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Assessment of environmental flow requirements for river basin planning in Zimbabwe

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Abstract

There is a growing awareness and understanding of the need to allocate water along a river to maintain ecological processes that provide goods and services. Legislation in Zimbabwe requires water resources management plans to include the amount of water to be reserved for environmental purposes in each river basin. This paper aims to estimate the amount of water that should be reserved for environmental purposes in each of the 151 sub-basins or water management units of Zimbabwe. A desktop hydrological method is used to estimate the environmental flow requirement (EFR). The estimated EFRs decrease with increasing flow variability, and increase with the increasing contribution of base flows to total flows. The study has established that in order to maintain slightly modified to natural habitats along rivers, the EFR should be 30–60% of mean annual runoff (MAR) in regions with perennial rivers, while this is 20–30% in the dry parts of the country with rivers, which only flow during the wet season. The inclusion of EFRs in water resources management plans will not drastically change the proportion of the available water allocated to water permits, since the amount of water allocated to water permit holders is less than 50% of the MAR on 77% of the sub-basins in the country.

Keywords: Environmental flow requirement; Desktop hydrological method; Coefficient of variation; Base flow index

1. Introduction

There is an increasing awareness of the need to reserve some water along a river to ensure the continued functioning of ecological processes that provide much needed goods and services for human use, and maintenance of biodiversity (Smakhtin et al., 2004; Tharme and King, 1998). Water which is allocated and made available for maintaining ecological processes in a desirable state is referred to as the instream flow requirement, environmental flows, or environmental flow requirement (Smakhtin et al., 2004; O'Keefe, 2000). The allocation of water to satisfy environmental uses initially developed out of the need to release from dams minimum flows to ensure the survival of often a single aquatic species with high economic value. However, the provision of environmental flows that attempt to preserve natural flow characteristics such as timing, frequency, duration, and magnitude of flows is considered important for the sustenance of freshwater ecosystems, since the flow regime is one of the major drivers of ecological processes on a river (Richter et al., 1997; Poff et al., 1997; Dyson et al., 2003; Gordon et al., 2004).

The 8th Meeting of the Contracting Parties to the Ramsar Convention (November 2002) adopted a resolution that called for the allocation of water for maintaining ecological functions of wetlands (www.ramsar.org). IWMI (2005) noted that insufficient water was being left in rivers in many parts of the world and urged policy makers to consider the allocation of environmental flows a top priority. The ability of some rivers to provide goods and services has been drastically reduced by the diversion and storage of water and the disposal of pollutants. The World Commission on Dams (WCD, 2000) recommended for the provision

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of environmental flows during planning and management of dams. The revised Southern Africa development community (SADC) protocol on shared waters (Southern Africa Development Community, 2000) defines use of water for preserving and maintaining ecosystems as an environmental use that must be taken into account together with other water uses when planning and managing shared waters. Almost every river in a landlocked country is part of a shared watercourse. Within the southern Africa region, the allocation of water for environmental uses is explicitly provided for in the legislation of few countries such as South Africa and Zimbabwe. Zimbabwe has been divided into seven river systems for planning and managing water resources, and the Water Act of 1998 (Zimbabwe, 1998) requires that a catchment outline plan be developed for each of the river systems. This plan is supposed to indicate

- the major uses of water,
- the proportion of the available water that has been and will be allocated to different sectors,
- priorities for utilization and allocation of water, and phasing of development,
- maximum permissible levels of water pollution within the river systems, and
- the proportion of the available water resources to be reserved for environmental purposes.

The determination of the proportion of available water resources to be reserved for environmental purposes has been constrained by the lack of guidelines for estimating the environmental flow requirement (EFR). The only EFR studies done so far in Zimbabwe are those by Topping (2000) on the Mazowe River, Pungwe River by the Zimbabwe National Water Authority (ZINWA) (Mott MacDonalds, 2004), and Symphorian et al., 2003 on the Save River basin in connection with determining flow release rules from Obsborne Dam. This paper aims to contribute towards the catchment planning process by determining environmental flow requirements that could be considered for inclusion in catchment outline plans.

2. The study area

Zimbabwe has an area of 390,757 km^2 and with altitude varying from 162 to 2592 m above sea level. Mean annual rainfall varies from 340 to 600 mm/yr in the southern, western, and northern parts of the country, 600–1200 mm/yr along the central part, to 1200–2000 mm/yr along the Eastern highlands. The Eastern highlands are located along the eastern border between Zimbabwe and Mozambique. The country has been divided into seven river systems for water resources planning and management (Fig. 1), and for each river system a catchment council made up of representatives of water users is responsible for planning and managing water resources including the production of a catchment outline plan, considering and granting applications for water allocations. Each of the river systems is further divided into sub-basins or hydrological sub-zones, and there are 151 sub-basins covering the whole country. There are about 600 river

