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Estimating environmental flow requirements downstream of the Chara Chara weir on the Blue Nile River

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Abstract:

Over the last decade, flow in the Abay River (i.e. the Blue Nile) has been modified by operation of the Chara Chara weir and diversions to the Tis Abay hydropower stations, located downstream. The most conspicuous impact of these human interventions is significantly reduced flows over the Tis Issat Falls. This paper presents the findings of a hydrological study conducted to estimate environmental flow requirements downstream of the weir. The *Desktop Reserve Model* (*DRM*) was used to determine both high and low flow requirements in the reach containing the Falls. The results indicate that to maintain the basic ecological functioning in this reach requires an average annual allocation of 862 Mm^3 (i.e. equivalent to 22% of the mean annual flow). Under natural conditions there was a considerable seasonal variation, but the absolute minimum mean monthly allocation, even in dry years, should not be less than approximately 10 Mm^3 (i.e. 3·7 m^3 s^{-1}). These estimates make no allowance for maintaining the aesthetic quality of the Falls, which are popular with tourists. The study demonstrated that, in the absence of ecological information, hydrological indices can be used to provide a preliminary estimate of environmental flow requirements. However, to ensure proper management, much greater understanding of the relationships between flow and the ecological condition of the river ecosystem is needed.

KEY WORDS Blue Nile; desktop reserve model; environmental flow requirements; Ethiopia; hydropower

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INTRODUCTION

Water resource management is critical to development, because of its numerous links to poverty reduction, through health, agricultural productivity and industrial and energy growth. However, strategies to reduce poverty should not lead to the unsustainable degradation of water resources or ecological services (World Bank, 2003). One of the major challenges for sustainable water resource management is to assess how much water can be taken from a river before its ability to meet social, ecological and economic needs declines.

The Blue Nile (known as the Abay River in Ethiopia) is the principal tributary of the main Nile River. The river and its tributaries drain a large proportion (172 254 km^2) of the central, western and south-western highlands of Ethiopia before dropping to the plains of Sudan. Mean annual flow at the border is 48 660 Mm^3. The river provides 62% of the flow reaching the Aswan High Dam and is a vital source of water for both Sudan and Egypt (World Bank, 2006). Despite the fact that almost all the flow is generated in the Ethiopian Highlands, currently Ethiopia utilizes very little of the Blue Nile water. To date, only two relatively minor dams have been constructed in the Abay catchment. Both are utilized for hydropower production. It is estimated that irrigation covers less than 10 000 ha. This compares to over 1 million hectares of irrigation in the Sudanese part of the Blue Nile catchment (Awulachew *et al*., 2008).

One of the dams constructed in Ethiopia, and the only one actually located on the main stem of the Abay River, is the Chara Chara weir. This is used to regulate flow from Lake Tana, for downstream electricity production at two power stations at Tis Abay (Figure 1). An environmental impact assessment (EIA) was conducted prior to construction of the weir. However, estimates of flow requirements were based largely on the aesthetic impact of different discharges over the famous Tis Issat waterfall, a major tourist attraction situated immediately downstream of the diversion to the power stations (Bellier *et al*., 1997). It was recommended that flows over the Falls should lie in the range 10–60 m^3 s^{-1} (Table I).

This paper describes a more ecological-based approach to determine environmental flows downstream of the Chara Chara weir. The current study determined the impact of the weir on flows from Lake Tana and estimated environmental flow requirements in the river reach containing the Falls. These were compared with the actual flows in the river since the weir became fully operational in 2001. The study is believed to be one of the first attempts to rigorously quantify a full range of environmental flow requirements (i.e. both high and low flows) and to assess the impact of flow regulation, anywhere on the Blue Nile River.

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Table I. EIA recommended flow over the Tis Issat Falls

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Flow ($m^3\ s^{-1}$)	60	60	10	10	10	10	20	20	40	40	40	60	
Volume (Mm^3)	161	146	27	26	27	26	54	54	104	107	104	161	995

Source: Howard *et al*., 1997.

