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MODELLING MULTIPLE RESERVOIR OPERATION SYSTEM FOR AGRICULTURAL AND URBAN WATER USES IN THE SAFARI-IGAVA AREA, MARONDERA DISTRICT, ZIMBABWE

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Abstract

Zimbabwe's land reform in the year 2000 caused huge impacts on agricultural production and management of water resources. In the Safari-Igava area in Marondera District, twenty farms were sub-divided into 600 smaller plots and allocated to new farmers. Reservoirs owned and managed by farmer consortiums were taken over by a state enterprise. In 2004, a new and larger Wenimbi Reservoir, located upstream, was commissioned, mainly for agricultural and water supply to the town of Marondera. The changes brought new water management and farming practices, new water supply and demand characteristics, more water users, more competition, shortages and some conflicts. This study determined the underlying causes of shortages and conflict among irrigators. A spreadsheet-based simulation model was developed and used for analysis of operation of reservoirs and formulation of water management strategies. Quantitative and qualitative data was gathered from institutions managing water, the irrigators, and field measurements. Data was collected on climate, available water, water allocation, reservoir operations, consumptive water use, irrigation practices, crops produced, and topology. Records showed that urban and agricultural water demand was rising, but were below the maximum allocations. Some farmers were expanding area under irrigation, but others experienced water shortages. Regulations for water abstraction from the canals were set up by farmers without outside intervention, checks or controls. Access and distribution rules for water were not changed after the land reform. The model simulation showed that there was enough water to meet all agricultural and urban water demands in the period 2006 to 2012, with shortages likely during peak

demand periods. New water management strategies were required for equity and efficiency in water distribution, as well as minimizing shortages and occurrence of conflict. Regulations enforcement, monitoring of irrigation water abstraction, accurate recording and billing of water abstractions, proper operation and maintenance of infrastructure, were required.

Keywords: Land reform, Irrigation, Reservoir operation, Modeling, Wenimbi River, Wheat, Tobacco

Introduction

Water is a finite resource which is under increasing stress as human population and per capita demands increase through out the world (IWMI, 2000). The demand for water for agricultural, industrial, power generation, domestic use and sanitation, waste collection, treatment and disposal uses on rivers are rising with the growth in world economies. Flows in most rivers of the world are affected by the random and cyclic seasonal fluctuations (Woodruff, 1991; Wurbs and James, 2001). Therefore reservoir storage plays a key role in regulating stream flow fluctuations. To develop reliable water supplies, optimal operation of the reservoirs is crucial (Wurbs and James, 2001).

In hydrological systems that comprised of several interlinked reservoirs and rivers systems, if the water demands and equitable allocation and distribution are complex computer simulation models are used as analysis tools for decision support (van Oel, et al., 2011; Asit, 1976). Simulation models of the hydrological systems are developed and several runs of the simulation models under various scenarios can be used to come up with optimal strategies for distribution and allocation of water (Tarboton, 1992; Wurbs and James, 2001; Ragad and Prudhomme, 2002). Exploited worldwide are ready to use/ commercial or generalized hydrological models designed for application to a range of problems dealing with systems of various configurations and locations, rather than being developed to address a particular problem at a specific site (Wurbs and James, 2001). Commercial models are very important but must be applied carefully and meticulously with professional judgment and good common sense (Wurbs and James, 2001; Savenije, 1995). Understanding both the process that is simulated and the commercial model helps in drawing up useful benefits out of a model.

Alternatives to commercial models are the spreadsheet based models. Savenije (1995) developed a spreadsheet model called WAFLEX for simulation of water resource systems. The cells of the spreadsheet replicate the upstream to downstream flow of water and apply the continuity equation.

The water resource system network can be made up of reservoirs, rivers and their tributaries, and abstraction points. Ground water seepage and river inflows and direct precipitation are the inflows into reservoirs and river's mainstream which are added fluxes, whereas abstractions, evaporation, overflows and groundwater leakages from reservoirs are fluxes subtracted from the water resources. The spreadsheet based model is simple to use and has been successfully applied in the Save and Thuli catchments (Symphorian et al., 2003; Khosa et al., 2008; Ncube et al. 2011). Also, all over the world all kinds of professionals have become acquainted with spreadsheets, because they have simple data base management facilities and built-in statistical packages (Savenije, 1995). Therefore in this study, the spreadsheet model (WAFLEX) was the decision support tool that simulated the management of water resources in the Wenimbi River basin.

The WAFLEX simulation model was used for analysis of operation of five reservoirs mainly used for irrigation water supply. The study was carried out during the period 2009-2012, but the river flow data used in simulation model was from period 2006 to 2012. Quantitative and qualitative data was gathered for input into the computer model, and for establishing the capacities of available water resources, irrigation water demand characteristics, allocations and underlying causes of shortages and conflict after the land reform. The simulation model was also used to analyse the impact of possible solutions to the shortages and conflicts.

Study Area

The study was conducted in the Safari Igava area, located in the Marondera district, which is part of the Macheke Sub-catchment in the Save Catchment in south eastern Zimbabwe, as shown in Figure 1. Zimbabwe is a country in Southern Africa.

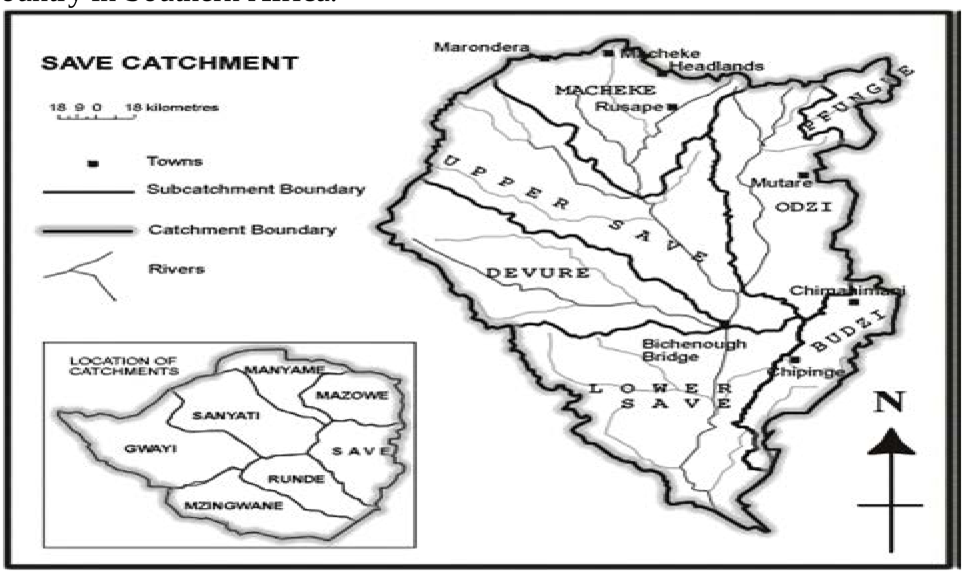

Figure 1: Map of catchments of Zimbabwe and Sub-catchments of Save Catchment

Physiography and Water Resources

Most of the Safari-Igava farming area can be classified as semi arid receiving erratic rainfall with a long term average of 870 mm per annum (Meteorology Department, 2009). The altitude of the area ranges from 1400 to 1600 m above sea level. Two main rivers, Wenimbi and Ruzawi Rivers drain through the area towards the Macheke River. Macheke sub-catchment is located in the Save Catchment (Figure 1). Like most rivers in Zimbabwe, flow in the Wenimbi River is mainly during the rainy season (Mazvimavi, 2003). To mitigate the unreliable rainfall and runoff, five reservoirs were constructed by government and a consortium of large scale commercial farmers to supply water for irrigation and urban water supply (Luxemburg, 1996).