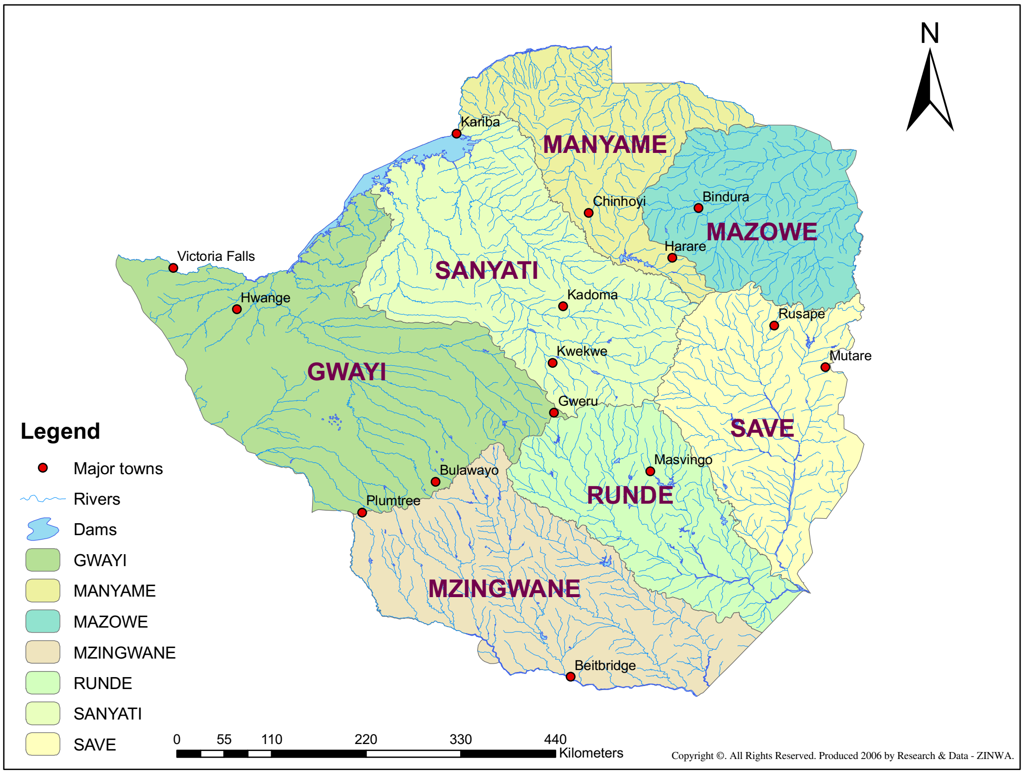

Fig. 1. The seven river systems used for planning and managing water resources in Zimbabwe (source: Zimbabwe National Water Authority).

flow measuring stations in the country, but the northern, north-eastern and southern parts are poorly covered. Some of the stations have records that are 50–80 years.

3. Methodology

Methods for estimating EFRs fall into the following four categories; (a) hydrological methods, (b) hydraulic rating, (c) habitat simulation, and (d) holistic methods (King et al., 2000; O'Keefe, 2000; Tharme, 2000; Dyson et al., 2003; Gordon et al., 2004). Hydrological methods use flow data for estimating EFRs (Tennant, 1976; Orth and Maughan, 1981; Richter et al., 1996, 1997; Hughes and Hannart, 2003; Smakhtin and Weragala, 2005; Smakhtin et al., 2006). The major advantage of these methods is that, where flow data is available, an EFR can be determined for a site within 1–2 days, while the weakness being incomplete knowledge about the relationships between hydrological indices derived from flow data, and ecological processes within a river especially for a specific site (O'Keefe, 2000; Dyson et al., 2003; Gordon et al., 2004). There is insufficient quantitative information about how different aquatic species respond to variations of hydrological indices. Consequently, hydrological methods are regarded as providing low confidence EFR estimates when applied to a site at which a specific water resources project is being proposed. EFR estimates made using hydrological methods are however considered to be suitable for basin wide water resources planning. Methods for estimating EFRs falling into the other categories require detailed fieldwork at a particular site, which can take weeks even up to a year depending on the method selected and are more appropriate when a specific project is being considered at a site along a river. Holistic methods require inputs from a multi-disciplinary team with diverse expertise (e.g. fisheries biology, aquatic invertebrates, limnology, botany, socio-economics) rarely available in most agencies responsible for water resources planning. Hydraulic rating, habitat simulation and holistic methods are therefore not suitable for basin wide estimation of EFRs for planning purposes.

This study uses a desktop hydrological method developed by Hughes and Hannart (2003) on the basis of EFRs estimated during several studies conducted using holistic methods in South Africa. The Hughes and Hannart method has also been used on a limited number of basins in Zimbabwe (Topping, 2000), and in Sri Lanka (Smakhtin and Weragala, 2005), and Nepal (Smakhtin and Shilpakar, 2005; Smakhtin et al., 2006). River basins in Zimbabwe have climatological, physiographic and hydrological conditions similar to some of the basins in South Africa, and the Hughes and Hannart method is expected to be generally applicable. Hughes and Hannart recommended use of their method in southern Africa.

The EFR depends on the environmental management class, which is considered as a desirable target to be maintained on a particular river section. The environmental management class considered as a desirable target to be maintained on any river depends on the decision of the relevant agency taking into account inputs from stakeholders. Four environmental management classes have been defined for South African rivers (O'Keefe and Louw, 2000), and these are; Class A rivers with unmodified habitats and therefore have natural conditions, Class B with few modifications and largely natural conditions, Class C moderate modifications with unchanged ecosystems, and Class D rivers with modifications which have caused substantial losses of habitats or degradation.

The Hughes and Hannart method assumes that the EFR decreases with increasing flow variability, and increases with increasing base flow contribution. The average of (a) the coefficient of variation of monthly flows during the three wet season months, (January–March), and (b) coefficient of monthly flows during the three dry season months, (September–November), is used as a measure of flow variability. This average is then divided by the base flow index (*BFI*) to give an index *CVB*, which Hughes and Hannart used to predict EFRs. The predicted EFRs are expressed as percentages of *MAR*, which in this study will be estimated using flow data from stations without significant abstractions or impoundments. Separate equations were developed by Hughes and Hannart for predicting the proportion of (a) lows flows, and (b) high flows that should constitute EFRs. The following equation was derived to reflect that low flow EFRs (*MLIFR*) decrease within increasing flow variability (*CVB*):

$$\mathrm{MLIFR} = LP4 + \frac{(LP1 * LP2)}{(CVB^{LP3})^{(1-LP1)}}, \tag{1}$$

where MLIFR is the low flow EFR as a percentage of the *MAR,* while *LP1, LP2,LP3* and *LP4* are parameters whose values depend on the desired environmental management class.

In semi-arid regions, most of the high flows are due to isolated events which increase the variability of flows. Hughes and Hannart therefore assumed that the EFR for high flows increases with increasing flow variability (*CVB*), and derived Eqs. (2) and (3) for estimating high flow EFR (MHIFR) as a proportion of *MAR.*

$$\mathrm{MHIFR} = \gamma^{*}HP2 + HP3 \tag{2}$$

If CVB > 15 then

$$\mathrm{MHIFR} = (\gamma^{*}HP2 + HP3) + (CVB - 15)^{*}HP4, \tag{3}$$

where *HP2, HP3* and *HP4* are parameters, which depend on the desired environmental management class. γ is a function of *CVB* and another parameter *HP1.*

This study estimates EFRs for Class A, B and C conditions. Although the results for Class D are not presented in this paper, the Hughes and Hannart method can be used for estimating EFRs, if Class D is the desirable target to be maintained on a particular river reach. *CVB* and *BFI* were estimated using the available flow data for those basins that are gauged. *BFI* was estimated from daily flows using the smoothed minima technique (Mazvimavi, 2003). Some of the flow measuring stations in Zimbabwe have been significantly affected by upstream abstractions and impoundments. However, this study applied flow data for stations with minimal influences of abstractions and impoundments. Regionalization methods developed for Zimbabwean basins (Mazvimavi, 2003; Mazvimavi et al., 2004; Mazvimavi et al., 2005) were used to estimate *CVB* and *BFI* for ungauged basins. The ZINWA maintains a database indicating the amount of water allocated for storage and/or abstraction for each water permit that has been granted. The main criterion for water allocation for storage purposes in Zimbabwe has been whether the proposed storage work is to provide the required yield at a specified reliability level taking into account the available water and other allocations that have already been made. Allocations for abstractions are similarly based on whether the prevailing flows will be able to sustain the required rates of abstractions. The ZINWA water permit database was used to estimate the amount of water committed to existing water permits. A comparison of the amount of water allocated to these permits with *MAR*, and EFR gives an indication of the intensity of water utilization in each of the sub-basins and the availability of water for EFRs. Smakhtin et al. (2004) used the ratio of the total amount of water allocated to water uses to the *MAR* as an indicator of whether current water uses adversely affect the availability of environmental flows.

