Chapter 17
Concepts of Environmental Flow Assessment and Challenges in the Blue Nile Basin, Ethiopia

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Abstract The degradation of riverine ecosystems, resulting from changes in natural flow regimes, is increasingly recognized as being amongst the most significant negative effects of hydraulic structures. Environmental flows are managed releases from a reservoir intended to mitigate these impacts. Numerous techniques have been developed to estimate environmental flows but, for a variety of reasons, these methods are rarely applied in developing countries. The Ethiopian Government is planning major hydropower and irrigation development in the catchment of the Blue Nile River. This paper reports the findings of a first attempt to rigorously quantify environmental flows in the Blue Nile River. Three desktop hydrological methods, the *Global Environmental Flow Calculator*, the *Desktop Reserve Model*, and the *Tennant Method,* were applied at three locations. With reasonable consistency they indicate that 21–28% of the mean annual flow may be sufficient to sustain basic ecological functioning. The results, which are low-confidence estimates, need to be confirmed with much more detailed studies, but provide a basis for discussion and can contribute to the early phases of planning.

Keywords Environmental flows · Blue Nile · Ethiopia · Water resources development

17.1 Introduction

In the past, water resources have been managed primarily from a supply perspective, with a focus on meeting accelerating demands for irrigation and hydropower as well as industrial and domestic needs. These demands, together with the manipulation of flows for navigation and flood control, require hydraulic infrastructure such as dams and weirs, as well as inter-basin water transfers, run-of-river

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abstractions and exploitation of aquifers. All of these can cause severe alterations to natural hydrological regimes (Tharme, 2003).

Past studies indicate that over half of the world's rivers are fragmented and regulated by dams and other hydraulic structures (Revenga et al., 2000; Nilsson et al., 2005). Many of these provide substantial benefits to human societies and economies. Hydropower schemes currently provide about 19% of the global electricity supply and dams related to irrigation schemes are estimated to contribute directly to 12–16% of food production worldwide (Richter and Thomas, 2007).

Although there are benefits, the alteration of natural flows results in a number of severe ecological effects ranging from genetic isolation through habitat fragmentation to declines in biodiversity. In turn these ecological impacts can have severe effects on ecosystem services (e.g. water purification, flood attenuation, fisheries, flood recession agriculture and recreational and cultural opportunities) often with profound consequences for the people who depend on them (Tharme, 2003). In many cases, the negative impacts extend for hundreds of kilometers downstream of the hydraulic structure (Richter and Thomas, 2007). These impacts are of particular significance in developing countries, where large proportions of the rural population are often directly dependent on the natural resource base and, so-called, common property resources, for their livelihoods (Millennium Ecosystem Assessment, 2005).

Due to the inter-linkages between the state of aquatic ecosystems and human welfare the topic of sustainable freshwater and related resources management ranks high on the international political agenda. With the exception of the EU Water Framework Directive, no international, legally enforceable, policies have been ratified to date. However, at the national level more progressive developments are occurring and policy frameworks that prioritize the allocation of water for ecosystem maintenance have been developed in several countries. In the Southern Hemisphere, South Africa and Australia have led the way and accordingly have the most advanced methodological and legislative frameworks relating to environmental flows. Several other African countries (e.g. Ethiopia, Tanzania and Kenya) have introduced new water legislation in recent years that is built on the general principles of sustainable and equitable resource use.

In this context, the growing recognition of the significance of the natural flow regime has driven the evolution of the science of environmental flow assessment (EFA) (Arthington et al., 2006; Dyson et al., 2003; Tharme, 2003). The goal of EFAs is to determine a flow regime that provides adequate patterns of flow quantity, quality and timing for achieving or sustaining a predefined condition of ecosystem functioning. These predefined objectives may be predicated on the conservation or rehabilitation of an entire river system, at maximizing commercial fisheries, at conserving certain key species, or elements of scientific, cultural or recreational value (Tharme, 2003). By preserving critical ecosystem functions (e.g. fisheries) the livelihoods and wellbeing of poor rural communities dependent upon such services can be safeguarded. Hence, EFAs make possible the incorporation of the interests and needs of these communities in water resource development plans.