There are four reservoirs on Wenimbi River; the most upstream and largest Wenimbi Reservoir with capacity of 21.3 Mm^3 and downstream is Safari Reservoir with a 10.4 Mm^3 capacity, followed by Eirene Farm 1 Reservoir and the most downstream Eirene Farm 2 Reservoir with capacities of 2.3 Mm^3 and 0.5 Mm^3 respectively. The fifth, Gairon Reservoir with a capacity of 6 Mm^3, is located on Ruzawi River, which originates in the Marondera Town as shown in Figure 2. The town discharges almost half of its wastewater into the Ruzawi River (Zimbabwe National Water Authority (ZINWA), 2009). Safari Reservoir, the main reservoir that supplies the farming community of the Safari-Igava area has two concrete lined canal systems (over 12 km in length), located on riparian and non-riparian farms of Wenimbi River. The two canals and all reservoirs apart from Wenimbi Reservoir were constructed by a consortium of the large scale farmers before the land reform. To ease water supply management on the two canals, some storage reservoirs were built as pumping sites. Interbasin transfer of water from Gairon Reservoir, into the right bank canal was done through pumping. At the end of the canals pipelines were use to convey water by gravity as far as farms numbered 18, 19 and 20 (in Figure 2). A new Wenimbi Reservoir, was built upstream of Safari Reservoir, commissioned in 2004, to supply water to Marondera Town, riparian areas and downstream farmers (Agricultural and Extension Department (AGRITEX), 2005). There are several reservoirs upstream of the Wenimbi Reservoir with a total storage of 5.4 Mm^3 (Government Gazzete, 2006). Figure 2 show the details of the layout of water resources and the farm boundaries. Table 1 and Table 2 summarise the available water resources to the Safari-Igava area.

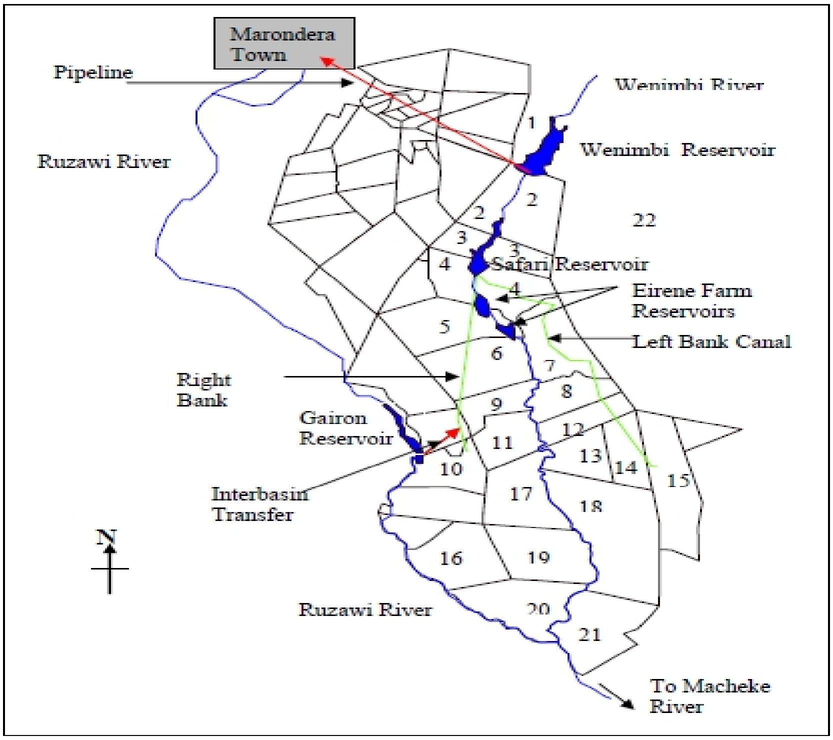

Figure 2: Water Resources and Large Scale Farm Boundaries before Land Reform
KEY: Rivers and reservoirs (blue polygons), farms
(black outlined polygons numbered 1 to 22) and canal (light green).

Table 1: Hydrological Properties and Artificial Reservoirs of the Study Area
(ZINWA, 2009; Government Gazette, 2006).

Reservoir Name	Wenimbi	Safari	Eirene Farm 1	Eirene Farm 2	Gairon
River	Wenimbi	Wenimbi	Wenimbi	Wenimbi	Ruzawi
Storage right priority dates (1976 Water Act)	6/4/1993	2/4/1991	24/4/1990	3/1/1990	
Storage(km^3)	21 268	10 400	2 300	500	6 200
Net Storage (km^3)	17 468	9 360	2 170	450	5 680
Catchment Area (Mm^2)	131.45	203.43	216.31	227	7 500
Intermediate Catchment Area (Mm^2)	131.45	71.95	12.88	10.69	7 500
MAR (Mm^3)	140	140	140	140	140
CV	0.9	0.9	0.9	0.9	0.9

Table 2: Water Storage & Allocation from Wenimbi and Ruzawi Rivers for the Safari-Igava Area (ZINWA, 2009; Government Gazette, 2006).

Mean Annual Runoff (MAR) (km^3)	140
Primary Use and Environmental Water Requirements at 10% MAR (km^3)	14
Storage Upstream of Wenimbi Reservoir (km^3)	5400
Total Allocations Wenimbi River system (km^3)	14687

Total Storage in Wenimbi River reservoirs (km^3)	34500
Carryover after exhausting allocations (km^3)	19813
Carryover in Wenimbi River (years)	1.35
Total storage available from Ruzawi &Wenimbi River reservoirs (km^3)	34800
Carryover of reservoirs on Ruzawi & Wenimbi Rivers (years)	1.37

The Legal System and Institutional Arrangements in the Study Area

The Zimbabwe Water Act of 1998 sets the rules for governance and management of water affairs in the Wenimbi River basin. As per government gazette of 26 January 2006, all the reservoirs under consideration in this study were owned by ZINWA on behalf of the government of Zimbabwe. The state owns all water resources; therefore any use of water, except for primary purposes must be approved by the state through ZINWA which issues permits. Access to water from state owned reservoirs for other consumptive and productive uses required an agreement/permit from ZINWA which users apply for through sub-catchment councils. The Macheke sub-catchment council was responsible for operation of Safari, Eirene Farm and Gairon Reservoirs, but during the study period the operation had been delegated to a farmers' committee. Wenimbi reservoir was operated by ZINWA.