4. Results

4.1. Characteristics of flow regimes

River flows are highly seasonal throughout the whole country with most of the flow confined to the rainy season, mid-November–March. Rivers on the dry western and southern parts of the country generally have flows for limited periods during the wet season with no flow during the dry season (Fig. 2a). Flow occurs in the form of few spells lasting about 15 days on some of the rivers in these dry parts of the country. Wet season flows tend to be prolonged on the central part of the country with some rivers drying up during the dry season (Fig. 2b). Rivers on the Eastern Highlands flow throughout the year (Fig. 2c). These flow characteristics have greatly influenced ecosystems that exist in the various rivers, and allocation of water for environmental purpose should attempt to mimic these natural flow regimes (Poff et al., 1997; Richter et al., 1997; Tharme and King, 1998; Dyson et al., 2003; Gordon et al., 2004). The *MAR* varies from 5 to 20 mm/year on the west, 50–150 mm/year on the central part, and 150–400 mm/year on the eastern part of the country (Fig. 3). The variation of annual flows increases with decreasing *MAR* as shown in Fig. 4. Rivers on the relatively sub-humid eastern part of the country have the coefficient of variation (CV) in the 50–75% range, while those located on the very dry western and southern parts of the country have CV in the 120–225% range.

The country is mostly underlain by crystalline rocks with generally low potential for groundwater occurrence; hence the *BFI* varies from 0.05 to 0.30 for most parts of the country (Fig. 5). Sub-basins with *BFI* values less than 0.20 will typically have no flows during the dry season (Fig. 2a). High *BFI* values, 0.50–0.70, are restricted to the well-watered Eastern Highlands, which also have steep slopes that promote subsurface flow to rivers, and these sub-basins have typically perennial rivers (Fig. 2c).

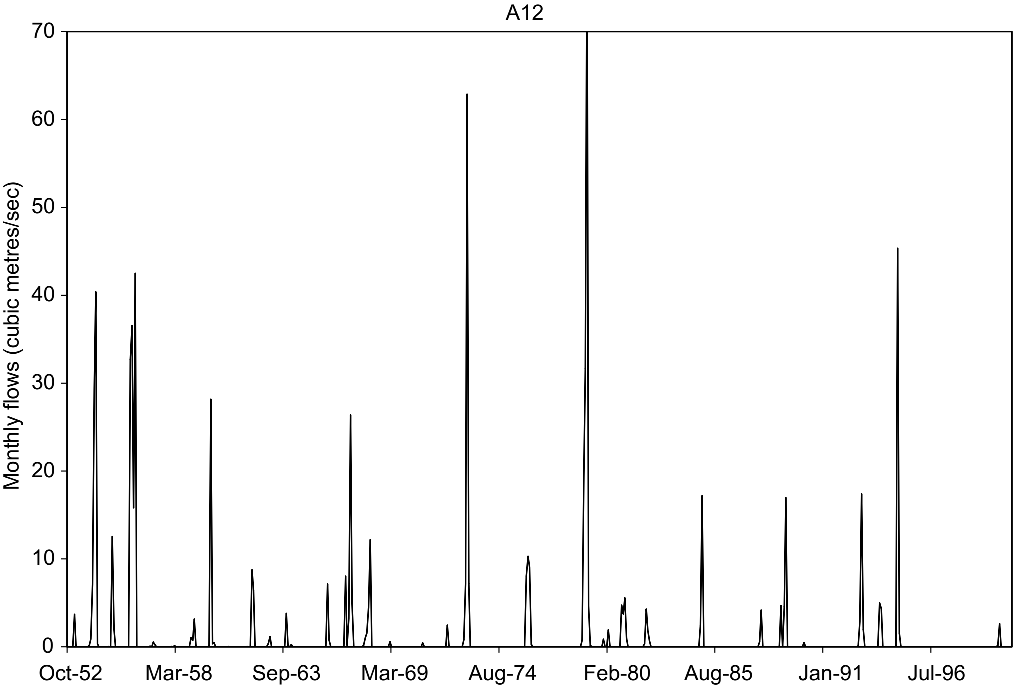

Fig. 2a. Monthly flows on a river draining the dry western part of the country, with the flows occurring during only a few days during the wet season.