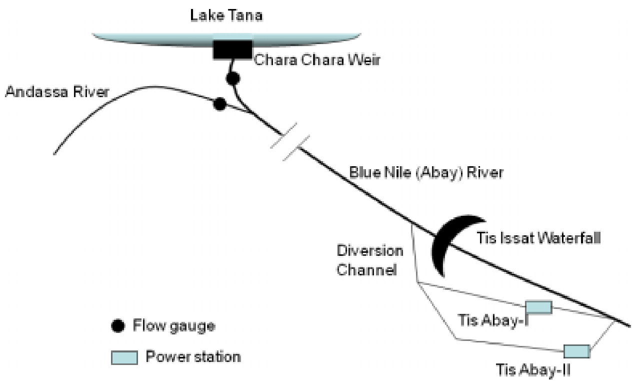

Figure 1. Schematic of the system (not to scale)

STUDY SITE

Lake Tana occupies a shallow depression (maximum depth 14 m) in the Ethiopian highlands. The geology of the area is primarily basaltic lavas of the Aden Volcanic series. The lake is believed to have formed as a consequence of damming by lava during the Pliocene (Mohr, 1962). The surface area of the Lake is 3156 km^2. The catchment area at the lake outlet is 15 321 km^2. The climate of the area is largely controlled by the movement of the inter-tropical convergence zone that results in a single rainy season between June and September. The mean annual rainfall over the catchment is estimated to be 1342 mm, with slightly more rain falling in the south than in the north of the catchment (Melkamu, 2005).

The mean annual inflow to the lake is estimated to be 114 $m^3\ s^{-1}$ (3595 $Mm^3\ y^{-1}$). Mean annual evaporation and rainfall are approximately balanced, and the mean annual outflow is estimated to be 120 $m^3\ s^{-1}$ (i.e. 3776 $Mm^3\ y^{-1}$) (Kebede *et al*., 2006). The outflow, which equates to approximately 8% of the total Blue Nile flow at the border with Sudan, represents 257 mm over the total catchment, giving a coefficient of runoff of 18%. Under natural conditions, discharge from the lake is closely linked to rainfall and there is considerable seasonal and inter-annual variability (Kebede *et al*., 2006).

The original power plant at Tis Abay (Tis Abay-I) was constructed by the Ethiopian Electricity Light and Power Authority (EELPA) and came online in 1964. Located approximately 35 km downstream of the lake outlet, the station was used to provide electricity for a textile factory and for domestic supply to the city of Bahar Dar. By diverting water from upstream of the Tis Issat Falls, the power plant makes use of the natural 46 m head of the Falls. The installed capacity of the power plant is 11·4 MW and initially it relied entirely on diversion of the natural flow of the river. On average less than 5% of the annual discharge was diverted to the power station, although this was substantially more (up to 34%) in dry season months.

The concept of building a weir to regulate the outflow from Lake Tana was first postulated in the early years of the twentieth century. However, it was not until 1977 that consideration was given to regulating the flow to provide water for a larger Tis Abay power station, which could contribute to the national grid (JICA, 1977). The scheme envisaged the construction of a weir at the outlet of Lake Tana and a second power house located 100 m downstream of the Tis Abay-I plant (Figure 1). Construction of the weir started in 1984, but was abandoned shortly afterwards (Coyne et Bellier, 1997). Construction was re-started in 1994 and the weir was largely completed by May 1996. Initially the weir had only two gates, each with a capacity of 70 $m^3\ s^{-1}$, and provided sufficient regulation only to improve the power production from Tis Abay-I. An additional five gates, each also with capacity 70 $m^3\ s^{-1}$, were added to the weir in 2001. The second power station (Tis Abay-II), with an installed capacity of 72 MW, was also completed in 2001. Since then the weir has been operated by the Ethiopian Electricity Power Corporation (EEPCO) (the successor to the EELPA) to maximize power production from both power stations. Currently the two power stations represent 11% of the total grid-based electricity-generating capacity of the country (731 MW), 90% of which is generated by hydropower (World Bank, 2006).

The Chara Chara weir regulates water storage in Lake Tana over a 3 m range of water levels from 1784 to 1787 masl. The active storage of the lake between these levels is 9100 Mm^3, which represents approximately 2·4 times the average annual outflow. At full supply level the total flow through the seven gates is 490 $m^3\ s^{-1}$. Approximately 110 $m^3\ s^{-1}$ (the total flow capacity of both Tisa Abay-I and II) can be released continuously with 95% reliability (Bellier *et al*., 1997).