Allocation of water for Irrigators and Urban Uses

Every farm had a fraction of water allocated to it from the river flow and the storage reservoirs. The allocation of water was based on water rights that the large scale farmers obtained under the Water Act of 1976, which depended on contribution to construction of reservoirs (for storage rights only) and the priority date system (for storage and flow rights). From the year 2000 to 2006 resettled individual farmers/irrigators were allocated individual permits which they paid for annually. Irrigation requirements were factored at 12 000 m^3 per hectare per year. The quantity of water allocated by a permit on each farm was subdivided among the new farmers so that the total amount of water allocated per farm remained constant and lower than the allocation under the Water Act of 1976. Due to the government gazette of 2006 all the reservoirs were now under government ownership, therefore irrigators required a permit from ZINWA for access.

Farmers/irrigators with access to both the river and canal could abstract from the two sources at the same time. In case of a shortage of water in the Safari Reservoir and Eirene Farm Reservoirs the sub-catchment council and the farmers' committee applied and paid for release of agreement water from the Wenimbi Reservoir. Farmers applied for water releases from Wenimbi Reservoir through the Macheke Sub-catchment council, the manager of the smaller four reservoirs and the intermediator between farmers and ZINWA. Allocation of agreement water from Wenimbi Reservoir for Marondera urban use was fixed at 4.2 M m^3 per year.

Issues That Arose in the Safari-Igava Area

The land reform of the year 2000 created new 600 plots with minimum sizes of 6 Ha per farmer, on an irrigation system that was designed for 20 large scale farms. The new farmers/irrigators had new crops and agricultural practices, hence new water demand characteristics, and operation of the reservoirs and abstraction from the canals changed. Access was relatively reliable for upstream farmers on both canals, but tail end farmers on the canals faced shortages during periods of high demand; during prolonged dry spells in the summer season and the dry winter season. Farmers pumping directly from the river did not experience shortage problems (AGRITEX, 2005). Irrigators experienced water shortages to the extent that the main reservoir (Safari Reservoir) that supply farmers dried up in the middle of the dry season, the peak period for irrigation water demand. These shortages resulted in conflicts among farmers, and between the water authority (ZINWA) and the farmers (AGRITEX, 2005). The fears of the stakeholders were that the water shortages could escalate when Marondera Town starts abstracting water from Wenimbi Reservoir. Hence careful operation of the reservoirs would be crucial for conflict reduction through judicious management of the water resources.

Methods

Qualitative and quantitative data was collected from government departments, the water authority, the sub-catchment council and farmers. Evaluation of canal leakages was done and the conveyance efficiencies of the two canals were determined. An unstructured questionnaire was used to acquire information from farmers, the water authority (ZINWA), the Macheke sub-catchment council and government departments. The data collected was on climate, water use, area under irrigation since the year 2000, agricultural practices, the number of resettled farmers and water allocation.

The simulation model based on the WAFLEX package was used to mimic the functioning of the Safari-Igava hydrological system, because the model could be used to solve water allocation and reservoir operation (Ncube eta al. 2011). The model was based on the water mass balance equation. The weekly change in storage was due to water inflows, less water losses from the system on a week time step, represented by the equation;

$$\Delta S = R - \left(S_p + E + Y_d\right)$$

Where;

ΔS is change in storage per week

R is sum of runoff flowing into the system, precipitation and ground water contribution into the system (m^3/week),

Y_d is the total abstractions per week (m^3/week),

E is the evaporation (m^3/week) and

S_p is the spillage and ground water outflow from the system (m^3/week).

Inflow excess of full reservoir capacity (FRC) was spilled and added to storage of the immediate downstream reservoir. Utility rule curves (URC1 and URC2) were used for rationing water supply once reservoirs levels had reached defined thresholds. No water was released when reservoir levels were at dead storage capacity (DSC). Water remaining in a reservoir at the end of the seasonal year called "carryover water," was credited to the following year's fill. The carryover water was used to assess the water security in the river basin (Simpson et al., 2011; Alexander, 1995). Allocations of water by the model satisfy the demand of upstream users ahead of downstream users.

