SOUTHERN AFRICAN FRIEND - RAINFALL-RUNOFF MODELLING.

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1 Introduction

The overall aim of the rainfall-runoff modelling component of the Southern African FRIEND project was to develop procedures and guidelines for the application of appropriate deterministic catchment models within the region for a variety of water resource assessment purposes. While both daily and monthly time-step models have been applied extensively in South Africa, there is much less documented experience of model application within the other countries of the region. The project selected one daily (the VTI model - Hughes and Sami, 1994) and one monthly (the Pitman model - Pitman, 1973) model for testing using a sub-set of the database that was established to represent the flow regimes of the region. The intention was to determine the general applicability of the models within the region through calibration and to identify any model, or data availability, shortcomings. Some limited specific tests were also carried out to determine the applicability of the models to simulating the impacts of land-use change.

2 The models

Both models are packaged within the HYMAS (Hughes, et al., 1994) software system (DOS based), which includes data (time series and parameters) preparation routines, plus a wide range of facilities to view and analyse the results. More details on the facilities available within HYMAS can be found in the main project report (Hughes, 1997). Both models are semi-distributed so that spatial variations in catchment response and hydrometeorological inputs can be allowed for.

The Pitman model is similar to many other, conceptual models consisting of storages linked by functions designed to represent the main hydrological processes prevailing at the catchment scale. It has interception, impervious area runoff, catchment absorption and surface runoff, soil and ground water runoff and evaporative loss functions. As it was designed for water resource assessment purposes in managed catchments, it also includes functions to account for losses and abstractions from small dams and direct abstractions from the river itself. Its data requirements are relatively limited, the minimum needed being a time series of monthly rainfall and mean monthly potential or reference evaporation. It is usually quite straightforward to calibrate and Pitman (1973) provides some guidelines for initial parameter setting. A major national water resource study of South Africa, Lesotho and Swaziland (WR90, 1994) made use of the model to generate simulated monthly time series for some 1200 catchments covering the whole area. The report includes regional parameter values which can be used as initial estimates in gauged catchments prior to calibration, or can provide best estimates of parameter values for ungauged catchments of sizes similar to those used to develop the regionalisation. These guidelines were also found to be useful for the other countries of southern Africa.

The VTI (Variable Time Interval) model (Hughes and Sami, 1994) is designed to operate at time steps of between 5 minutes and 1 day, the steps being controlled by rainfall intensity thresholds, although in the FRIEND project the time-step was fixed at 1 day. The
model is somewhat more physically-based than the Pitman model and HYMAS includes routines to provide initial estimates of many of the parameter values from relatively simple indices of catchment characteristics, such as soil, geology and vegetation. The model includes routines to simulate interception losses, infiltration and infiltration excess runoff, soil moisture dynamics in a two layer soil, saturation excess and saturated interflow runoff, ground water recharge, springflow and ground water rise and channel transmission losses. As with the Pitman model, allowance is also made for abstractions from small farm dams and the channel itself. As the model operates with a sub-catchment distribution system (rather than a grid system) many of the quasi-physics based functions have been developed to implicitly allow for variations within the sub-catchments (sub-grid effects). For example, a re-infiltration function is included to account for the fact that infiltration excess runoff generated on the upper slopes of a sub-area, where soils may be at their thinnest, may infiltrate into deeper soils of mid- and bottom-slope areas. The VTI model requires greater data resources than the Pitman model to be operated successfully and is also far more complicated to calibrate. It is always useful to have a reasonably accurate impression of the catchment physiography and a sound understanding of the hydrological response characteristics of the catchment. Without such information, the calibration process can become a purely numerical exercise that can be very time consuming for a model with a great many parameter interactions. The results can also end up being somewhat meaningless as approximately the correct response, in terms of catchment outflow, may be simulated for the wrong reason.

