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Water resources estimation in less developed regions—issues of uncertainty associated with a lack of data

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Abstract There is an urgent need within less developed regions for tools to quantify water resources and their variability and to determine the impacts of development scenarios. While there has been a relatively long history of the practical application of hydrological and water resource models in southern Africa, the quality of the results are constrained by the limitations of the available data. There are unanswered questions about what the scientific and practical priorities should be in terms of improving predictions and reducing uncertainty. The paper provides some background to the problem through a brief review of the use of models in the region, the quality of the available data and some of the constraints. The overall conclusion is that there is a need to improve the access to, and the reliability of, model input data. Unless these issues are resolved, improvements in modelling approaches are unlikely to result in reducing uncertainties in simulation results.

Key words developing regions; hydrological models; uncertainty; water resources

INTRODUCTION

The development and application of hydrological models in southern Africa has focused on conceptual type models, with a relatively large number of parameters, largely due to the tradition of using manual calibration, where intuitive understanding of the model and the basin response characteristics are used to establish appropriate parameter sets. Automatic calibration procedures have not been used very extensively and the problems of parameter interaction (Gupta, 2005) largely ignored. The emphasis has been on simulating streamflow time series to provide estimates of yield from reservoirs with relatively high storage capacities. However, an improved understanding of the low flow characteristics of rivers, under both natural and modified regimes, is now required. If hydrological models are to contribute to improved estimates of water resource availability and vulnerability, there are several questions that require answers, most which should be relevant to other developing regions. Are the available input data spatially representative and of sufficiently good quality to provide adequate input into models? If they are not, what opportunities exist to improve the data, given the financial and human resource constraints that exist in developing regions? Are the models currently in use appropriate to the water resource problems? Are other modelling technologies likely to offer better solutions given the constraints of available data? If new technologies are introduced are there sufficient resources to ensure the development of local capacity and the sustainability of model applications into the future?

This paper highlights some of the approaches to model applications in southern Africa and focuses on the limitations of the available data with respect to prediction uncertainties and the prospects for future improvements.

AVAILABLE MODELLING TOOLS

Hughes (2004b) emphasized the need to link model development to the practical requirements of water resource estimation in developing countries where an urgent need for information, as well as limited research resources, have largely directed model developments. The emphasis has been on conceptual type models, expert judgement and regional parameter estimation, rather than simple models and mathematical calibration methods. One reason is the lack of extensive databases of physical basin properties, observed flow or hydro-meteorological variables that can be relied upon for use in automated model fitting approaches. Where there are large errors or inconsistencies in the available data, automated calibration methods have been found to generate parameters that are fitted to the errors (Mwelwa, 2005). It is also difficult to constrain parameter value searches in a way that generate regionally consistent parameter value sets (Hughes, 2004b). However, more recently developed automatic optimization approaches could offer improved calibration methods (Beven, 2004).

The Pitman (1976) model is one of the most widely used water resource estimation models in the region. The main processes of runoff generation are represented in a conceptual, explicit moisture accounting scheme and improved surface–groundwater interaction routines have recently been included (Hughes, 2004a). While the model has been successful as a water resource estimation tool, its limitations cannot be ignored, especially now that more detailed and reliable information is required to solve increasingly complex water resource problems. Run-of-river abstraction schemes and accurate low flow simulations have assumed greater importance in attempts to supply rural communities with reliable water supplies and satisfy environmental water requirements. Previous Pitman model applications have not always resulted in reliable low flow estimates, a problem compounded by relatively inaccurate low flow gauging at some streamflow recording stations.

In general terms, no model can generate satisfactory results in situations where the available input data are unreliable, there is a poor understanding of the mechanisms of the rainfall–runoff processes, or where models are applied incorrectly by inexperienced users. The Pitman model has been demonstrated to be applicable to large parts of southern Africa with respect to the way in which it represents real basin responses to runoff (Hughes, 1997). The main issue is whether or not it is reliable enough for simulating flow regimes in ungauged catchments after the determination of suitable parameter values.