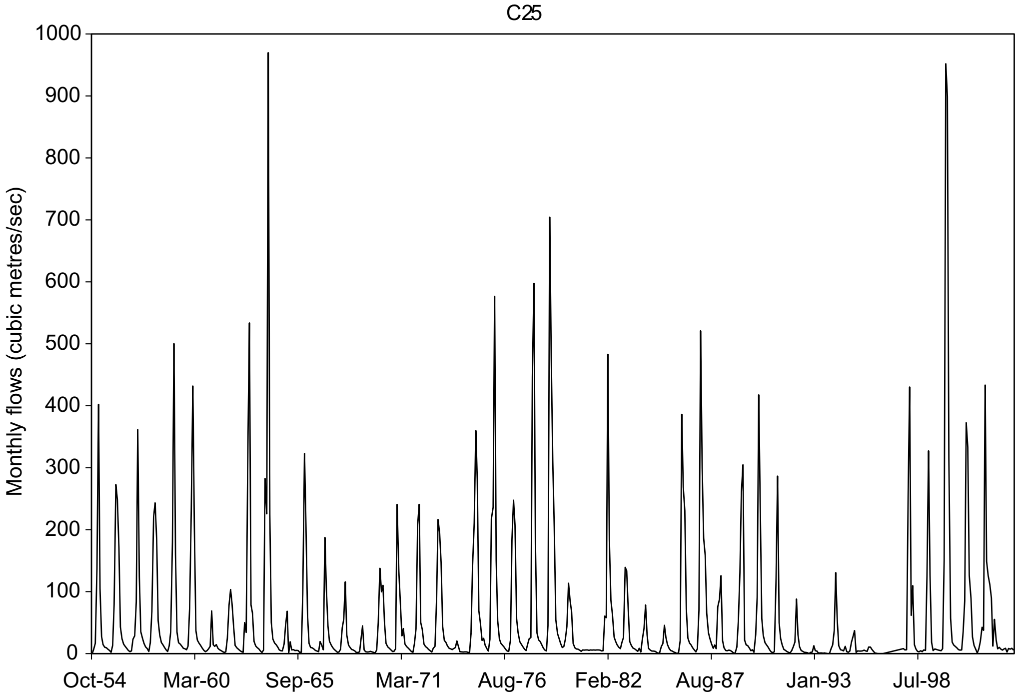

Fig. 2b. Monthly flow variation on a typical river on the central part of the country with flow occurring for quite a substantial part of the year during most years.

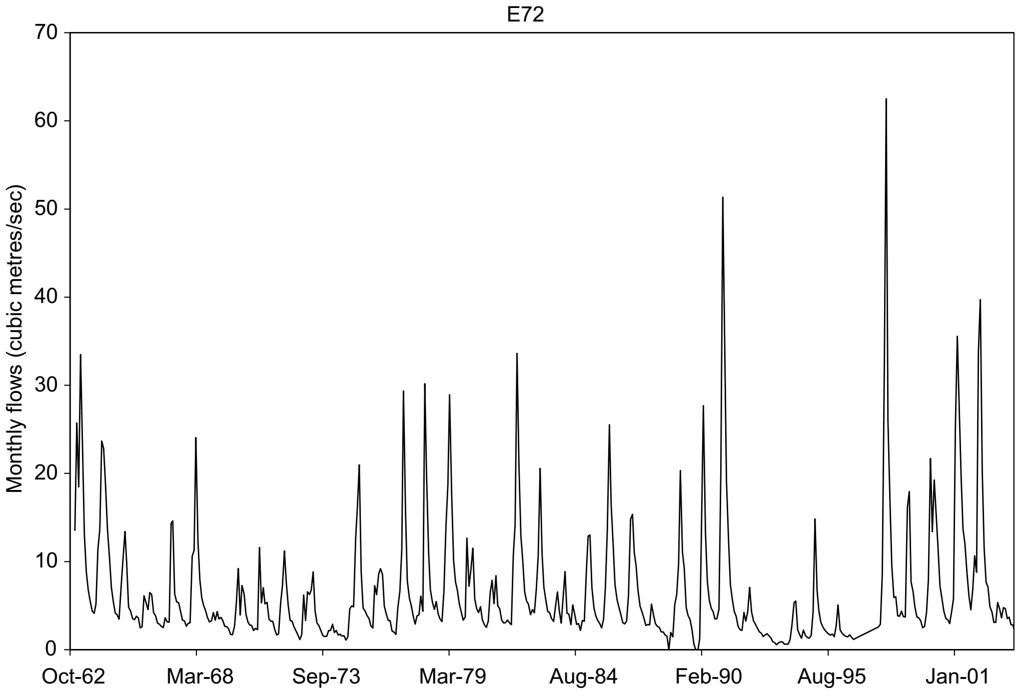

Fig. 2c. Monthly flow variation on a typical perennial river draining the Eastern Highlands.

Sub-basins located on the Eastern Highlands, and the highveld region stretching from the east towards the northern central part of the country have low *CVB* values, less than 10 (Fig. 6). Basins in these regions have annual flows with low variability with the coefficient of variation (CV) of annual flows being 50–100%, and *BFI* being greater than 0.30. River basins on the dry western, extreme northern and southern parts have high *CVB* values, generally greater than 31.

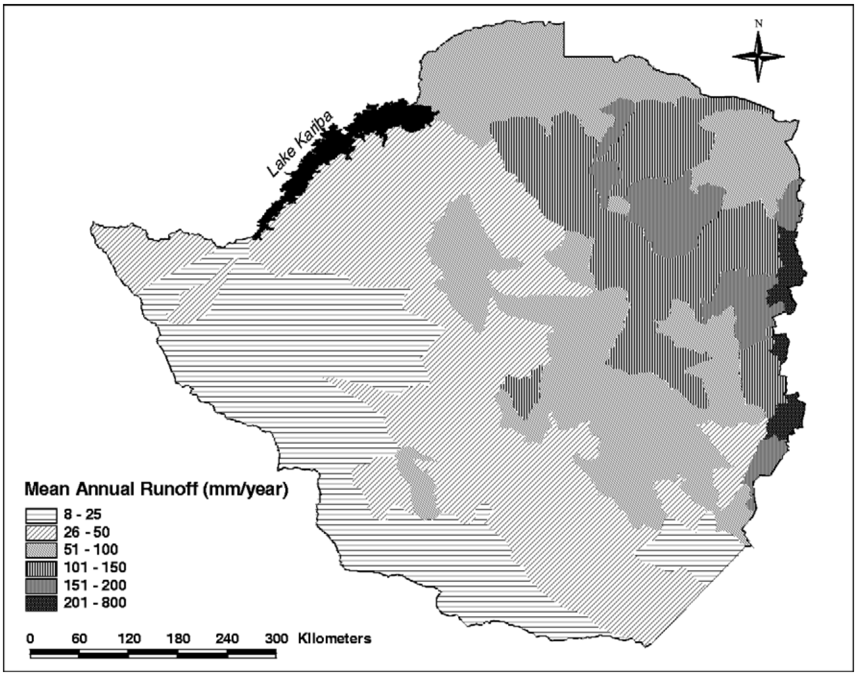

Fig. 3. Variation of mean annual runoff (mm/yr) among the sub-basins of Zimbabwe.

