A comparative analysis of the PRMS and J2000 hydrological models applied to the Sandspruit Catchment (Western Cape, South Africa)

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Abstract

The applicability of distributed hydrological models to the semi-arid conditions in the Western Cape was investigated through the application of PRMS and J2000 in the Sandspruit Catchment. The Sandspruit is an annual river, with the catchment receiving 300-400 mm/a of rainfall. The catchment exhibits shallow soils, with the dominant land uses being cultivated lands and pastures. To optimise the parameterisation of the models, 21 boreholes were drilled throughout the catchment for data collection and to get a better conceptual understanding of the catchment's hydrologic conditions. Field evidence suggests that subsurface flow is the dominant contributor of streamflow and thus the models were calibrated accordingly. The models were run for a 20 year period. Both models were able to match the timing of seasonal hydrograph responses, however they were not able to match annual discharge volumes. Annual discharge was overestimated in certain cases and underestimated in others. Both models exhibited daily Nash-Sutcliffe Efficiencies of below 0.4. As the models were parameterised and calibrated manually, the feasibility of using automatic techniques needs to be investigated.

Keywords: Sandspruit, PRMS, J2000, semi-arid climate, distributed hydrologic modelling, parameterisation, calibration, Nash-Sutcliffe Efficiency.

1 Introduction

Hydrological modeling has in recent years become essential for effective and holistic management of water resources at a catchment scale. It enables officials and scientists to address a variety of engineering and environmental problems, e.g. assessing anthropogenic impacts on water resources, evaluating the assurance of water supply, assessing the impacts associated with land use change, forecasting floods, etc. In South Africa, however, hydrological modeling is being used to a limited extent as a management tool. The feasibility of applying distributed hydrological models was thus investigated for application in semi-arid Southern African environments. The models chosen for this study were the U.S. Geological Survey's Precipitation-Runoff Modeling System (PRMS) [1, 2] and J2000 as part of the Jena Adaptable Modeling System (JAMS) [3]. The Sandspruit catchment, located in the Western Cape Province of South Africa (Figure 1) was identified as being a suitable study area due to its environmental significance to the Berg River, a major source of water to the Western Cape. The Sandspruit River is interpreted to be significantly contributing to the increasing trend of salinization observed in the Berg River [4].

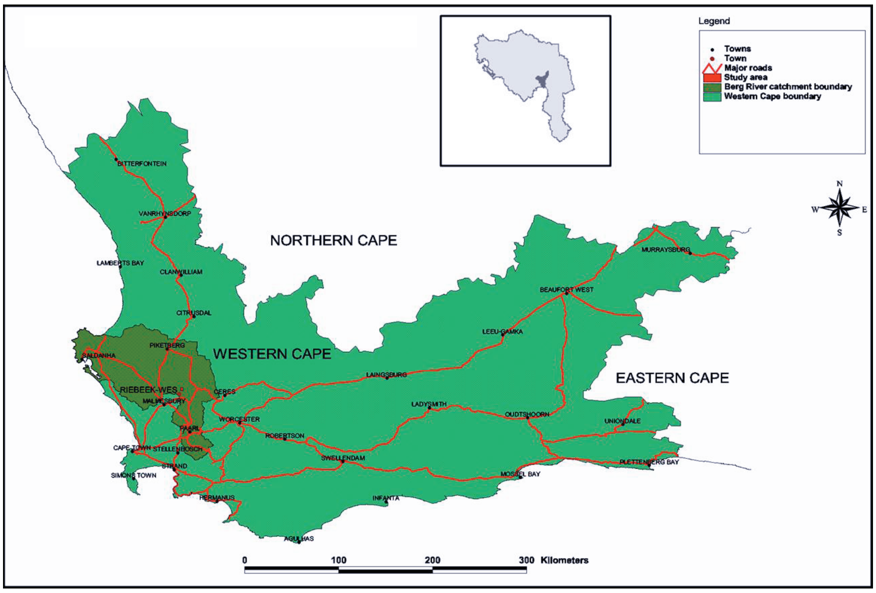

Figure 1: The location of the Berg River in the Western Cape. The location of the Sandspruit catchment within the Berg catchment is shown in the insert [5].

