INVESTIGATING ENVIRONMENTAL FLOW REQUIREMENTS AT THE SOURCE OF THE BLUE NILE RIVER

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ABSTRACT

Environmental flow assessment and maintenance are relatively new practices for the water sector, especially in developing countries. The concept of environmental flow assessment is new to Ethiopia, despite the fact that the country is endowed with many natural lakes and rivers. In 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 of the rivers source, Lake Tana. The most conspicuous impact of these human interventions has been 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 South African *desktop reserve model* 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 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^3s^{-1}). This study provides sound options that could be used to improve the current situation and to alleviate the environmental problems in the downstream of Laka Tana; especially in the vicinity of the Tis Issat Falls, in order to maintain the aquatic biodiversity and to keep the visual amenity of the Falls.

Key Words: *Abay River, Chara Chara Weir, Desktop Reserve Model, environmental flow, Tis Issat Falls.*

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INTRODUCTION

Water is an important part of any ecosystem, both in qualitative and quantitative terms. Reduced water quantity and deteriorated water quality both have serious negative impacts on ecosystems. The water environment has a natural self cleaning capacity and resilience to water shortages. But when these are exceeded, biodiversity is lost, livelihoods are affected, and natural food sources (e.g. Fish) are damaged and high clean-up and rehabilitation costs result.

Over half of the world's accessible surface water is already appropriated by humans, and this is projected to increase to 70% by 2025 (Postel et al., 1996; Postel 1998). Water resource developments such as impoundments, diversion weirs, inter basin water transfer; run-of-river abstraction and exploitation of aquifers for the primary uses of irrigated agriculture, hydropower generation, industry & domestic supply are responsible worldwide for impacts to riverine ecosystems (Rosenberg et al., 2000)

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 of the central, western and south-western highlands of Ethiopia before dropping to the plains of Sudan. 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 10,000ha. This compares to over 1 million hectares of irrigation in the Sudanese part of the Blue Nile catchment (World Bank, 2000).

One of the dams constructed in Ethiopia, and the only one actually located on the mainstem 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 located at Tis Abay (Figure 1). An environmental impact assessment was conducted prior to construction of the weir and estimates of flow requirements were derived based largely on the aesthetic impact of different discharges over the famous Tis Issat waterfall, which is a major tourist attraction situated immediately downstream of the diversion to the power stations (Howard *et al*., 1997).

This paper describes a more rigorous 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.

STUDY AREA

Lake Tana is the largest freshwater lake in Ethiopia and is the source of the Blue Nile River in the central Plateau of the Ethiopian Highlands. The lake has a catchment area of 15320 km^2, length of 70km, a width of 60km, a maximum depth of 14m, and a mean depth of 9m. Presently the lake is modified at its outlet by the Chara Chara weir. This is used to store large amounts of water in the rainy season and to deliver water persistently in the dry season to the Tis Abay II hydro power station, which is located 35 km downstream of the Lake Tana (Howard et al., 1997)

The mean annual inflow to the lake is estimated to be 114 m^3s^{-1} (3,595 Mm^3y^{-1}). Mean annual evaporation and rainfall are approximately balanced and the mean annual outflow is estimated to be 120 m^3s^{-1} (i.e. 3,776 Mm^3y^{-1}) (Kebede *et al.*, 2006). The outflow equates to 257 mm over the total catchment, giving a coefficient of runoff of approximately 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 on line in 1964. Located approximately 35 km downstream of the lake outlet the station was used to provide electricity for a local textile factory and for domestic supply to the nearby 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 the natural flow of the river.

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 100m downstream of the Tis Abay-I plant (Figure 1). Construction of the weir started in 1984, but was abandoned shortly afterwards (Howard *et al*., 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 capacity of 70 m^3s^{-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^3s^{-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 Power Corporation (EEPCO) (the successor to the EELPA) to maximize power production from both power stations.