In recent years numerous EFA methodologies have been developed. Each method is applicable under specific conditions of time, data, and financial and technical resource availability and the specific issues to be addressed (Tharme, 2003). The types of methods range from relatively simple, quick and cheap hydrological approaches to more resource-intensive methods that incorporate comprehensive ecological assessments (e.g. habitat simulation and holistic methods). With this multitude of possible approaches the suitability of specific methods and their results have to be evaluated on a case-by-case basis. This chapter discusses environmental flows within the context of developing countries and presents a case study from the Blue Nile basin in Ethiopia.

17.2 Approaches to Environmental Flow Assessment

Early applications of EFA methods focused mainly on the maintenance of economically important target fish species, or other highlighted ecological features, neglecting other ecosystem components. However, the importance of flow management with regard to entire ecosystems has repeatedly been advocated in limnological research (e.g. Junk et al., 1989; Hill et al., 1991) and intensive studies relating to the development and advancement of EFA methods are progressing on a global scale. A recent inventory of EFA methods recorded 207 different approaches in use in 44 countries (Tharme, 2003).

Broadly there are four types of methods ranging from relatively simple, quick and cheap hydrological approaches, such as hydrological index and hydraulic rating methods, to more resource-intensive methods that incorporate ecological assessments (e.g. habitat simulation and holistic methods) (Table 17.1).

Hydrology-based EFA methods are the simplest and most commonly used methods, especially in situations where ecological data are scarce (Tharme, 2003). As the name implies, these methods rely solely on historical hydrological data, such as long-term daily or monthly discharge records. The recommended environmental flows are usually given as specific flow percentiles from a flow duration curve

Table 17.1 Types of environmental flow assessment

	Advantages	Disadvantages
Hydrological index	• Rapid • Few monetary and human resources	• Recalibration of parameters necessary • Low resolution
Hydraulic rating	• Rapid, simple, flexible • Moderate resource requirements	• Solely based on hydrologic data • Focus on target biota
Habitat simulation	• Flexible • Data processing efficiency	• High resource requirements • Focus on target biota
Holistic	• Multi-disciplinary • Natural flow paradigm • Flexible, robust, pragmatic	• Substantial resource requirements • Recalibration parameters necessary

or some other fixed percentage of the annual, seasonal, or monthly flow (King et al., 1999). Worldwide, the Tennant (or Montana) Method is the most widely applied of these methods (Tharme, 2003). It aims to satisfy environmental flow needs by linking specific percentages of the average annual flow to different conditions of instream habitat. Perhaps the most advanced hydrology-based EFA method is the Desktop Reserve Model (DRM) that has been developed by Hughes and Münster (2000) and further refined by Hughes and Hannart (2003). This method was developed to generate rapid, low-confidence estimates of environmental flow requirements for rivers in South Africa.

The advantages of this type of method are that they can be applied in a relatively short period of time and require few monetary and human resources. However, because they are often based on research conducted in specific geographical locations they are not easily transferable between different regions. Strictly they should be re-calibrated whenever they are used in locations in which they were not developed. Additional criticisms are their low temporal resolution regarding natural flow variability and the absence of ecological input data.

Hydraulic rating methods are based on the assumption that habitat integrity of riverine ecosystems is directly linked to changes in various hydraulic variables (wetted perimeter, width, depth, velocity), which are dependent on discharge. Measured stage-discharge data for one or more cross-sections and other hydraulic data (e.g. water depth, average velocity) in combination with ecological expertise are required to generate environmental flow recommendations from this type of approach. Environmental flows are usually determined in the form of a discharge value that is presumed to represent the optimal minimum flow, below which the available habitat (for many species) decreases rapidly (King et al., 1999). In this category, the wetted perimeter method (Reiser et al., 1989) is reported to be the most commonly applied method globally (Tharme, 2003).

