Resolving uncertainties in the source of low flows in South African rivers using conceptual and modelling studies

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Abstract Low flows play an important role in the eco-hydrology of any natural system and within South Africa are mainly derived from near-surface interflow or deeper groundwater processes. In South Africa there is much uncertainty about the dominant source of low flows in any specific basin. Understanding surface–groundwater interactions and determining the source of low flows are important for sustainable water management strategies and the integrated exploitation of ground and surface water resources; a critical issue for water-stressed regions. This study uses a monthly rainfall–runoff model that includes surface–groundwater interactions in which low flow responses can be simulated either as interflow or groundwater discharges to the river (or both). If the model is to provide useful information for integrated water management any uncertainties in the simulated source of low flows need to be resolved. The paper explores different approaches to resolving these uncertainties (using limited water quantity and quality data) in three basins where the surface–groundwater interaction processes are assumed to be different.

Key words hydrological modelling; low flows; surface–groundwater; wetlands

INTRODUCTION

Historically, managing water in South Africa was focused on the estimation of the yield from relatively large reservoirs, while more recently there has been a shift to integrated management of surface and groundwater as well as accounting for environmental water requirements (EWR). The previous focus on yield meant that the outputs from estimation models were required to satisfactorily simulate the seasonal distribution and sequences of runoff over critical dry periods, typically lasting several years. With the exception of some projects where the water requirements were expected to be supplied from run-of-river flows, accurate representation of low flow volumes during the dry season months was never a critical issue, nor was there much focus on the source of the low flows. In the strongly seasonal flow regimes of South Africa these types of design situation were relatively rare as the dry season flows are typically insufficient to satisfy the needs of most supply schemes and storage is almost always necessary. However, the information requirements of EWR studies are quite different and low flows are now known to play a major role in the ecological sustainability of rivers (Richter *et al.,* 1997). Low flows can be a result of complex interactions between surface and sub-surface hydrological processes and can be affected by the exploitation of groundwater resources. There are many remote rural water supply schemes that are reliant on either run-of-river flow or very low volume storage (small in-channel weirs). The importance of these for social well-being and community health purposes was largely neglected during the Apartheid years.

This paper reports on the use of available information to try and resolve the uncertainties in our knowledge of the source of low flows in three South African basins and to guide the parameter estimation process for a monthly rainfall–runoff model that is widely used for water resources decision making in the country. The assumption is that low flows can be derived from near-surface storages (soils and unsaturated rock material above the phreatic zone), discharge to river channels from saturated groundwater storage, or valley bottom surface storages that cause attenuation of upstream inflows (e.g. flood plains and wetlands).

THE PITMAN MONTHLY MODEL

The Pitman monthly time-step rainfall–runoff model has been widely used as a practical water resource assessment tool in South Africa for many years. It is a semi-distributed (sub-basin), conceptual type model with some 18 main parameters that are used to quantify hydrological processes at sub-basin scales of between 50 and 10 000 km^2. The model has been through a number of development phases and Hughes *et al.* (2006) provide a description of the version of the model that is used in this study, including routines to explicitly simulate surface and groundwater interactions at the sub-basin scale (Hughes, 2004). A new wetland function is still being tested. There are two main processes in the model that determine the low flow regime of a basin. The first is a nonlinear relationship (with a power of POW) between the level of the model moisture storage (S mm) and runoff (up to a maximum of FT mm $month^{-1}$ at maximum storage ST mm). This runoff is assumed to represent all types of interflow and could include saturated soil water runoff as well as fracture zone flow above the general level of the groundwater in steep sub-basins (Hughes, 2010). The second function is based on a similar nonlinear relationship (power of GPOW) with S, but is used to estimate the groundwater recharge (up to a maximum of GW mm $month^{-1}$ at maximum storage ST mm). Outflow to surface water from the groundwater storage is determined by the storage level together with parameters representing the drainage density, storativity, transmissivity and riparian evapotranspiration losses.

EVIDENCE FOR SOURCES OF LOW FLOWS

While detailed field investigations would always be the best scientific approach to identify sources of low flow, they typically require resources, time and money that are not available for most practical water resources assessments. This study has therefore focused on the type of information that is more generally available and provides an assessment of the value of these information sources for identifying low flow sources.

Gauged streamflow data One of the problems with many of the gauged streamflow records is the fact that they are often affected by poorly defined upstream developments which can substantially affect the interpretation of the data, specifically during periods of low flow. There are some gauges which have relatively long records (pre-1960) but the extent to which these represent natural conditions remains uncertain.

