Evaluation of the effects of different water demand scenarios on downstream water availability: The case of Thuli river basin

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Abstract

Thuli river basin, in south western Zimbabwe, is situated in a semi-arid area, where surface water resource availability is a constraint. There is intensive use of blue water in the upper catchment more than its lower reaches. The paper presents the evaluation of the effects of upstream water demand scenarios on downstream users in the river basin. A model was applied as a tool to simulate the effects.

The impacts of different water demand scenarios on downstream water availability were evaluated. The water demand scenarios used were based on government recommendations and future plans on water resources development, drought risk mitigation, implementation of environmental water requirement and implementing inter basin transfer (IBT) to Bulawayo, the second largest city in Zimbabwe. The study showed that implementing IBT will increase water shortages for downstream users while enforcement of environmental water requirements, implementation of government plans on water resources development in the catchment and drought risk reduction; decreases water shortages for downstream users.

It is therefore clear that while the IBT is an important development for Bulawayo, the river basin management of the Thuli river basin requires a holistic approach. Downstream users in the form of domestic and agricultural users should be considered while allocating water for the IBT.

Keywords: Downstream water availability; Limpopo Basin; Water demand scenarios; Water resources management

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1. Introduction

Modelling water demand scenarios can be a powerful tool in water resource system analyses. Such models can be used to understand and predict the future sustainability of water supplies for the environment (King *et al.*, 2003; Love *et al.*, 2006) and for different users (Xu *et al.*, 2002). Models can also be helpful to understand basin-scale river behaviour (Gibson *et al.*, 2005), to develop basin-scale or national water resources management plans (Warwick *et al.*, 2003; Juízo and Líden, 2008) and to evaluate the effect of climate change on a given water resource or supply (Moyo *et al.*, 2005; Cohen *et al.*, 2006). Modelling water demand scenarios can, in other cases, be used to plan supply and demand for a particular water use (Shnaydman, 1993) or to examine how policies effect water management, currently (Gómez-Límon *et al.*, 2002), and in the future (Warwick *et al.*, 2003).

The management of the water resources, in Zimbabwe is being implemented based on the two new acts, the Zimbabwe National Water Authority Act (1996) and the Water Act (1998). These two acts have given powers to stakeholders to run and manage water resources through the catchment councils. Decisions by these new bodies have to encompass all the stakeholders and the support of decision support tools may prove critical. In recent years, considerable effort has gone into developing decision support models (e.g. Hughes and Hannart, 2003; Juízo and Líden, 2008). The models contribute to a better understanding of the real-world processes and provide quantitative information to support decision-making activities.

The Thuli river basin is a basin were the water use is increasing. Currently, the basin is more developed in its upper than lower reaches. There is intensified use of blue water in the upper catchment and demand from powerful sectors such as urban is increasing (Love *et al.*, 2005). Furthermore, two irrigation schemes and two dams have been proposed to be constructed downstream in the basin. Requirements based on policies such as satisfying the ecological water needs and inter basin water transfer are also likely to be implemented. These interventions will increase the pressure on the already limited resources water resources. For these developments to be sustainable, proper understanding of the effects of water demand scenarios, brought about by such developments, on downstream water availability is essential for effective management of the water resource.

Waflex, a flexible spread sheet based model (Savenije, 1995), which has been used successfully elsewhere in southern Africa (Juízo and Líden, 2008), was applied to the Thuli river basin to assess the effect of the water demand scenarios on water availability to downstream users in the river basin so that better decisions are arrived at when allocating the water to different uses. The water demand scenarios were based on:

- Government plans on water resources development
    - Inter Basin Transfer
    - Environmental Flow Requirements

- Technological improvement
    - Dam improvement
    - Increase irrigation efficiency
- Drought risk reduction
    - Changing cropping patterns

2. Study Area

2.1 Thuli River Basin

The Thuli river basin, which is situated in the south west semi arid areas of Zimbabwe, is a tributary basin to the Shashe River, which is a tributary of the Limpopo. It flows from Matopo Hills World Heritage site at an approximate altitude of 1450 m above mean sea level through resource poor communal lands and discharges in the semi-arid area south of Zimbabwe, on the edge of the Shashe-Thuli trans-frontier conservation area (Fig. 1).