Conceptual Model of the Safari-Igava Water Resources and Uses

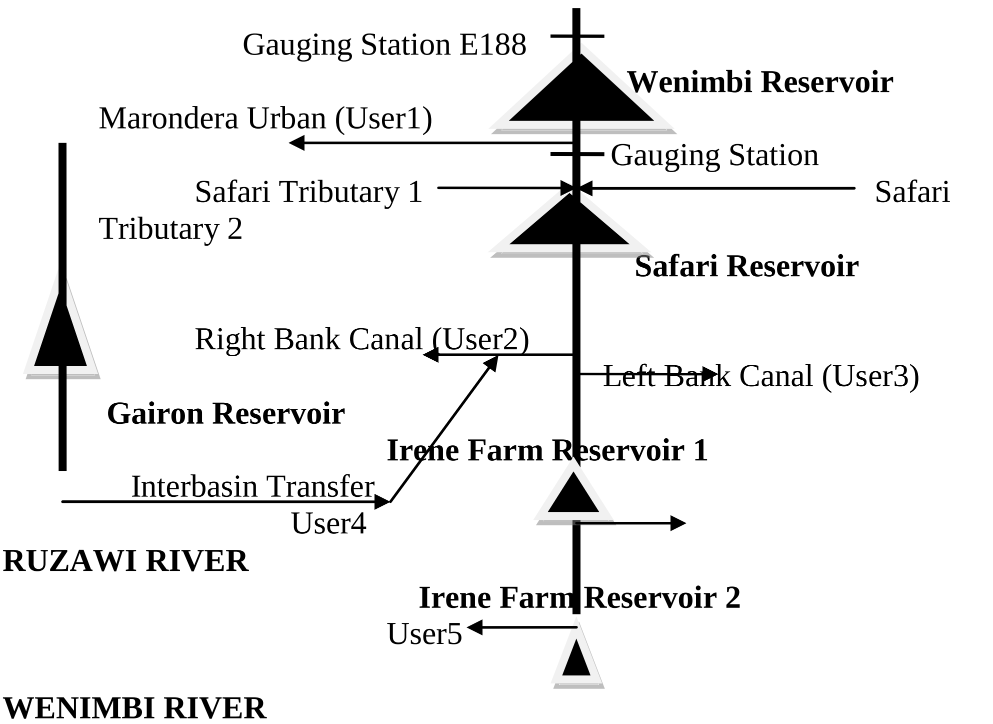

Figure 3: Conceptual Model of the Safari-Igava Water Resources and Uses

Calibration and validation of the simulation model was done using ZINWA's records of storage levels of Wenimbi Reservoir for the respective periods 2006 to 2009 and 2009 to 2012. Simulated and actual storage levels were compared using Pearson's correlation coefficient (Gurung et al., 2013) and the mean absolute error which gave indication of relative difference between simulated and actual data (Almasri and Kaluarachchi, 2007). Information on times when Safari and Irene Reservoirs were at full supply capacities and dead storage/dry was obtained from interview of farmers and the operator of Safari Reservoir, because there were no written records for water abstracted from the Safari and Irene reservoirs. Also there were no records and measurements for irrigation water used, therefore weekly irrigation water demands were calculated using a CROPWAT 8.0 model (Ncube et al., 2011), which use the Penman-Monteith equation (Balkhair eta al, 2013). The area under irrigation, from each point of abstraction was used in the CROPWAT 8.0 model to calculate the weekly irrigation water demands.

The WAFLEX model was used to analyse impact of water management practices by running simulations under high and low water demand scenarios. Due to the difficulty of projecting water politics for the study area, recorded historical average water transfers between dams, water and agronomic data collected from government departments, water allocations by the sub-catchment council and data on agricultural management practices obtained from farmer interviews were used in the simulation model (Tapia et al., 2014).

Safari Reservoir's annual time series capacity was developed from response to an questionnaire administered to operators. The unknown intermediate capacity was assumed to be the average of the full capacity and dead storage capacity (1.04 Mm^3). There were no records on Safari Reservoir water levels, and water releases, hence simulations were run at different irrigation efficiencies (different water demand scenarios), in order to find the best fitting Safari Reservoir storage curves, and the curves were used to estimate the irrigation water releases from the Safari Reservoir. Hence, average irrigation efficiencies were obtained for the periods of conflict, when some farmers experienced shortages (2005-2008) and periods without shortages/conflicts (2009-2012). For each time step, the average irrigation efficiency was equal to the irrigation water demand determined using CROPWAT 8.0 model divided by water released from Safari Reservoir.

Estimation of Flow in Ungauged Streams

For ungauged streams that flow into Safari Reservoir, the similar catchments method was used, on the basis of inflow at gauging station E188, located upstream of Wenimbi Reservoir. The runoff per unit catchment area was multiplied by the catchment area of the streams.

Scenarios

Records of irrigated area and urban water consumption were used to draw graphs and trendlines. Several scenarios were drawn after an analysis of the trendlines, annual variation of urban water demand, wastewater release and area under irrigation. The stability or robustness of the simulation model was checked by analyses and comparisons of results produced by the simulation model after running it under different scenarios against observed data. The sensitivity of the simulation model was tested by running it after changing input data (e.g. climatic and water demand) and analysis of the results on shortages and reservoir capacity. The different scenarios provided the variations in input data. In the different scenarios the simulation model was subjected to the following conditions;

1. Historical and recorded water abstraction in the years 2005 to 2008 (period of shortages and conflicts) and from 2009 to 2012, a period without water supply shortages.
2. Low abstraction/ water demand; when area under irrigation was reduced e.g. the 2009 agricultural year shown in Figure 6.
3. Low inflow into reservoirs e.g. hydrological drought year 2008/09 with a 15% non-exceedance probability. Global climate model HadCM2 predicted that climate change could cause annual average summer rainfall to decrease by 10 to 15% in Southern Africa (Ragad and Prudhomme, 2002).
4. Increased water availability through interbasin transfer from Ruzawi River into the right bank canal (RBC).
5. No rationing, hence no restriction to water released from farmer operated reservoirs. (During the study period farmers had no operation rules for rationing water releases from the Safari Reservoirs and the two farm reservoirs).
6. High demand scenario, whereby demand would be equal total allocations by ZINWA.

Assumptions Made

The following assumptions were made in the development of the simulation model;

- Soils and hydrographical conditions were relatively homogenous in the Wenimbi basin. Climatic data recorded at Marondera Town weather station 15 km from the Safari-Igava area was used in the modeling. The impact of climate change was negligible.
- Wheat and tobacco were the irrigated crops, but other crops which took less than 7% or irrigated area had negligible water demand. Average irrigation efficiency was used for all irrigators.

- In the absence of design data and reservoir capacity measurements, dead storage capacity of Eirene Farm Reservoirs was estimated at 10% of full capacity. Effect of siltation was negligible. Net seepage from all reservoirs was not considered as a loss from the system and evaporation from Eirene Farm Reservoirs were considered negligible because they had relatively small capacities.
- River normal flow was fixed at 10% of mean annual runoff (MAR) and was considered adequate for environmental and primary purposes for users downstream of the Safari-Igava area. The supply from reservoirs with a combined storage 5.4 Mm^3 located upstream of Wenimbi reservoir was considered too small to help in alleviating shortages in the Safari-Igava Area. The water use and operation of the reservoirs by upstream irrigators was steady in all scenarios.

Results analysis and discussions
Questionnaire

The unstructured questionnaire administered to farmers, water authorities and government departments revealed the following information about water use in the Safari-Igava area;

- Farmers managing Safari Reservoir said that in average rain seasons the Safari Reservoir is at full capacity at the end of the rainy season, i.e. at the end of March. It would be at dead storage capacity by end of August, unless water has been released by ZINWA from the upstream Wenimbi Reservoir, after a request and a payment by the farmers. Operators were not keeping records of water releases from Safari and Eirene Farm reservoirs.
- Competition for water might increase since most of the farmers wished to expand their area under irrigation; therefore reallocation of water and/or controls of expansion were required as conflict prevention measures.
- There was no evidence that farmers were employing well calculated irrigation scheduling methods as a water management tool. Scheduling irrigation could be one of the solutions to water shortages in the canal system.

Analysis of the results of the questionnaire, helped to understand the management of the water resources in the study, and the following inferences were made;

a. Monitoring, measurement and recording of irrigation water abstraction (especially on the canals) was not done which made water allocation and demand management in the system to be ineffective and inefficient. Over abstractions by upstream farmers and shortages for canal tail end farmers was possible under such situations and conflicts were inevitable.

b. Accurate measurement and recording at Safari Reservoir, each demand (point of abstraction) on the two canals and the Wenimbi River could help to locate points where there were water wastages, either in conveyance or in use.
c. It was difficult to use pricing of water as a water demand management tool in the Safari-Igava system because billing was not based on measured quantities of water used but on allocated amounts.
d. ZINWA and the Macheke Sub-catchment Council were not involved on the release of water from Safari and Eirene farm reservoirs, but the new farmers (with little training), were responsible for the releases which weakened management of the water resources.

