MODELLING SEMI-ARID AND ARID HYDROLOGY AND WATER RESOURCES – THE SOUTHERN AFRICAN EXPERIENCE.

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Abstract: The paper reviews the current situation with respect to the status of hydrological modelling of the semi-arid and arid basins within the southern African region. Hydrological modelling in the region has developed against a background of a high degree of spatial and temporal variability in hydrometeorological 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. The main limitations are related to the lack of an adequate quantitative understanding of channel transmission losses and a lack of spatial and temporal detail in the available rainfall data. 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.

INTRODUCTION

Southern 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 many 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, etc.) adds to the complexity of managing water resources at the regional scale.

The political and socio-economic history of the region has not been conducive to the collection and maintenance of hydrological records. Even today, despite the recognition of the importance of well-managed water resources to the health and socio-economic well being of the region, the acquisition of the necessary information does not appear high on the agendas of many of the regions government institutions. Similar constraints have limited the development of local capacity within both the hydrological sciences and water resource management fields. While development aid funding for often quite grandiose schemes has been made available, they have been largely based on expertise hired from outside the region, with little of that experience and expertise remaining within the region at the end of the project. At the same time, financial rewards and incentives for local staff are frequently inadequate and do not encourage participation and further training in the field.

During the colonial era, several countries developed quite detailed water resource monitoring networks. However, in many cases, war, inadequate economic resources and shifting social and political priorities have meant that these networks have not been maintained and in some cases the historical data are not readily accessible. Water resource utilisation and land use changes likely to impact on natural hydrological processes are also less than well documented in many areas. Even where licensing systems are in operation, the amounts of water abstracted or returned to the river can be highly temporally variable. This makes it difficult to calibrate and validate hydrological model results against historical data, even where they exist.

The development and successful application of hydrological models has therefore been seriously hampered by:

- A high degree of spatial and temporal variation in hydrometeorological variables and resulting streamflow.
- A lack of adequately long or continuous records of rainfall (and other hydrometeorological variables) and streamflow.
- A lack of information on land use changes and both spatial and temporal variations in water utilisation.
- A lack of quantitative understanding of the mechanisms of some critical hydrological process (notably channel transmission losses and surface-ground water interactions).
- A lack of capacity in some parts of the region, frequently associated with a lack of political commitment to addressing that lack of capacity.

Despite these limitations, there are a number of examples of the successful development and application of hydrological models within the region. The methods and models that have been applied need to be seen in the context of limited data availability and the water resource information requirements of the region. They have therefore generally tended to be pragmatic, rather than scientifically ideal, solutions. This paper will review some of the problems with the application of hydrological models, some of the developments that have been achieved as well as some of the opportunities that exist, through the integration of existing methods with new technologies.

CHARACTERISTICS OF SOUTHERN AFRICAN SEMI-ARID DRAINAGE BASINS

As with arid and semi-arid basins worldwide, one of the most important characteristics is the high degree of spatial variability of rainfall inputs during individual storm events. Coupled with relatively complex associations between soil characteristics (depths and hydraulic properties) and topography, this variability 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.

Mostert et al. (1993) identified a potentially important process that contributes to the understanding of the inter-annual water balance of some Namibian basins. Wet seasons contribute to the development of improved vegetation cover in these otherwise poorly vegetated regions. In the following season, the improved vegetation cover can lead to improved infiltration, as well as more effective evapotranspiration losses and a reduction in the relative amount of runoff that occurs (compared to similar rainfall after a dry year). This effect appears to last for over three years following a wet season and was incorporated into the NAMRON model (Mostert et al., 1993). While this process has not been studied in detail elsewhere in the semi-arid parts of the region, it is likely that similar non-seasonal vegetation cover dynamics could play a major role in explaining the high degree of inconsistency in relationships between rainfall and streamflow.

There have been very few direct studies of channel transmission losses in the region (Crerar et al., 1988; Hughes and Sami, 1992; Görgens and Boroto, 2003), despite the fact that this process has been recognised as one of the most important components of the water balance of many of the regions semi-arid basins. At the small scale, runoff generated during relatively small storm events has to satisfy in-channel pool storage before progressing downstream and contributing to more widespread streamflow. Both pool storage and channel flow are subject to seepage into the bed and banks, the amounts highly dependent upon the local nature of the soil or rock material. The process of recharge into alluvial aquifers is well documented at various scales (Crerar, et al., 1988; Görgens and Boroto, 2003), but it remains difficult to develop generalised quantitative approaches to the estimation of such losses. The highly fractured nature of the material underlying some rock-bed channels (which tend to be found along fracture lineations and zones of geological weakness), suggests that losses from non-alluvial rivers can also be substantial. Unfortunately, there is only anecdotal evidence available for this process and there have been no attempts at quantification in the region. The presence of small farm dams, further contributes to the spatial discontinuity found in channel flow in medium sized semi-arid basins. Identifying their presence is a relatively simple matter using remote sensing approaches. However, quantifying their storage capacities is a different matter, as only the larger developments are usually documented.

At the larger scale, transmission losses and the associated ground water resources of alluvial aquifers, play a major role in some of the regions major basins. Many of the tributaries of the Limpopo River are permanently flowing in their headwaters and then pass through much drier regions and become seasonal rivers due to natural losses, as well as abstractions. The situation can be exacerbated by the utilisation of the alluvial ground water resources in the main Limpopo valley. This increases the storage capacity of the alluvial material at the start of the dry season and can delay the onset of channel flow downstream (Görgens and Boroto, 2003). The Namibian experience (Wheeler et al., 1987) suggests that managing transmission losses to alluvial material can be used as an effective alternative water resource development strategy to conventional surface water storage, which is subject to large evaporative losses.