The Chara Chara weir regulates water storage in Lake Tana over a 3m range of water levels from 1784 masl to 1787 masl. The active storage of the lake between these levels is 9,100 Mm^3, which represents approximately 2.4 times the average annual outflow. At full supply level the total flow through the seven gates is 490m^3s^{-1}. Approximately 110 m^3s^{-1} (the total flow capacity of both Tis Abay-I and II) can be released continuously with 95% reliability (Howard *et al*., 1997).

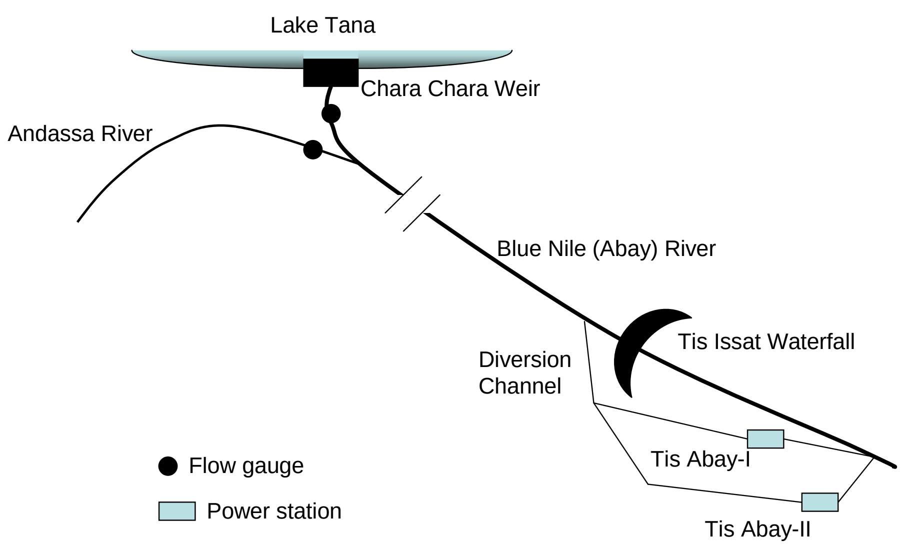

Figure 1: *Schematic of the Abay River flow system (not to scale)*

METHOD

The current study comprised two elements. First, analyses of river 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, 2000).

Change in hydrological regime

A flow gauging station, located immediately downstream of the outlet from Lake Tana, has operated continuously since 1959. The intermediate catchment between Chara Chara weir and the diversion to the Tis Abay power stations has an area of 1,094 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 operated 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 2005. Daily flow series were obtained for both stations from January 1973 to December 2005. 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 Tis Abay-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.

Estimated environmental flows

The flows of the world's rivers are increasingly being modified through impoundments such as dams and weirs, abstractions for agriculture and urban supply, maintenance of flows for navigation, drainage return flows, and structures for flood control. These interventions have had significant impacts, reducing the total flow of many rivers and affecting both the seasonality of flows and the size and frequency of floods. In many cases these modifications have adversely affected the ecological and hydrological services provided by water ecosystems, which in turn has increased the vulnerability of people especially the poor who depend on such services. There is an increasing recognition that modification of river flows for human needs should be balanced with maintenance of essential water dependent ecological services. The flows needed to maintain these services are termed “environmental flows and the process for determing these flows are termed environmental flow assessment or EFA.” (Brown & king 2003).

A key constraint to the application of comprehensive methods, particularly in developing countries, is 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 flow 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 Desk Top Reserve Model, 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 and Louw, 1998; Tharme and King, 1998; King *et al*., 2000), and is widely recognised as a scientifically legitimate approach to setting environmental flow requirements (Hughes and Hannart, 2000).

The Building Block Method is underpinned by the premise that, under natural conditions, different flows play different roles in the ecological functioning of a river. Consequently, to ensure sustainability, it is necessary to retain key elements of natural flow variation. Hence, so called Building Blocks are different components of flow which, when combined, comprise a flow 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 between high and low flow components. The flow needs in drought years are referred to as “drought requirements” (Hughes, 2001). The desktop reserve model provides estimates of these building blocks for each month of the year.

