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Estimating transmission losses along the Limpopo River: an overview of alternative methods

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Abstract This paper gives a summary of methods that were considered to investigate transmission losses along the Limpopo River. Four criteria (information, practicality, solution-type, and time and spatial scale) were set to evaluate possible approaches. These include: statistical methods; methods using a storage loss concept; methods using a streamflow aquifer interaction equation based on the head difference between surface and groundwater; and finally methods coupling unsteady surface flow equations with groundwater flow equations. Each method is described and evaluated against the specific conditions of the Limpopo River. This paper provides a basis for further investigation of transmission losses along the Limpopo River and recommends an approach with a moderate level of complexity given the limited information available and the benefits associated with each method for the Limpopo River.

Keywords Limpopo River; semiarid; Southern Africa; transmission losses; water balance

INTRODUCTION

The water resources of the Limpopo River are shared by Botswana, Mozambique, South Africa and Zimbabwe. The Limpopo main-stem is semiarid throughout its length and its flow is not perennial. The river is some 1750 km long, serving as the border between South Africa on one side and Botswana and Zimbabwe on the other. It then flows into Mozambique and discharges into the Indian Ocean.

The geomorphology of the Limpopo River is characterized by alluvial deposits of width of 100 to 500 m and estimated to vary between 5 and 10 m in thickness. Rocky outcrops and wide floodplains can be found in the upper and middle reaches, but in the lower reach, the river is entirely characterized by alluvial deposits and a floodplain with a width of more than 4 km in places.

Given the characteristics described above, transmission losses occurring along the Limpopo River are of the order of 30% of the water balance. They can be in the form of recharge of storage in alluvial channel sand beds or alluvial river banks, and subsequent evaporation and evapotranspiration; direct evaporation from the free water surface; recharge of deep groundwater; and finally as losses to floodplain flows during more extreme events. The only four flow gauging stations in operation along the Limpopo River (Fig. 1) are: Seleka Farm (A5H003/A5H007); Beit Bridge (A7H004/B35); Combomune (E33) and Chokwe (E35). Each one has its own problems.