Water Availability

There was little security of water supply in the Safari-Igava area because the carryover was 1.35 years, and 1.37 years with interbasin transfer, as shown in Table 2. Recommendations by Alexander (1995) are that the safe reservoir carryover for Southern Africa, where river flow is seasonal is 2 to 5 years. For the Safari-Igava area, in the event that there were two consecutive dry years, most of water supplied would be from reservoir releases. Hence the reservoirs in the Wenimbi River system may not be able to meet peak demand.

Canal Conveyance Efficiency

The canal conveyance efficiencies were found to be above 95%. Field measurements were done during the rainy season when the canals' water levels were less than half full and the surrounding soil was relatively moist. Determining the conveyance efficiencies of the two canals during the dry season at maximum canal water levels would give the best information on water losses from the canals.

Reservoirs Operational Rules

ZINWA was responsible for operation of the Wenimbi Reservoir, hence ZINWA kept a record of the reservoir water levels; inflow, natural out flow, and the releases to farmers. Releases to farmers were done after the farmers had formerly applied and paid for the water. Also, as a minimum, 10% of mean annual runoff was released from Wenimbi Reservoir for downstream environmental requirements, and hence the downstream reservoirs also released the same amount for downstream environmental requirements. Safari Reservoir, Eirene Farm Reservoirs on Wenimbi River and Gairon Reservoir on Ruzawi River were operated by resettled farmers on behalf of the Macheke Sub-catchment and ZINWA. The operators were not keeping records on reservoir water levels, water inflows and releases.

Model Calibration: Simulation of Wenimbi Reservoir Capacity between March 2006 and September 2009

The model underestimated the dynamic storage in the Wenimbi Reservoir. A mean absolute error of 4% was attributed to the estimation of ungauged runoff contributed by groundwater sources and ungauged streams. The graphs in Figure 4 show the simulated and recorded time series capacities of the Wenimbi Reservoir between the years 2006 to 2008.

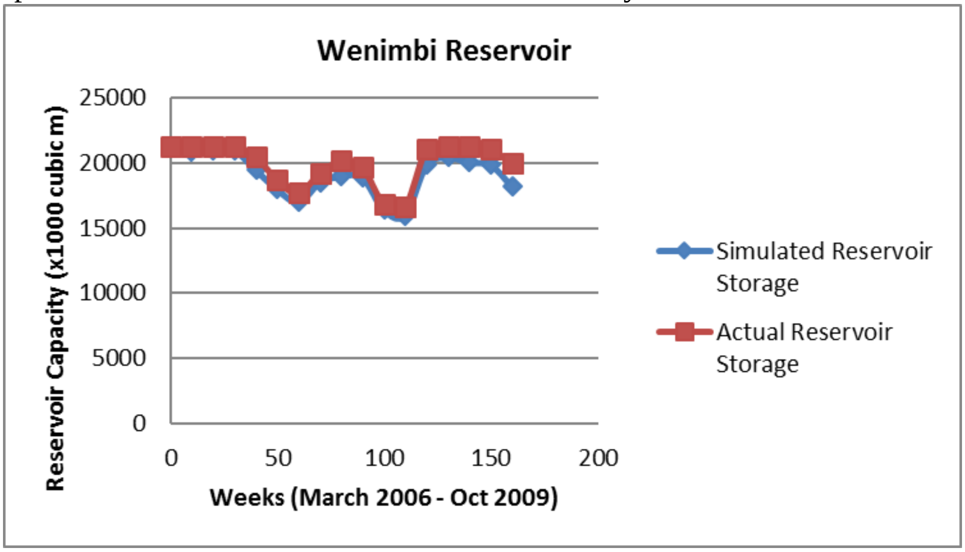

Figure 4: Simulated and Actual Capacity of Wenimbi Reservoir, March 2006 to September 2009.

The simulation mean absolute error of 4% was considered acceptable (Almasri and Kaluarachchi, 2007); therefore the model was validated using Wenimbi reservoir storage data obtained between 2009 and 2012 as shown in Figure 5. The Pearson correlation coefficients were 0.98, 0.994 and 0.986 for the hydrologic years 2006/07, 2007/8 and 2008/9 respectively, which showed that the model could simulate the water storage levels satisfactorily (Gurung et al., 2013).

Model Validation: Simulation of Wenimbi Reservoir Capacity between October 2009 and September 20012

Simulated reservoir levels and ZINWA records for Wenimbi Reservoir were compared The Pearson correlation coefficients were 0.856, 0.013 and 0.971 for the hydrologic years 2009/10, 20010/11 and 2011/12 respectively, which showed that the model simulated the water storage levels satisfactorily for the first and third hydrologic years. The Pearson correlation coefficient for the three hydrologic years (combined) was 0.647, which was a satisfactorily simulation, hence the model was used for simulation of the Wenimbi River basin (Gurung et al., 2013). The simulation mean absolute error of 5.6% was considered acceptable (Almasri and Kaluarachchi, 2007); therefore the validated model was used for analysis of operation of the reservoirs and estimation of agricultural water use efficiency. All the water released for the farmers from the Wenimbi reservoir into Safari reservoir was ultimately used for irrigation. The two reservoirs are situated in similar topography and hydrological conditions, therefore it was assumed that the same model could simulate Safari reservoir's response to water release with a similar degree of accuracy, and hence analyse irrigation water management in the Safari-Igava area.

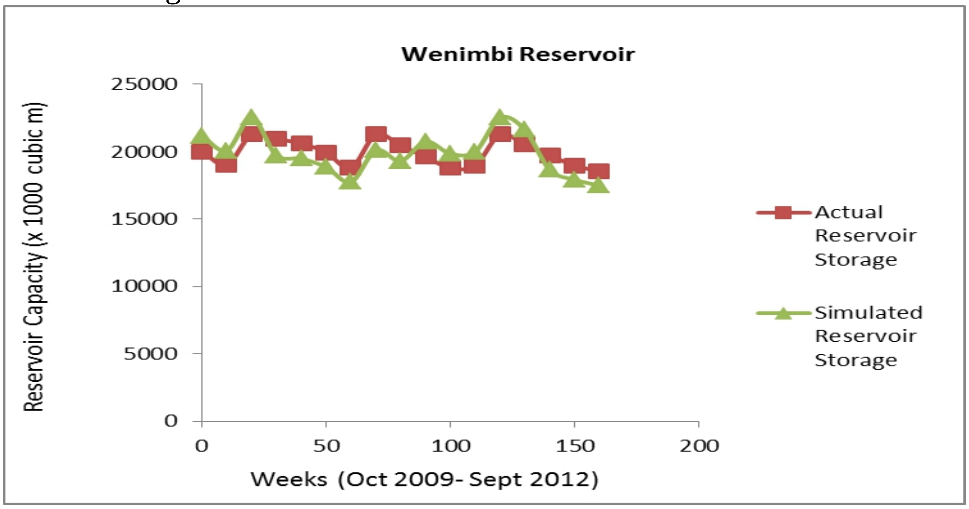

Figure 5: Simulated and Actual Capacity of Wenimbi Reservoir, October 2009 to September 20012.