In this study, the desktop reserve model 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 infilled 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 four months were filled by interpolation and six 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). In contrast to the analyses conducted for the environmental impact assessment, no allowance was made for the aesthetic quality of flows over the Falls.

RESULTS AND DISCUSSIONS

Impacts of the Abay River flow regulation

The issue of determining the allocation of water between the Hydropower station and the Tis Issat Falls has been the major focus of the Environmental Flow Assessment. The current study incorporates all the available monthly time step data of the water discharge from Tis Abay I and Tis Abay II power stations and the hydrological flows of both the Andassa as well as the Abay River. The deduction of flows of the discharge from flows of the rivers would result in the flows over the Tis Issat Falls. Although the Tis Abay I Power station was commissioned in 1964 its impact on the water allocation of the Tis Issat Falls and the environment in general were very insignificant as compared to the new Power station II established in 2001 See Tables 1 and 2 below.

As shown in Table 1, the dry months of the year are May and June with mean monthly runoff of 40.341 MMC (15.564 m^3/s) and 43.152 MMC (16.648 m^3/s) respectively; giving the corresponding 11.163 m^3/s and 11.624 m^3/s of the minimum dry flow over the Falls. Maximum runoff occurs after the rainy season which are September and October with mean monthly runoff of 943.597 MMC (364.042 m^3/s) and 831.149 MMC (320.659 m^3/s); giving the corresponding 357.322 m^3/s and 314.030 m^3/s to have a spectacular natural event over the Tis Issat Falls for the period specified. The Mean Annual Runoff (MAR) of the Abay river during 1964-2000 was 3852.93 MMC; about 46.1% of the MAR was obtained only from both the peak months of September and October which together provide a mean sum of 1774.75 MMC. However; the MAR of the Abay River during 2001-2005 was 5820.17 MMC (i.e. 51.1% increment of the total flow).

Table 1 Summary of the Mean Monthly Flow distributions of the Abay River prior to the establishment of the new Chara Chara weir for the period of **(1964-2000)**

	Sum of Abay at Bahir Dar and the Andasa River (**1964-2000**)		Tis Abay I Discharge from power station (**1964-2000**)		Flow over the Tis Issat Falls (**1964-2000**)	
Month	**MMC**	**M^3/s**	**MMC**	**M^3/s**	**MMC**	**M^3/s**
MAY	40.341	15.564	12.065	4.655	28.935	11.163
JUN	43.152	16.648	13.022	5.024	30.129	11.624
JUL	149.186	57.556	14.608	5.636	134.578	51.920
AUG	528.776	204.003	17.501	6.752	511.275	197.251
SEP	943.597	364.042	17.419	6.720	926.178	357.322
OCT	831.149	320.659	17.214	6.641	813.967	314.030
NOV	518.180	199.915	18.172	7.010	500.346	193.035
DEC	326.488	125.960	17.854	6.888	308.634	119.072
JAN	200.872	77.497	17.686	6.823	183.631	70.845
FEB	125.097	48.263	16.597	6.403	108.898	42.013
MAR	86.392	33.330	16.156	6.233	70.792	27.312
APR	59.696	23.031	13.665	5.272	46.500	17.939

(Source: Own Computation)

As indicated in Table 2, the minimum flow of the Abay River in the normal dry season of May and June were 254.937 MMC (98.355 m^3/s) and 253.869 MMC (97.943 m^3/s) respectively. If we compare these values of the dry months with that of the values of the year 1964-2000; of May 40.341 MMC (15.564 m^3/s) and June 43.152 MMC (16.648 m^3/s); the former exceeds the later more than five times, this indicated that the water level of the Abay River in the upstream of the Falls to the weir has increased significantly during the dry seasons. On the one hand; this may have a great significance to some aquatic organisms because of the increased dry season flow and may have created a suitable water environment for their ecological functions. On the other hand, it may have perturbed the natural cycle of some aquatic organisms and it is likely to harm others some way. Besides, the all year round submersion of the root system of the trees would be detrimental to the trees themselves.