DOMINANT CAUSES OF UNCERTAINTY

Input data uncertainties

While, the phrase "*garbage in, garbage out*" applies worldwide, in developing regions it is far more difficult to resolve the "*garbage in*" issue. A recent history of political, social and economic turmoil in some developing regions has meant that hydro-meteorological gauging networks have not been high on government agendas. Consequently, modelling studies are frequently faced with short, patchy and unreliable hydro-meteorological records that have poor spatial coverage. The situation with respect to basin physical property data is at least as bad. In many areas, knowledge of the geology, soil and land cover characteristics is based on coarse scale maps, which have not been generated using hydrologically relevant source data. Many soil maps are based on agricultural development potential, which is difficult to translate into hydrologically useful information about water holding capacity, permeability and depth. The information on existing water use and land use modifications is also scarce and unreliable.

Satellite derived land surface and hydro-meteorological data has the potential to provide improved data inputs to models. However, adequate ground truthing and matching with historical records from ground-based stations is essential. Figure 1 illustrates two satellite derived land use maps (Fairbanks *et al*., 2000) for a 1700 km^2 South African basin that has extensive citrus orchards. The 1996 map (based on Landsat 5 TM at an effective mapping scale of 1:250 000) correctly shows some of the citrus areas classified as 'permanent commercial irrigation'. The more detailed 2000 map (based on Landsat 7 ETM at an effective mapping scale of 1:50 000) contains no land uses related to irrigated orchards.