Currently Ethiopian law (through a proclamation passed in 2002) requires that, for all major development projects, an EIA is conducted and that environmental impacts should be minimized. However, there is no specific requirement for environmental flows to be maintained. Although the Chara Chara weir was constructed prior to the EIA proclamation, an EIA was conducted. As a part of this, an attempt was made to estimate the flow requirements over the Tis Issat Falls. However, the focus was on tourist needs and so this evaluation was based primarily on the appearance of the Falls under different flow regimes (Bellier *et al*., 1997). The maximum flows were recommended not for the wet season when flows would naturally be highest, but to make the Falls look most dramatic during the peak tourist season from December to February (Table I).

METHOD

The current study comprised two elements. First, analyses of flow data to quantify the changes in the hydrological regime of the river arising from operation of the weir, and diversions to the power stations. Second, an evaluation of environmental flow requirements, derived from hydrological indices, through application of the South African Desktop Reserve Model (DRM) (Hughes and Hannart, 2003).

Change in hydrological regime

A gauging station, located immediately downstream of the outlet from Lake Tana, has been operated continuously since 1959. The intermediate catchment between the Chara Chara weir and the diversion to the Tis Abay power stations has an area of 1094 km^2. The principal tributary between the lake and Tis Abay is the Andassa River, which is gauged just upstream of its confluence with the Blue Nile (Figure 1). The catchment area at the gauging station (which has also been in operation since 1959) is 573 km^2.

Time series of monthly flow data were obtained from the Ministry of Water Resources for both gauging stations, from January 1959 to December 2006. Daily flow series were obtained for both stations from January 1973 to December 2006. An estimate of the contribution from the ungauged portion of catchment downstream of the lake outlet was derived simply by multiplying the flow series derived from the Andassa gauge using an area-weighting. The flows downstream of Lake Tana were added to the flows from the outlet to provide an estimate of the total flow at the diversion to the power stations. Turbine discharge data for both Tis Abay-I and II power stations were obtained from EEPCO and used to estimate the monthly flows diverted to produce electricity as well as the water remaining in the river to flow over the Falls.

Analyses of flows were conducted over three time periods: May 1959–April 1996, May 1996–December 2000 and January 2001–December 2006. These periods correspond to different levels of regulation of the Lake Tana outflow (Table II). Standard hydrological techniques including flow frequency analyses and the development of flow duration curves (using the daily data) (Gustard *et al*., 1992) were used to compare the flow regimes in each of these periods.

Estimated environmental flows

Environmental flows are the water that is left in a river, or released into it (e.g. from a reservoir), in order to maintain valued features of the ecosystem (Tharme and King, 1998). In recent years, there has been a rapid proliferation of methods for estimating environmental flows, ranging from relatively simple, low-confidence, desktop approaches, to resource-intensive, high-confidence approaches (Tharme, 2003). The comprehensive methods are based on detailed multi-disciplinary studies that often involve expert discussions and collection of large amounts of geo-morphological and ecological data (e.g. King and Louw, 1998). Typically they take many months, sometimes years, to complete.

Table II. Periods of different flow regulation from Lake Tana

Period	Description
May 1959–April 1996	No regulation of outflow from Lake Tana. Diversions to the Tis Abay-I power station commenced in January 1964.
May 1996–December 2000	Two-gate Chara Chara weir becomes operational in May 1996. Weir operated to regulate flow to the Tis Abay-I power station.
January 2001–December 2006	Five new gates constructed and new weir becomes operational in January 2001. Weir operated to regulate flow to both the Tis Abay-I and Tis Abay-II power stations.

A key constraint to the application of comprehensive methods, particularly in developing countries, is the lack of data linking ecological conditions to specific flows. To compensate for this, several methods of estimating environmental flows have been developed that are based solely on hydrological indices derived from historical data (Tharme, 2003). Although it is recognized that a myriad of factors influence the ecology of aquatic ecosystems (e.g. temperature, water quality and turbidity), the common supposition of these approaches is that the flow regime is the primary driving force (Richter *et al*., 1997).