Water quality data Water quality data are available for many of the streamflow gauging stations in the country and there are also limited amounts of borehole water quality data that can be used to assess the quality signature of groundwater. The majority of the river water quality samples are taken at weekly to monthly intervals and generally during moderate to low flow conditions. The water quality parameters included in the data sets are typically pH, TDS (total dissolved solids), EC (electrical conductivity), major cations and anions and some nutrient data. The available data provide some basic information about the variations in river water quality, but are not sufficient for detailed hydrochemical tracing studies. While temperature has potential as a water quality indicator, such data are rarely included in the South African datasets.

Topography, geology, soils and land cover In general terms the availability of this type of information is adequate over most parts of South Africa. Specifically, the AGIS (2007) database provides detailed information on land types which includes geology, soil depth and texture (for different topographic units). All of these data are very useful for defining the physical setting of sub-basins and are used to assist with model parameter estimation (Kapangaziwiri & Hughes, 2008, 2009). However, to be useful for establishing sources of low flows, they need to be interpreted through a conceptual understanding of hydrological processes. Unfortunately, there have been relatively few scientific studies covering the very diverse conditions found in South Africa that would have contributed to this understanding.

RESULTS

The study has included three groups of quaternary sub-basins (the main sub-division used in South Africa; Midgley *et al.*, 1994). All of the rainfall and evaporation demand data used in the model runs has been taken from the WR90 reports (Midgley *et al.*, 1994), while the observed flow and water quality data have been accessed from the websites of the Department of Water Affairs (flow data: http://www.dwa.gov.za/Hydrology/CGI-BIN/HIS/CGIHis.exe/Station; water quality data: http://www.dwa.gov.za/iwqs/wms/data/000key.asp, accessed December 2010).

Buffelsjag River, Western Cape Province

This river drains quaternary sub-basins H70C and H70D (total area of 457.8 km^2) and there are two gauging stations, one at the basin outlet (H7H003 at 34.00°S 20.66°E) and the other on a 28km^2 tributary (H7H004 at 33.91°S 20.72°E). The basin is within the steep topography of the Cape Fold Belt and a ridge of Table Mountain Sandstone (TMS) runs east–west separating H70C from H70D, while the remaining area is underlain by interbedded shales and sandstone of the marine-derived Bokkeveld series. The modelling has been based on three sub-basins and calibrated against observed flow data for 1950–1965 to avoid impacts of recent increases in irrigation. H70C was split into two areas, one to represent the tributary at H7H004 (lying just to the north of the crest of the ridge) and one to represent the remainder of H70C (in the rainshadow to the north of the ridge). The third sub-basin is H70D, which includes the southern ridge slopes and the lower lying area to the south. Mean annual rainfall varies from over 900 mm year^{-1} on the ridge to less than 400 mm year^{-1} to the north. Based on borehole water quality data for the region, the groundwater in the TMS generally has TDS values of less than 200 mg L^{-1}, while the Bokkeveld shales are substantially more saline (> 400 mg L^{-1} and often over 1000 mg L^{-1}). Low flows are expected to be derived from a combination of groundwater discharges in the main valley bottoms together with springs on the steep rocky hillsides derived from temporally saturated fracture zones (Hughes, 2010).

Figure 1 illustrates flow *vs* TDS relationships for both gauging sites together with the simulated results based on applying TDS signatures to the three modelled runoff components (Table 1). Given that the observed relationships are based on daily flows it is expected that the simulated TDS values would be more scattered and generally lower than the daily values for the equivalent flow volume as the monthly simulations contain a combination of runoff events and low flows. The data for H7H004 shows a strong power relationship indicating a dominant poor quality source diluted during higher flows with a better quality source. The H7H003 data suggest a greater mixture of (and lower TDS) water quality signals, consistent with its more downstream position and the dominance of water derived from the TMS rather than Bokkeveld shale formations.

