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Effects of selected dams on river flows of Insiza River, Zimbabwe

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Abstract

This paper examines effects of three dams on flow characteristics of Insiza River on which they are located. The storage capacities of these dams varies from an equivalent of 48–456% of the mean annual runoff. Mean annual runoff and annual maximum flood flows have not been modified by the presence of these dams. The average number of days per year without runoff had decreased downstream of two dams. A comparison was made of flow duration curves at sites upstream and downstream of the selected dams. Significant differences were detected between the flow duration curves of upstream and downstream sites. Exceedance frequencies of low flows had decreased downstream of two dams, while these had increased downstream of the other dam. The study recommends development of operating rules for these dams that will ensure that changes detected in low flows do not adversely affect instream flow requirements.

Keywords: Dams; Flow duration curve; Flow modification; Low flows

1. Introduction

Zimbabwe like most of the southern African region receives rainfall during a four month rainy season (mid-November to mid-March) with the rest of the year being dry. Most rivers have flows during the rainy season only due to the seasonality of rainfall. Rainfall has also a high inter-annual variability resulting in water shortages during some years if there is no adequate carry-over storage. The development of dams to store water during the rainy season for use in the dry season, and also storing water during years with above average rainfall for use during years with below average rainfall has been a major strategy for improving the reliability of water supply (Mazvimavi, 1998). The development of commercial agriculture, mining, and urban areas has always been associated with dam development in Zimbabwe. There are over 10000 dams of various capacities in the country, and the proportion of the total storage capacity to mean annual runoff, the storage ratio, varies from 1 to 4 on several catchments particularly on the central part of the country (Mazvimavi, 1998). Flow regimes for catchments with high storage ratios (>1) are likely to have been modified by the developed dams (Graf, 1999; Batalla et al., 2004). There has not been a study which has investigated effects of dams on flow regimes in Zimbabwe. Previous studies on anthropogenic influences have examined effects of land use changes on river flow characteristics (Andrews and Bullock, 1994; Lørup et al., 1998). The importance of identifying and managing environmental effects of dams including modification of river flows was highlighted by the World Commission on Dams (WCD, 2000). Within southern Africa, knowledge of effects of dams on river flows is increasingly becoming important as national legislation (e.g. Water Act of Zimbabwe, Water Act of South Africa) require allocation of water for environmental uses before a permit for abstracting or storing water is granted (King

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et al., 2000; Hughes, 2001; Hughes and Hannart, 2003). This paper aims to determine the effects on river flows of dams developed across a selected river in Zimbabwe. Such a study will provide information which can be used to derive operating rules that satisfy instream flow requirements.

2. Study area

The study has been done on the Insiza River catchment (3401 km^2) located within the semi-arid southern part of Zimbabwe (Fig. 1). Insiza River is a tributary of Mzingwane River that drains into the Limpopo River, and contributing around 9% of the runoff of the latter river (Görgens and Boroto, 1997). Mean annual rainfall varies within the study area from 480 mm/y on the southern lower part which is at an altitude of about 1100 m, to 690 mm/y on the northern upper part with altitude of 1420–1500 m. Precipitation tends to occur in the form of wet spells followed by dry spells during the rainy season which extends from November to March.

The catchment of Insiza River is underlain by gneissic and granitic rocks, giving rise to moderately shallow, coarse grained kaolinitic sands, and moderately shallow clays and loams (Ashton et al., 2001). Land use is mainly a mixture of croplands, pastureland and woodland (Hearn et al., 2001). The northern part with moderately high rainfall has low open woodland of *Combretum–acarcia–terminalia* on granitic or gneissic derived sandy soils. Towards the south sparse low *mopane* woodland is gradually replaced by *Terminalia sericea* open woodland (Kileshye Onema, 2004; Timberlake, 1989). Cropping includes commercial farming (largely resettled) in the north, often under irrigation, and smallholder farming (mostly rainfed) in the south. Irrigation in the south includes schemes managed by farmer committees, and household vegetable gardens (Maisiri et al., 2005; Chigerwe et al., 2004).