In certain parts of river courses, flow occurs only during the wet months (October to March); while during the dry months (April to September) the riverbed is a sandy alluvial bed, which provides for dry season storage of water (Görgens and Boroto, 1997). The amount of storage in these alluvial aquifers has yet to be determined, but similar aquifers in the adjacent Mzingwane Basin have been estimated to hold more than 38 Mm^3 of water (Moyce *et al.*, 2006). While the temporal distribution of rainfall follows the general pattern of the Southern African region with wet months between November and March (Unganai and Mason, 2002), the spatial distribution of rainfall is quite variable over the entire catchment. The annual rainfall ranges from 250 mm a^{-1} in the south to 550 mm a^{-1} in the north of the catchment, with average of about 350 mm a^{-1} over the entire catchment.

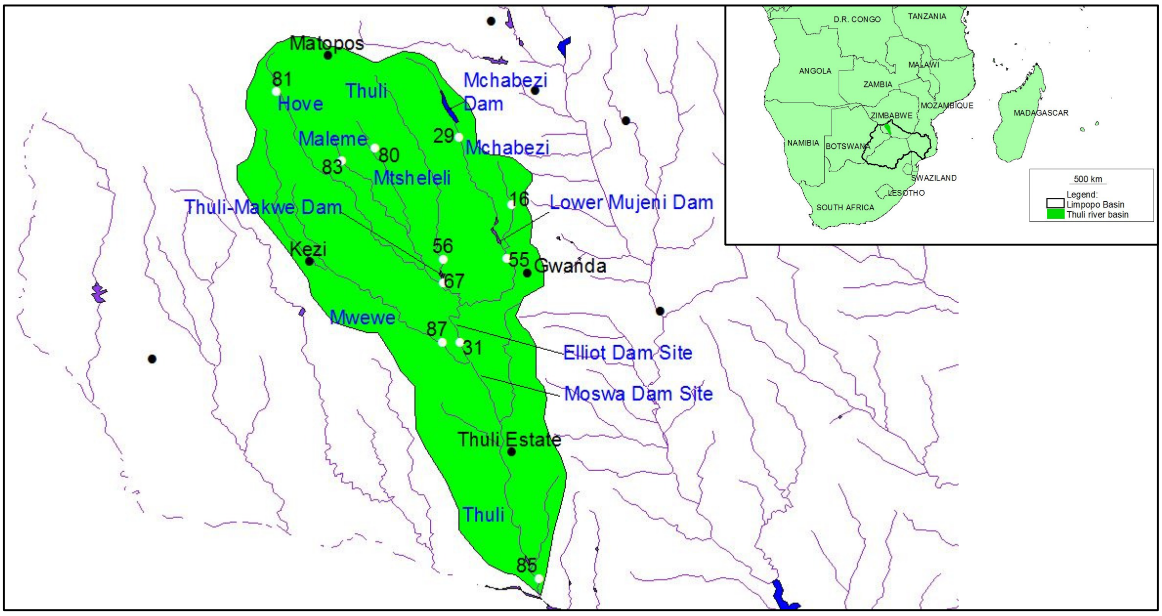

Figure 1. The study area (green), showing rivers, existing and proposed dams, gauging stations (white dots) and settlements (black dots) and (inset) location within the Limpopo Basin and southern Africa.

Thuli River is managed under the Shashe–Thuli Sub-catchment council. The catchment area is 79.1 km^2. There are several water users, in river basin categorized into agriculture, domestic, urban and mines. The major water users are City of Bulawayo, Gwanda Town, Blanket and Vubachikwe mines and the Thuli-Makwe irrigation scheme. Satisfying the demand for these various users requires a management strategy for optimal utilization of the water resources (Nyagwambo, 1998).

2.2 Water resource developments in the Thuli River Basin

The Thuli river is only developed to 31% of mean annual runoff (MAR) of which Mtshabezi dam makes up to 18% MAR (Chibi *et al.*, 2006). Gwanda municipality also takes water from Lower Mujeni (Blanket) dam on Mtshabezi river. There is a large irrigation scheme at Thuli-Makwe, managed by a farmer's committee. There are three large dams in the river basin and two more are proposed (Table 1).

Table 1. Dams in Thuli river basin. For locations, see Fig. 1.

Dam	River System	Dam Capacity (Mm^3)	Date Constructed
Thuli-Makwe	Thuli	8.3	1967
Lower Mujeni (Blanket)	Mtshabezi	10.5	1961
Mtshabezi	Mtshabezi	52.2	2001
Moswa	Thuli	419	proposed
Elliot (Manyange)	Thuli	33	proposed

3. Methods

3.1 Runoff data

Historical monthly runoff data was collected for the five selected gauging stations (B85, B87, B31, B67, and B55, see Fig. 1 for locations) as inputs for the model. The gauging stations had the runoff records varying from 31 to 48 years (Table 2).