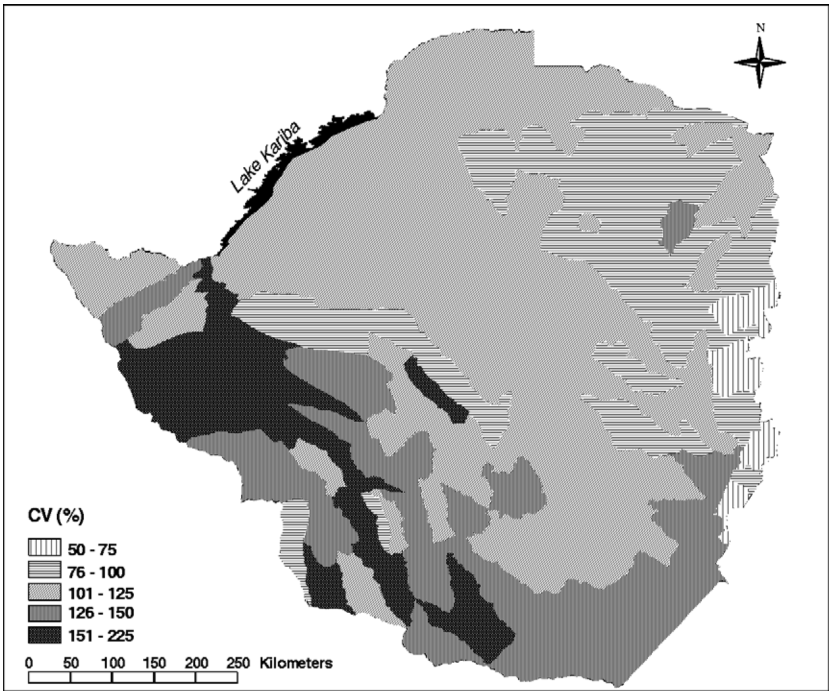

Fig. 4. Coefficient of variation (%) of annual flows.

4.2. Estimated EFRs

The sum of EFR for low flows and high flows gives the Total EFR (TEFR), and this increases with increasing values of *BFI* (Fig. 7). Rivers with high *BFI* values tend to be perennial and therefore supporting important ecosystems, while rivers with low *BFI* values will have flows for limited periods and with ecosystems that have adjusted to the lack of water. EFRs decrease with increasing *CVB* values (Fig. 8). High *CVB* values are characteristic of rivers with highly variable flows often with no flow during the dry season and some year. Ecosystems on these rivers have adjusted to dry conditions, hence the low EFRs.

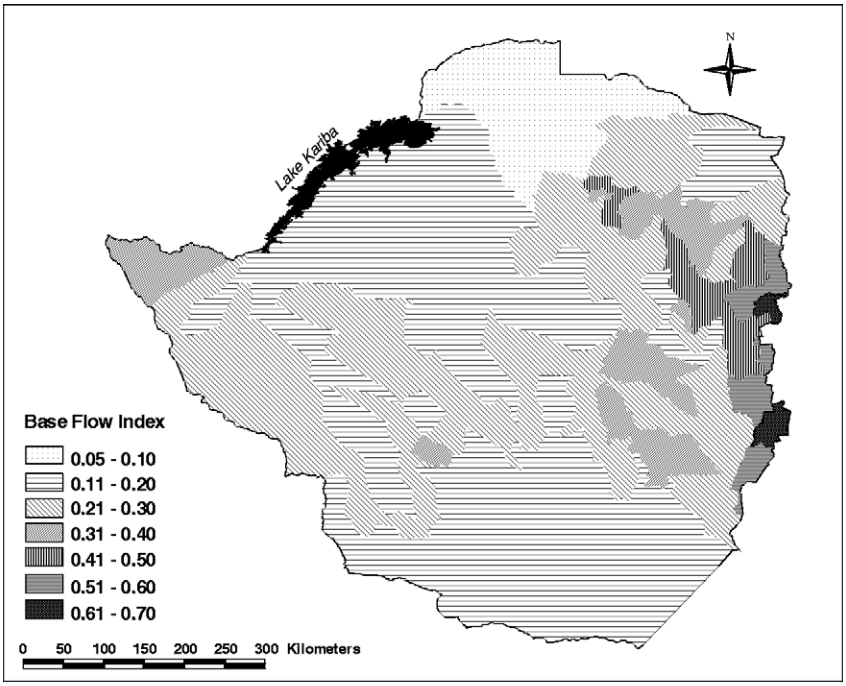

Fig. 5. Spatial variation of base flow index.

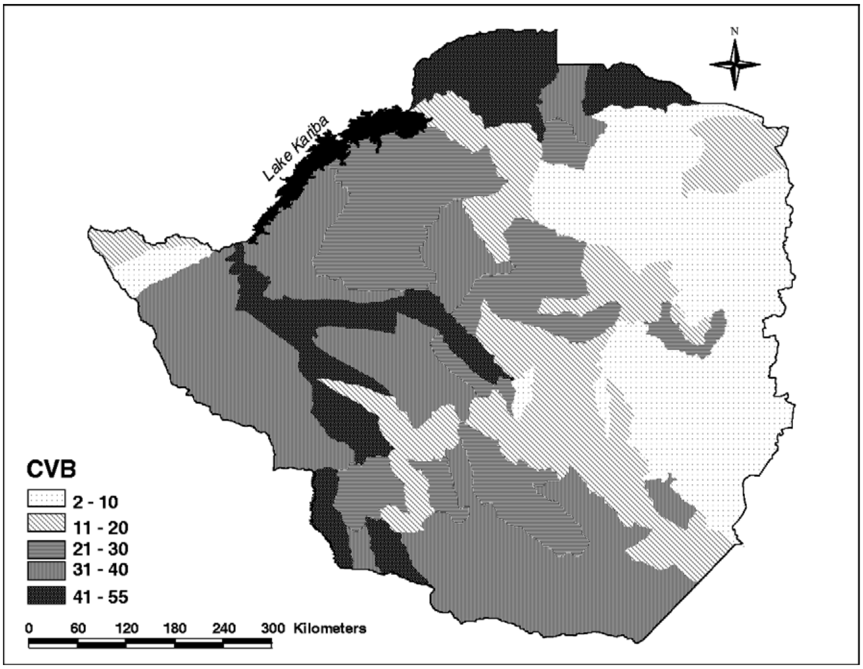

Fig. 6. Estimated values of *CVB*.