The Zimbabwe National Water Authority Water Permit Database shows that there were 59 water permits for both abstraction and storage of water within the Insiza catchment in year 2004. The total capacity of all the impoundments within the Insiza catchment was $27\,860 \times 10^3$ m^3. Table 1 presents the year of first filling, and full supply

Table 1
Fully supply capacity of dams on Insiza River which have been selected for investigating their effects on river flows

Name of dam	Year constructed	Full supply capacity (10^3 m^3)
Silalabuhwa	1966	23 454
Upper Insiza	1967	8 829
Insiza	1973	173 491
Total		205 774

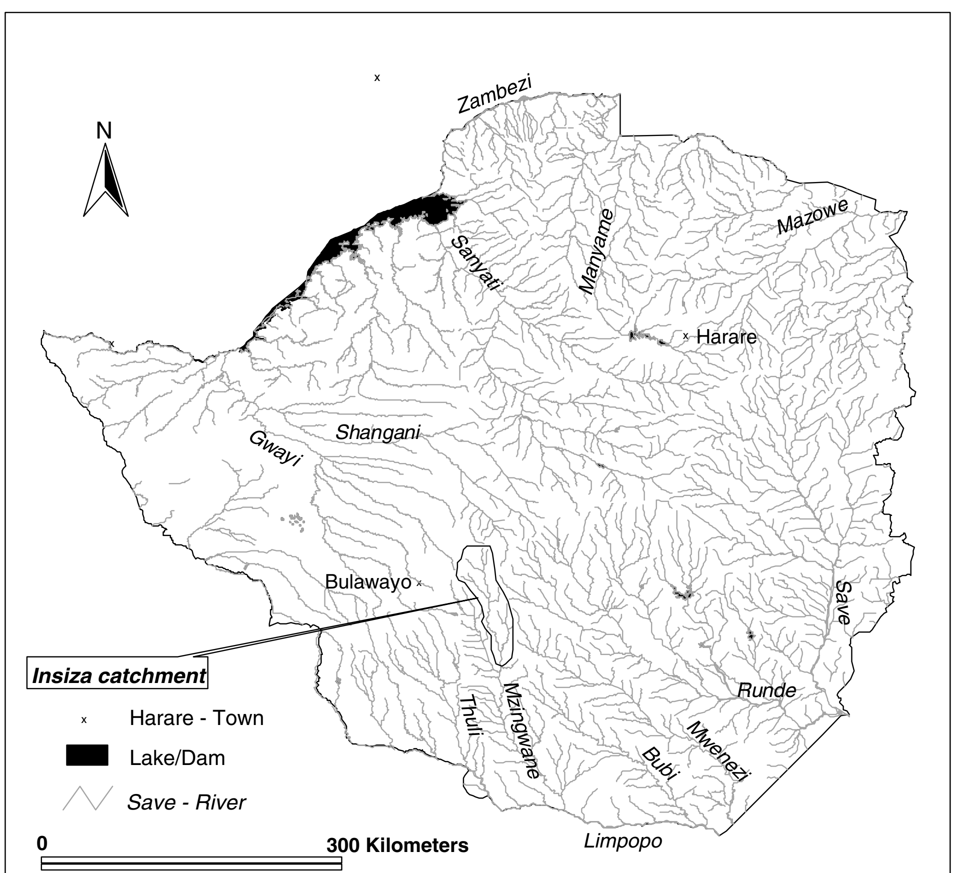

Fig. 1. Location of the study area in Zimbabwe.

capacity of Upper Insiza Dam, Insiza Dam, and Silalabuhwa Dam located within the Insiza catchment, and developed mainly for urban water supply to the City of Bulawayo, Zimbabwe's second largest city. These three dams have a total storage capacity of $205\,860 \times 10^3$ m^3 and have been selected for this study as they account for 90% of the total storage capacity on this catchment.

3. Methodology

The study investigates the effects of (a) Upper Insiza Dam, (b) Insiza Dam, and (c) Silalabuhwa Dam on river flows. For each dam, an upstream gauging station and a downstream gauging station were identified (Table 2 and Fig. 2). Gauging station B57 has been used as a station downstream of Upper Insiza Dam, and then as an upstream station for Insiza Dam. Thus B75 is compared with B57 for Upper Insiza Dam, B57 against B51 for Insiza Dam, and B69 against B65 for Silalabuhwa Dam. Daily and annual flow statistics of these stations have been compared to identify any differences that can be attributed to each of these dams.