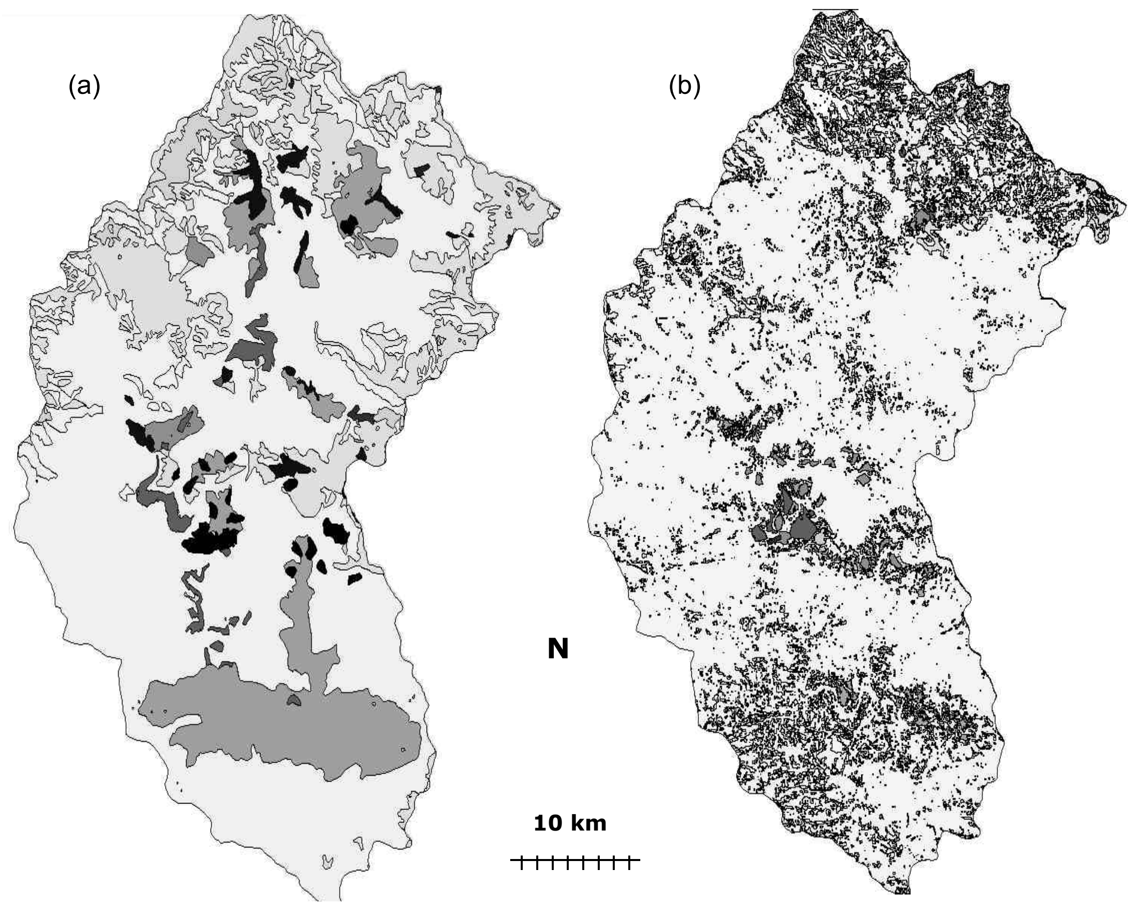

Fig. 1 Land use derived from two different satellite imagery interpretations (see text for details). (a) 1996 with low spatial resolution, (b) 2000 with higher spatial resolution.

Gauged rainfall and streamflow data, for the upper part of the Okavango River basin (Angola, Botswana and Namibia), spans a period from 1960 to about 1972, while observed flow data are available at downstream gauging sites from the 1950s to the present day (Andersson *et al.*, 2003). The calibrations of the Pitman model using the 1960s data were considered satisfactory based on Nash-Sutcliffe coefficients of >0.8 and errors in mean flow statistics of <5% for key flow stations. However, when the model was applied with 1990s satellite generated rainfall data, the model over-simulated the observed flows. The satellite data were generated by the University of Sussex using data from TRMM (Tropical Rainfall Measuring Mission), SSM/I (Special Sensor Microwave Imager) and METEOSAT as part of the WERRD (Water and Ecosytem Resources in Regional Development—http://www.okavangochallenge.com) project. The satellite data suggest higher rainfalls than during the gauged period (Fig. 2), despite streamflow evidence that the 1990s was a much drier period. A simple, nonlinear correction equation was applied to the satellite data to produce rainfall frequency characteristics that were similar to the historical gauged rainfall data and the resulting streamflow simulations for the 1990s were vastly improved. Figure 3 provides a comparison with observed Zambian rainfall data (same latitude and some 5^{o} to the east) over the whole period. The general pattern and range of annual rainfalls for the Okavango and Zambian gauged data for the 1960s are similar, while the original satellite data are clearly much higher.

Quantitative understanding of hydrological processes

Without an understanding of both hydrological processes, and how the processes are represented in a specific hydrological model, it is difficult to assess whether a model is generating the right results for the right reason. If it is not, extrapolation of the model to other situations (different land use, climate, basin, etc.) is unlikely to produce satisfactory results. If the dominant hydrological processes are understood, it should be