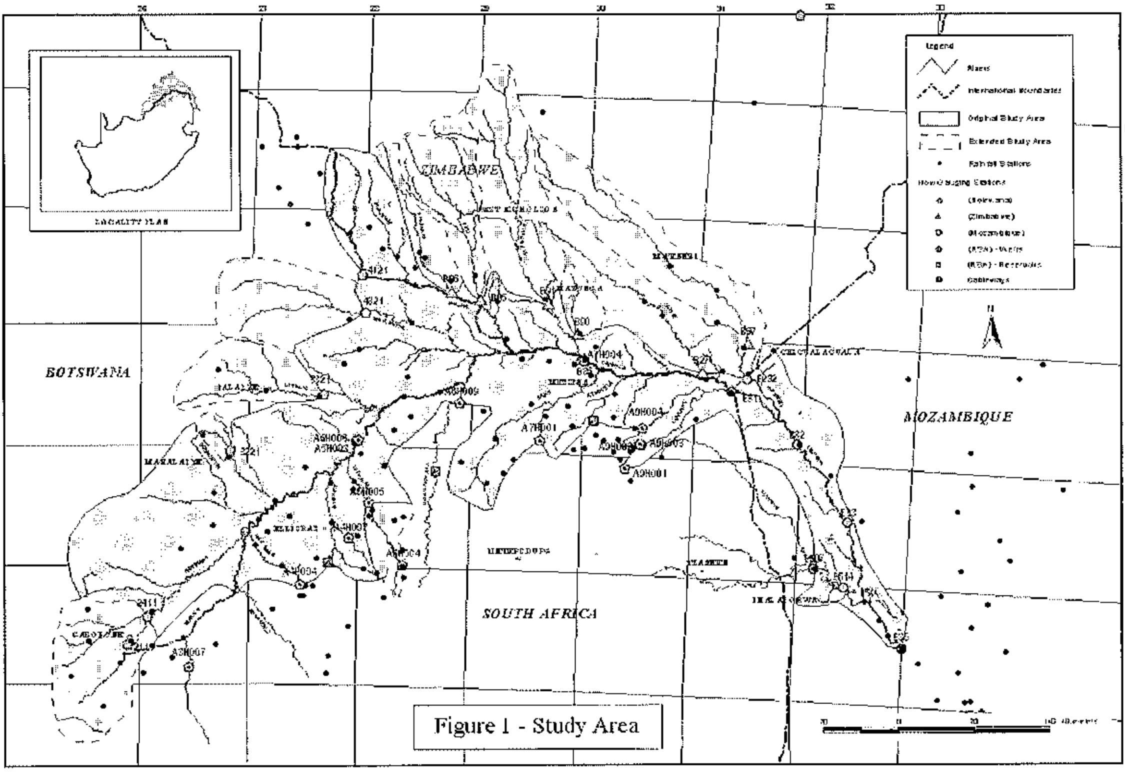

Fig. 1 Map of the Limpopo River basin.

These transmission losses can be estimated using different methods, each with its own data requirements and level of complexity. Four categories of method are examined in this paper, with their relevance and applicability to the Limpopo River.

DESCRIPTION OF METHODS SELECTED

Statistical methods using regression techniques on streamflow data

The most direct way of estimating transmission losses consists of measuring streamflow at two stations on the same stream. The conditions to be met are that there should be no contributing tributaries between the stations and no runoff from the drainage area between two gauging stations (Jordan, 1977).

From such a set of pairs of streamflow records, a regression analysis can be conducted to determine the relationship between the upstream and the downstream flows, or between the upstream flows and the transmission losses (obtained by subtracting the flow measured downstream from those measured upstream). Applications of the method include Sharp & Saxton (1962), Walters (1990), Jordan (1977) and Rao & Maurer (1996).

Methods using a loss storage concept

Two methods were examined. The first by Berg *et al.* (1991) is a module forming part of the SHELL modelling system using a monthly time step. It is a channel loss module consisting of a sand reservoir/riparian use concept which estimates transmission losses occurring within a reach given the initial state of the sand reservoir and the incoming upstream flow. Before flow can be transferred to the next reach, the sand reservoir has first to be filled.

The second method in this category is the Variable Time Interval (VTI) model (Hughes & Sami, 1994), a semi-distributed hydrological model run on a daily (or shorter) time step which comprises a channel transmission losses module that uses infiltration rate to fill a soil zone moisture storage over an area that includes the channel bed area, and/or a floodplain area if overbank flows are known to occur. The estimation of channel losses is refined by using factors which account for the variation in flow width and depth with upstream inflow, and for a declining hydraulic gradient below the surface as channel loss storage is implemented. The VTI model could be used to compare a coarse approach such as SHELL and more detailed approaches as described below.

Methods using a Streamflow Aquifer Interaction (SAI) equation based on the head difference between the surface and the groundwater

A general formulation of the interaction between streamflow and aquifer has been established and can be described by the following relationships (Rushton & Tomlinson, 1995) of which the first is a version of the Darcy's Law:

$$Q_r = RC(h - z_r) \qquad \text{for } h > z_b \tag{1}$$

$$Q_r = -RC \qquad \text{for } h < z_b \tag{2}$$

where:

Q_r is the flow from the aquifer to the river ($\text{m}^3\ \text{day}^{-1}\ \text{km}^{-1}$),
RC is the river coefficient ($\text{m}^2\ \text{day}^{-1}\ \text{km}^{-1}$),
H is the groundwater head (m),
z_r is the elevation of the river surface (m),
z_b is the river bed elevation (m).

Two positions of h, the groundwater head, in relation to z_r, the river surface elevation and z_b, the river bed elevation are relevant to transmission losses:

- h is slightly below z_r but above z_b: there is a small flow from the river to the aquifer; equation (1) holds although it probably over-estimates the river loss.
- h is significantly below z_b; from equation (2) the loss from the river to the aquifer is constant and is equal to the river constant.

Applications of this method, in one form or another, include Rushton & Tomlinson (1979, 1995), Chen & Soulsby (1997) and Sophocleous & Perkins (1993).

Methods coupling unsteady channel flow and groundwater flow equations

These methods are mainly models formulating the process of interaction between surface- and groundwaters into detailed mathematical equations. Transmission losses can be indirectly derived from them. The surface flow movement is represented by the St Venant equations for unsteady flows while the groundwater movement is represented by the Boussinesq equation for two dimensional groundwater flow. The two are coupled with the Darcy equation or with infiltration rates (when the two are not hydraulically connected). The method has been applied by, amongst others, Cunningham & Sinclair (1979) and Mwaka (1994).