Other models available within the HYMAS package and relevant to the Southern African FRIEND project, include daily and monthly reservoir simulation models (Hughes, 1992) and a simple time series patching or extension model based on flow duration curves (Patching Model, Hughes and Smakhtin, 1996). The reservoir models are typically used in conjunction with either the VTI or Pitman models when relatively large impoundments occur within a catchment that cannot be managed with the small dam routines included in the rainfall-runoff models. They can also be used to determine impacts on water supply yield given different inflow scenarios. The Patching model is still being developed as a pragmatic tool for the generation of daily time series data using regional relationships developed from observed data.

3 Data availability and catchments used

The time series data were collected from the hydrometric agencies of the varies countries by staff of the Institute of Hydrology (Andrews and Bullock, 1994) and consisted of daily streamflow data, daily or monthly rainfall data and a mixture of different types of potential evaporation data, ranging from monthly time series to mean monthly values. At the same time, sources of catchment description data were identified and obtained where possible. The catchment selection process, for model assessment purposes, was mainly based on the amount and length of available rainfall data, as it transpired that these data, and their perceived representativeness, were the most critical from a model application point of view. The fact that the national agencies responsible for rainfall data collection are different to those responsible for streamflow data presented some difficulties to the project team. It was not always easy to gain access to all the available rainfall data and it was sometimes necessary to be satisfied with the sample supplied. This is an issue that needs to be addressed if rainfall-runoff models are to properly contribute to water resource management and planning.
Table 1 provides some information on the catchments used within the study, as well as a summary of the results of applying the models. No data for Angola were available during the course of the project and no catchments were modelled for Lesotho as the daily rainfall data were not considered adequate and experience of the use of the Pitman model was available from the Lesotho Highlands project (LHWP, 1986). No model results are given for South Africa as the use of the Pitman model is adequately covered in the several volumes of the Surface Water Resources of South Africa publications (WR90, 1994) and the use of the VTI model is discussed in detail in Smakhtin and Watkins (1997). The latter is a report on a project that the Institute for Water Research were carrying out in parallel with the FRIEND project.

In general terms the amount of information that was available to the project team was less than usually considered sufficient for model testing purposes. However, it should be recognised that the objectives of the project were not to test the models as such, but to test their applicability to simulating the catchment hydrology of the region. Part of that applicability must include an assessment of the availability of relevant data and whether it is sufficient to successfully apply models. The model tests therefore represent examples of the type of situation that would be likely to prevail in cases of practical model application.

4 Summary and brief discussion of results

Hughes (1997) provides a detailed discussion of the catchments used in each country, tables of model results and graphical comparisons of observed versus simulated flows or duration curves. Table 1 is a highly abbreviated summary of that information and provides the range of results (using the percentage error in mean flow and coefficients of determination - $R^2$ and efficiency - CE for untransformed monthly or daily flows). The Pitman model results are based on monthly flow values, while the VTI model results are based on daily values. In most cases the lower values for $R^2$ and CE represent outliers that can be accounted for by poor input data or similar problems that are unrelated to the models structures. The models were usually calibrated on a sub-set of the available time series data and the calibrated parameters tested using the remaining period. Except in certain cases (specifically some arid areas), there was not found to be any systematic difference between the two sets of results. However, this could be related to the careful selection of the calibration years so that they were representative (in terms of high and low flow conditions) of the total available period.

In general terms, and all other factors being equal, the models were simpler to calibrate and performed better in the sub-humid to humid parts of the region, with the most consistent results being obtained for the wetter parts of South Africa and Zimbabwe, Swaziland and Moçambique. The Pitman model results for Malawi were strongly affected by the limited amount of available rainfall data and the presence of quite steep rainfall gradients across the catchments. A similar problem existed in some Tanzanian catchments and there also appear to be some problems with the flow data in that country (runoff depths exceeding rainfall depths). The upper range of the values given for the statistics ($R^2$ and CE) are the sort of values that might be expected from the application of the models to South African catchments that do not lie in the more arid areas and for which rainfall inputs can be satisfactorily defined. South Africa has a fairly comprehensive daily rainfall database which is backed up by median monthly data for each 1° x 1° grid covering the whole country and including Lesotho and Swaziland (Dent, et al., 1989) which can be used.
in a weighting procedure to estimate mean catchment (or sub-catchment) rainfalls. The project team also had better access to information on historical patterns of water usage within the catchments, and although far from perfect, was far better than that which was available for the other countries.