The Berg River is currently receiving much attention, particularly as increasing pressure is being placed on water resources due to rapid population growth in the Western Cape. The trend of increasing inorganic salt concentration observed in the river has therefore become a cause for major concern, and thus two Water Research Commission (WRC) projects have been initiated, with one nearing completion, to address this concern. These projects aim to address the environmental issues, i.e. water quality, soil salinization, vegetation growth, etc, associated with human-induced/secondary dryland salinization, which is evident throughout the mid- to lower-parts of the catchment. The salinization of the landscape is attributed to land use change. In addition, this land use change has altered the water balance, leading to the mobilization of salts and subsequent concentration downstream. It is therefore essential to be able to track and predict the movement of hydrosalinity fluxes, which is envisaged to be achieved through distributed hydrological modelling. Due to the size and complexity of the Berg catchment, the Sandspruit catchment was identified as a feasible test catchment.

According to Beven [6], as cited by Ajami *et al.* [7], the main advantages of distributed models are the spatially distributed nature of their inputs and the use of physically based parameter values. Distributed catchment scale hydrological models such as PRMS and J2000 generally encompass numerous model parameters and the modeller thus requires extensive knowledge of the study area or extensive modelling experience to make valid estimates of these parameters. Many hydrological models incorporate a priori parameter estimation techniques, however, these have not been fully validated through testing using retrospective hydrometeorological data and corresponding land surface characteristics data [8]. Duan *et al.* [8] further state that there is a considerable degree of uncertainty associated with parameters obtained using current a priori techniques. According to Breuer *et al.* [9], the majority of model parameters should be assessable from catchment information. The available data from field investigations, e.g. geological information from borehole logs, data from pumping tests, soil maps and analysis (texture, density, retention curves, etc), vegetation maps, etc. should be used to define spatial patterns of parameter estimates [10].

The objective of this study was to investigate and evaluate the applicability of PRMS and J2000 to the semi-arid conditions evident in the Western Cape (South Africa). An intensive field investigation was undertaken in the study catchment to identify the dominant hydrological processes evident in the catchment and to apply rigorous and thorough parameterisation and manual calibration processes. This investigation was undertaken as reliable simulation results can only be obtained if parameter values for processes being considered are known with a certain degree of accuracy. The application of automatic calibration techniques falls outside the scope of this paper.

2 Description of the study area

The Sandspruit catchment is regarded as a medium sized catchment. It is an annual stream, i.e. it only flows between the months of June and November, exhibiting a catchment area of approximately 152 km^2. The climatic conditions evident in the area may be classified as semi-arid, characterised by long dry summers and cool wet winters. The annual rainfall in the area ranges between 300–400 mm, being dominated by long duration and low intensity frontal rainfall between the months of April and October. All precipitation occurs in the form of rainfall with winter extreme minimum temperatures measured to vary between 2-4^{0}C and summer extreme maximum temperatures measured to vary between 38-40^{0}C. Mean Annual Potential Evaporation (MAPE) for the area was calculated to be 1615 mm, with marked seasonal differences between evaporation losses in summer (250 mm per month) and winter (50 mm per month) [5].

The dominant land uses in the area are cultivated lands and pastures, with the dominant vegetation types being dryland winter wheat, lupins and canola. Farmers in the area generally follow a three-year planting rotation, i.e. cultivation only occurs every 3rd year. Lands are left fallow between planting rotations and used for grazing. Erosion is minimized through the use of man-made anti erosion contours, which are evident throughout the catchment.