Table 2. Selected gauging stations and range of hydrological years from which the runoff records were obtained

Gauging station	Range of hydrological Years data available	Number of years
B85	1971/72 – 2005/06	35
B87	1972/73 – 2004/05	31
B31	1958/59 – 2005/06	48
B67	1966/67 – 2005/06	40
B55	1965/66 – 2004/05	40

Some of these runoff stations selected had the flow characteristics that had been significantly affected by upstream impoundments or flow abstractions and hence required naturalisation. The monthly data selected as input for the model was from the data records of 1983 to 2005 because this was the period with few data gaps in the recorded runoff data.

The runoff data were naturalized using the following equation (Wurbs, 2005):

$$QN = QG + \sum D - \sum RF + \sum E + \frac{\sum \Delta S}{\sum \Delta t} \qquad \textbf{(1)}$$

Where;
Q_N is the naturalized runoff
Q_G is the gauged runoff
ΣD is water diversion from river system upstream of gauge
ΣRF is return flows from river system upstream of gauge
ΣE is the net evaporation from reservoirs allocated upstream of gauge
$\Sigma\Delta s/\Sigma\Delta t$ is the change in storage of upstream reservoirs.

The equation does not take into account seepage and transmission losses.

3.2 Water demand

In the absence of continuous abstraction monitoring, water demand for most of the users has been taken from the water permit issued by the Zimbabwe National Water Authority. An assumption is made that the volume specified on the water permits is equal to the water demand. To include the water use which does not have a water right, interviews have been done and the data collected (such as area and crop irrigated) has been used to calculate the water demand. Some permits holders are currently not active and these are therefore not incorporated as a water demand.

3.3 The Waflex model for the Thuli river basin.

The model is based on a network of spreadsheet cells which are interlinked. The inputs into the model are inflows (naturalised runoff) and water demand. Water balance is calculated for each cell. Each cell sums the flow that comes from upstream. For each time step (month), the flow is calculated in each cell adding up the flows of upstream and adjacent cells. Flow availability on each node is calculated by adding the inflows from upstream to downstream as (inflow subtracted by demand). Reservoirs can be incorporated into the network. A reservoir consists of three cells; an inflow cell, a storage cell and a release cell. The release cell acts as an inflow point to the downstream branch. The storage and release of the reservoir is determined in a macro subroutine and takes into account the flood rule curve(FRC), the utility rule curve (URC) and the dead storage curve (DSC). The storage can never exceed the FRC and the DSC may never be crossed as a result of a release. Thus the FRC and the DSC are hard boundaries. The URC is a soft boundary that separates two zones of differing operating rules in the reservoir.

The network of the Thuli Waflex model is shown in Fig. 2. Five large dams that have been modelled in the catchment (see Table 1). The model incorporates twenty nine water abstraction nodes, see Table 2.