Part of the reason for the better success of the calibration exercises in the relatively humid areas relates to the fact that there are more ‘signals’ in the observed data which can be used to understand the likely processes responsible for the rainfall-runoff response and to guide the calibration process. These ‘signals’ include high flow responses, short term recessions (mainly for daily data) and longer term seasonal recessions. Most of these are generally less evident, if present at all, in semi-arid to arid areas and can be confused by highly spatially variable rainfall inputs that are inadequately represented by the (usually) sparse gauging networks. In terms of the monthly model, the inter-monthly distribution of rainfall can be highly variable in nature and is not always adequately represented by the fixed distribution procedure used within the Pitman model (Hughes, 1995). A further limitation exists in that some of the processes that are active in these areas are not very well represented by the models. Specifically, the Pitman model has no transmission loss function and the function within the VTI model is highly empirical and has not been adequately tested.

Although the statistics for semi-arid simulations can be relatively poor, observed and simulated duration curves compare quite favourable over the main range of flows. The Pitman model does, however, have a tenancy to over-simulate the number of months with flow, but the volumes of runoff involved are negligible. From a water resource assessment point of view, the simulation of long representative time series that reproduce the frequency of occurrence characteristics of the observed regime may be more important than the accurate reproduction of individual monthly or daily flows. This issue was investigated using the Namibian data, where observed and simulated (two versions of the Pitman model and a model developed for Namibia catchments) flow time series were used as upstream inflows to the reservoir simulation model and the yield differences analysed. While quite large differences in estimated yield (between 20 and 30% of observed MAR) were obtained, these could not easily have been predicted from the small differences in the calibration results for the three models.

There was rarely sufficient information on physical catchment characteristics (except for the South Africa examples) to be able to express any great confidence in the initial estimates of the VTI model parameter values. Therefore many of the calibrations were largely numerical exercises, supported by the authors perceptions of the likely hydrological response characteristics. The lack of available data on land use changes and water abstractions meant that it was not possible to account for such effects in the calibrations and there are certainly examples where this type of information would have been useful.

The specific tests of the two models abilities to simulate land use change effects were relatively successful and it was found that the parameter value changes required to differentiate between runoff from natural vegetation and afforested areas were broadly consistent with the models conceptual structures and therefore the changes that might be expected.
5 conclusions

Neither model could be applied successfully when the rainfall data were not adequate to represent the real catchment input. This may relate to inadequate representation of spatial variations in mean annual rainfall depths, or to shorter term inputs. Many of the rainfall records are not coincident in time, even for gauges within a single catchment, and there are often extended periods of missing data. It is therefore not always a simple task to generate stationary mean catchment rainfall inputs.

Both models were found to be more difficult to apply to the drier catchments of the region, partly as a result of the lower raingauge density in such areas and partly because of some model deficiencies. More information is required about catchment scale processes (such as transmission losses) and the most appropriate methods of incorporating them into rainfall-runoff models. Some limited improvements to the Pitman model (added function flexibility) have improved the applicability of this model to the semi-arid catchments of the region and particularly to the Namibian catchments.

Apart from the reservations related to the suitability of the available data, the models were found to be generally applicable to the region and can be applied successfully. The VTI model requires greater resources in terms of information, experience, time and effort, but does not generate much better results at the resolution of monthly flow volumes. It is therefore suggested that the monthly model is more appropriate, when high resolution flow estimations are not required.