A thorough understanding of the total water resource availability of semi-arid basins should include 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. However, there have been very few studies where these have been considered together.

DATA AVAILABILITY

Ideally, any development of hydrological models should be based on a sound conceptual understanding of the processes being modelled and backed up with quantitative information that can be used to parameterise a model for a specific application. While there exists a relatively sound conceptual understanding of the processes involved, providing sufficient information to quantify the processes is a different matter.

Rainfall data

Rainfall is one of the key driving variables of any hydrological model, regardless of the climate region. In the semi-arid basins of the region, the spatial variability of the occurrence and depth of rainfall (over almost any time scale, but particularly short periods), coupled with the relatively sparse observation networks, makes it extremely difficult to satisfactorily quantify the main water inputs. Most of the available rainfall records are based on daily observations, precluding the possibility of defining the real intensity characteristics that are of great importance in semi-arid runoff generation processes.

The poor spatial distribution of rainfall measuring stations is partly due to the difficulties of access in the sparsely populated semi-arid regions of southern Africa. The data availability situation is made worse by frequent missing data, closure of stations or the complete collapse of hydrological monitoring during periods of social and political upheaval. Satellite derived rainfall estimates have the potential to provide much more spatial detail in basin rainfall inputs. However, if this relatively new technology is to be used in conjunction with existing historical rainfall records, it is important that the two data sources are checked for consistency. This is not always as simple as it may appear at first sight due to a lack of overlapping data (see Wilk at al., 2005, for an example from the Okavango basin).

Many of the water resource modelling approaches used in the region are based on monthly time intervals. While, aggregating rainfall data into monthly totals reduces the degree of spatial variability, a great deal of intensity information that can be critical to runoff generation processes in semi-arid areas is lost.

Evaporation data

In general terms, the availability of evaporation data is far worse than for rainfall data. Given that evapotranspiration is the second largest component of the water balance of semi-arid basins this would seem to be a critical issue with respect to hydrological modelling. However, for many rainfall events that occur in semi-arid basins, the generation of runoff is less dependent upon the antecedent moisture storage characteristics (which are dependent on evaporative losses) than on the rainfall intensity characteristics and soil surface conditions.

One area where evaporation data could play a significant role is in the quantification of channel losses through direct evaporation or transpiration from the riparian vegetation (see the study of Orange River losses by McKenzie et al., 1993). However, whether the accurate quantification of potential evaporation demand, or a thorough understanding of the seepage characteristics of the channel banks is of greater importance remains to be seen.

Streamflow data

Many modellers would argue that the future for simulating the hydrology of ungauged catchments lies in the so-called ‘physically-based’ approach and the use of information on spatially distributed catchment properties (Schulze, 2000 for example). However, there seems to be little doubt that testing the validity of any model formulation, as well as the adequacy of the available input data, still relies upon the availability of observed streamflow data.

Earlier comments about the problems of maintaining raingauge networks apply to an equal, if not greater, extent with respect to streamflow data. Both Namibia and South Africa make use of weir or flume structures as part of their national streamflow monitoring network. These two countries have relatively good networks within arid and semi-arid areas, despite the large costs of construction and maintenance involved (especially on large rivers with substantial sediment movement). However, there are nevertheless a relatively small number of gauges to cover very diverse hydrological conditions. The situation in most of the other countries is not as good and they rely upon rated sections in rivers with quite dynamic bed conditions, suggesting relatively low confidence in the accuracy of some of the historical data. In some countries the resources (financial and human) available to check ratings, service the gauges in the field and process the raw data are inadequate to maintain continuous records.

In terms of extreme flows, which frequently dominate the long-term mean volumes of streamflow from semi-arid catchments, it has to be recognised that few of the gauging approaches are able to quantify these accurately.

Water abstraction and land use information

Reference has already been made to the influence of small farm dams on the streamflow dynamics of southern African semi-arid basins. While their impacts are generally straightforward to understand and the spatial extent of their occurrence available from analyses of satellite imagery or aerial photography, there is little quantitative information generally available about their storage capacities. Hughes and Sami (1993) illustrated the importance of small farm dams through a study of a 670 km^2 basin in the Eastern Cape province of South Africa. Over 50% of the dams (a total of 364) have a full supply volume of less than 2000 m^3 and catchment areas of less than 2 km^2. The runoff storage capacity (dam volume divided by catchment area) of 60% of the dams is less than 2 mm, while 20% have storage capacities of between 5 and 20 mm. While these capacities may appear quite low, they are more than sufficient to absorb runoff generated in a substantial proportion of storm events.

The situation with respect to information on major dams is far better, although an improved understanding of rates of sedimentation, and hence their medium- to long-term storage dynamics would be an advantage.

The other major source of water in semi-arid basins is ground water. The impacts on the surface water resources of semi-arid basins are mainly where abstraction takes place from alluvial aquifers, thereby affecting the dynamics of channel transmission losses. Information is generally available for large alluvial aquifer abstraction schemes (Görgens and Boroto, 2003), but not for smaller, more distributed abstractions.