Gauging stations on the Insiza River were established at almost the same time when the three dams were developed. There is inadequate or no river flow data before the development of each of these dams to enable a comparison of flows before and after dam development. Thus the approach adopted for this study is to compare flow statistics of a station upstream and that downstream of a particular dam so as to determine differences that can be attributed to the presence of the respective dam. The *t*-test has been used to determine if (a) mean annual runoff, (b) mean annual maximum flood, and (c) number of days with zero flows per year are significantly different between gauging stations immediately upstream and downstream of each of the three dams. There is a possibility that statistics of river flows at an annual time interval may not significantly reflect the effect of the presence of a dam. An analysis of daily flows is therefore warranted to investigate changes that may not be detectable at the annual interval. A comparison has been done of selected percentile daily flows between an upstream and downstream gauging station. This enables identification of effects of any of the dams on either flood (wet season) flows, low (dry season) flows, or both. Daily flows (q) at each of the stations have been divided by the average daily flow (q_{avg}) in order to obtain dimensionless flows which can be compared between stations without the size of the catchment area affecting the magnitude of flows. These dimensionless flows for each station have been used to construct a flow duration curve. The Kolmogorov–Smirnov test has been used to test the hypothesis of no difference at the 5% significance level between the flow duration curve of an upstream and downstream gauging station.

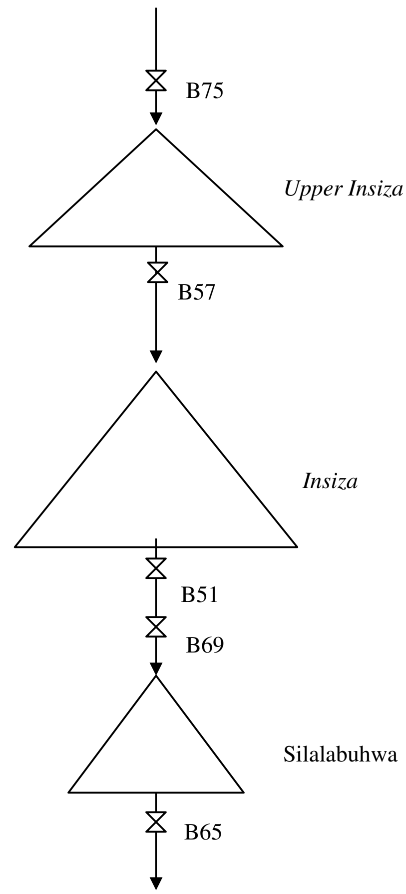

Fig. 2. Layout of dams and gauging stations along the Insiza River.

Table 2
Flow measuring stations located along Insiza River catchment whose data have been collected for analysis

Station number	River	Location	Catchment area (km)^2	Starting date
B75	Insiza	Upstream of upper Insiza Dam	401	30/10/1968
B57	Insiza	Downstream of upper Insiza Dam	570	5/11/1965
B51	Insiza	Downstream of Insiza Dam	2000	17/09/1964
B69	Insiza	Upstream of Silalabuhwa Dam	2260	5/10/1966
B65	Insiza	Downstream of Silalabuhwa Dam	3025	22/09/1966

4. Results and discussion

Runoff statistics of the stations used in this study are presented in Table 3. Mean annual runoff increases slightly going downstream along the Insiza River, from 16.7 to 25.9 mm/y. Annual runoff at all the stations has a high variability with the coefficient of variation being 150–216%. The mean annual maximum flood per unit area tends to decrease in the downstream direction from 0.092 to 0.050 $m^3/s/km^2$. Insiza River has no flow for almost over half a year, about 176–245 days per year without any flow.

Table 3
Runoff statistics of stations studied within the Insiza River

Station	Mean annual runoff (mm/y)	Coefficient of variation (%)	Average annual maximum flood ($m^3/s/km^2$)	Average number of days with no flow per year (days/y)
B75	16.7	150	0.092	245
B57	19.2	193	0.097	176
B51	19.6	178	0.041	200
B69	15.4	216	0.035	236
B65	25.9	181	0.050	126

The null hypothesis of no significant difference in (a) the mean annual runoff, and (b) mean annual maximum flood between an upstream and downstream gauging station was no rejected for all the three dams (Table 4). The storage ratio is 0.91, 4.56, and 0.48 for Upper Insiza, Insiza, and Silalabuhwa Dams respectively. Lack of difference in the mean annual runoff for Insiza Dam which has a very high storage ratio is rather unexpected. A possible explanation is that the amount of water stored during the wet season almost balances with releases made during the dry season. Annual maximum floods have not been affected by the presence of each of the dams. The highest floods in Zimbabwe tend to occur during the January to February period, which coincides with the period when most dams spill as a result of earlier inflows during the November to January period. Annual maximum floods have therefore not been affected by any of the three dams as they are likely to have been spilling when these floods occurred. Batalla et al. (2004) concluded that dams had reduced flood flows in north-east Spain demonstrating that the effects of dams on river flows cannot always be generalized but will largely depend on how these dams are operated.