The main advantage of these methods is that they are generally relatively rapid and simple procedures, flexible enough to accommodate the habitat requirements of various species, with only moderate resource requirements. Despite these strengths and their apparent improvement over hydrological index methods (e.g. by making use of ecologically based data such as physical instream habitat requirements), in recent years hydraulic rating methods have been surpassed by more sophisticated habitat simulation methods or incorporated within holistic methods that use microhabitat and biological information in addition to pure hydrologic data (King et al., 1999).

Habitat simulation methods, the second most widely used type of EFA approach, are based on hydrological, hydraulic and biological response data. They aim to generate environmental flow recommendations with respect to habitat availability and its suitability for target species, life stages or assemblages over time and space. The most common technique is the use of habitat/flow curves and the determination of a so-called "diminishing return" point, where proportionately more habitat is lost with decreasing flow than is gained with increasing flow (Jowett, 1997).

By far the most widely used approach in this category is PHABSIM (Physical Habitat Simulation Model) (Bovee, 1982). The beneficial characteristics of high flexibility, data processing efficiency and the possibility of creating dynamic hydrological and habitat time series at high spatial and temporal resolutions are counterbalance by the very high resource requirements in terms of time, data and expert knowledge. Furthermore, habitat simulation methods still focus almost entirely on target biota and therefore only partially provide the tools for fully-fledged, holistic EFA. Generally speaking, habitat simulation methods are most appropriate in trade-off situations, where the degree of habitat alteration can be weighed against the gains from resource use (Jowett, 1997).

Holistic methods are essentially integrated frameworks, consisting of a combination of hydrological index, hydraulic rating and habitat simulation methods, rather than separate approaches. They focus on the entirety of riverine ecosystems, including floodplains, estuaries, and coastal systems that are linked through riverine processes. As a consequence, comprehensive primary hydraulic and hydrological data, combined with as much supporting ecological data as possible, are pre-requisites for their implementation. In addition, information on the needs of local people dependent on riverine common property resources should also be used (King et al., 1999).

The South African Building Block Methodology (BBM) (King and Louw, 1998) and the Australian Holistic Approach (Arthington et al., 1992) were the first attempts of this kind and served as foundation for the development of more recent, innovative scenario-based approaches, such as the Downstream Response to Imposed Flow Transformation (DRIFT) method (King et al., 2003). The major advantage of holistic methods is that they address all components of riverine ecosystems and their links to flow regimes, and they can also incorporate socio-economic aspects. Furthermore, these flexible, robust and pragmatic methods can generate outputs at several levels of spatial and temporal resolution. However, a substantial amount of expert input and primary data collection is required, rendering holistic methods very time and resource intensive. Generally, these approaches require extensive fieldwork and lots of data and inputs from teams of experts with detailed local knowledge over prolonged periods of time.

Globally, North America is at the forefront of the field of EFAs and the first attempts towards the realization of the concept can be traced back to the late 1940s (Tharme, 2003). In North America and other developed Northern Hemisphere countries the application of habitat simulation methods predominates primarily because of the presence of economically important game fish species (e.g. salmon) and associated lobby groups (King et al., 1999). However, these methods are of limited importance in developing countries where data availability is scarce and analyses of the impact of flow regulations on the livelihoods of rural people dependent on natural resources have to be prioritized.

King et al. (1999) and Tharme (2003) identified a trend towards a hierarchical application of EFA methods, comprising two major steps. Often basin-wide scoping, planning or reconnaissance studies are conducted first, based on hydrological methods using historic flow records. These are then followed by more comprehensive assessments applying either habitat simulation or holistic methods. Examples for such a two-step approach are provided for Alaska (Estes, 1996) and the Czech

Republic (Bernadová, 1998). In other countries, such as Australia (Arthington and Zalucki, 1998), South Africa (Tharme, 1997), Lesotho (King and Brown, 2003) and the UK (Petts et al., 1996), an adaptable multiple-step method is applied, starting with simple hydrological methods proceeding to more comprehensive methods as additional resources become available.