One such method is the DRM, which is intended to quantify environmental flow requirements in situations when a rapid appraisal is required and data availability is limited (Hughes and Hannart, 2003). The model is built on the concepts of the building block method, which was developed by South African scientists over several years (King *et al*., 2000), and is widely recognized as a scientifically legitimate approach to setting environmental flow requirements (Hughes and Hannart, 2003). The model comprises empirically derived statistical relationships developed through an analysis of comprehensive environmental flow studies conducted in South Africa. This found that rivers with more stable flow regimes have relatively higher flow requirements than rivers with more variable flow regimes. This is because in highly variable flow regimes the biota would have adjusted to relative scarcity of water, while in more reliably flowing rivers the biota are more sensitive to reduction in flow (Hughes and Hannart, 2003).

The Building Block Method is underpinned by the premise that, under natural conditions, different flows play different roles in the ecological functioning of a

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river. Consequently, to ensure sustainability, it is necessary to retain key elements of natural flow variation. Hence, the so-called Building Blocks are different components of flow which, when combined, comprise a regime that facilitates the maintenance of the river in a pre-specified condition. The flow blocks comprise low flows, as well as high flows, required for channel maintenance and differ between 'normal years' and 'drought years'. The flow needs in normal years are referred to as 'maintenance requirements' and divided between high and low flow components. The flow needs in drought years are referred to as 'drought requirements' (Hughes, 2001). The DRM provides estimates of these building blocks for each month of the year.

In this study, the DRM was used to estimate environmental flow requirements in the river reach between the diversion to the Tis Abay power stations and the point where the water is returned to the river (Figure 1). This reach includes the Tis Issat Falls. To estimate environmental flow requirements, the model needs a naturalized flow series as input. Prior to the construction of the two-gate Chara Chara weir (in 1996), outflows from Lake Tana were unmodified and so represent a naturalized flow series. These data were used as input to the model. For the flow over the Falls, the contribution of flow from the Andassa River and the rest of the catchment between Lake Tana and the Falls was added to the Lake Tana outflow series. Some data were missing. Single months of missing data during periods of declining flow were filled by interpolation. However, in cases where there were consecutive months of missing data, or missing data occurred during periods when flows were rising, this was not possible and so the whole year was eliminated from the analyses. A total 4 months were filled by interpolation and 6 years were eliminated. Hence, a total of 31 years of data were used as input to the model.

In South Africa, rivers are classified in relation to a desired ecological condition and flow requirements set accordingly. Six management classes are defined, ranging from A to F. Class A rivers are largely unmodified and natural and Class F rivers are extremely modified and highly degraded (DWAF, 1999). Classes E and F are deemed ecologically unsustainable, so Class D (i.e. largely modified) is the lowest allowed 'target' for future status. This classification system is used in conjunction with the building block method and flow requirements are computed accordingly; the higher the class, the more water is allocated for ecosystem maintenance and the greater the range of flow variability preserved. In the current study, to reflect the importance of water abstractions for hydropower production, the desired ecological condition of the Blue Nile was set as C/D (i.e. moderately to largely modified). This means that the flow regime will change in such a way that there is likely to be loss and change of natural habitat and biota (possibly including fish), but the basic ecosystem functions of the system will only be moderately altered (Kleynhans, 1996). In contrast to the analyses conducted for the EIA, no allowance was made for the aesthetic quality of flows over the Falls.

Flow variability plays a major role in determining environmental flow requirements. Within the model, the long-term variability of wet and dry season flows is based on calculating the coefficient of variation (CV) for all monthly flows for each calendar month. The average CVs for the three main months of the both the wet and the dry seasons are then calculated and the final CV-Index is the sum of these two season's averages (Hughes and Hannart, 2003). A limitation of the model is that in computing CV-Index, the model assumes that the primary dry season months are January—March as occurs over much of South Africa. Within the model this cannot be altered. However, for the Blue Nile the key months are August–October and March–May for the wet and dry seasons, respectively. To ensure that the model computed a flow variability index closer to reality, the input time series of flows was shifted so that each year began in June rather than in October, which is the practice in South Africa. After running, the model outputs were corrected to ensure that model results were applied to the correct months.