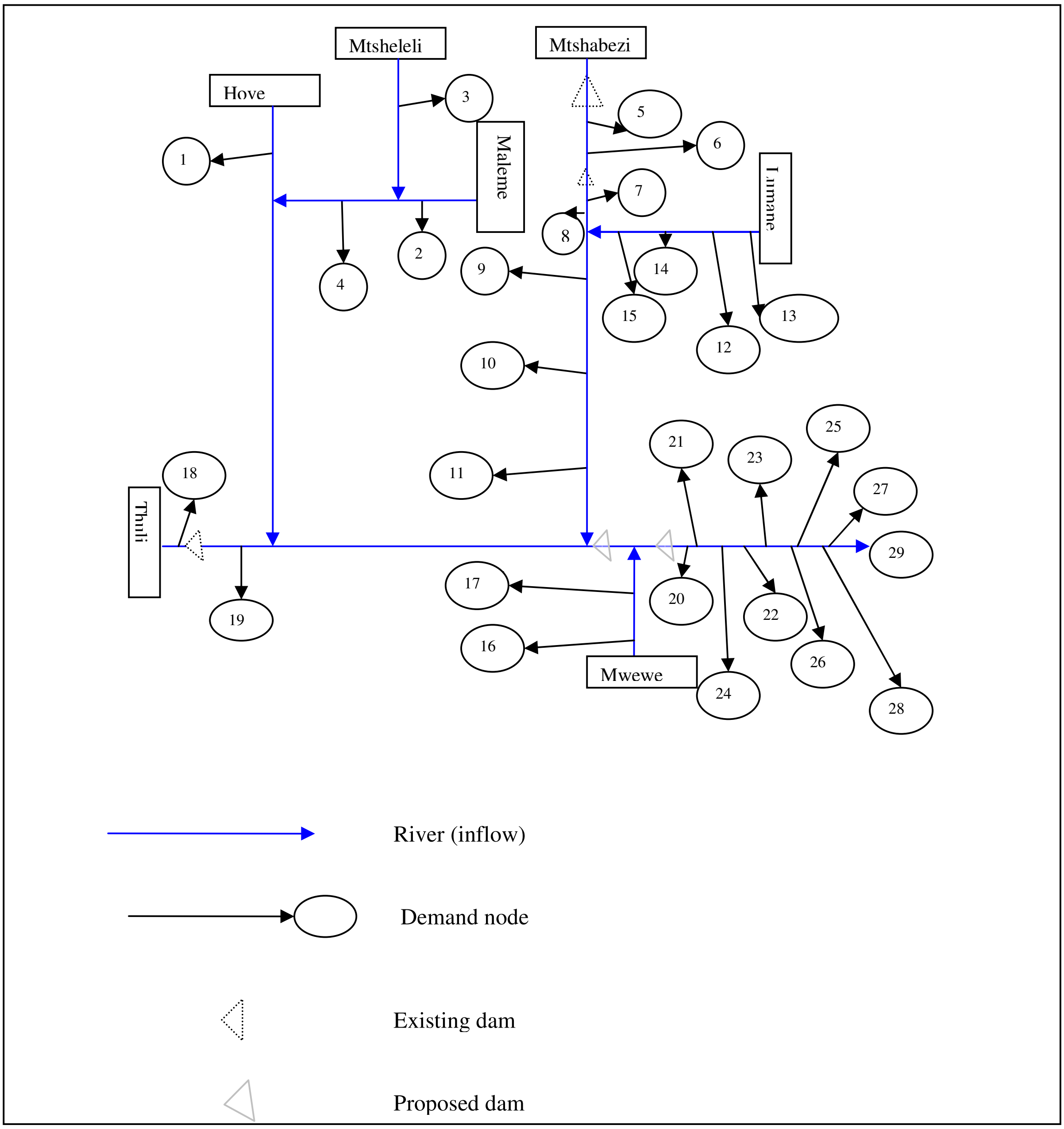

Figure 2. Conceptualisation of the Thuli river system, showing the modelled tributaries, dams and demand nodes.

Table 3. Location of the demand nodes in the Thuli river basin, WAFLEX model

Demand node #	Water user	Purpose	Demand (*$10^3 m^3 a^{-1}$)	River system
1	Anglesea	Agriculture	140	Hove
2	Maleme/Damara	Agriculture	8,800	Maleme
3	Khumalo communal land	Domestic	840	Mtsheleli
4	Matopo National Park	Park	4,840	Maleme
5	Bulawayo (proposed)	Urban	7,100	Mtshabezi
6	Mtshabezi Irrigation scheme (proposed)	Agriculture	4,200	Mtshabezi
7	Blanket mine	Mining	1,120	Mtshabezi
8	Vubachikwe mine	Mining	650	Mtshabezi
9	Gwanda	Urban	1,100	Mtshabezi
10	Hampden	Agriculture	700	Mtshabezi
11	Mtshabezi mission	Domestic	36	Mtshabezi
12	Matopo communal land	Domestic	48	Lumane
13	Lumane resort	Domestic	1,400	Lumane
14	Lumane communal land	Domestic	24	Lumane
15	Longville	Agriculture	1,980	Lumane
16	Kezi	Domestic	140	Mwewe
17	Walmer/Anton	Agriculture	140	Mwewe
18	Matopo mission	Domestic	72	Thuli
19	Thuli Irrigation scheme	Agriculture	1,500	Thuli
20	Gwaranyemba	Domestic	1,940	Thuli
21	Guyu	Domestic	60	Thuli
22	Chelesa irrigation scheme	Agriculture	300	Thuli
23	Manama	Domestic	40	Thuli
24	Great Thuli Irrigation (proposed)	Agriculture	42,000	Thuli
25	Mankokoni irrigation scheme	Agriculture	200	Thuli
26	Rustlers irrigation scheme	Agriculture	1,310	Thuli
27	Shashe communal land	Domestic	110	Thuli
28	Dibilishaba communal land	Domestic	1,240	Thuli
29	Environment	Environmental flow	*	Thuli

* For environmental flow requirements, see section 4.3 below

4. Results and Discussion

4.1 Model performance

The model was initially run using the current water demand and historical runoff. Water demand for the environment and planned developments were not considered. To evaluate the model, the simulation of the observed runoff was analysed (Fig. 3).