CRITERIA FOR EVALUATION OF METHODS

The following criteria are used to assess the methods examined:

The information criterion assesses the level of information needed to satisfy the method's requirements. Two kinds of data are involved: the first is hydrological information such as rainfall, evaporation and streamflow data. The second kind of data is information on the physical characteristics of the medium such as dimensions, shape, slope, geophysical structure, soil type, storativity, and hydraulic conductivity. If the information required by the method can be easily obtained, then the method meets this information criterion.

The practicality criterion evaluates a method in terms of the effort and time required to obtain significant results. Some methods have immense data requirements and use sophisticated techniques requiring extensive training without warranting reliable results. Other methods are time consuming and are not suitable, for example, for quick sensitivity analysis. If the method is relatively easy to apply and is not cumbersome, then it meets the practicality criterion.

The solution-type criterion evaluates a method in relation to the formulation of the processes that it deals with. The following levels of solutions are possible: (a) a method can be based on a mathematical formulation of the processes; (b) it can represent the processes using relational rules derived from statistical analysis of the data; (c) it can simulate the processes using simple rules derived intuitively; finally (d) it can consist of a coarse representation of the processes without detailed mathematical formulation. For this criterion, the closer the method represents the processes, the more attractive it is, provided the first two criteria are met.

The scale criterion assesses a method in terms of its space and time resolution requirements and capabilities. A method can be applied either to the entire study area or can be site or reach specific; it could be applied to time frames varying from minutes, hours (event specific) to years. This criterion is used to assess the time and space scales to which the model can be used.

RELEVANCE TO THE LIMPOPO RIVER AND CONCLUSION

Table 1 provides an evaluation of the four methods in terms of their applicability to the Limpopo River. Each one has its advantages and scope of application. For the purpose of water balance assessment, a coarse approach is recommended because it satisfies most of the criteria effectively, despite its limitations. The SHELL hydrological model

Table 1 Summary of methods and applicability to the Limpopo River.

	Statistical methods	Storage loss concept	Streamflow–aquifer concept	Interaction between surface and groundwater
Information criterion	There is very limited data to make the method applicable to the Limpopo River at present.	Most information is easy to obtain, except for the depth of the storage loss reservoir. VTI model would require additional data	Would require information, especially the river coefficient, which is difficult to determine	Would require extensive information for both components, difficult to obtain, especially for groundwater component
Practicality criterion	Practical but conditions for applicability not met	SHELL is practical and has been applied to the Limpopo. VTI is also practical, even in a spreadsheet environment	Can be time consuming and cumbersome for adjusting to the Limpopo River	Unless model is user friendly, otherwise, cumbersome and time consuming.
Solution type criterion	Acceptable, but cannot be generalized in the case of the Limpopo River because of spatial variability	Coarse representation of processes because of monthly time step. The VTI model is more advanced compared to SHELL	River coefficient assumed constant poses problem for Limpopo River for losing stream	Best representation of processes and ideal if data is available and model user friendly
Scale criterion	More likely localized rules because of spatial variability. Will be reach specific.	SHELL is applicable to large scale in terms of time and space. SHELL is monthly, VTI is daily or lower.	Would be reach specific and not applicable to a large scale	Would be more event specific and could be applied to the whole river
Conclusion	Cannot be used at present as a dense network of flow data and long records are required	SHELL has been used by Görgens & Boroto (1999), best at present for water balance despite limitations. VTI can only be used if daily data is available.	Not recommended because of uncertainties linked to solution type criterion	Has been tested on a tributary of the Limpopo but would require extensive information for the Limpopo River; will be costly.

Table 2 Flow balance details for primary sub-reaches of the Limpopo River main-stem for the period 1971–1995 ($10^6 m^3 year^{-1}$).