RESULTS

Impacts of flow regulation

Figure 2 shows the mean monthly flow, measured immediately downstream of the Chara Chara weir, for the three periods investigated. The May 1959–April 1996 results indicate the extreme seasonal variability in the natural flow regime ranging from a mean of 346 $m^3 s^{-1}$ in September to just 12 $m^3 s^{-1}$ in June. On average only 12% of the natural discharge from the lake occurred in the 5 months, February–June. In the period May 1996–December 2000, both wet and dry season flows were significantly higher than that occurred in the previous period. The higher dry season flows were a consequence of partial flow regulation by the two-gate Chara Chara weir. The higher wet season flows were a consequence of above average rainfall in these years, particularly in 1998. MAF in 1998 (196·0 $m^3 s^{-1}$; 6182 Mm^3) was the highest annual discharge measured in the whole 48-year record. The results for the period

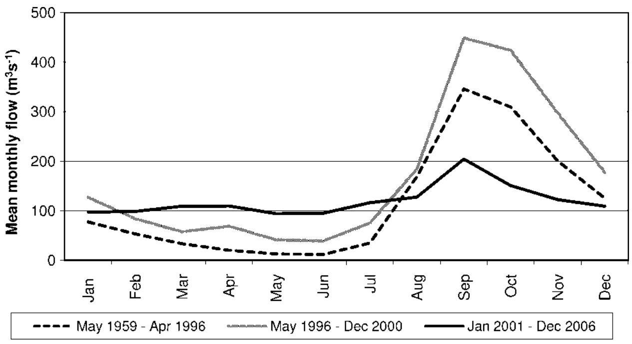

Figure 2. Mean monthly flow from Lake Tana for three periods of different flow regulation

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from January 2001 to December 2006, illustrate the much higher dry season flows and reduced wet season flows arising as a consequence of the full flow regulation by the Chara Chara weir. As a consequence of regulation there is much less seasonal variability in flow from the lake. After 2001, 43% of the discharge from the lake occurred in the 5 months, February–June.

Flow duration curves, which show the percent of time that a specified discharge is equalled or exceeded, were derived for the period for which daily data were available (i.e. from January 1973–December 2006) (Figure 3). These confirm the significant impact of the new seven-gate Chara Chara weir on flow from the lake. Since 2001, there has been a significant increase in flows lower than Q_{50} (i.e. the mean daily flow exceeded 50% of the time), and a significant decrease in flows above Q_{50}. Q_{95} and Q_{90} increased from 9·0 m^3 s^{-1} and 11·9 m^3 s^{-1} to 59·3 m^3 s^{-1} and 64·5 m^3 s^{-1}, respectively. In contrast, Q_{10} and Q_5 decreased from 285·8 m^3 s^{-1} and 382·6 m^3 s^{-1} to 195·5 m^3 s^{-1} and 246·3 m^3 s^{-1}, respectively.

Impact of hydropower diversions

The data provided by EEPCO indicate that when only the Tis Abay-I power station was operational (i.e. between 1964 and 2000) average annual turbine discharge was just 192 Mm^3 (i.e. 6·1 m^3 s^{-1}). Throughout this period just 4·5% of the average annual discharge at Tis Abay (4227 Mm^3) was diverted. Since 2001, when Tis Abay-II came online, the average annual turbine discharge has increased to 3090 Mm^3 (i.e. 97·9 m^3 s^{-1}). This equates to 72% of the average annual discharge at Tis Abay (4306 Mm^3) between 2001 and 2006.

Diversions to the original Tis Abay-I power station had very little impact on the flows over the Tis Issat waterfall. Between 1964 and 2000 average annual discharge over the Falls is estimated to have been 128 m^3 s^{-1} (i.e. 4040 Mm^3). By comparison, between 2001 and 2006 the average annual discharge over the Falls is estimated to have been just 41 m^3 s^{-1} (i.e. 1305 Mm^3), with a minimum of just 4·7 m^3 s^{-1} (i.e. 147 Mm^3) in 2004 and less than 12 m^3 s^{-1} (i.e. 378 Mm^3) in both 2003 and 2005. Between 2001 and 2006, in many months, the mean discharge was less than 50%, what it was prior to 2001 (Figure 4).

Environmental flow requirements

Figure 5 presents a comparison of the observed time series and the DRM derived environmental flow series for the river reach including the Falls. Results from the model indicate that to maintain the river at Class C/D requires an average annual environmental flow allocation of 862 Mm^3 (i.e. equivalent to 22% of the natural MAF) (Table III). This is the average annual 'maintenance flow' calculated from the mean of both the maintenance low flows (i.e. 626 Mm^3) and maintenance high flows (i.e. 236 Mm^3). The drought flows correspond to 11% of the MAF (i.e. 440 Mm^3).