The topography of the area is relatively flat, with the elevation ranging between 320 mamsl in the upper parts of the catchment to 80 mamsl in the lower parts of the catchment. The geology of the catchment is dominated by Table Mountain Group sandstone in the upper parts and Malmesbury shale in the mid to lower parts. An alluvium cover is also evident which increases in thickness towards the lower parts of the catchment.

Soils are generally poorly developed and usually shallow on hard or weathered rock. The topsoil varies in thickness between 0.5-1 m and exhibits red and yellow colouring. The soil water holding capacity is predominantly between 20 and 40 mm, but it can be up to 80 mm in the upper and lower reaches of the Sandspruit catchment. Soil drainage is somewhat impeded by the low hydraulic conductivity of the semi-weathered Malmesbury shale throughout the Sandspruit catchment, and it is particularly poor in the lower reaches.

The hydrogeological conditions may be characterised by a regional deep, i.e. in excess of 40-140 m, aquifer in the Malmesbury shale overlain by winter perched aquifer within the alluvium cover. Aquifers are generally low yielding, due to the low hydraulic conductivity of the Malmesbury shale and exhibit poor groundwater quality.

3 Model description

3.1 PRMS

PRMS is a modular-design, distributed parameter physical-process catchment model that was developed to evaluate the effects of different combinations of precipitation, land use and climate on the catchment water balance (Figure 2, [11]). For a detailed description of the model, the reader is referred to Leavesley and Stannard [1] and Leavesley *et al.* [2].

3.2 J2000

J2000 is a meso- to macro-scale hydrological model developed at the Friedrich-Schiller University Jena (Germany). J2000 simulates the water balance in large

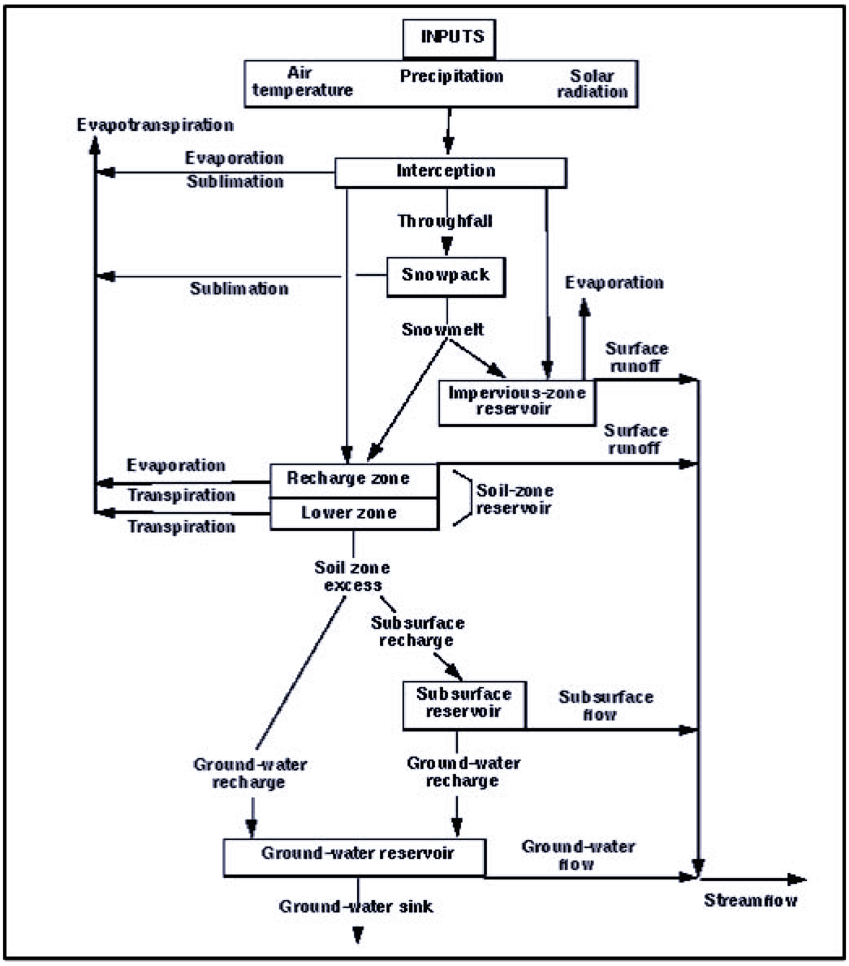

Figure 2: The PRMS flow chart [11].