17.3 Challenges to Environmental Flow Assessment in Developing Countries

EFAs are an essential component of Integrated Water Resources Management (IWRM). Many developing countries are in the process of drafting new water laws that are underpinned by IWRM principles. For example in Asia, various countries are reforming their water sectors in accordance with these principles (e.g. Turner, 2008; Lincklaen and Arriens, 2004). Similarly many countries in Africa have, in recent years, re-drafted water legislation in compliance with these currently widely accepted notions of best practice, focusing on integrated catchment-wide approaches to management and emphasizing the need for environmental sustainability. Recognition of environmental requirements in water resources policies and legislation provides an essential foundation for their inclusion in basin and catchment water resource plans (Brown and Watson, 2007).

Against this background there is increased interest in environmental flows and numerous case studies for the development of national environmental flow tools have been conducted (e.g. Sri Lanka (Smakhtin and Weragala, 2005), Nepal (Smakhtin and Shilpakar, 2005), India (Venot et al., 2008; Smakhtin et al., 2007; Smakhtin and Anputhas, 2006), South Africa (King et al., 2000) and Tanzania (Kashaigili et al., 2006)). However, there remain significant constraints to the successful application of EFAs in many developing countries. These arise for technical reasons as well as limitations in human, financial and institutional capacity.

The lack of data, even basic biophysical data (e.g. on river flows), is often a key limitation to the successful application of EFAs. Even today, despite the recognition of the importance of well-managed water resources, the acquisition of basic hydrometric data is rarely given high priority by government institutions (Houghton-Carr, 2006). Often data are not of sufficiently high spatial or temporal resolution to assist planning and decision-making at a local level. Even where it exists, administrative challenges of accessibility to data, including lack of familiarity of government officials with requests for information, deficient protocols for requesting data and lack of common data standards that promote data sharing, all hinder its use. In some instances, particularly in transboundary basins (e.g. the Nile), issues of national security also lead to restrictions on data sharing. There is need for much greater efforts in data collection, which is vital for EFA methods. There is also need for better coordination among different data collection agencies and improved data sharing.

Limited understanding of the complex environmental and social interactions, caused by changes in flow regimes is in developing countries, as elsewhere in the world, a major constraint to the planning and design of environmental flow regimes. To address this requires much more research into the links between modified flow regimes and the environmental and social impacts caused by changes in flow. It is also important that specific evaluation of uncertainty and risk should, as far as possible, be key components of EFA methods.

In addition, the limited pool of qualified professionals to develop and implement EFAs is often a major constraint to their application in developing countries. Technical capacity in the fields required (e.g. water resources, hydrology, botany, fisheries, ecology, public health, socio-economics etc.) and, particularly in the integration of different disciplines, is frequently insufficient. To address this challenge requires comprehensive professional training and capacity building programs. Sufficient training, retention of qualified personnel, continuing education and long term capacity building must all be part of a general educational strategy targeted at improving the management of water resources. There is particular need for cross-disciplinary programs that can provide future engineers and scientists with holistic understanding of EFA methods. Wider dissemination of existing guidance materials is also essential.

17.4 Case Study: EFA in the Upper Nile River Basin

17.4.1 Basin Characteristics

The Blue Nile basin, which is situated in the central, western and south-western highlands of Ethiopia and in the eastern plains of Sudan (Fig. 17.1) is the major tributary of the Nile River. Known as the Abay River in Ethiopia it supplies 62% of the flow reaching Aswan, with a mean annual discharge of 48.3 km^3 (at Khartoum) from a total drainage area of 311 and 548 km^2.

The basin is characterized by considerable variation of altitude (350–4,250 m) and corresponding temperature variations with an average temperature fall of 5.8°C for every 1,000 m increase in elevation. A monsoonal climate results in high inter- and intra-annual variability in precipitation. Within the basin rainfall varies significantly with altitude and is considerably greater in the Ethiopian highlands than on the Plains of Sudan. Within Sudan, the average annual rainfall over much of the basin is less than 500 mm. In Ethiopia, it increases from about 1,000 mm near the Sudan border to between 1,400 and 1,800 mm over parts of the upper basin and exceeds 2,000 mm in some places. The flow of the Blue Nile is characterized by extreme seasonal variability. Typically, more than 80% of the flow occurs during the flood season (July–October) while only 4% of the flow occurs during the dry season (February–May) (Awulachew et al., 2008).

