russian developed ECOMAG model in South African basins. This has been prompted by the possibility of using the model for regional water resources and hydro-geochemical assessments in the country. While the best approach would have been to set up the model in a few test catchments and evaluate the results both in their own right and against results from local models, this could not be done as concerted efforts to acquire the software were unsuccessful. Consequently, it is it is not possible to make concrete conclusions about its applicability.

The most significant aspect arising from this review is the stark differences in the environment conditions between the region of model development and potential application and South Africa. It is a fact that each model is constructed for, and to solve practical problems in, a particular environment. The ECOMAG was developed specifically for the boreal environment, which implies that the processes conceptualised and represented in the model would be fundamentally boreal. Given that South African conditions are different to the boreal environment, it is logical to expect that the ECOMAG model may not be set up and used in South Africa without fundamentally compromising internal conceptual integrity. This does not mean that it will fail to produce acceptable results, but the question that may need to be asked is if it would be modelling the processes in the right way. A model can have its parameters calibrated to produce excellent results for the wrong reasons. In such situations there is no learning from the model that can take place. And one of the reasons for using models is to increase knowledge about environmental processes by learning from them.

In terms of process representation and outputs, there is very little to separate the ECOMAG from the local models. At this juncture however, there is insufficient evidence and data to suggest that the ECOMAG model will add any value to water resources assessment, as the local models cover the most significant bases and their results have served the country well for the past four decades. On-going improvements of these models (e.g. a daily version of the Pitman model will be re-introduced soon) will make them better as process understanding is improved through targeted research (e.g. Lorentz *et al.*, 2004).

Unfortunately there is little available literature on the geochemical component of the ECOMAG model to make a value judgement. The ACRU model has managed to fulfill a practical need for water quality assessment using the ACRU-NPS, while research with the Pitman incorporation of water quality modules is on-going. Finally, if there is a real need for the ECOMAG model, based on the premise that there is a gap that it will fill, then it is imperative that it is practically evaluated in a number of catchments spanning the different geophysical and hydro-meteorological conditions obtaining in the country.

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