river basins, i.e. typically larger than 1000 km^2. It simulates the hydrological cycle in a spatially distributed process orientated manner, with the model core focussing on methods of runoff generation and concentration. The model accounts for the increasing heterogeneity of a catchment's environmental parameters coupled with decreasing data accuracy and availability. For a detailed description of the model, the reader is referred to Krause [3].

4 Data availability

Meteorological input data in daily time steps were provided from 3 nearby precipitation stations and 2 temperature stations. All stations are located outside the catchment within a distance of 30 km. The temporal extent of the data set is approximately 20 years. For calibration of modelling results a 20 year long data record of observed discharge at the Sandspruit gauge, close to the confluence with the Berg River, is also available from the database of the South African Department of Water and Environmental Affairs. In addition, a 4-year data record of volumetric soil water content, measured at a nearby experimental site is available to estimate seasonal soil moisture conditions. Hydrologic Response Unit (HRU) delineation was achieved using a 20 m digital elevation model (DEM) as well as land use, soil and geological raster data sets.

The available data allowed for accurate estimates of soil water contents, soil type, vegetation rooting depths, vegetation types, vegetation cover densities and annual evapotranspiration to be made across the catchment.

5 Conceptualization of the system

To thoroughly assess the feasibility of using PRMS and J2000 in semi-arid Southern African conditions an intensive field investigation was undertaken to optimise the parameterisation of the models. 21 boreholes were drilled (rotary percussion) across the catchment, i.e. in the upper-, mid-, and lower-reaches. Data gathered from the investigation includes topsoil thickness, soil moisture, thickness of the alluvium deposits, estimates of porosity, depth to the water table and geological information. It was envisaged that the data would provide a good indication of the dominant contributing streamflow component, the storage capacity of water holding reservoirs, flow rates and estimates of other hydraulic characteristics of the system.

The field investigation allowed the hydrological and hydrogeological drivers of the system to be conceptualized. The typical geological succession for the area is shown in Figure 3. Streamflow is interpreted to be driven by the layers above the Malmesbury shale through subsurface flow (Figure 3). The thickness of these layers increases in a downstream direction and varies between 15-50 m. The shale exhibits a very low infiltration capacity and hydraulic conductivity (K). Annual recharge to the perched water tables in the area are estimated to be approximately 70 mm/a and the shale is reported to exhibit a K of 1 m/a [12]. These properties result in the accumulation of water above the shale in winter. Although infiltration is observed to be extremely low in summer, the vegetation roots are interpreted to act as a preferential pathway in winter thereby recharging the layers above the shale [5]. Moist areas within this layer, further provide evidence for the build-up of a temporary (winter) water table.

6 Model results

The models were run for the entire data record. The commonly used goodness-of-fit measure, i.e. Nash-Sutcliffe Efficiency (NSE) [8], between observed and simulated values was used to evaluate model performance. It is expressed as:

$$NS = 1 - \frac{\sum_{\mathrm{i}=1}^{n} \left(\mathrm{Q}_{\mathrm{i}} - \mathrm{Q}_{\mathrm{i}}^{*}\right)^{2}}{\sum_{i=1}^{n} \left(Q_{i} - Q_{i}^{*}\right)^{2}} \tag{1}$$

where Q_i and Q_i^* are the simulated and observed values, respectively, at time i, and n is the number of data points. Q_i^- is the average of observed values. Values for NSE vary from negative infinity to 1. A value of 1 indicates a perfect fit between Q_i and Q^*_i, while a value < 0 implies that the simulated value is (on average) a poorer predictor than the long-term average of the observations.