The parameter estimation routines for the VTI model that are included in HYMAS appear to be appropriate to the region, given that a reasonable amount of information is available to describe the characteristics of the catchment and that an experienced user of the model can interpret this information in the context of the model's conceptual structure. However, it is often the case that such data are not readily available and this makes the initial parameter estimation procedure much less certain and the whole calibration exercise more complex. Soils information is important to the *a priori* estimation of several parameters in the VTI model, but what soils information that is generally available within the region is frequently of limited value due to low spatial resolution and an emphasis on agricultural, rather than hydrological use. The ground water parameters of the VTI model are very important in catchments with sustained low flow regimes, yet there is very little information available on aquifer properties. Fortunately, these parameters are relatively easy to calibrate.

No firm conclusions have been reached about the regionalisation of parameter values for the purposes of future estimation at ungauged sites. This is particularly relevant to the Pitman model, which has been used in the regionalisation of water resources in South Africa (WR90, 1994). There are indications that similar approaches would be worthwhile investigating in Zimbabwe, Moçambique, parts of Botswana, Zambia and Tanzania. However, a greater number of calibration catchments would be required before these indications could be confirmed.
<table>
<thead>
<tr>
<th>Country</th>
<th>Range of areas (km(^2))</th>
<th>Range of record lengths (months)</th>
<th>Pitman Model</th>
<th>VTI Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No. of catchments</td>
<td>Mean % errors</td>
<td>(R^2)</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>146 : 3320</td>
<td>66 : 264</td>
<td>14</td>
<td>-8.7 : 10.8</td>
</tr>
<tr>
<td>Malawi</td>
<td>18 : 1460</td>
<td>31 : 141</td>
<td>5</td>
<td>-12.4 : 6.5</td>
</tr>
<tr>
<td>Swaziland</td>
<td>166 : 1305</td>
<td>120 : 268</td>
<td>7</td>
<td>-5.2 : 10.0</td>
</tr>
<tr>
<td>Botswana</td>
<td>570 : 21216</td>
<td>90 : 228</td>
<td>10</td>
<td>-8.7 : 11.8</td>
</tr>
<tr>
<td>Moçambique</td>
<td>3100 : 26314</td>
<td>127 : 159</td>
<td>5</td>
<td>-9.0 : 6.1</td>
</tr>
<tr>
<td>Tanzania</td>
<td>140 : 1940</td>
<td>128 : 250</td>
<td>6</td>
<td>-7.6 : 3.3</td>
</tr>
<tr>
<td>Zambia</td>
<td>256 : 65983</td>
<td>157 : 235</td>
<td>14</td>
<td>-20.1 : 6.5</td>
</tr>
<tr>
<td>Namibia</td>
<td>212 : 14096</td>
<td>219 : 350</td>
<td>9</td>
<td>-2.5 : 3.5</td>
</tr>
<tr>
<td>Lesotho</td>
<td>403 : 7950</td>
<td>280 : 400</td>
<td>10</td>
<td>See LHWP (1986)</td>
</tr>
<tr>
<td>South Africa</td>
<td>10 : 5000</td>
<td>120 : 900</td>
<td>Many results available from WR90 reports</td>
<td>Many results available from Smakhtin and Watkins (1997)</td>
</tr>
<tr>
<td>Land use</td>
<td>0.21 : 2.88</td>
<td>144 : 276</td>
<td>7</td>
<td>-12.6 : 39.0</td>
</tr>
</tbody>
</table>

**Table 1**: Catchments used in the study and a summary of the simulation results. The Pitman and VTI model statistics are based on monthly and daily data, respectively. Mean % errors refer to the range of % differences in simulated and observed mean monthly or daily flow, while \(R^2\) and CE refer to the coefficients of determination and efficiency.
5 References


Pitman, W V (1973) : A mathematical model for generating monthly river flows from meteorological data in South Africa. Hydrological Research Unit, Univ. of the Witwatersrand, Report No. 2/73.