Land use changes in the semi-arid basins of the sub-continent are less of an issue than in the wetter parts of the region. However, as many of the larger semi-arid rivers have their headwaters in wetter areas, their channel flow dynamics are still affected. The Sabie-Sand system rises in the Eastern Escarpment of Mpumalanga Province of South Africa, which has experienced substantial commercial afforestation over the past 60 years or more. It then passes through the relatively arid lowveld region, where tributary flow is seasonal. During the dry season, baseflows have been considerably reduced and the relative impacts of transmission losses (largely as a result of transpiration from riparian vegetation) are now greater than under the natural flow regime.

HYDROLOGICAL MODELLING APPROACHES

A large number of models have been applied within the region, but this discussion will focus on models that have been developed specifically for the region. There is not room for detailed descriptions of the models and reference should be made to the original material. The focus will therefore be on any model components that have been specifically designed to cater for semi-arid hydrological processes, the perceived advantages and disadvantages of the models and on the successes and failures of application that have been reported.

Most of the models that have been developed within the region have been moderately detailed ‘conceptual’ type models with a relatively large number of parameters. The traditional approach to application has been the manual calibration of the models against observed data and the use of regionalised parameter sets for use in ungauged basins (Midgley et al., 1994, for example). There has therefore been a focus on identifying the associations between model parameter values and measurable basin properties, rather than on the mathematics of parameter interaction and automatic optimisation procedures. Most of the models used have been continuous time series (rather than single event) type models designed for water resource estimation and design purposes. Developments have therefore been driven by the pragmatic requirements of water resource engineers rather than research orientated scientific understanding.

Pitman monthly time-step model

This model has been more widely applied within the southern African region than any other hydrological model and has also been applied outside the region (Wilk and Hughes, 2002). It was developed in the 1970s (Pitman, 1973) and has undergone a number of revisions since then. It now exists in several forms, each with different additional components added by a range of different developers. However, the core concepts of the original model have been preserved in all the revised versions. The model is an explicit soil moisture accounting model representing interception, soil moisture and ground water storages, with model functions to represent the inflows and outflows from these. The Institute for Water Research has developed one of these versions and added a number of ‘refinements’ based on assessments throughout the sub-continent as part of the Southern Africa FRIEND programme (Hughes, 1995; 1997). Subsequently, the IWR has added more explicit ground water recharge and discharge functions (Hughes, 2004a). Figure 1 illustrates the structure of the model.

In semi-arid basin applications the dominant runoff generating component is a triangular ‘catchment absorption’ function controlled by two variables (ZMIN and ZMAX). The rainfall rate during one time interval of the model is used to determine what proportion of the catchment (the relative area under the triangle between ZMIN and the rainfall rate) will contribute to surface runoff. Hughes (1997) added a third parameter (ZAVE) to allow the triangle to assume an asymmetric shape. The model operates over several iterations (typically four, but user determined in some versions) and therefore allows the monthly rainfall depth to be sub-divided. The original model used a fixed rainfall distribution function, while Hughes (1997) modified this to allow for regional differences in the distribution of rainfall within a month (see Hughes et al., 2003 for a detailed analysis of Zambian rainfall data in relation to establishing a suitable parameter value). These two model components (the rainfall distribution and the absorption function) strongly interact with each other in determining the monthly response of runoff to rainfall in semi-arid applications.

Most of the current versions of the model operate using a semi-distributed, sub-catchment scheme, whereby each sub-area has its own hydrometeorological inputs and parameter set. The model includes components to allow for abstractions from distributed farm dams, direct from the river, as well as major storage dams at the outlet of each sub-area. While the model has no explicit function to estimate channel transmission losses, these have been frequently included in a modelling scheme through the use of 'dummy' dams representing the loss storage and evaporating area (Görgens and Boroto, 2003; Hughes et al., 2003). The problem with this approach for perennial rivers flowing through arid areas (e.g. the Lower Okavango) is that the 'dummy' reservoir is always full and the losses dependent only on the evaporation rate and the surface area. A new approach, linked to the revised ground water routines, is being tested on the Okavango. The algorithm is based on two factors; one related to the near channel ground water storage level and one to the relative flow rate in the channel. Thus losses increase with increasing channel flow and with lower ground water storage.

There are 24 model parameters in the modified ground water version of the model and typically 14 of these are established *a priori* or through some initial calibration test runs. This leaves 10 parameters, which are normally the focus of the calibration effort. The catchment absorption function (3 parameters), the maximum size of the soil moisture storage and the channel loss parameter frequently dominate the calibration process in semi arid areas.

One version of the model included a scheme to allow for the 'growth and decay' of surface cover conditions based on antecedent moisture storage conditions (Hughes and Metzler, 1998). The result is that the catchment absorption and evaporative loss parameters vary with time to simulate dynamic vegetation cover. This was added to compare the model with the Namrom model (de Bruine et al., 1993) for application in Namibian basins, where this phenomenon has been identified as being very important in the understanding of inter-annual runoff responses (Mostert et al., 1993).

One of the advantages of the Pitman model is the availability of guidelines for parameter estimation provided by the WR90 study (Midgley et al., 1994) that reports on the application of the model to 1946 so-called quaternary catchments covering South Africa, Lesotho and Swaziland. These guidelines can be used to establish initial parameters for almost any climate region of the sub-continent, which can then be refined through local calibration (where available data allow). Figure 2 illustrates a typical example of a simulation result using the regional parameters (compared with observed data). This study is in the process of being updated and one component of the revision (referred to as WR2005) will be the integration of all recent improvements to the Pitman model and the development of a new 'official' version.