Irrigation Water Demand

There were no records on irrigators' water abstractions; therefore the size of land under wheat was used as the optimum area that was under irrigation. Records available at government departments and farmers' organization were from the years 2006 to 2012. Figure 6 show that there was a general increase in area under irrigation between 2006 and 2008 which corresponds to a period of water shortages and conflicts, and a second phase of reduced area under wheat from 2009 to 2012. The increase in area under irrigated wheat between 2006 and 2008 was attributed to government subsidies on inputs (fertilizer, seed and fuel for tillage) for wheat production, as well as marketing of the crop. The decrease in irrigated area under wheat may have been caused by a change in government policy, after a new government of national unity formed in 2009, reduced subsidies for wheat production. From 2010 to 2012 area under wheat was on a decreasing trend, because of marketing problems (AGRITEX, 2012). The farmers reduced the area under wheat, but increased area under irrigated tobacco in the same period. Farmers had a new cropping program, hence irrigation water demand characteristics effectively changed in the year 2009. No complaints of water shortages were reported since 2009 (AGRITEX, 2012). There were no water shortages and complaints because tobacco is mainly a summer crop and hence supplementary irrigation is practiced and therefore irrigation water demand from the reservoirs is lower compared to wheat, a dry season and winter crop. Also, the total area under irrigation was reduced since 2009 hence irrigation water demanded by the farmers was lower.

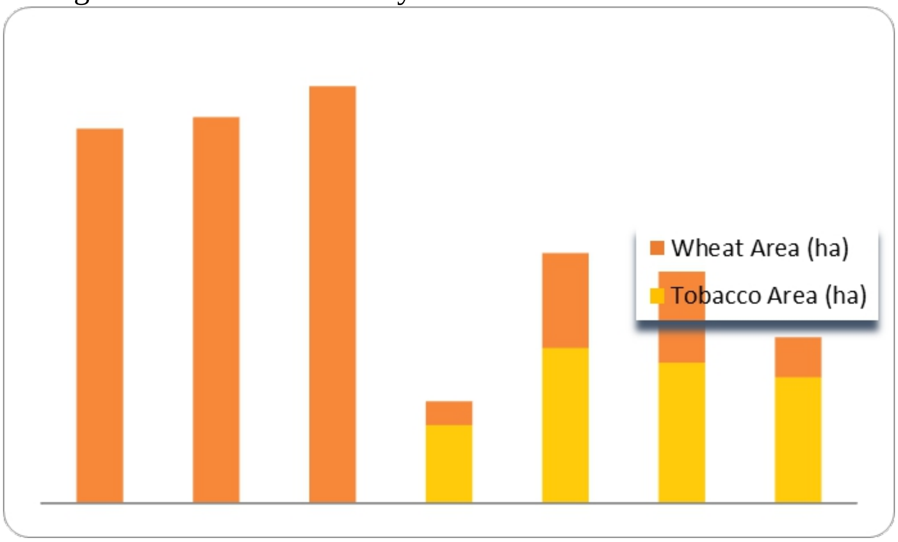

Figure 6: Estimated Area under Irrigation in Safari-Igava, Years 2006-2012 **(**Department of Agricultural Research and Extension, 2009 & 2012)

Model Simulation for Analysis of Safari Reservoir's Capacity and Agricultural Water Demand

Irrigation efficiency was estimated at 75%, that is, the average for portable sprinkler systems (Savva and Frenken, 2002). The computer model produced simulation results for the temporal variation of the capacity of the Safari Reservoir (due to irrigation water demand/releases), between the years 2006 and 2009, as shown in Figure 7.

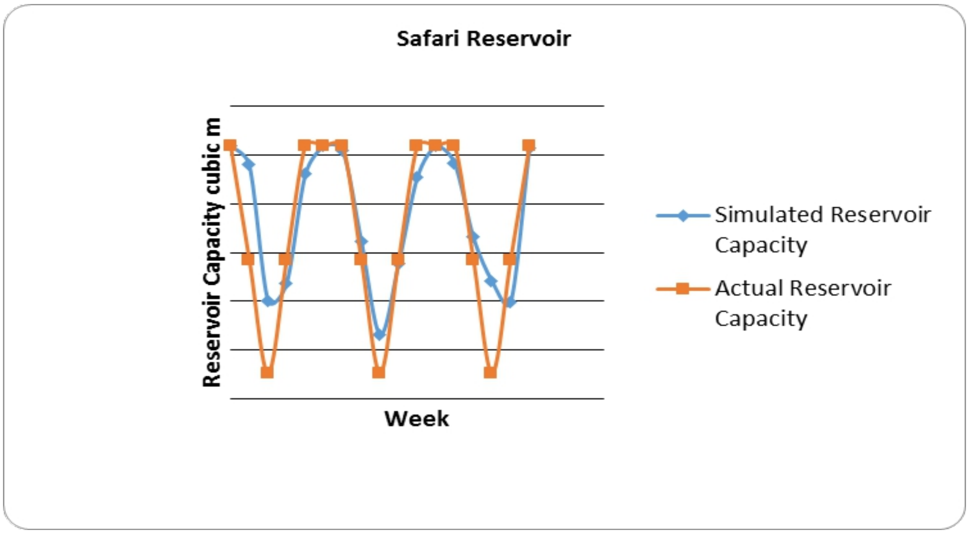

Figure 7: Safari reservoir simulated and actual capacity curves, irrigation efficiency at 75% from October 2006 to September 2009.

Simulation mean absolute error was 17% and the reservoir was never at dead storage capacity. This showed that actual water abstracted from the dam was higher than the estimated water demand for the portable sprinkler irrigation systems. High irrigation inefficiency could be one cause of the high error in simulation. Therefore the actual irrigation efficiency was lower than 75%.

The model was run when irrigation efficiency had been reduced to 40%, which was a relatively high water demand scenario. The computer model produced simulation results as shown in Figure 8.