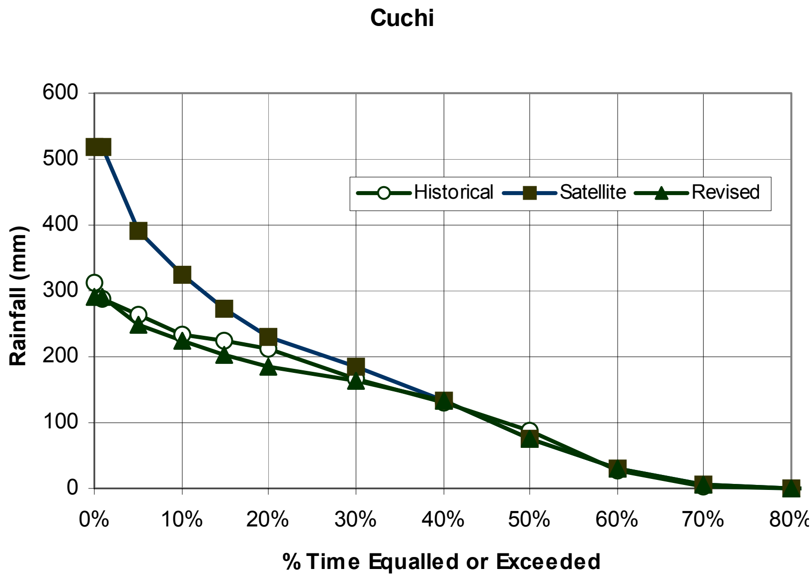

Fig. 2 Comparison of rainfall frequencies (Historical, Satellite and Revised Satellite) for one sub-basin in the Okavango basin (see text for source of satellite data).

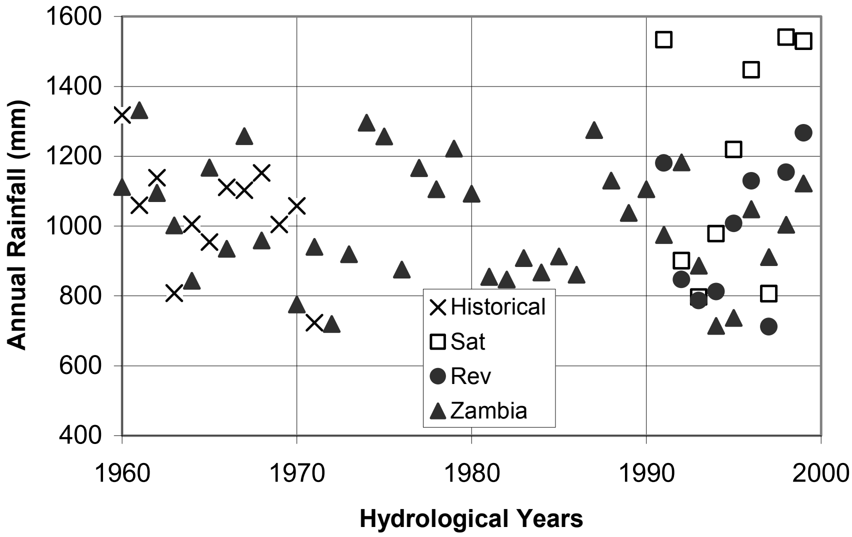

Fig. 3 Comparison of annual rainfalls for the original (Sat) and revised satellite (Rev) data with Zambian rainfall data (see text for source of satellite data).

possible to intuitively assess the model response. There have been few detailed studies of hydrological processes in southern Africa. The limited studies that have been carried out, however, have contributed to the understanding of processes at relatively small scales and in limited parts of the region (Maaren, 1989; Hughes & Sami, 1992; Hickson *et al*., 1999). For example, land use change impacts have received a great deal of attention (Gush *et al*., 2002), but there are still doubts about how to apply models to simulate such changes.

Within the wetter parts of the region, surface and groundwater interactions and the extent to which low flows in rivers are a result of groundwater discharge processes are not well understood. Large parts of the region are underlain by fractured rock aquifers, in which water storage and movement is highly heterogeneous. Regionalized estimates of some groundwater parameters exist for South Africa (e.g. Bredenkamp *et al*., 1995), but these have been difficult to use in interpreting interactions with surface water. Recent improvements to the Pitman model (Hughes, 2004a) have the potential to allow existing groundwater information to be used in conjunction with a well-established surface water model to assess our intuitive understanding of the interaction processes at the basin scale.

Within semiarid parts of the region channel transmission losses are of great importance in understanding the dynamics of alluvial aquifers adjacent to some of the larger rivers in southern Africa. However, understanding the processes represents a major challenge and they have proved difficult to effectively incorporate into models (Hughes, 1997; Görgens & Boroto, 2003), largely due to a lack of quantitative information about the controlling factors.