Table 2 Summary of the Mean Monthly Flow distributions of the Abay River after the establishment of the new Chara Chara weir for the period of **(2001-2005)**

Month	Sum of Abay at Bahir Dar and Andassa River (**2001-2005**)		Tis Abay I & II Discharge from Power St. (**2001-2005**)		Flow over the Tis Issat Falls (**2001-2005**)	
	MMC	**M3/s**	**MMC**	**M3/s**	**MMC**	**M3/s**
MAY	254.937	98.355	240.671	92.851	20.975	8.092
JUN	253.869	97.943	261.987	101.075	7.138	2.754
JUL	378.092	145.869	237.689	91.701	158.937	61.318
AUG	401.099	154.745	294.288	113.537	126.034	48.624
SEP	441.260	170.239	289.091	111.532	200.831	77.481
OCT	368.072	142.003	243.591	93.978	150.619	58.109
NOV	304.211	117.365	241.749	93.267	102.479	39.537
DEC	282.549	109.008	243.832	94.071	80.123	30.912
JAN	273.468	105.505	228.445	88.135	53.060	20.471
FEB	253.721	97.886	237.112	91.478	39.497	15.548
MAR	308.869	119.163	270.232	104.256	40.302	15.549
APR	297.024	114.593	284.406	109.725	24.327	9.385

(Source: Own Computation

Furthermore, because of the constant diversion of large volume of water in the 300m upstream of the Falls to the power station; both the ecological and the recreation values of the flows over the Falls are critically affected. A Previous study indicated that, the minimum flow likely to satisfy the visual requirements of the waterfalls was 60 m^3/s (Nicolas 1996); however, currently only in the two months of the year is this requirement met the (Table 2), the rest of the months were not suitable for the tourists. The Mean Annual Runoff (MAR) of the Tis Issat after the construction of the weir was found to be 1004.32 MMC; this indicated that a 72.59% flow decline from the pre 2001 MAR.

According to, the data obtained from the Tis Abay Tourism Bearu the peak months of the Tis Issat visitors were in December and January but the average flows on the Falls over the period of 2001-2005 for the months specified were *80.123 MMC (30.912 m^3/s) and 53.060 MMC (20.471 m^3/s)* respectively (Table 2). One can imagine the disappointment this reduced flow might cause for tourists who have traveled to see the water Falls. Consequently this could lead to a drastic drop in the number of visitors in the near future and cause an inevitable negative impact to the national economy at large; apart from the destruction of the aquatic ecosystem.