Table 4
Results of testing (t-test) the null hypothesis of no significant difference in (a) the mean annual runoff, (b) mean annual maximum flood and (c) average number of days per with no flow between an upstream and downstream gauging station

Flow statistic	Calculate t-value	Probability of t	Reject or accept null hypothesis
Upper Insiza Dam upstream station B75 and downstream B57			
Mean annual runoff	−0.32	0.7503	Accept
Mean annual maximum flood	−0.13	0.8983	Accept
Days with zero flows	2.04	0.0451	Reject
Insiza Dam upstream B57 and downstream B51			
Mean annual runoff	0.05	0.9602	Accept
Mean annual maximum flood	−1.68	0.0979	Accept
Days with zero flows	0.63	0.5312	Accept
Silalabuhwa Dam upstream B69 and downstream B65			
Mean annual runoff	−1.07	0.2893	Accept
Mean annual maximum flood	−1.12	0.2685	Accept
Days with zero flows	6.44	0.0000	Reject

The hypothesis of no significant difference in the number of days per year with no flow has been rejected on Upper Insiza Dam and Silalabuhwa Dam. For each of these dams, the downstream gauging station has fewer days with no flow than the upstream station. This is likely due to flow releases during the dry season. The reduction in the number of days with no flow has however not affected the magnitude of the mean annual runoff as has already been determined from application of the t-test. The likely reason is that the value of the mean annual runoff for rivers in semi-arid regions is often mainly influenced by few large wet season flows, and least affected by dry season flows.

The result of applying the Kolmogorov–Smirnov test reveals that the flow duration curve of B75 upstream of Upper Insiza Dam is significantly different from that of the downstream station B57 at the 5% significance level. The presence of this dam has decreased the frequency of exceeding flows that are 5–50% of the average daily low (Fig. 3). This reduction being 10% for flows equal to 5% of the average daily flow and 1% for flows equal to 50% of average daily flow. The t-test results did not detect a change in the mean annual flow and average number of days per year without flow. Thus the change in exceedance frequencies of low flows are rather small and without significant effects on the mean annual flow and the average days per year without flow.

The presence of Insiza Dam has reduced the exceedance frequencies by about 8–15% for flows less than 5% of the average daily flow. This dam increased the exceedance frequencies for all other flows greater than 5% of the average daily flow (Fig. 4). Application of the t-test to annual flows, annual maximum flows and average number of days per year without flow did not reveal any significant difference between the upstream and downstream stations. Thus the small changes in exceedance frequencies of daily flows have had no effect at the annual level.

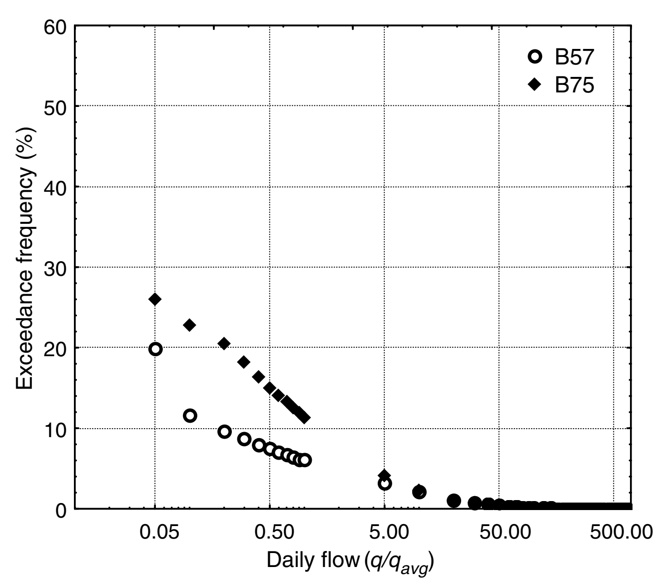

Fig. 3. A comparison of the flow duration curve of station B75 upstream and B57 downstream of Upper Insiza Dam.