Maintenance of natural habitats (Class A) requires an allocation of EFRs equivalent to 31–35% of the *MAR* for the western half of the country (Fig. 9), while 50–67% of *MAR* is required for sub-basins on the Eastern Highlands. The high proportion of *MAR* required on the Eastern Highlands is due to the low variability and high *BFI* on these sub-basins. The perennial rivers on the Eastern Highlands have sensitive ecosystems with trout fish occurring on some of the rivers. Major modifications of flow regimes of these rivers will cause significant changes to these ecosystems. Maintenance of largely natural conditions with few modifications (Class B) requires EFRs in the 31–42% of *MAR* range on the Eastern Highlands, and 21–25% of *MAR* on the western half of the country (Fig. 10). Class C conditions require 21–25%, and 15% of *MAR* as EFRs on the Eastern

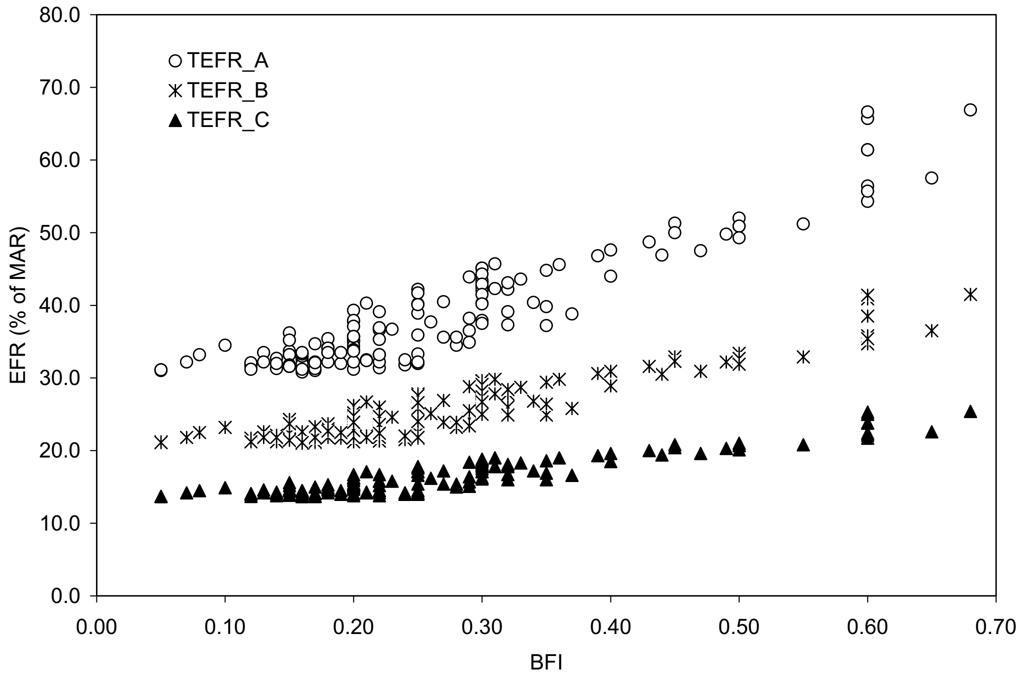

Fig. 7. Relationship between EFRs and *BFI* for Class A (TEFR_A), Class B (TEFR_B), and Class C (TEFR_C) conditions.

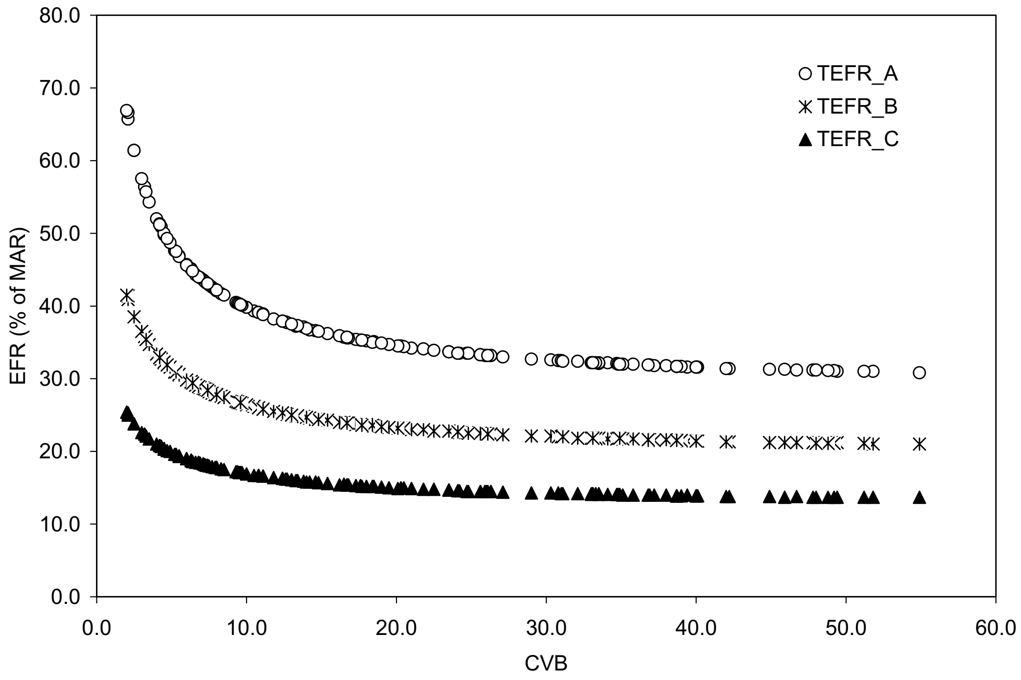

Fig. 8. Relationship between EFR and *CVB*.

Highlands and western half of the country, respectively (Fig. 11). The magnitude of the estimated EFR are broadly in agreement with Tennant (1976) recommendations. Tennant concluded that 30% of the *MAR* was sufficient to maintain good habitats, while optimum conditions required 60–100% of the *MAR*.

4.3. Comparison of EFRs and current water allocations

The total amount of water allocated for both storage and abstraction is less than 50% of the *MAR* on 77% of the sub-basins, and more than 100% of *MAR* on 20% of the sub-basins (Fig. 12). The total amount of water