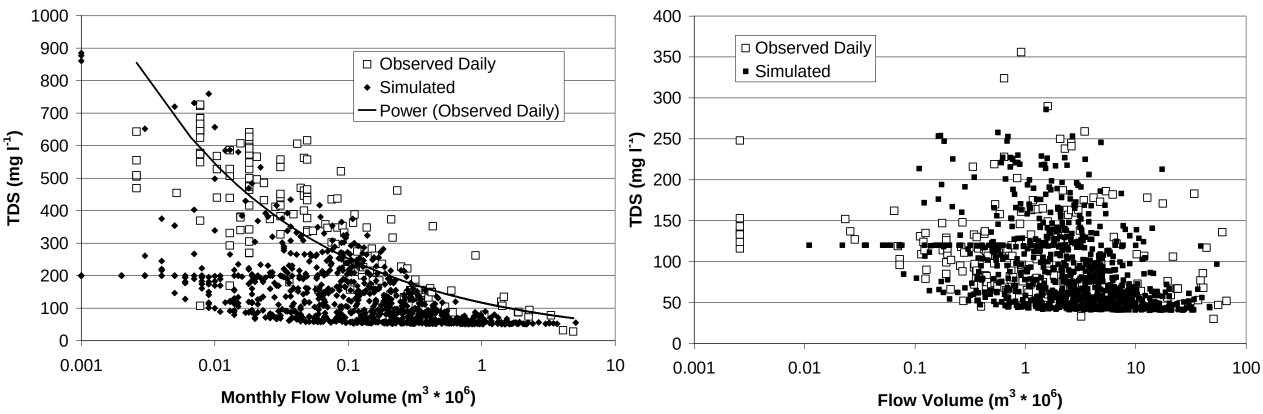

Fig. 1 Comparison of observed (daily; converted to equivalent monthly volumes) with simulated (monthly) flow volume v TDS relationships for H7H004 (left) and H7H003 (right).

The simulated runoff components given in Table 1 have been based on manual calibration to achieve the best possible fits to the observed flow duration curves. Figure 1 suggests that these model outputs (together with the very simplified approach to estimating simulated TDS) can approximately account for TDS variations. However, it was also possible to achieve almost equally good simulations without the groundwater runoff component. Replacing the interflow with groundwater as the main source of low flows produced poorer flow simulations and could not match the observed TDS variations regardless of the TDS signature used. While the evidence is far from conclusive and there are a number of low flow quantity and quality processes that have been neglected (such as pool evaporation and some anthropogenic impacts), the balance of evidence suggests that the low flows are mainly derived from interflow in saturated fractures above the general water table level but with some contributions from groundwater.

Table 1 Simulated runoff components and water quality signatures.

Sub-basin	Runoff component	Surface	Interflow	Groundwater
H7H004	TDS signature (mg L^{-1})	50	200	900
	Simulated % of total runoff	89.2	9.6	1.2
H7H003	TDS signature (mg L^{-1})	40	120	400
	Simulated % of total runoff	82.5	14.4	3.1

Seekoei River, northern Province

This river drains quaternary sub-basins D32A to D32J and has a total area of 8330 km^2 with a flow gauging station (D3H015 at 30.53°S 24.96°E) at the outlet of D32J. The majority of the area is relatively flat and semi-arid with very infrequent and intermittent flow. However, the downstream reaches of the river pass through a dolerite ridge and low flows are sustained for much longer periods of time. A previous study of the quantity and quality of the streamflow in the lower part of the basin was based on the streamflow data, some limited borehole level observations as well as water quality data from the river, the groundwater and several springs emerging in tributary channels of the dolerite ridge. These data were used to establish the parameters of the Pitman model, as well as a water quality extension to the model (Hughes, 2009). The overall conclusions were that the majority of the low flows were derived from the springs, which appear to flow almost continuously. However, the low flow quantity and quality are modified by evaporative losses from the relatively large pools that exist in the main channel. Discharge to the river channel from the regional groundwater was not considered to make a significant contribution, based on groundwater levels being close to the channel bed elevation and very low hydraulic gradients in the vicinity of the channel.

Mkuze River, KwaZulu-Natal Province

This river drains sub-basins W31A to W31L and W32A with a total area of 5048 km^2 and two gauging stations; one upstream (W2H008 at 27.61°S 31.96°E; area of 2 578 km^2) and one at the basin outlet (W2H011 at 27.66°S 32.42°E). A large flood plain (approx. 40 km^2 in extent) wetland occurs just upstream of the catchment outlet and the effects of attenuation of upstream flows can be quite clearly seen in Fig. 2(a) during the seasonal recession in 1975. However, the lower upstream peaks at the end of the wet season in 1973 are not attenuated. Figure 2(a) also includes a very approximate simulation of the water balance of the wetland (using a daily version of the wetland routine recently added to the Pitman model), but ignoring the incremental flows below gauge W3H008. The approach is based on a volume threshold above which a proportion of the channel water is diverted to the wetland. Return flows back to the channel are based on a nonlinear function of the wetland storage volume. While the daily flow data confirm that the wetland has a variable attenuation effect, the quality of the records (many missing high flow values) is too poor to properly test the wetland functions included in the model. Figure 2(b) shows the results for the Pitman model with and without the wetland function and the effects are not very noticeable at the monthly time scale. Both simulations are equally good based on several objective functions and the shapes of the flow duration curves compared with the observed flows.