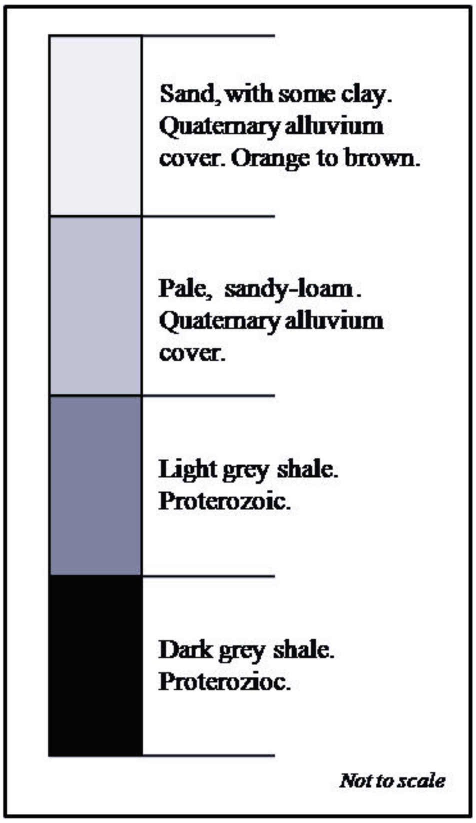

Figure 3: The typical geological succession in the study area.

6.1 PRMS

The observed and simulated streamflow is shown in Figure 4. Annual discharge amounts were constantly overpredicted by the model, showing large variations in certain cases. A correlation between annual observed and simulated streamflow

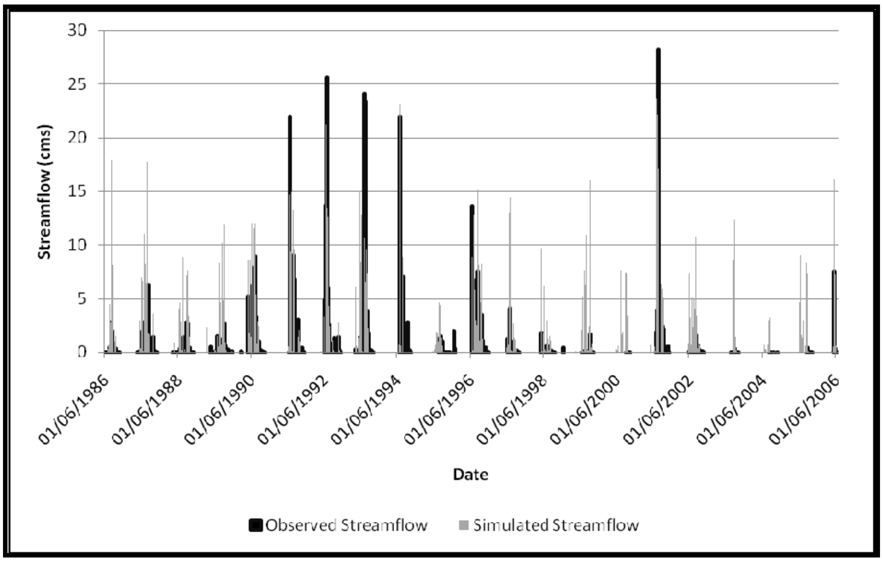

Figure 4: A comparison of daily observed and simulated streamflow (PRMS, cms = cubic meters per second).