Regionalization of model parameters

Model applications in ungauged catchments can involve regional extrapolation from calibrated parameter sets, or more explicit approaches to evaluating parameter values from available physical basin property data. *A priori* regional extrapolation schemes can be based on an understanding of the conceptual meaning of parameter values. The model calibration in gauged basins would be guided by the same scheme and could partly be used to test and revise the scheme. While this approach can be useful where only limited quantitative information is available for the physical properties, it relies on the correct conceptual interpretations of differences in sub-basin runoff generation processes and their effects on model parameter values. Where more detailed quantitative data are available, more statistical relationships between parameter values and physical properties can be established. The potential pitfall of both approaches is that there are rarely sufficient gauged streamflow data to be able to effectively test the regionalization process. In practice, the number of gauges is often so small that they are all needed to develop the extrapolation approach. The uncertainty is related to the degree to which the selected physical basin properties are appropriate in relation to the functions of the parameters within the model and the accuracy with which the basin properties can be evaluated.

One of the issues associated with the use of physics-based models and the direct measurement of parameter values using field observations is differences in scale (Beven, 1989; Blöschl & Sivalapan, 1995), while the appropriateness of the available information should not be neglected. An example would be the use of FAO soil maps to establish the parameters of multi-layer soil moisture models based on Richards' equation. The FAO maps are coarse scale and have no information content that is specifically relevant to the parameters of the Richards' equation. Access to high resolution spatial data sets (topography, soil and land cover) is improving and they have the potential to be incorporated into parameter estimation methods for a wide range of different model types.

Capacity and experience in model application

Modern software tools facilitate the application of models, but they should not be considered substitutes for a sound understanding of basic hydrology, the specific model and the limitations of the data. In experienced hands, such software tools increase the efficiency of any modelling exercise, but they also have the potential to make it easy to generate unreliable results. Many of the countries of southern Africa have limited technical capacity and have to rely on imported expertise. While satisfying the immediate requirements for a specific study, the lack of local expertise makes it difficult to use the modelling results for management purposes in the long term.

IDENTIFYING PRIORITIES FOR THE FUTURE

The objective of any future developments of models and the way in which they are applied in developing regions should be to reduce the uncertainty associated with water resource management decision making. The following priorities can be identified.

Building capacity

Without the human resources required to apply models, no improvements in the available models are likely to produce tangible results. Given that the resources to achieve higher levels of local capacity in developing regions are limited, the implication is that only a limited number of models and modelling systems should be recommended so that there is a greater opportunity for shared experience amongst small groups of practitioners.

Improving access to existing data

Experience suggests that there is a limited knowledge in some developing countries of either the existence, or the methods of application, of data sets that have a potential value in regional water resource assessments. This includes global, or near-global coverage of hydro-meteorological time series data, basin physical property data and water use data.

Generating new data

This is perhaps one of the highest priorities for developing countries and yet the most difficult to achieve. The first priority is to identify what data improvements will lead to the highest reductions in uncertainty. Even where relatively good networks of rainfall and streamflow observations exist, a lack of information about water use makes it difficult to differentiate natural from modified flow regimes, thereby creating difficulties in calibrating hydrological models. There are several countries within southern Africa where hydro-meteorological gauging networks have almost collapsed with little prospect of being restored or improved in the immediate future. A major priority is to investigate alternative remote sensing approaches and to establish these as routine methods for generating the necessary data, bearing in mind the need to check for consistency against existing historical records. Developing countries have not adopted remote sensing methods for establishing parameter values to the same extent as developed countries. This approach offers advantages in terms of greater consistency in regional data interpretation, but it is necessary to check that satellite generated data are appropriate for a specific purpose.

Model developments

The relative success of previous applications of models in the southern Africa region has been referred to and the main problems are normally associated with the priorities already identified (input data and parameter estimation). While improvements can be made, the available models are able to generate sufficiently reliable results in many situations and further development is not considered to be a major priority, unless associated with an improved conceptual understanding of some hydrological processes.

The overall conclusion is that improvements in the reliability of, and access to, model input data is likely to be the key to reducing the uncertainty in water resource estimations obtained from hydrological models.