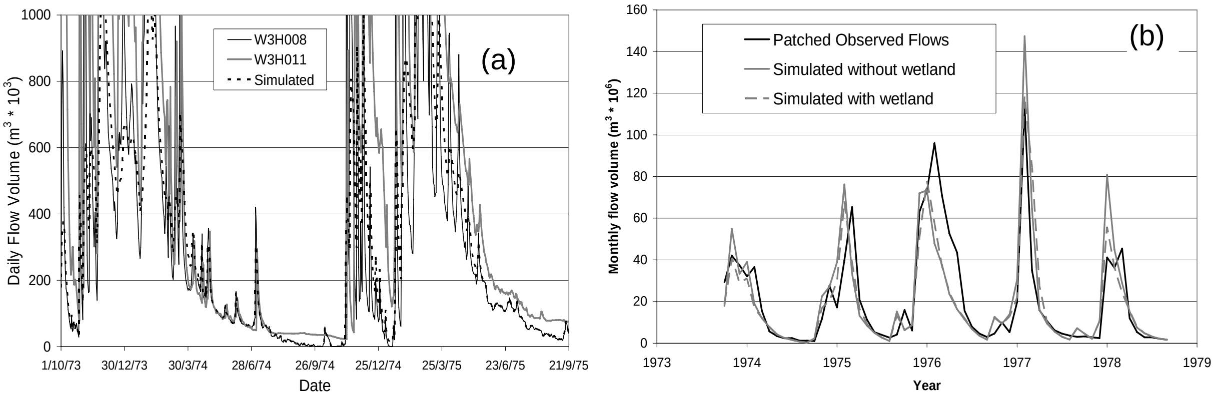

Fig. 2 (a) Comparison of observed (daily) flow volumes at W3H008 and W3H011 and a simple simulation of the effects of a wetland. (b) Results of the application of the Pitman model.

There is very little information available to determine whether the upstream (above the wetland) low flows are being simulated for the correct reason. The simulated recharge volumes are in close agreement with available regional estimates (Conrad, 2005) and the simulated groundwater contribution is approximately 13% of total runoff, while interflow represents 39%. The river water quality data at both gauges show a relatively good (R^2 = 0.4) negative power relationship with flow, with TDS varying from greater than 1000 mg L^{-1} at low flows, to less than 200 mg L^{-1} at higher flows. Samples from boreholes suggest groundwater TDS signatures that cover a wide range from less than 200 to more than 1300 mg L^{-1}. There would therefore not appear to be any clear distinction between the quality of different runoff components and the interflow component may have a highly variable quality signature. Overall, the amount and quality of the available data are insufficient to reach firm conclusions about the source of low flows in this area.

DISCUSSION AND CONCLUSIONS

The assessments at all three sites are largely based on typically available data and no site specific studies have been undertaken, with the exception of some additional groundwater information collected during field visits for the Seekoei River. The available evidence for conceptualizing the different contributions to low flows is very variable. The results for the Seekoei River are conclusive from both water quantity and quality perspectives and they have enabled the hydrological model parameters to be established with high confidence. The results for the Buffelsjag River are less conclusive and more site specific groundwater data would have been very useful. There are many catchments in the regions of steep topography associated with the Cape Fold Belt and a better understanding of the water quantity and quality dynamics of sub-surface water (both “real” groundwater as well as flow in fractures above the regional groundwater table) in the different strata (mainly TMS and Bokkeveld) could potentially contribute to the management of water resources in these areas. The Mkuze River example illustrates that although there may be a clear relationship between flow and water quality (confined to TDS in this study) it is not always a straightforward task to translate this into useful concepts of flow generation processes.

The Mkuze River also provides an example of daily flow data being able to demonstrate the effects of a wetland and that a relatively simple wetland inflow–outflow water balance model can approximately reproduce the variable attenuation impacts. However, the wetland effects are largely masked at the monthly time-scale and it is difficult to assess the validity of the new wetland function in the Pitman model given many of the other uncertainties associated with establishing appropriate parameter values and climate inputs.

This study is part of a larger research programme designed to identify, quantify and reduce the uncertainty in water resources assessments in South Africa. One of the objectives is to improve understanding of sub-basin scale hydrological processes and apply that understanding to the application of hydrological models in ungauged basins. The search for appropriate catchments (and associated information sources) to use for this study reinforced the perception that many of the hydrological records are of limited value to hydrological understanding. This is because they are affected by largely un-quantified upstream anthropogenic impacts (reservoirs, abstractions, return flows, etc.) and the signals contained within the records are difficult to interpret from a hydrological perspective. There is clearly a need for additional information that is targeted at filling in some of the gaps in our understanding of hydrological processes at the scale of sub-basins. Given the limitations of human and financial resources that exist in South Africa, it is important to clearly identify what those gaps are and what is the most focused and cost effective methods of filling them.

Acknowledgements The first author recently completed his PhD on aspects of model uncertainty analysis and was partially supported by the Water Research Commission of South Africa (Project K5/1838). The third author is a PhD student supported by the Sub-Saharan Africa Water Resources Network (SSAWRN), part of the Regional Initiative for Science Education (RISE) funded by the Carnegie Foundation.

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