There is little doubt that the model is easier to apply and is generally more successful in the humid and temperate parts of the region, rather than the more arid parts (Hughes, 1997 – see Table 1 for some summary results). This could be a consequence of the relatively poor definition of the real spatial variations in rainfall input that is typical for many basins, the limitations of the model in terms of the temporal distribution of rainfall within a single month or the relatively simplistic approach to simulating runoff generation. To isolate which of these influences dominate would require rather more data than are available in most arid parts of the region. Given that it is not always possible to achieve a very good one-to-one fit with observed streamflow, it is important to satisfactorily reproduce those statistical properties of the streamflow time series that are critical from a water resource planning and management perspective (Hughes and Metzler, 1998).

Namrom model

This model was designed specifically for use in Namibian basins (de Bruine et al., 1993; Mostert et al., 1993) and therefore includes components to simulate processes that were identified as important in this arid region. Specifically, it has been designed to address the issues of dynamic, non-seasonal, surface cover conditions, as well as transmission losses to alluvial aquifers. While it has been applied with a reasonable degree of success to a number of basins in Namibia, it has not been applied elsewhere and therefore its general applicability is largely untested. The basic concepts are sound and other models could possibly benefit from being adapted to include similar approaches (Hughes and Metzler, 1998).

The model is based on a single equation for total effective precipitation, using four parameters; antecedent weighting factor (seasonally varying), initial loss, sub-catchment loss factor and loss exponent. A regression equation is then developed for observed runoff and total effective precipitation. The model is therefore more of a statistical regression type model with weighting parameters having some perceived physical meaning.

Hughes and Metzler (1998) compared the original Pitman model and a modified version (including a dynamic vegetation cover process) with the Namron model. In general terms the 20 years of data available for calibration indicated that the Namrom model performed the best with the modified Pitman model a close second (Table 2). The simulated means and standard deviations of monthly flow were all very similar. However, when the calibrated models were applied to all the available rainfall data (68 years) and a reservoir yield assessment undertaken, the results for the three models were quite different. For 5 existing reservoirs and a demand of 40% MAR, the simulated shortfalls varied substantially for the three models (between 1 and 17% of the design demand across the five reservoirs). This serves to further illustrate the point made at the end of the previous section and empasises the issue discussed by Görgens (1983) about the minimum length of calibration data required for semi-arid modelling purposes.

ACRU model

The ACRU model has been developed by the Bioresources and Environmental Engineering Hydrology School of the University of KwaZulu-Natal (Schulze, 1994). It is a daily time-step model designed around a multi-layer soil moisture accounting scheme and has a large number of parameters that require quantification. It is designed to be used in ungauged basins on the basis of parameters evaluated through default relationships with measurable catchment properties (soils, vegetation, management practices, etc. – see Schulze, 2000). It has been mostly applied in the temperate and humid parts of South Africa and has been frequently used for assessing the impacts of various land use modifications, specifically commercial afforestation. It has been less widely applied in the drier parts of the region and there appears to be very little documentation of the success of its application in semi-arid to arid basins. It is still very unclear how the model performs with default parameters under different situations of catchment data availability (in terms of spatial resolution, accuracy, etc.).

VTI model

The Variable Time Interval model was developed at the IWR, Rhodes University as part of a detailed study of the catchment response characteristics of a medium sized semi-arid basin (670 km^2) in the Eastern Cape Province of South Africa (Hughes and

Sami, 1994). It has subsequently been applied to a wide range of basins (Table 3) within the region under the Southern African FRIEND programme (Hughes, 1997). It is essentially a daily model that can use shorter modelling time intervals during periods of assumed high process activity (based on thresholds of rainfall intensity), given that shorter time interval rainfall data are available. Figures 3 and 4 illustrate the structure of the model and indicate that the main moisture accounting routines are quite complex with a number of feedback mechanisms. It has explicit functions for most of the processes recognised as being important in semi-arid catchments and is, as a consequence, relatively complex with a large number of parameters. The difficulties of applying the model are associated with the large number of parameter interactions and the fact that many of the parameters are not easy to estimate from known catchment properties. Further details of the parameters and suggestions for the derivation of default values from typically available physical catchment information are provided in Hughes and Sami (1994). In excess of 35 parameters are required for each element (sub-catchment) of the spatial distribution system. However, there are between 5 and 8 parameters that are typically modified during calibration, depending on the perceived runoff generation characteristics of a specific catchment. The successful use of the model requires a relatively detailed understanding of its structure, a sound conceptual understanding of the dominant runoff generation mechanisms of the catchment, as well as good quality input climate data.

The results for several Botswana basins (Hughes, 1997) suggested that, while the model is capable of reproducing daily flow duration curves (Fig. 5), the correspondence statistics based on daily flows is quite poor. This may be due to the model structure, but is almost certainly also related to the lack of spatial detail in the available rainfall data. The results for seasonal rivers in Zimbabwe were somewhat better (Fig. 6), which may be a reflection of the smaller size of the Zimbabwean basins. Results for many of the wetter parts of southern Africa, and where reasonable confidence can be expressed in the available rainfall data, are very encouraging.

Monash model

SMEC (1991) applied the monthly Pitman model as well as the daily Monash model to basins in Botswana. However, the results are presented as monthly summaries and it is therefore difficult to evaluate the model in terms of its ability to simulate daily flows. While the monthly simulations using the Monash model appear to be slight improvements over the monthly Pitman model, no attempts were made to use the ‘dummy dam’ approach to simulating transmission losses for the latter.