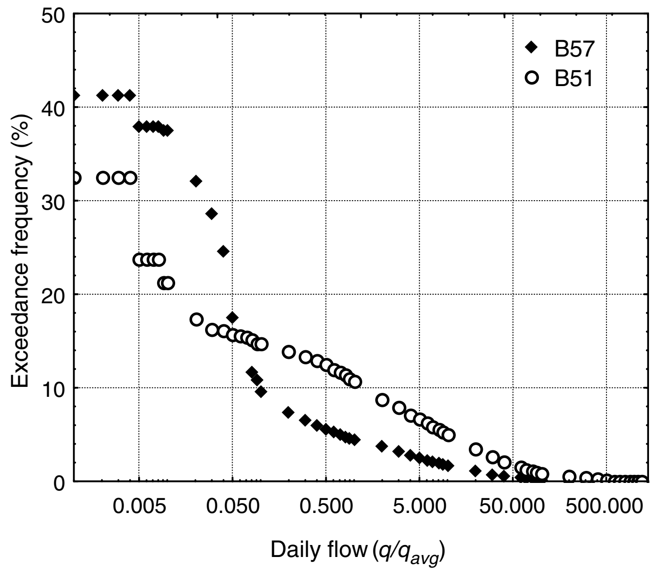

Fig. 4. A comparison of flow duration curves for B57 upstream and B51 downstream of Insiza Dam.

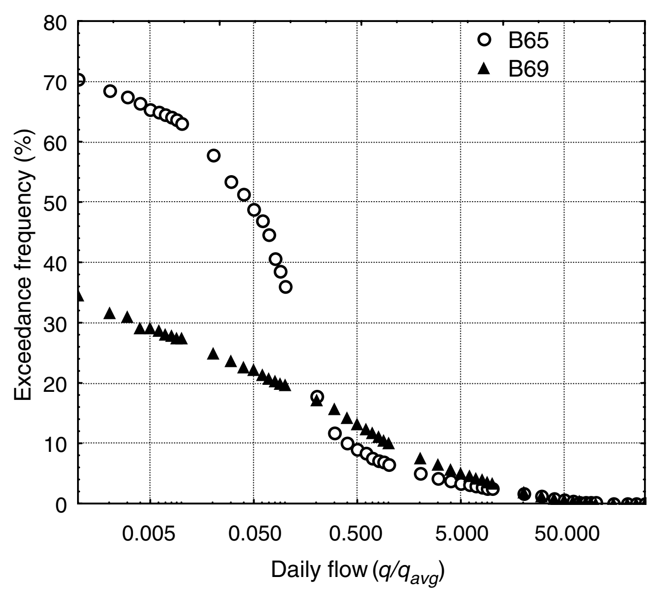

Fig. 5. A comparison of the flow duration curve for station B69 upstream.

The Kolmogorov–Smirnov test revealed that the flow duration curve of B69 upstream of Silalabuhwa Dams differs from that of the downstream station B65 at the 5% significance level (Fig. 5). Silalabuhwa Dam has the effect of increasing considerably exceedance frequencies of flows less than the average daily flows. The increase being 10% for the average daily flow and up to 30% for flows equal to about 0.1% of the average daily flow. This result is in agreement with the reduction in the average number of days per year without flow which has been detected by the *t*-test.

5. Conclusion

The presence of the three dams examined in this study has not changed the mean annual runoff and annual maximum floods. The average number of days without flows have decreased on two of the dams. The analysis of daily flows shows that these dams have caused changes of exceedance frequencies of daily flows, but which are not reflected in river flow statistics at the annual level. Exceedance frequencies of low flows have been reduced on two of the dams, while the lowest dam has had an opposite effect. A pattern could not be established between the nature and magnitude of the river flow modification and the storage ratios of dams studied, as the changes seem to depend mostly on the way the respective dams are operated.

This study has established that low flows have been significantly affected by the dams developed. Modification of low flows in semi-arid environments characterised by lack of flows during the dry season has considerable adverse effects on aquatic and non-aquatic ecosystems that depend on these flows. Therefore, the design of operating rules of dams and allocation of environmental flows has to take into account such possible changes in low flows in order to minimize adverse environmental effects.

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