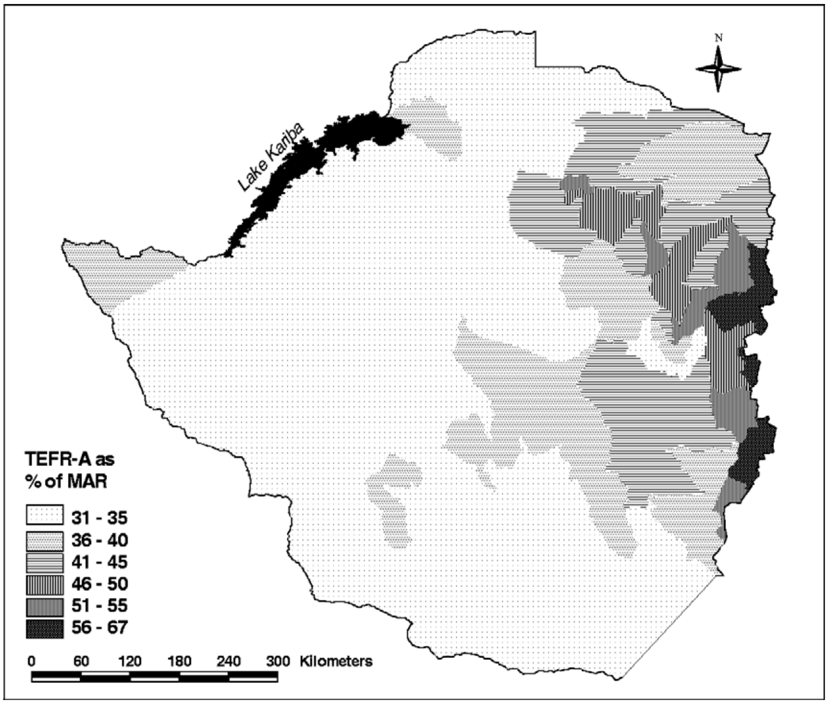

Fig. 9. Environmental flow requires expressed as a % of MAR required to maintain natural habitats (Class A) within sub-basins of Zimbabwe.

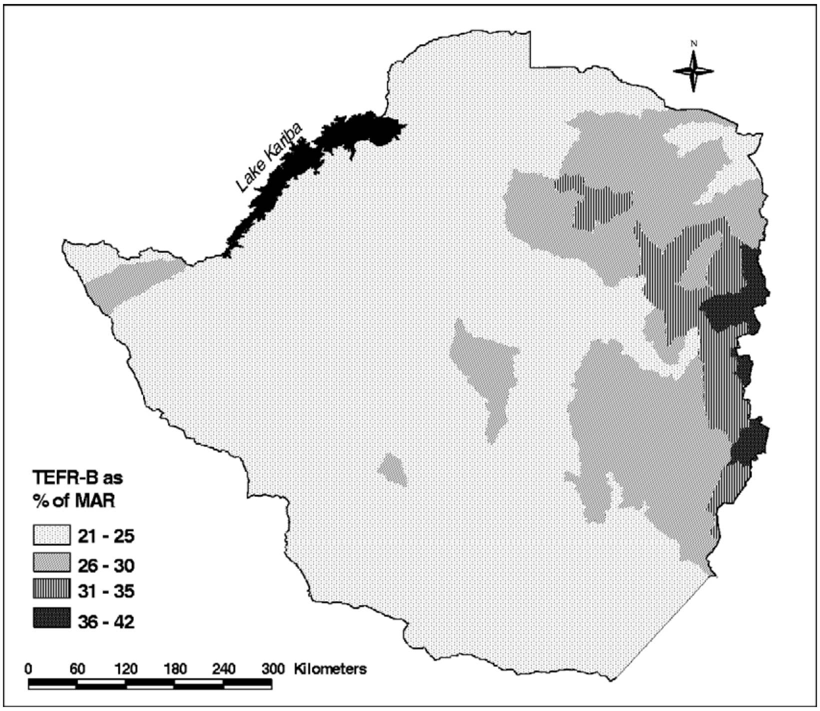

Fig. 10. Environmental flow requires expressed as a % of MAR required to maintain largely natural habitats with few modifications (Class B) within sub-basins of Zimbabwe.

allocated to storage works for the whole country was calculated using data contained in the ZINWA database, and this is about 14×10^9 m^3. According to Smakhtin et al. (2004) when the water allocated is less than 30% of MAR, the environmental flow is being slightly used, 30–60% moderate utilization, 60–100% heavy utilization, and greater than 100% over exploitation of water that should have been reserved for environmental purposes.

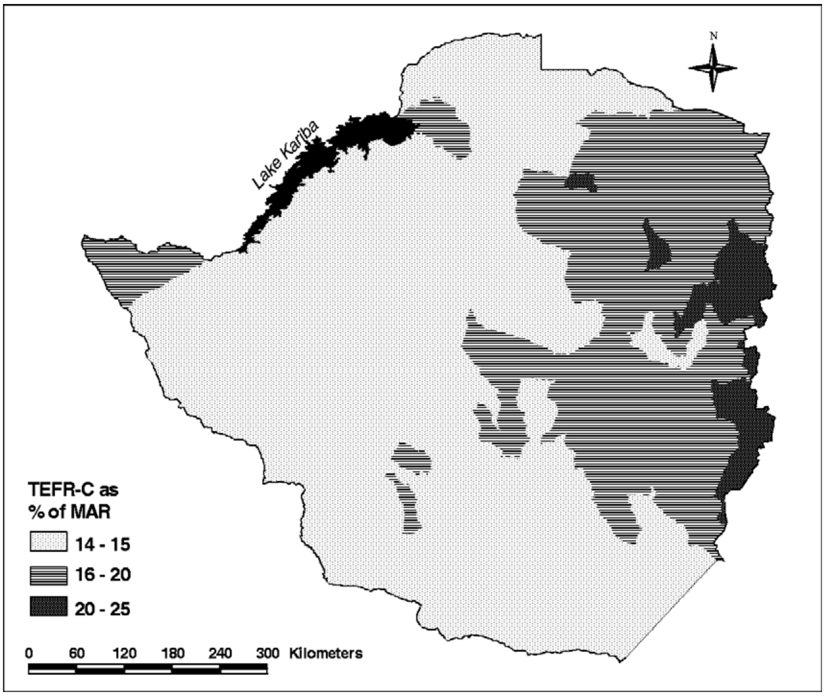

Fig. 11. Environmental flow requires expressed as a % of *MAR* required to maintain moderately changed habitats (Class C) within sub-basins of Zimbabwe.