For the period 2001–2006, average annual flows over the Falls (i.e. 1305 Mm^3) exceeded the annual total maintenance flow requirements predicted by the model (i.e. 862 Mm^3). However, more detailed analysis shows that in most months average flows were significantly less than the environmental flow requirements predicted by the model. For several months average flows were less than 70% of the estimated requirement (Table IV). Only in months July–October (i.e. wet season months) did the average flow over the period 2001–2006 exceed the recommendation of the DRM (Table IV; Figure 6). This suggests that, in recent years, dry season flows have been insufficient to maintain even basic ecological functioning of this reach of the Abay River. Furthermore, even though the average over the period exceeds the DRM recommendation, in several years even the wet season flow was a lot less than recommended. For example, in September and October 2005, flows over the Falls

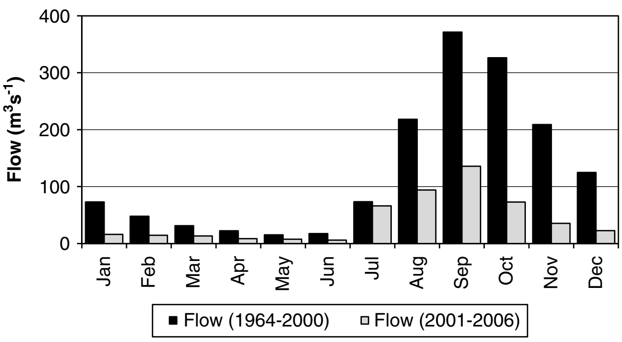

Figure 4. Comparison of flow over the Tis Issat Falls for the periods 1964–2000 and 2001–2006

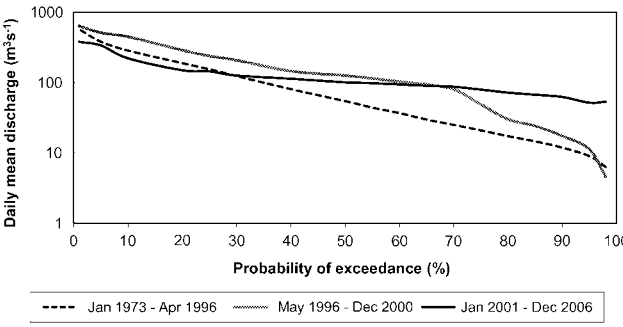

Figure 3. Flow duration curves for the Blue Nile River, at the outlet from Lake Tana. Note that flows are shown on a log scale to illustrate clearly the differences in low flows in the three different time periods

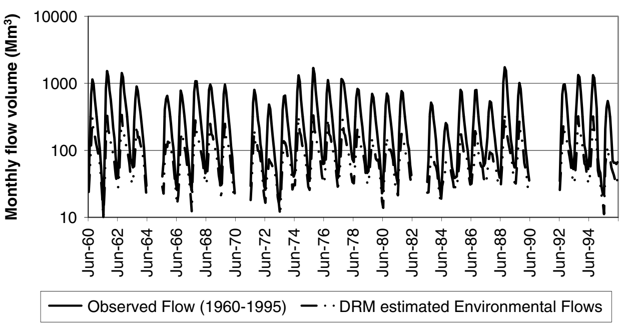

Figure 5. Time series of monthly observed flows and estimated flows (1960–1995) for the reach of Abay River that includes the Tis Issat Falls (log scale on the *y*-axis)

Table III. Summary output from the DRM applied to the reach of the Tis Issat Falls based on 1960–1995 monthly flow series

Annual flows (Mm^3 or index values)

MAR = 4017	**Total Environmental flow** = 862 (22% MAF)
SD = 1293	**Maintenance Low flow** = 626 (16% MAF)
CV = 0·322	**Drought Low flow** = 440 (11% MAF)
BFI = 0·37	**Maintenance High flow** = 236 (6% MAF)

Month	Observed flow (Mm^3)		Environmental flow requirement (Mm^3)			
			Maintenance flows			Drought flows
	Mean	CV	Low	High	Total	
Jan	217	0·35	68	0	68	48
Feb	135	0·34	56	0	56	39
Mar	97	0·31	42	0	42	30
Apr	58	0·29	28	0	28	20
May	42	0·35	22	0	22	16
Jun	44	0·46	20	1	21	10
Jul	180	0·43	27	11	39	20
Aug	590	0·38	51	33	83	36
Sep	946	0·39	77	115	192	54
Oct	839	0·36	84	33	117	59
Nov	526	0·33	78	31	109	55
Dec	345	0·33	74	12	86	52