MODELLING ENVIRONMENTS

One of the limitations identified by a SADC (Southern Africa Development Community) report on the implementation of regional water resource assessments (SADC, 2001) was the lack of access to appropriate models and modelling tools. The need for a common approach and shared methods was also identified as something that could address some of the issues of lack of capacity in hydrological assessment within the southern African region. The SA FRIEND project made use of an integrated modelling environment package (HYMAS – see Hughes et al., 1994 and Hughes, 2004b), but this was developed in a DOS environment and had become outdated and was not very ‘user friendly’. Subsequently, the Institute for Water Research has developed the SPATSIM (Spatial and Time Series Information Modelling) system for Windows (Hughes, 2002). This package makes use of an ESRI Map Objects spatial front end, linked to a database table structure, for data storage and access and includes relatively seamless links to a range of hydrological and water resource estimation models. It also includes a wide range of data preparation and analysis facilities typically required in hydrological modelling studies. It was originally developed to bring together many of the environmental flow assessment procedures used in South Africa (Hughes, 2004b), but has much wider applicability. The SPATSIM approach has been adopted as the core modelling environment to be used for the update of the South African water resource information system (WR90 – see Midgley et al., 1994). Further details about the SPATSIM package can be accessed through the IWR web site at http://www.ru.ac.za/institutes/iwr and looking for the 'Hydrological Models and Software' link.

The SPATSIM version of the Pitman monthly model has been applied extensively within South Africa, as well as the Okavango basin, Tanzania, Swaziland, Lesotho and Mozambique. One of the perceived advantages of SPATSIM is that it can be extended to include new modelling approaches quite easily and that these can be developed and added by organisations, other than the IWR, after some initial training.

There are similar packages available internationally, such as Mike Basins, ArcHydro, etc., which are now being introduced into the southern African region. There have been no comparative studies of their relative effectiveness in terms of transferring modelling technology and building capacity in regional water resource assessment. This issue is important in a region that has limited existing capacity.

DISCUSSION AND CONCLUSIONS

The previous sections have briefly identified some of the issues that are relevant to the application of hydrological models in the semi-arid and arid regions of southern Africa. This section summarises the limitations that are related to process understanding, available data and modelling methods, as well as the opportunities that exist to address these limitations.

Process understanding

There is little doubt that the main limitation to the further development of existing models is the general lack of quantitative understanding of the process of channel transmission loss at various scales. The current lack of research resources, in terms of finances and personnel, suggest that there will only be very limited progress in this regard in the foreseeable future. This is, of course, regrettable in that any future development of model algorithms to account for this important process in the semi-arid catchments of the region will be based on only a very restricted conceptual appreciation of real life.

Establishing networks of ground water observation boreholes in the large-scale alluvial systems of the region could prove to be a relatively inexpensive and useful approach to quantifying the product of transmission losses (aquifer recharge). However, these observations would need to be coupled with a better understanding of evaporative losses from the alluvial aquifers to be of real benefit.

Available data

Perhaps the main limitation from a data perspective is the lack of adequately representative (certainly in space and frequently in time) rainfall data. There are clear indications that the uncertainty associated with the results of many modelling studies could be reduced if additional information was available about the space-time distribution of rainfall. The prospects for improving the network of ground-based measurements would seem to be poor and therefore the future probably lies in the use of satellite and radar measurements. However, the importance of establishing relationships between new remotely sensed data and historical ground based measurements has already been noted (Wilk et al., 2005; Hughes et al., 2005).

Obviously, additional streamflow monitoring stations would be of great value in providing additional calibration data for modelling studies. However, apart from the normal data collection issues associated with a lack of resources in the region, many years are required to accumulate sufficiently representative data in semi-arid regions.

In terms of physical catchment data (such as land use, vegetation, soils, etc.), remote sensing methods appear to have been applied successfully elsewhere in the world. The priority therefore seems to be to adopt similar approaches in southern Africa and adapt the existing models to be able to make better use of such data.

Model developments

In a recent review of South African modelling approaches, Hughes (2004c) concluded that the available models have proved to be invaluable for managing water resources in the region, but that the future challenges lay in integrating international developments in model application with local models that have been demonstrated to ‘work’. However, for the semi-arid parts of the region there are still water resource management issues that the available models are less capable of addressing with confidence (Hughes and Metzler, 1998; Hughes, 2005).

Given the difficulties, referred to above, of addressing the lack of understanding of some processes and of resolving data deficiency problems in the short term, it is not a straightforward task to identify how existing models should be improved. However, the requirement for more detailed information and more reliable estimates of development, or climate change impacts suggest that the models currently in use do need to be improved. For example, within South Africa the priority for practical model applications used to be the design of water supply storage reservoirs, where the accurate simulation of dry season low flows was not all that important. The recent emphasis on environmental flows and ecologically sustainable water resource development has changed these priorities and the reliable estimation of low flows under natural and modified streamflow regimes is of far greater importance. This does not necessarily mean that the models that have been used in the past need to be replaced. In many cases it is only the approaches to using a model (changing the emphasis of the calibration, for example) that need to be modified.

Ultimately, the success of any modelling study depends upon the quality and appropriateness of the model, the quality of the data inputs to the model and the experience of the user applying the model and assessing the results. Adopting a pragmatic approach to improving model estimates and focussing on what might be achievable in the future, it is suggested that there is a need for:

- Only limited changes to existing models.
- Better use of available data (hydrometeorological and spatial basin property data).
- Improved guidelines for model use and training of model users.