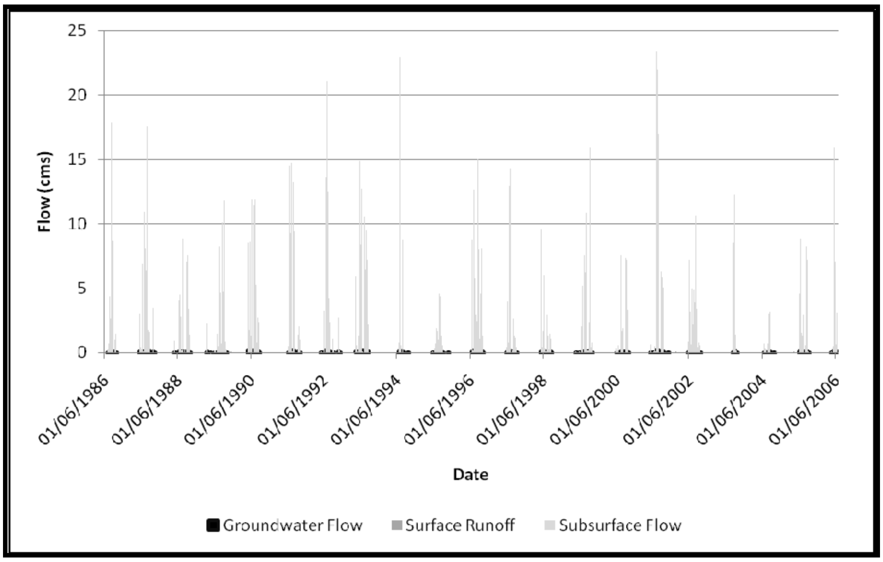

Figure 5: The different components of streamflow (PRMS, cms = cubic meters per second).

yielded a R^2 value of 0.66. The model was able to match the timing of observed streamflow response with a reasonable degree of accuracy. When simulation results were observed on a seasonal time scale, simulated and observed streamflow were comparable in certain cases, e.g. 1994, however no correlation could be observed to explain this. The model exhibited a daily NSE of 0.27.

The contributions of the different components of simulated streamflow are shown in Figure 5. Subsurface flow was observed to be the dominant contributor, which is in accordance with field observations.

6.2 J2000

The observed and simulated streamflow is shown in Figure 6. J2000 exhibited variability in terms of the annual discharge, i.e. annual discharge was over-estimated in certain years and under-estimated in others. A correlation between annual observed and simulated streamflows yielded a R^2 value of 0.76. A detailed observation of simulation results showed that the model was not able to account for extreme events, e.g. 1991, 1992, 1993 and 1994 and thus wet years were under-estimated. The annual simulated hydrograph also exhibited a more gradual recession, which is interpreted to be a result of an excessive contribution of groundwater to streamflow. The model exhibited a daily NSE of 0.30.

The dominant contributor to streamflow was interflow from the soil zone, which is in accordance with field observations. The contribution of overland flow was more pronounced with J2000 when compared to PRMS. This is interpreted to be due to the nature with which it is estimated, i.e. J2000 accounts for infiltration excess overland flow whereas saturation excess overland flow is more dominant in PRMS. J2000 was able to match the timing of observed

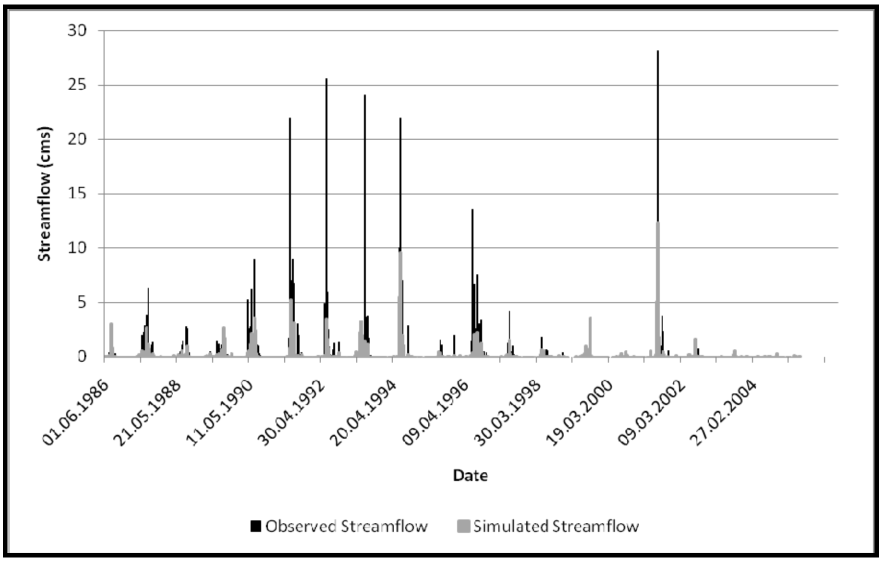

Figure 6: A comparison of daily observed and simulated streamflow (J2000, cms = cubic meters per second).