REFERENCES

Andersson, L., Gumbricht, T., Hughes, D., Kniveton, D., Ringrose, S., Savenjie, H., Todd, M., Wolk, J. & Wolski, P. (2003) Water flow dynamics in the Okavango River basin and delta—a prerequisite for the ecosystems of the delta. *Physics and Chemistry of the Earth* **28**, 1165–1172.

Beven, K. J. (1989) Changing ideas in hydrology—the case of physically-based models. *J. Hydrol*. **105**, 157–172.

Beven, K. J. (2004) Towards environmental models of everywhere: advances in modelling and data assimilation. In: *Hydrology: Science and Practice for the 21st Century* (Proc. British Hydrological Society Int. Conf., Imperial College, London, July 2004). Vol I, 244–250.

Blöschl, G. & Sivalapan, M. (1995) Scale issues in hydrological modelling—a review. *Hydrol. Processes* **9**, 251–290.

Bredenkamp, D. B., Botha, L. J., van Tonder, G. J. & van Rensburg, H. J. (1995) Manual on quantitative estimation of groundwater recharge and aquifer storativity. *Water Research Commission Report no. TT 73/95, Pretoria, South Africa.*

Fairbanks, D. H. K., Thompson, M. W., Vink, E. R., Newby, T. S., van den Berg, H. M. & Everard, D. A. (2000) The South African land-cover characteristics database: a synopsis of the landscape. *South African J. Sci*. **96**, 69–81.

Görgens, A. H. M. & Boroto, J. (2003) Estimating transmission losses along the Limpopo River: an overview of alternative methods. In: *Hydrology of Mediterranean and Semiarid Regions* (ed. by E. Servat, W. Najem, C. Leduc & A. Shakeel). (Proc. Montpellier Conf.), 138–143. IAHS Publ. 278. IAHS Press, Wallingford, UK.

Gupta, H. V., Beven, K. J. & Wagener, T. (2005) Model calibration and uncertainty estimation. In: *Encyclopedia of Hydrological Sciences* (ed. by M. G. Anderson). John Wiley & Sons Ltd., Chichester, UK (in press).

Gush, M. B., Scott, D. F. Jewitt, G. P. W., Schulze, R. E., Lumsden, T. G., Hallowes, L. A. & Görgens, A. H. M. (2002) Estimation of streamflow reductions resulting from commercial afforestation in South Africa. *Water Research Commission Report No. TT 173/02, Pretoria, South Africa*

Hickson, R., Lorentz, S. & Volans, S. (1999) Identifying dominant processes on Molteno formations of the northern Eastern Cape Province. In: *Proc. of the 9th South African National Hydrological Symposium*. University of the Western Cape, Cape Town, South Africa, November 1999.

Hughes, D. A. (1997) Southern African FRIEND—The application of rainfall–runoff models in the SADC region. *Water Research Commission, Report no. 235/1/97, Pretoria, South Africa.*

Hughes, D. A. (2004a) Incorporating groundwater recharge and discharge functions into an existing monthly rainfall–runoff model. *Hydrol. Sci. J.* **49**(2), 297–311.

Hughes, D. A. (2004b) Three decades of hydrological modelling research in South Africa. *South African J. Sci.* **100**, 638–642.

Hughes, D. A. & Sami, K. (1992) Transmission losses to alluvium and associated moisture dynamics in a semiarid ephemeral channel system in southern Africa. *Hydrol. Processes* **6**, 45–53.

Maaren, H. (1989) Fifteen years of small catchment research through the Water Research Commission. In: *Proc. of the 5th South African National Hydrological Symposium*, 74–83. University of Pretoria, Pretoria, November 1989.

Mwelwa, E. M. (2005) The application of the monthly time step Pitman rainfall–runoff model to the Kafue River basin of Zambia. MSc Thesis, Rhodes University, Grahamstown, South Africa (unpublished).

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