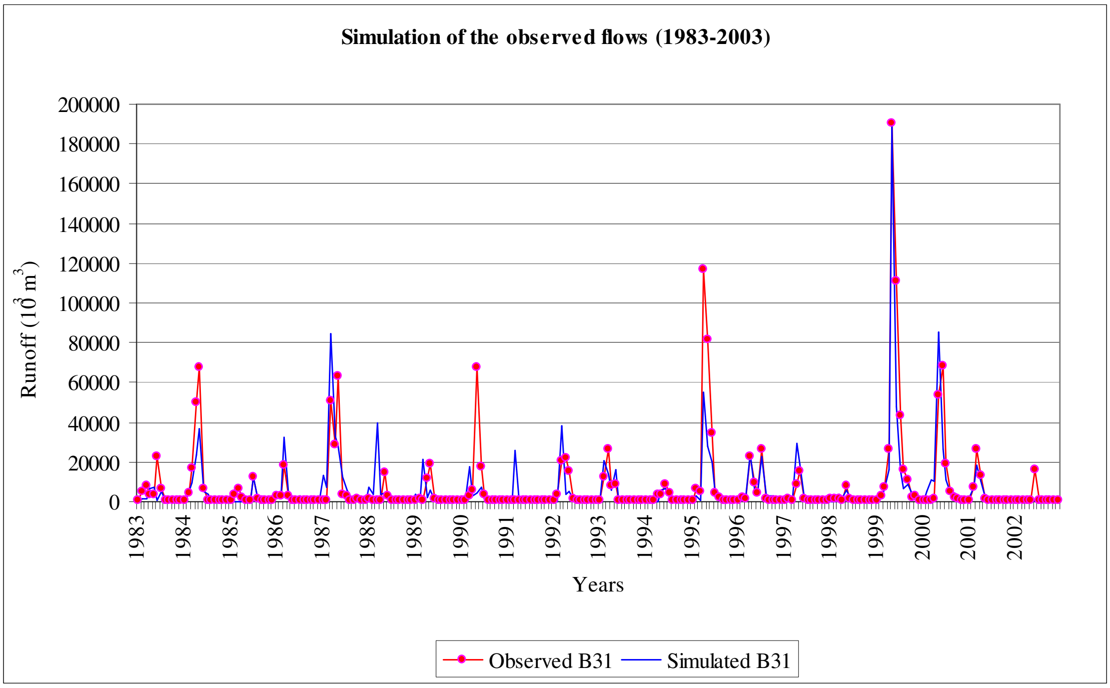

Figure 3. Comparison of observed and simulated flows at Thuli Gorge (station B31), 1983-2003.

The model simulated well the observed flows in most of the years. This is supported by the regression results, which showed that there was a closer relationship between the observed and simulated runoff, ($r^2 = 0.7$, $p<0.05$). Objective functions for the model are given in table 4, and show good efficiency for simulation of B31, reasonable for B55 but less so for B85.

Table 4. Objective functions for the Thuli Basin WAFLEX model

	B31	B55	B85
C_{NS}	0.69	0.40	0.07
R	0.83	0.67	0.49

4.2 Current water demand scenario

A summary of the set-up of the various scenarios is given in table 5.

Table 5 Overview development scenarios

	run1	**run2**	**run3**	**run4**	**run5**	**run6**	**run7**	**run8**	**run9**
Existing water users	X	X	X	X	X	X	X	X	X
Environment		X	X	X	X	X	X	X	X
Irrigation efficiency			X						
Changing cropping				X					
Mtshabezi irrigation scheme					X				X
Greater Thuli irrigation scheme						X			X
Inter Basin Transfer (IBT)					X		X		X
Construction of Moswa and Elliot dam						X		X	X

The model has been run with all existing water demands (Run 1). Future water demand, environmental water requirements and proposed dam developments have not been considered in the run. Out of the 25 water demand nodes, 16 users have their water demand satisfied by 100 % (Table 6). Eight water users show water shortages of which Matopo National Park has the highest shortage with more than 60% shortages and the rest less than 50% shortages.