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Table 1 Summary of SA FRIEND project results for the Pitman model (based on monthly flows).

Country	No. of Basins	Range of Mean Monthly % Error	Range of R^2	Range of CE
Namibia	9	-2.1 to 1.5	0.06 to 0.72	-0.84 to 0.68
Botswana	10	-8.7 to 11.8	0.39 to 0.77	0.27 to 0.70
Zimbabwe	14	-8.7 to 2.6	0.45 to 0.90	0.33 to 0.88
Tanzania	5	-7.6 to 3.3	0.33 to 0.81	0.27 to 0.78
Zambia	13	-14.0 to 6.5	0.41 to 0.79	0.29 to 0.78
Malawi	4	-12.4 to 0.9	0.35 to 0.84	0.24 to 0.82
Swaziland	7	-5.2 to 10.0	0.45 to 0.81	0.39 to 0.80
Mozambique	5	-9.0 to 6.1	0.37 to 0.84	0.21 to 0.84

Note: R2 is the coefficient of determination, while CE is the coefficient of efficiency (Nash and Sutcliffe, 1970)

Table 2 Summary of the results of applying the NAMROM, Pitman and modified Pitman (NAMPit) to 5 Namibian basins

Model	Range of Mean Daily % Error	Range of R^2	Range of CE
NAMROM	-4.1 to 2.3	0.39 to 0.90	0.30 to 0.90
Pitman	-2.1 to 0.6	0.23 to 0.72	0.15 to 0.68
NAMPit	-2.5 to 3.5	0.22 to 0.82	0.10 to 0.82

Table 3 Summary of SA FRIEND project results for the VTI model (based on daily flows).

Country	No. of Basins	Range of Mean Daily % Error	Range of R^2	Range of CE
Botswana	3	-3.3 to 2.8	0.40 to 0.49	0.23 to 0.43
Zimbabwe	6	-3.5 to 20.0	0.45 to 0.77	0.32 to 0.70
Tanzania	5	-15.2 to -0.2	0.14 to 0.67	-0.13 to 0.62
Swaziland	7	-6.0 to 8.9	0.14 to 0.63	-0.51 to 0.59
Mozambique	5	-9.2 to 4.5	0.44 to 0.75	0.33 to 0.71