Table IV. Comparison of environmental flow requirements computed by the DRM and observed mean monthly flows in the river reach that includes the Tis Issat Falls, between 2001 and 2006

Month	Total maintenance requirements (Mm^3 month^{-1})	Observed flows (Mm^3 month^{-1})	Ratio of Observed to environmental flow requirement
Jan	68	44	0·64
Feb	56	36	0·64
Mar	42	36	0·85
Apr	28	22	0·81
May	23	21	0·96
Jun	21	16	0·76
Jul	39	178	4·57
Aug	83	252	3·03
Sep	192	352	1·83
Oct	117	196	1·68
Nov	109	92	0·85
Dec	86	61	0·71
Annual	862	1305	

were estimated to have been just 44 and 7·6 Mm^3, respectively; less than even the recommended minimum drought flows.

DISCUSSION

Operation of the Chara Chara weir has altered the flow regime of the Abay River. Between the outlet from Lake Tana and Tis Abay, the regulation has significantly increased dry season and significantly decreased wet season flows. No ecological surveys have been conducted, but there is little doubt that the reduced inter-seasonal variability will have had an impact on the ecology of the river, benefiting those species that depend on more regular flows while adversely impacting those species adapted to seasonal drying. The changes in flow are likely to have affected sediment transport and altered water chemistry and temperature regimes. Although the consequences of these changes may not be apparent for many decades, it is possible that they will modify, among other things, channel morphology and substrate composition, as well as river biota (McCartney *et al*., 2000).

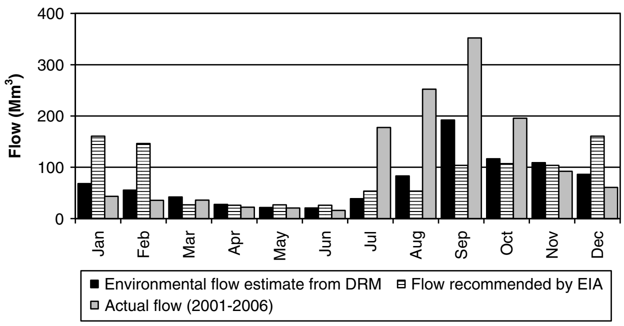

Figure 6. Comparison of mean monthly environmental flow requirements estimated using the DRM with the recommendation of the EIA, and the actual flows over the Tis Issat Falls

In addition to ecological impacts, the change in flow regime has also had social impacts. For instance the reduced wet season flows have resulted in less flooding. In a recent survey, local communities expressed satisfaction at the reduction in flooding, which in the past used to destroy their crops (Gebre *et al*., 2008). Some farmers have also benefited from the higher dry season flows since they enable increased dry season irrigation. This means that they are able to produce a dry season crop, part of which is used for household consumption and part of which is sold (Shiferaw, 2007). The increased dry season flows have also benefited women who have to collect household water supplies from the river (Shiferaw, 2007). Thus riparian communities located between the weir and Tis Abay largely perceive the weir to have brought livelihood benefits.

Since 2001, flows in the reach containing the Falls have been significantly reduced, in both the wet and dry seasons, as a consequence of diversions to the power stations. Again, although no ecological surveys have been conducted, there is little doubt that the reduction in flows would have had very severe consequences for many species including aquatic macrophytes, benthic organisms and fish (Staissny, 1996; Seddon, 2000). The reduced flows are also very likely to have had adverse impacts on many riparian species. By changing the magnitude and extent of inundation and altering land–water interaction the change in flows might have disrupted plant reproduction. Overtime it may allow the encroachment of upland plants previously prevented by more frequent flooding (Nilsson *et al*., 1997).