Table 6 Water shortages for the users in the Thuli river basins for each scenario

Node	Water user	run1	run2	run3	run4	run5	run6	run7	run8	run9
1	Anglesea	0%	3%	0%	0%	3%	2%	2%	3%	3%
2	Maleme/Damara	0%	3%	3%	3%	3%	3%	3%	3%	3%
3	Khumalo communal land	0%	2%	2%	2%	2%	2%	2%	2%	2%
4	Matopo National Park	60%	62%	62%	62%	62%	62%	62%	62%	62%
5	Bulawayo (proposed)	-	-	-	-	-	-	0%	-	7%
6	Mtshabezi Irrigation scheme (proposed)	-	-	-	-	0%	-	-	-	22%
7	Blanket mine	0%	0%	0%	0%	20%	20%	20%	0%	62%
8	Vubachikwe mine	0%	0%	0%	0%	22%	22%	22%	0%	63%
9	Gwanda	0%	0%	0%	0%	16%	16%	16%	0%	33%
10	Hampden	0%	17%	1%	1%	20%	20%	20%	1%	39%
11	Mtshabezi mission	0%	28%	6%	6%	32%	32%	32%	6%	46%
12	Matopo communal land	0%	0%	0%	0%	0%	0%	0%	0%	0%
13	Lumane resort	0%	0%	0%	0%	0%	0%	0%	0%	0%
14	Lumane communal land	0%	0%	0%	0%	0%	0%	0%	0%	0%
15	Longville	0%	4%	4%	4%	4%	4%	4%	4%	4%
16	Kezi	0%	0%	0%	0%	0%	0%	0%	0%	0%
17	Walmer/Anton	0%	0%	7%	7%	7%	7%	7%	7%	7%
18	Matopo mission	0%	1%	6%	6%	1%	0%	0%	1%	1%
19	Thuli Irrigation scheme	0%	6%	6%	3%	6%	6%	6%	0%	0%
20	Gwaranyemba	18%	4%	3%	3%	5%	5%	5%	0%	0%
21	Guyu	26%	5%	4%	3%	5%	5%	5%	0%	0%
22	Chelesa irrigation scheme	21%	5%	5%	3%	5%	5%	5%	0%	0%
23	Manama	28%	5%	4%	3%	5%	5%	5%	0%	0%
24	Great Thuli Irrigation (proposed)	-	-	-	-	-	48%	-	0%	0%
25	Mankokoni irrigation scheme	29%	5%	5%	3%	5%	5%	5%	0%	0%
26	Rustlers irrigation scheme	31%	5%	4%	3%	5%	5%	5%	0%	0%
27	Shashe communal land	35%	5%	4%	4%	5%	5%	5%	0%	0%
28	Dibilishaba communal land	37%	5%	4%	3%	5%	5%	5%	0%	0%
29	Environment	-	1%	1%	1%	1%	1%	1%	0%	0%

4.3 Implementing environmental flow requirements

In the second scenario (Run 2), the effect of implementing environmental flow requirements (EFR) has been assessed. All Consideration has been given to the objective of the draft catchment outline plan of Thuli river basin of prioritising the environmental requirements in water allocation. Although the determination of EFR is quite complex (Hughes and Hannart, 2003; King *et al.*, 2003; Love *et al.*, 2006), current planning by ZINWA allocates a simple 5% of the runoff in the river basin to the environment (Chibi *et al.*, 2006). The results show that some of the upstream users now experience shortages, more downstream it actually decreases the shortages. The level of water demand satisfaction for the downstream increased because the environment is a non-consumptive water user, reserving water for environment will mean an increase in the downstream flow. Large users on the Mtshabezi river (Gwanda town and the two mines) are not affected. This scenario provides the minimum EFR for national planning purposes, but a proper EFR evaluation is needed.

4.4 Agricultural water management improvements

Two scenarios of improved agricultural water management have been considered: improving irrigation system efficiency (Run 3) and changing the cropping pattern (Run 4). The impact of improving the irrigation system has been assessed by converting the irrigation system of existing government irrigation schemes (Thuli, Chelesa, Mankokoni and Rustlers) from flood irrigation to drip irrigation, which is 90% efficient (Savva and Frenken, 2002). EFR of 5% of the catchment runoff (as per Run 2) has been maintained. This water demand scenario affects only the water users downstream of these irrigation schemes. The results of Run 3 show that increasing the irrigation system efficiency to 90 % does not change the water demand satisfaction significantly.

Run 4 shows the impact of changing the current cropping pattern by replacing maize on the government irrigation schemes with the government-recommended drought resistant crops of sorghum and millet, and reducing the cropping intensity. The EFR of 5% of the catchment runoff (as per Run 2) has been maintained, but no changes in irrigation efficiency have been considered. This change does not show significant differences.