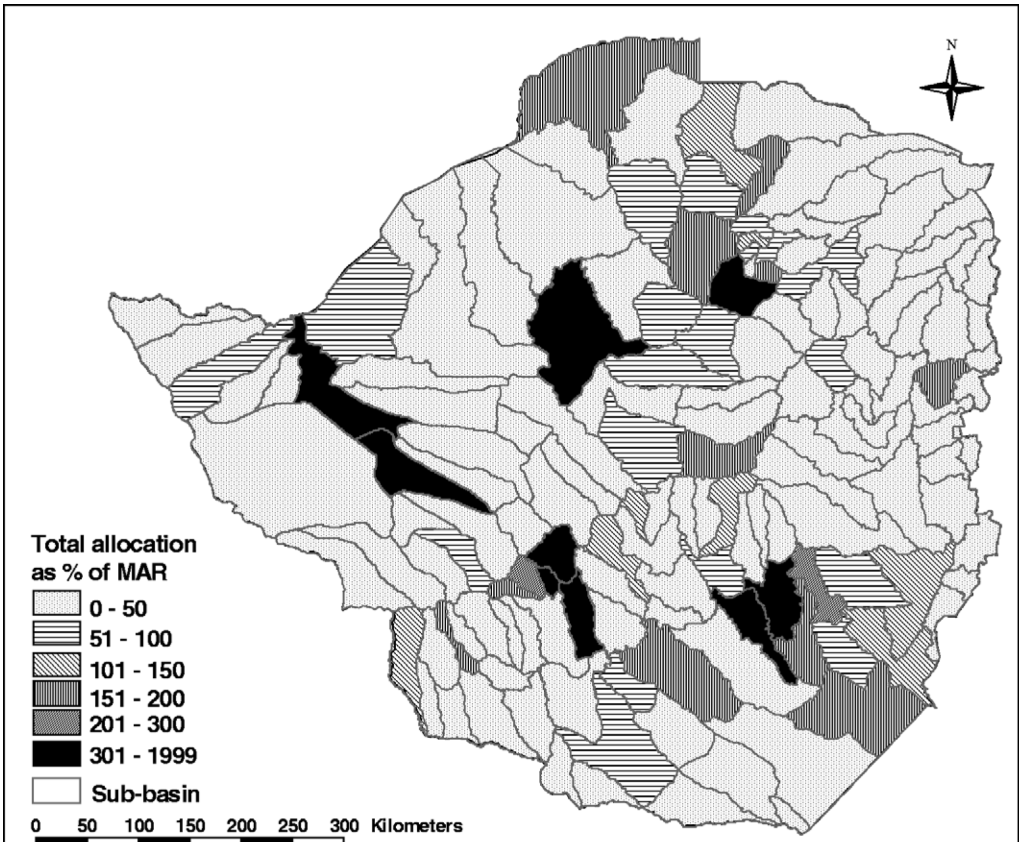

Fig. 12. Total amount of water allocated to water permits expressed as a percentage of *MAR* and the boundaries of the sub-basins used are also shown.

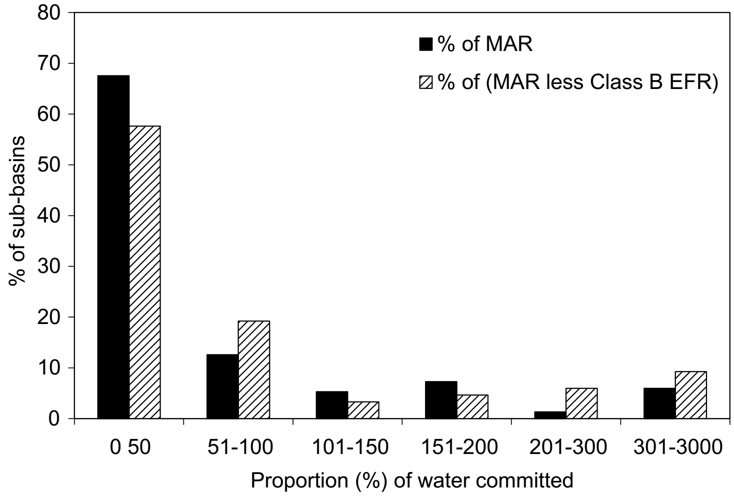

Fig. 13. Comparison of the amount of water allocated with (a) *MAR*, and (b) *MAR* less EFR for Class B.

Using these criteria, water which should be reserved for environmental purposes is being heavily and over exploited on 28% of the sub-basins.

The total amount of water allocated to water permits was expressed as a proportion of the *MAR* after deducting the EFR to determine whether the inclusion of EFR will change the level of the amount of water committed to water permits. The EFR for Class B conditions was used for this purpose, since most rivers have been modified to a certain degree.

The inclusion of EFR increases slightly the commitment levels in some sub-basins resulting in the number of sub-basins with over 100% commitment increasing by 3% (Fig. 13). The inclusion of EFR has not drastically changed the amount of water committed to water permit holders. A major fear for consideration of EFRs in water resources planning is that this would reduce the amount of water available, but the results of this study show that the inclusion of EFRs will not cause major changes to the existing commitments. Fig. 13 shows minor changes to the category to which sub-basins belong to when EFRs are included. A challenge will however be to operationalize the inclusion of EFR in the form of release rules within each sub-basin. Although most basins have very low levels of the amount of water committed to water permits (<50% of *MAR*) these commitments are often to numerous small storage works within each sub-basin. The development and implementation of coordinated release rules that take into account EFR within each sub-basin will therefore be a challenge in view of these numerous small storage works. Further research is therefore required to address this challenge.

5. Conclusion

The desktop method developed by Hughes and Hannart (2003) enables rapid estimation of EFRs, if the relevant hydrological data area available. The method is appropriate for estimating EFRs that can be included in basin wide water resources planning even at the national level. The predictive equations used are conceptually valid as the EFRs estimated increase with the increasing contribution of base flows to total flow, and decrease with increasing flow variability, which is expected. The results of this study suggest that EFRs for relatively wet areas such as the northern central part and Eastern Highlands will be about 30–60% of *MAR*, and 20–30% for the rest of the country. These values are similar to those derived by Tennant (1976), and Orth and Maughan (1981) for some basins in the USA. About 77% of the sub-basins in the country have the total amount of water allocated to existing water permits being less than 50% of *MAR*. The inclusion of EFRs will not drastically change the proportion of water allocated when compared to the *MAR* as is sometimes feared by some of the water users.

The Hughes and Hannart method has been used in this study with coefficients of predictive equations developed from EFR studies done in South Africa. Further EFR studies are required so as to improve or determine the validity of these equations for basins in Zimbabwe and in southern Africa. EFRs estimated in this study are recommended for inclusion in catchment outline plans. However, as additional information becomes available, these EFRs have to be adaptively refined, which is an approach that was also recommended by Richter et al. (1997), and the use of flow statistics reflecting natural river conditions is important since the aim is to maintain natural relationships between river flows and other elements of the river system. For those basins, whereby the only available river flow records have been significantly affected by upstream impoundments and abstractions, naturalization of these flow data should be considered when improving EFR estimates.

Acknowledgements

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