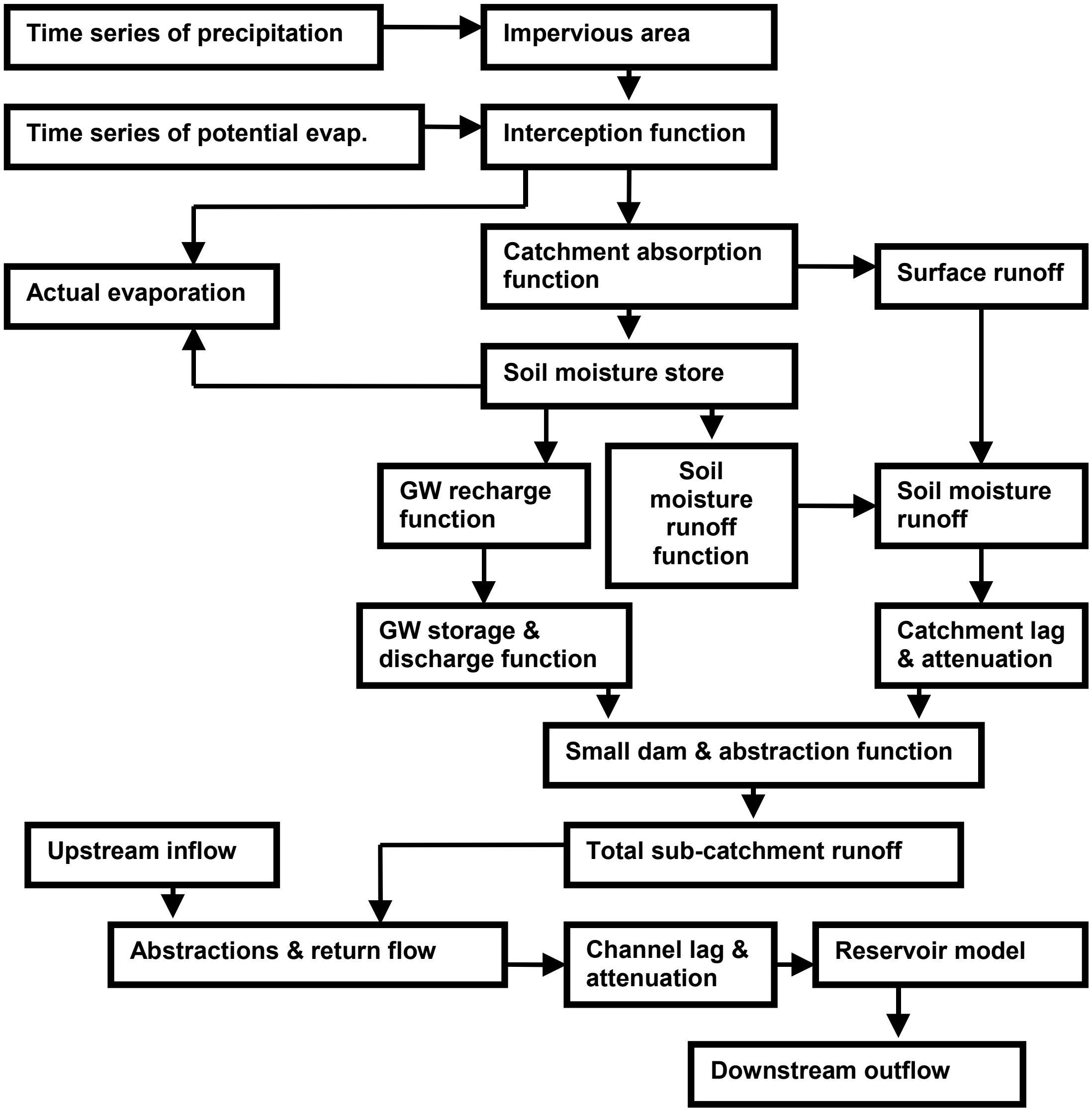

Figure 1 Structure of the Pitman model with revised ground water recharge and discharge routines.

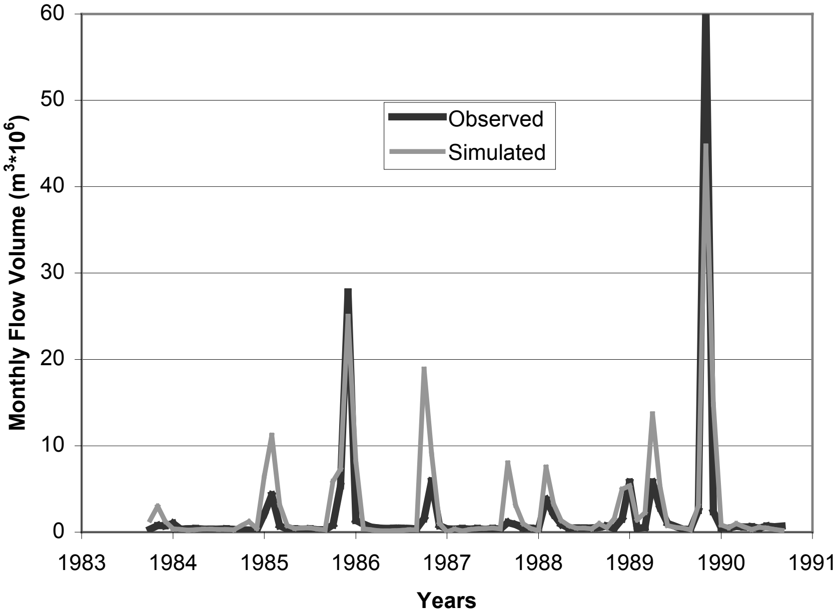

Figure 2 Typical Pitman model result for a semi-arid quaternary catchment simulation based on default regional parameters (Little Fish River, Eastern Cape Province).

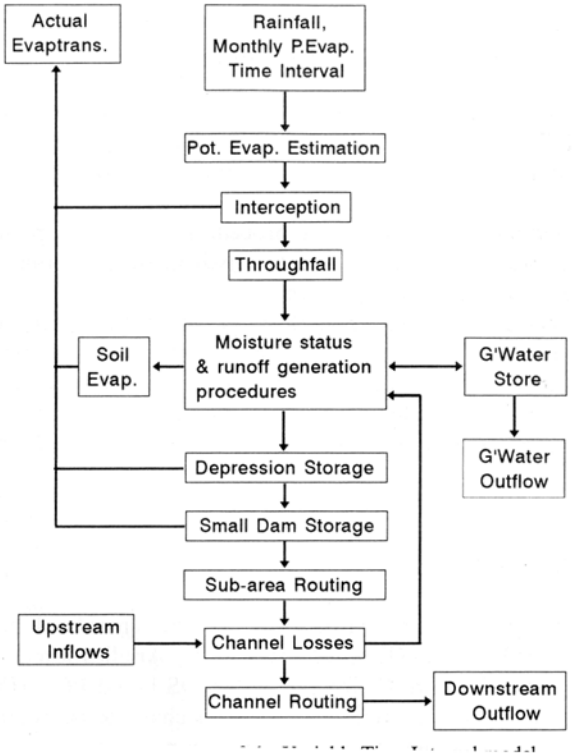

Figure 3 Main structure of the Variable Time Interval (VTI) Model (from Hughes and Sami, 1994).