The above findings suggest that proposed changes to the current government irrigation schemes have only a marginal affect on the basin water balance. However, it is likely that this is not due to the impact of the proposed changes but rather to the small scale of these irrigation schemes.

4.6 New irrigation schemes

Two proposed government irrigation schemes have been considered: Mtshabezi (Run 5) and Greater Thuli (Run 6). For both runs, the water demand scenario included allocating 5% of runoff to the EFR (as per Run 2). The impacts of development of Mtshabezi irrigation scheme (Run 5) are significant. Users abstracting water from Mtshabezi river face reductions of 20 to 30% (See Table 5) and allocating water to Mtshabezi irrigation scheme (demand node 5) as per projected demand. The impacts of development of Mtshabezi irrigation scheme were evident to users those abstracting water from the Mtshabezi river, who face reductions of 20 to 30.

The planned 3,000 ha Great Thuli Irrigation Scheme irrigation scheme (node 24) has been considered in Run 6. Due to its location in the lower part of the river basin, and the fact that the EFR requirement also meets the needs of the small irrigation schemes downstream of node 24 (e.g. Mankokoni), the proposed scheme does not affect most downstream users, but does impose demand on the Mtshabezi River, resulting in increasing shortages for users on that river compared to Run 2 (Table 5). Furthermore, the demand for the proposed scheme, according to Waflex model can only be met to a satisfaction level of 38 %.

4.7 Inter basin water transfer (IBWT) scenario

The scenario (Run 7) considers EFR (Run 2), implementation of Mtshabezi irrigation scheme (Run 5) and implementation of the (currently under construction) inter basin water transfer from Mtshabezi dam to the City of Bulawayo, via Mzingwane Dam in the upper Mzingwane sub-catchment. If the IBT is met with 100 % satisfaction, then an increase shortage of around 20 % is recorded for all other users on the Mtshabezi River (Table 5).

4.8 Construction of Moswa and Elliot dams

The government of Zimbabwe plans construction of two dams on the lower Thuli River: Moswa and Elliot (see Table 1). (Run 8) considers the construction of these dams, the Greater Thuli Irrigation Scheme (Run 7) and the 5 % EFR. The results show that the operation of these dams reduces the shortages in the lower Thuli Basin (Table 5).

4.9 Implementation of all the proposed plans

The final scenario (Run 9) considers the 5 % EFR, the proposed IBT, the two new irrigation schemes and the two proposed dams. The results of the run show that the combined implementation of all the development plans leads to reasonable levels of satisfaction, except for Matopo National Park (which is not met in all scenarios) and users on the Mtshabezi River. Water supply to Gwanda Town is compromised (satisfaction of 67 %) and supply to the two mines even more so (Blanket mine 38%, Vubachikwe mine 37%). However, all downstream commitments are met. It is possible that this impact on Mtshabezi River users could be mitigated through preferential releases from Thuli-Makwe Dam, rather than Lower Mujeni Dam, to meet downstream demand.

5. Conclusions and recommendations

Implementing the proposed 5% allocation to the environmental flow requirements by the catchment outline plan (Chibi *et al.*, 2006) can be achieved without major stress to water users. Improved agricultural water management has a minimal effect on the basin water balance, although this may be due to the low total agricultural water demand at present. Water demand measures at new developments such as Greater Thuli and Mtshabezi irrigation scheme may be required.

The inter basin water transfer (IBT), to Bulawayo (7.1 Mm^3/a), though important to the city in terms of urban water use, reduces the water availability to downstream users on the Mtshabezi River (Run 7 / Table 5). Stress on these users is substantially increased when there is greater demand downstream, notably from the Greater Thuli Irrigation Scheme (Run 6 / Table 5). This suggests that the water balance of the basin is insufficient to meet all of the following needs simultaneously: (i) urban and mining demand from Gwanda Town and Blanket and Vubachikwe Mines, (ii) urban demand from the City of Bulawayo via the IBT and (iii) expansion of agricultural demand in the lower Thuli area through the Greater Thuli Irrigation Scheme.

The construction of the Moswa and Elliot dams are essential for the Greater Thuli Irrigation Scheme, and can provide sufficient storage for this scheme to operate at design capacity. However, in the light of these findings, and the fact that construction of the IBT to Bulawayo has already commenced, it may be necessary to reconsider the scale of the proposed scheme, as its full design capacity cannot be met without compromising water supply for Bulawayo, Gwanda and the mines. In the event that development of the Greater Thuli Irrigation Scheme is pursued, stakeholders at local and national level will have to consider the trade offs that will necessary between the scheme and the large upstream users of Bulawayo and Gwanda/Blanket/Vubachikwe.