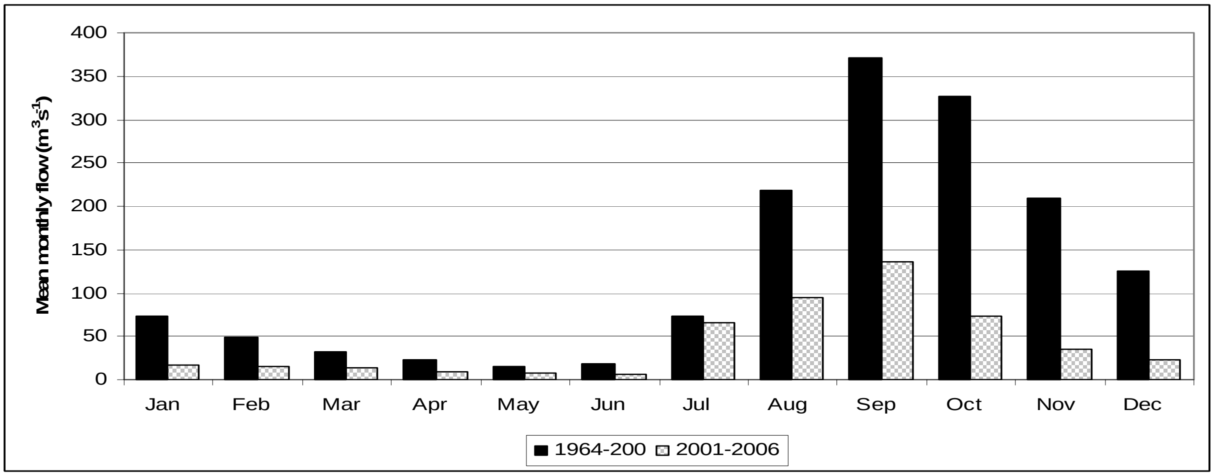

Figure 2: *Comparison of flow over the Tis Issat Falls for the periods 1964-2000 and 2001-2006*

Environmental flow requirements

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 mean annual discharge) (Table 3). 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 mean annual flow (i.e. 440 Mm^3).

Table 3: *Summary output from the desktop reserve model 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)	
S.D.	= 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)	
	Observed flow (Mm^3)		**Environmental flow requirement (Mm^3)**			
			Maintenance flows			Drought flows
Month	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

For the period 2001 to 2006, average annual flows over the Falls (i.e., 1,305 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 over the Falls 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.

Only in months July to October (i.e. wet season months) did the average flow over the period 2001 to 2006 exceed the recommendation of the DRM (Table 4). 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 were estimated to have been just 44 Mm^3 and 7.6 Mm^3 respectively; less than even the recommended minimum drought flows.

Table 4: Comparison of environmental flow requirements computed by the desktop reserve model and Observed mean monthly flows in the river reach that include the Falls, between 2001 and 2006

Month	Over the Tis Isaat Falls		
	Total maintenance requirements Mm^3/month	Observed flows Mm^3/month	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	

The biggest limitation of the Desktop Reserve model is that the out put results given by the desk top reserve model have to be considered as an initial low confidence estimates for ecological description and should not be considered as the final solution. Since the variability of climate, geology, topography, vegetation, etc. that can be found within a country might have different effect and may be difficult to explain using hydrological index only. Therefore it is reasonable to suggest that a single relationship, between the annual totals of the building blocks and a hydrological index (CVB) is unlikely to be adequate; hence the result needs to be compared with detailed and time-consuming studies of the effects of flow modifications on ecological functioning. However, the ability of determining environmental requirements within short period of time and its inexpensiveness; and also its application in the absence of long term hydrological data, and any ecologists made it preferable especially in developing countries.

CONCLUSIONS AND RECOMMENDATIONS

The concept of environmental flow requirements has a paramount function in evaluating the conflict of interest between development and ecological maintenance of rivers. Recognizing the indispensable role of rivers in national economic development and establishing environmentally adequate and socially acceptable limits of their exploitation is of utmost importance. The provision of environmental flows is not only a scientific question, but also a social, economic and political issue. Therefore, establishing an EF regime should involve many different actors, from the highest levels of government officials through to local communities.

The environmental problems associated with the Tis Issat Falls are surely reversible provided that a joint effort is made to overcome the situation. Therefore; the Ministry of water resources should take the initiative and work in collaboration with other organizations such as: Ethiopian Electric Power Corporation (EEPCO) Environmental Protection Authority (EPA), Tourism Commission, Cultural and heritage protection and the scientific community to arbitrate the conflict of interests and come up with sustainable solutions.

The current impacts of the Chara Chara weir on the terrestrial and aquatic ecology are not clearly known. So, further more detailed scientific assessments are recommended in this regard. In the absence of any specialist knowledge on the relationship between hydrology and ecological functioning of the river, the desk top reserve model was felt to be the most appropriate method for estimating the environmental flow requirements needed to maintain the aquatic biodiversity. The study has clearly demonstrated the values of the relatively simple model results combined with other computations. As such the study has provided a credible scientific basis to underpin decisions relating to environmental water allocation

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