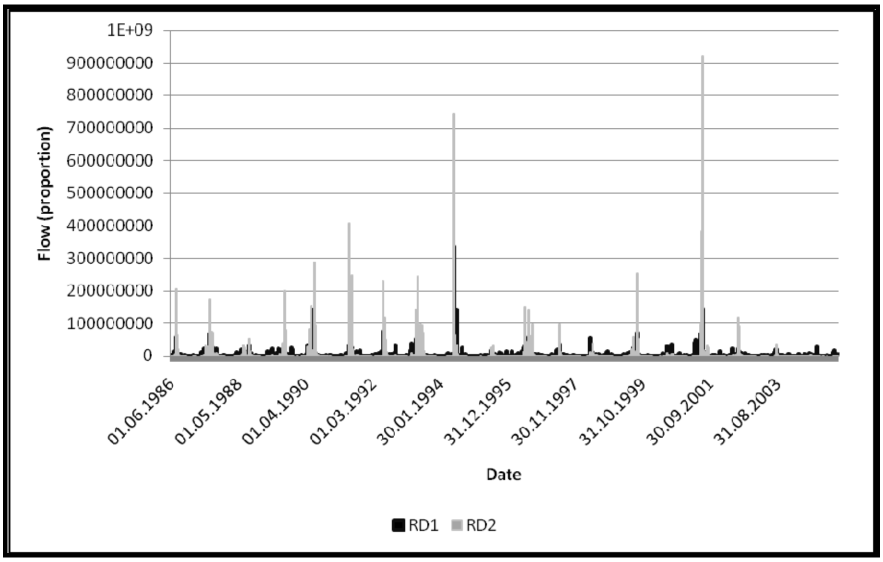

Figure 7: The dominant components of streamflow (J2000, cms = cubic meters per second) (RD1 = overland flow, RD2 = interflow from soil zone).

streamflow responses but showed poor correlations with observed annual discharge totals.

7 Discussion

Based on the NSE both models performed poorly, exhibiting efficiencies below 0.4. The models were able to match the timing of annual observed streamflow responses but showed poor correlations with observed annual discharge totals. According to Gan *et al.* [13] catchments with streamflow/rainfall ratios of 0.2 or less, such as the Sandspruit, are more difficult to simulate than wet catchments or catchments with relatively high streamflow/rainfall ratios. This is due to the former exhibiting more complex and variable hydrological processes than the latter.

The poor model performance may however be attributable to certain factors, which include:

- The anti-erosion contours are interpreted to have a significant influence on the water balance, which currently is not accounted for in the models. These contours are designed to restrict overland flow, thereby reducing soil erosion and thus to accurately simulate the water balance of the catchment, this effect needs to be accounted for.
- Frontal rainfall usually exhibits spatial variation and thus the fact that all climate gauging stations are located outside the catchment might be significantly influencing model results. The feasibility of using

alternative methods of rainfall distribution, as well as temperature and other input data therefore needs to be investigated.

- Based on observations made during the field investigation, the input data sets of land use and soil properties are not interpreted to be of a sufficient resolution and thus these need to be refined.
- Land use changes seasonally and this cannot be directly incorporated into the parameterization of the models.

The results presented in this study were achieved through manual calibration, using extensive geological data gathered during an intensive field investigation. Both software packages however incorporate automatic calibration techniques, which could prove to be a more feasible approach.

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