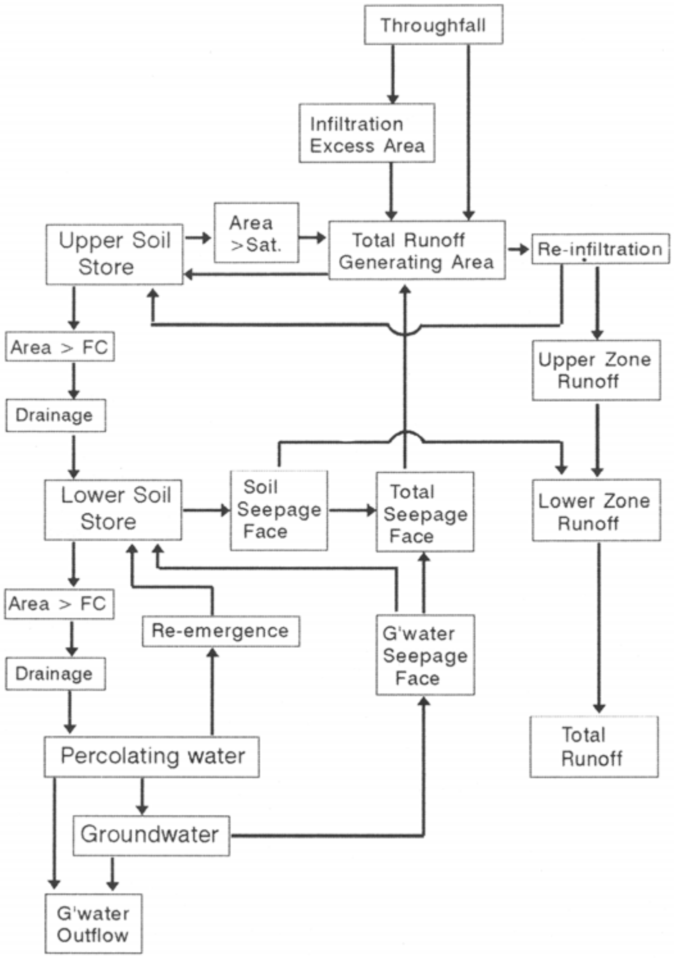

Figure 4 Structure of the moisture accounting and main runoff generation components of the VTI model (from Hughes and Sami, 1994).

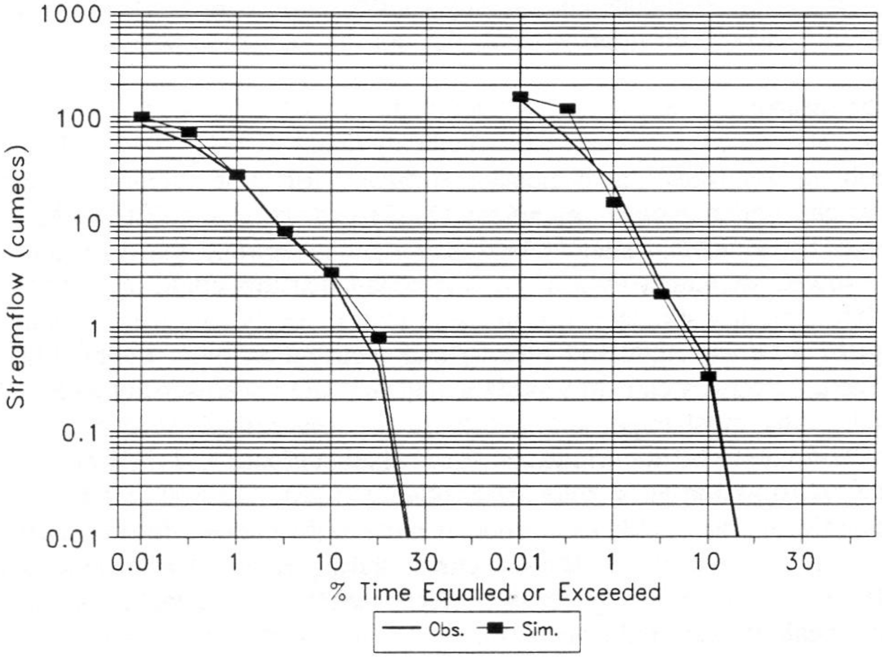

Figure 5 Daily flow duration curves for the Ntse River, Botswana (extracted from Hughes, 1997). The left hand side is the calibration period (1973 to 1979); the right hand side is the validation period (1980 to 1990).

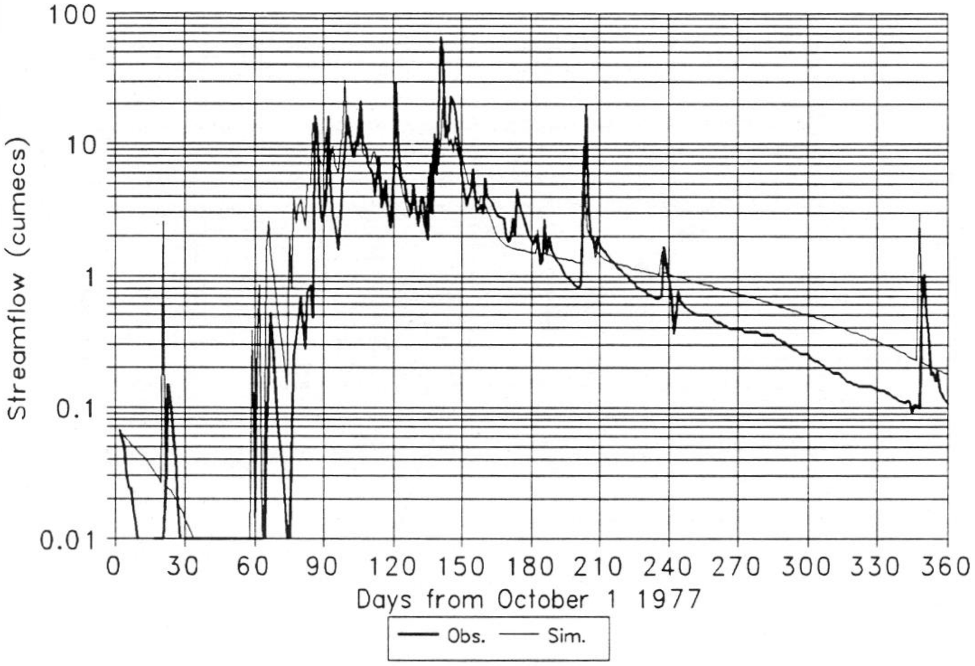

Figure 6 Observed and simulated (VTI model) daily flows for the Lumani River, Zimbabwe for 1 year (extracted from Hughes, 1997).