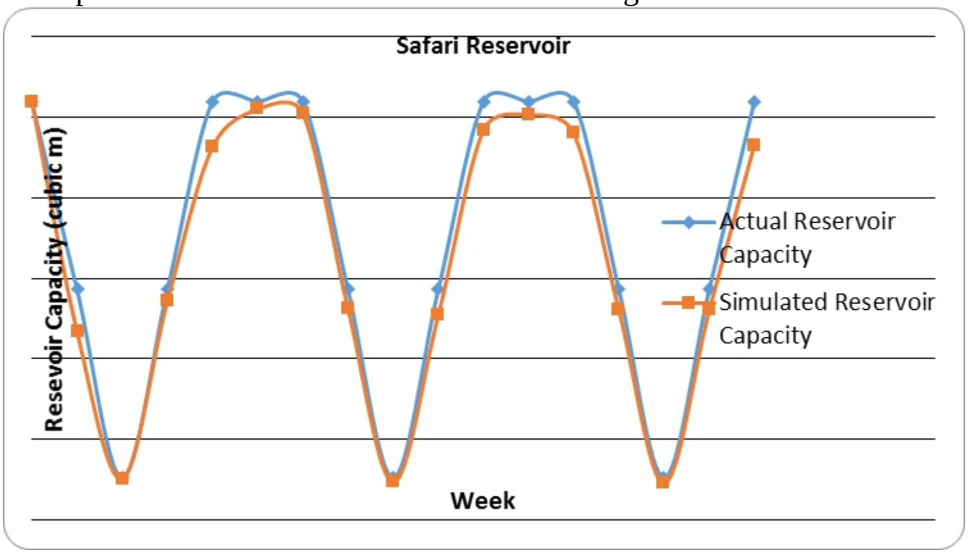

Figure 8: Safari reservoir actual and simulated capacity curves; irrigation efficiency is 40% from October 2006 to September 2009.

Mean absolute error was 7% which meant that the average irrigation efficiency in the Safari-Igava area could have been less than 40%. Decreasing the efficiency below 40% did not produce perfectly fitting curves of simulated and actual reservoir capacity and mean absolute error increased above 7%. The minimum mean absolute error was 7 % and the range was 7 to 9.4 % between irrigation efficiencies of 40% and 50 % respectively. Therefore other factors could have a significant influence to the mean absolute error. Some of the factors were;

(i) Errors in estimation of irrigated area.
(ii) Errors in derivation of the actual time series Safari Reservoir capacity curve.
(iii) Variations in water demand due to farmers that used other methods of irrigation, like surface irrigation instead of portable sprinkler in order to cope with lack of adequate equipment and different topological conditions.
(iv) Variations in water demand due to production of other crops like horticultural crops which were planted at the same growing period with the wheat crop.

For the period 2009 to 2012, the simulation result for Safari Reservoir had a mean absolute error of 6% at an irrigation efficiency of 65%. There were no water shortages and hence no conflict in this period (AGRITEX, 2012). Also the simulation model had no shortages. Probably inefficient farmers stopped producing wheat possibly preferring a summer crop like tobacco, especially after the new government had stopped subsidizing wheat production and stopped support in the marketing of the crop. Hence it was inferred that government policy or water governance and external factors like markets had strongly influenced water use and access, hence reduced conflict in the Safari-Igava farming community.

Simulation under Various Scenarios of Available Water, Demand and Allocations

In the years 2006 to 2009 urban water supply system was not yet connected and agricultural production was rising but had not yet reached its peak. Downstream famers using the canals were experiencing water shortages. The model simulation, with an irrigation efficiency of 75%, showed that there was enough water for all irrigators in the Safari-Igava area. The model showed that the shortages (for six months of each year) could only begin if water use efficiency was less than 40%. Therefore the shortages experienced were caused by inefficient use of water by upstream farmers using the canal.

For the peak demand scenario; Marondera Town water supply would be connected and the irrigation water demand would be at peak, hence water demand would be equal to allocations as in records at ZINWA (2009). The simulation model showed that irrigators would not get water shortages for three years. Figure 9 and Figure 10 show the respective storage changes for Wenimbi and Safari Reservoirs.

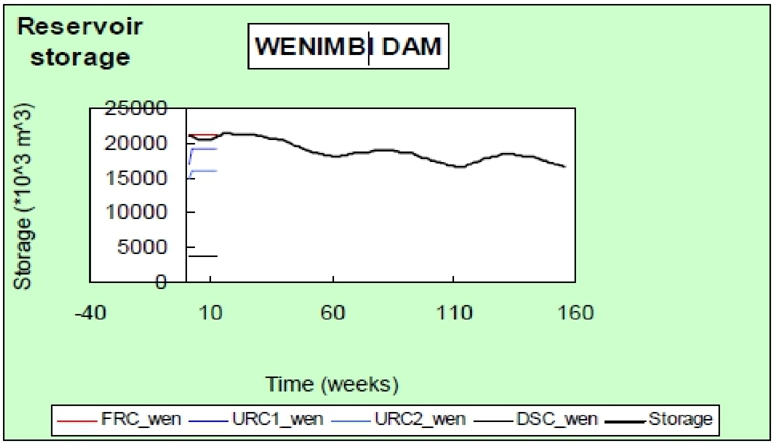

Figure 9. Wenimbi Reservoir storage at peak demand (Marondera Town water supply connected and 75% irrigation efficiency)

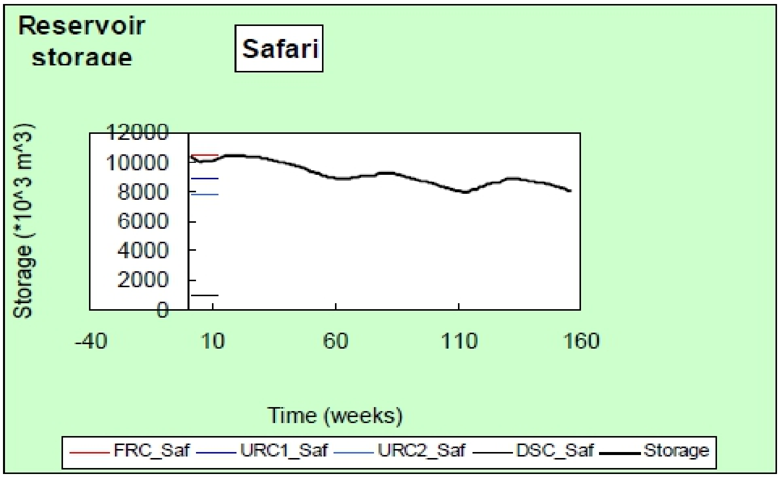

Figure 10. Safari Reservoir storage at peak demand (Marondera Town water supply connected and 75% irrigation efficiency)

The model showed a continuous depletion of storage on Wenimbi and Safari Reservoirs whereby rainy seasons between 2006 and 2009 could not fill up the reservoirs. The rainy seasons had a combined average annual rainfall above 800 mm, and the 2008/9 rainy season was drought year with non-exceedance probability of 15% (Santos et al., 2000). The continuous reduction in storages indicated low water security which was also indicated by a carryover of 1.35 years in Table 2. Therefore water management under a maximum allocation or a peak demand scenario may require; either review of allocations, use of alternative supplies, enforcement of strict rationing combined with/ or strict water demand management measures that ensure farmers utilize irrigation methods with efficiencies above 75%. Figure 11 and Figure 12 respectively showed insignificant storage changes in Eirene Farm Reservoir 1 and Eirene Farm Reservoir 2. Therefore farmers pumping directly from the river downstream of Eirene Farm Reservoirs 1 and 2 should get water releases from these two reservoirs until they are depleted to minimum/dead storage capacity before getting water from Safari and Wenimbi Reservoirs, thereby reducing direct demand on the Safari and Wenimbi Reservoirs.