The change in flows over the Falls has also had social consequences. Surprisingly, the number of tourists visiting the Falls increased in recent years (Shiferaw,

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2007). This is partly the result of greater numbers of tourists generally in Ethiopia and partly because the Falls are still promoted as a major tourist attraction. Many of the tourists who visit Bahar Dar are unaware that flows over the Falls have decreased. According to local people, many visitors are now unhappy with the visual spectacle and, because they are annoyed, refuse to buy locally made handicrafts. In the past, the selling of these products contributed significantly to the income of many local people. Although a few people have gained employment at the power stations, many have not. Consequently, the loss of income from tourists has had a negative impact on the livelihoods of many local people which has not been compensated through alternative opportunities (Gebre *et al.*, 2008). The local community also complain that they have no access to electricity, despite the fact that the power stations are located very close to their village. Furthermore development opportunities (e.g. a school and clinic), promised when Tis Abay-II was built, have not been forthcoming. Consequently, many people living in the village closest to the power station feel that they have gained nothing and have in fact lost as a consequence of the construction of the weir and the power stations (Gebre *et al.*, 2008).

The DRM has been used extensively in South Africa. Its use in other countries is limited, but it has been applied in Swaziland, Zimbabwe, Mozambique (Hughes and Hannart, 2003) and Tanzania (Kashaigili *et al.*, 2007). For the current study, the accuracy of the model results cannot be substantiated without further study. However, given that it is underpinned by empirical equations developed specifically for South Africa, and is only intended to be a 'low-confidence' approach, the results must be treated with caution. Nonetheless, despite the limitations, in the absence of quantitative information on the relationships between flow and the ecological functioning of the river ecosystem, it is a valuable first estimate of environmental flow requirements in this reach of the river.

In this study, by selecting a C/D classification for the reach the importance of electricity for the socio-economic development of the country is acknowledged. A C/D classification recognizes that, in the interests of Ethiopia's development, it is necessary to modify the river from its natural condition (Whittington, 2002). However, for reasons of equity and sustainability, it is nevertheless necessary to maintain the basic ecosystem functions of the river. If flows are changed too much, the lotic system will be modified completely with major loss of natural habitat and the destruction of basic ecosystem functions. This, which may be happening under the current flow regime, could have dire long-term consequences not only for biota, but also people living in the area. It is therefore necessary to derive an adequate compromise between the ecological character of the river and the level of direct human utilization. In the long-term, it may be better to forego some electricity production in order to maintain the basic ecosystem functions of the river.

To improve the environmental flow estimates, detailed studies need to be undertaken to investigate the ecological sensitivity of the river to flow modification throughout its length from the Lake Tana outlet to the Falls and, indeed, downstream of the point where the diverted flows are returned to the river. The impact of maintaining environmental flows on water levels and, hence, the ecology of Lake Tana should be very carefully assessed. Furthermore, in order to make informed decisions about the desired ecological state of the river, both the implications for hydropower production and the social implications (positive and negative) of different flow regimes should be carefully evaluated. It is very important that, as far as possible, such evaluations go beyond simple cost-benefit analyses and also include intangible benefits that cannot be expressed in monetary terms. Finally, other detailed studies should be conducted at different locations on the Abay and its tributaries, and also on other rivers, to calibrate and improve the DRM for more general application on the Nile and elsewhere in Ethiopia.

With many more dams planned in Ethiopia in the near future, it is essential to ensure that environmental and social safeguards are developed and implemented (Hathaway, 2008). Ethiopia would therefore benefit from a long-term program to build capacity in environmental flow assessment. As a starting point, this should be developed using the expert opinion of national ecologists, hydrologist, social scientists and others who have detailed knowledge and experience of the country's rivers. Even if the initial results are uncertain, attempting environmental flow assessment utilising an expert panel approach would develop team building and assist interactions between different disciplines (King *et al.*, 2000). This would be a useful first step in the development of national expertise in environmental flow assessment.

CONCLUSION

In recent years, the Tis Abay power stations have been vital for electricity production and have contributed significantly to the economic development of Ethiopia. However, although detailed studies have not been conducted, there is little doubt that operation of the Chara Chara weir, in conjunction with diversions to the power stations, has resulted in some negative environmental and social impacts. Although preliminary and requiring verification through further research, the results presented in this paper illustrate the viability of using the DRM to provide a scientific base for an initial assessment of water allocation to mitigate some of the negative consequences. Much more detailed hydroecological and social studies are now required to validate these findings.

Environmental flows are increasingly recognized as a critical component of sustainable water resources management. However, in Ethiopia, in common with many developing countries, their estimation and implementation are impeded by lack of data and expertise. Given the dam building program currently being planned and implemented in Ethiopia, the country would be wise to initiate a capacity building program in environmental flow assessment.

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