Component	Upstream Seleka Farm	Seleka Farm to Shashe	Shashe to Beit Bridge	Beit Bridge to Pafuri	Pafuri to Chokwe
Inflow: upstream	0	497(obs.)	608	1369	1833
Inflow: tributaries	720	305	1182	599	1940
Study area incremental runoff	15	22	8	15	90
Total entering the reach	734	824	1799	1982	3864
Irrigation abstraction/other use: main-stem and lower sections of tributaries in study area	82	53	15	18	517*
Alluvial channel and riparian vegetation losses	110	163	416	132	188
Simulated at sub-reach exit	541	608	1369	1833	3159
Recorded at flow gauging station	497				4087
Difference	+8.8%				–22.7%

* Diverted to Chokwe Irrigation Scheme, but a significant proportion is returned, unused, to the Limpopo downstream of the flow gauging station.

was indeed the only one that could be applied to the entire Limpopo River main-stem (Boroto, 2001) given the limitations and constraints set by the four criteria as described in Table 1.

The SHELL hydrological model made it possible to derive the flow balance given in Table 2 for the period from 1971 to 1995. It shows that transmission losses in the form of alluvial channel, riparian and flood-plain recharge, evaporation and consumptive use, are significant components of the water balance and have in the recent past been markedly greater than irrigation and other water use. This result is sufficient for the purpose of water resources assessment for a river of the scale of the Limpopo River. Using the other models would require intensive field trips and subsequent detailed modelling with no certainty of better results.

The collection of data required by the other methods is not a priority and could be envisaged in the medium to long term, given other water resources management imperatives in the four co-basin states of the Limpopo River. Such data collection should be part of a comprehensive information gathering for the Limpopo River.

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REFERENCES

Berg, R. R., Beuster, H. & Görgens A. H. M. (1991) Innovative modelling strategies for flow generation in developed winter rainfall catchments. In: *Proc. Fifth SA National Hydrological Symposium, Stellenbosch*, 2-3-1–2-3-8.

Boroto, R. A. J. (2001) Limpopo River: steps towards sustainable and integrated water resources management. In: *Regional Management of Water Resources* (ed. by A. H. Schumann, M. C. Acreman, R. Davis, M. A. Marino, D. Rosbjerg & Xia Jun) (Proc. Symp. at Maastricht, The Netherlands, July 2001), 33–39. IAHS Publ. no. 268.

Chen, M. & Soulsby L. (1997) Risk Assessment for a proposed groundwater abstraction scheme in Strathmore, North-East Scotland: a modelling approach. *J. Inst. Water Environ. Manage.* **11**, 47–55

Cunningham, A. B. & Sinclair, P. J. (1979) Application and analysis of a coupled surface and groundwater model. *J. Hydrol.* **43**, 129–148.

Görgens, A. H. M. & Boroto, R. A. J. (1999) Limpopo River: hydrological investigations to prepare for integrated water resources planning. In: *Proc. Ninth SA National Hydrological Symposium*, Cape Town, South Africa.

Hughes, D. A. & Sami, K. (1994) A semi distributed, variable time interval model of catchment hydrology-structure and parameter estimation procedure. *J. Hydrol.* **155**, 265–291.

Jordan, P. R. (1977) Streamflow transmission losses in Western Kansas. *J. Hydraul. Div. ASCE* **193**(HY8), 905–919.

Mwaka, B. (1994) Analysis of hydrological impacts due to sedimentation. PhD Thesis, Department of Civil Engineering, University of Newcastle Upon Tyne, UK.

Rao, X. R. & Maurer, E. P. (1996) A simplified model for predicting daily transmission losses in a stream channel. *Water Resour. Bull.* **32**(6), 1139–1146.

Rushton, K. R. & Tomlinson, L. M. (1979) Possible mechanisms of leakage between aquifers and rivers. *J. Hydrol.* **40**, 49–65.

Rushton, K. R. & Tomlinson, L. M. (1995) Interaction between rivers and the Nottinghamshire Sherwood sandstone aquifer. In: *Modelling River Aquifer Interactions* (ed. by P. L. Younger). British Hydrological Society Occasional Paper 6, 101–116.

Sharp, A. L. & Saxton, K. E. (1962) Transmission losses in natural streamflow valleys. *J. Hydraul. Div. ASCE* **88**(HY5), 121–142.

Sophocleous, M. & Perkins, S. M. (1993) Calibrated models as management tools for stream-aquifer systems: the case of central Kansas, USA. *J. Hydrol.* **152**, 31–56.

Walters, M. O. (1990) Transmission losses in arid regions. *J. Hydraul. Engng* **116**(1), 129–138.