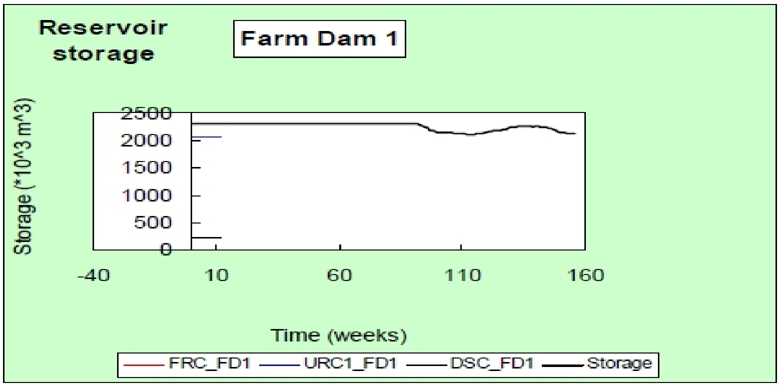

Figure 11. Eirene Farm Reservoir 1 storage at peak demand (Marondera Town water supply connected and 75% irrigation efficiency)

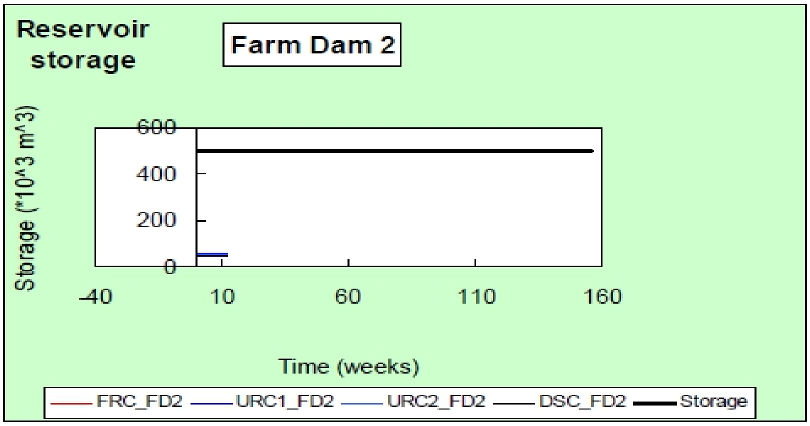

Figure 12. Eirene Farm Reservoir 2 storage at peak demand (Marondera Town water supply connected and 75% irrigation efficiency)

Two consecutive dry years (15% non-exceedance like the 2008/2009 hydrologic year), at the 2006-2009 water demand (where urban water supply was not yet operational) have an impact on water availability, hence demand could not be met 43% of the time, which indicated low water security. This was in agreement with the results in Table 2 which gave a respective carryovers of 1.35 and 1.37 years without and with interbasin transfer (Finnerty and Hecht, 1992; Alexander (1995).

To alleviate shortages strict monitoring of water consumption and adherence to allocations could be required. Therefore supporting external organisations like government departments or national water authorities must help in enforcing the installation of flow meters at all pump stations, and making sure that water measurement devices on the canals are functioning, and water bills are derived from quantity of water used. Area under irrigation and method of irrigation could be used to determine the quantity of water consumed. The supporting organisations must review and fractionally allocate water in times of shortages for equity at peak demand (Derbile, 2012). Investigating transmission losses of the canals at peak flow rates and farmers' water use efficiencies for maintenance combined with a review of operations of Safari Reservoir are required for formulating effective strategies for water release.

Sensitivity Analysis of the Computer Model

A sensitivity analysis was carried out to test the overall responsiveness of the model to some input parameters (Zheng and Bennett, 1995 and Oyarzun et al., 2007). The model was run when there was no rationing (control of water released), both Wenimbi and Safari Reservoirs were depleted to dead storage, but the Eirene Farm Reservoirs were spilling. The algorithm made the water released equal to the demand when there was no rationing as long as storage was above dead storage. With a water release control instruction, the model started to regulated water release proportionally as long as there was enough water above the dead storage capacity (DSC). Therefore the model was responsive and hence it was an appropriate decision support tool for reservoir operation.

The simulation model was run when storage in reservoirs was at dead storage capacity and irrigation water demand was for 540 ha, and negative releases equivalent to the net evaporation and 100% shortages were obtained. This was accurate result since the there were no water supply at DSC, but evaporation was the only net loss from the system.

Interbasin transfer whereby 80% of water supplied to Marondera Town was released into the Ruzawi River as treated wastewater, then transferred into the downstream end of the right bank canal (RBC) had insignificant impact on water security for the Safari Igava Area. The model showed that interbasin transfer reduced water shortages by 3% for 3 months which indicated the sensitivity of the model.

Conclusion

The quantity of water available for the Safari-Igava area was enough for irrigating over 540 hectares of wheat, provided irrigation efficiency was at least 75%. In the 2006-2008 period there was over abstraction of water from the reservoirs due to low efficiency of the irrigation methods.

The increase in area under irrigated wheat was driven by subsidies on wheat production.

Policies and marketing factors that led to increased area under wheat resulted in increased irrigation water demand causing water shortages and conflicts among irrigators. Replacing wheat with tobacco which only required supplementary irrigation reduced shortages and conflicts.

In case of consecutive two years of drought, the water available in the reservoirs cannot satisfy total allocations especially in the second year, which means there was little water security in the Safari-Igava Area. The computer model simulated well, the multiple reservoir system in the Safari-Igava area. Therefore the model could be used as a decision support tool for regulation, water distribution, allocations and analysis of reservoir operational strategies. The model could be used to analyse the long term impact of weekly inflows and abstractions on reservoir storage and hence assess the impact of management strategies for conflict resolution. Also, the model can be used in impact assessment before developments of new area for irrigation or new water demand scenarios.

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