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References

Chibi, T., Kandori, C., Makone, B.F. 2006. *Mzingwane Catchment Outline Plan*. Zimbabwe National Water Authority, Bulawayo.

Cohen, S., Neilsen, D., Smith, S., Neale, T., Taylor, B., Barton, M., Merritt, W., Alila, Y., Shepherd, P., McNeill, R., Tansey, J., Carmichael, J. and Langsdale, S. 2006. Learning with local help: expanding the dialogue on climate change and water management in the Okanagan Region, British Columbia, Canada. *Climate Change*, 75, 331-358.

Gibson, C.A., Meyer, J.L., Hey, L.E. and Georgakakos, A. 2005. Flow regime alterations under changing climate in two river basins: implications for freshwater ecosystems. *River Research and Applications*, 21, 849-864.

Gómez-Límon, J.A., Arriaza, M. and Berbel, J. 2002. Conflicting implementation of agricultural and water policies in irrigated areas in the EU. *Journal of Agricultural Economics*, 53, 259-281.

Görgens, A.H.M. and Boroto, R.A. 1997. Limpopo River: flow balance anomalies, surprises and implications for integrated water resources management. In: *Proceedings of the 8th South African National Hydrology Symposium*, Pretoria, South Africa.

Hughes, D.A. and Hannart, P. 2003, A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. *Journal of Hydrology*, 270, 167-181.

King, J., Brown, C. and Sabet, H. 2003. A scenario-based holistic approach to environmental flow assessments for rivers. *River Research and Applications*, 19, 619-639.

Juízo, D. and Líden, R. 2008. Modeling for transboundary water resources planning and allocation. *Hydrology and Earth System Sciences Discussions*, 5, 475-509.

Love, F., Madamombe, E., Marshall, B. and Kaseke, E. 2006. Balancing Water for the Environment, Water for Human Needs and Water for National Economic Purposes: A Case Study from the Rusape River, Save Basin, Zimbabwe. *Water Institute of Southern Africa Biennial Conference and Exhibition*, Durban, South Africa, May 2006.

Moyce, W., Mangeya, P., Owen, R. and Love, D. 2006. Alluvial aquifers in the Mzingwane Catchment: their distribution, properties, current usage and potential expansion. *Physics and Chemistry of the Earth*, 31, 988-994.

Moyo, B., Madamombe, E. and Love, D. 2005. A model for reservoir yield under climate change scenarios for the water-stressed City of Bulawayo, Zimbabwe. In: Abstract Volume, *6th WaterNet/WARFSA/GWP-SA Symposium*, Swaziland, November 2005, p38.

Nyagwambo, N. L. 1998, *'Virtual Water' as a water demand management tool: the Mupfure River Basin Case*. M.Sc. dissertation (unpublished), IHE Delft, the Netherland.

Savenije, H.H.G., 1995. Spreadsheets: flexible tools for integrated management of water resources in river basins. In: Modelling and Management of Sustainable Basin-scale Water Resources Systems. *IAHS Publications* 231, pp. 207–215.

Savva, A.P. and Frenken, K. 2002. Planning , development monitoring and evaluating of irrigated agriculture with farmer participation. FAO of UNs, Sub-Regional Office for East and Southern Africa (SAFR), Harare, Zimbabwe.

Shnaydman, V.M. 1993. The influence of climate variations on an irrigation water resources system performance strategy. *Water Resources Management*, 7, 39-56.

Unganai, L.S. and Mason, S.J. 2002. Long-range predictability of Zimbabwe summer rainfall. *International Journal of Climatology*, 22, 1091 – 1103.

Warwick, C., Bakker, K., Downing, T. and Lonsdale, K. 2003. Scenarios as a tool in water management: considerations of scale and application. In: Alsharan, A.S. and Wood, W.W. (eds.) *Water Resources Perspectives: Evaluation, Management and Policy*, Elsevier Science, Amsterdam.

Wurbs, A. R., 2005. Modelling river/reservoir system management, water allocation, and supply reliability. *Journal of Hydrology*, 300, 100–113.

Xu, Z.X., Takeuchi, K., Ishidaira, H. and Zhang, X.W. 2002. Sustainability analysis for yellow river water resources using the system dynamics approach. *Water Resources Management*, 16, 239-261.