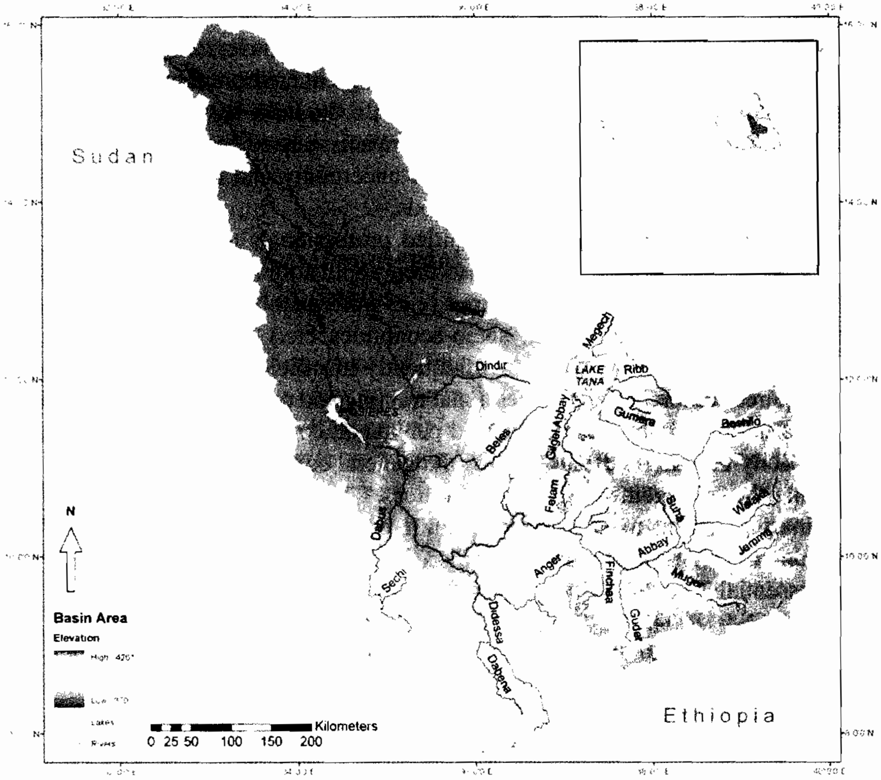

Fig. 17.1 Location and topography of the Blue Nile basin

17.4.2 Water Resources Use and Development

To date, only two minor hydraulic structures have been built in the Ethiopian part of the basin (Table 17.2). One of the two is the Chara Chara weir, a dam built on the outlet of Lake Tana to regulate flow for hydropower production at the downstream Tis Abay power station. . The second is the Finchaa scheme which comprises one dam and a somewhat larger hydropower station on the Finchaa River and another smaller reservoir on the Amerty River, from which water is transferred to the Finchaa. Together the Tis Abay and Finchaa power stations have an installed capacity of 218 MW, which represents approximately 27% of the total 814 MW grid based electricity-generating capacity of the country (EEPCo, 2009).

Only a very small area in the Abay basin is under formal irrigation. At present, the only modern irrigation schemes in the Abay are the Finchaa sugarcane plantation with an area of roughly 8,000 ha and the Koga irrigation scheme which will cover an area of 7,200 ha once fully operational in 2010 (McCartney et al., 2009).

Currently, the water resources of the Abay are mainly used to sustain the capabilities, assets (including both material and social resources) and activities that are

Table 17.2 Existing hydrologic structures in the Abay catchment area

Dam	River	Storage (Mm^3)	Year of construction	Purpose
Chara chara	Abay	9,100	1996	Hydropower production (installed capacity 84 MW)
Finchaa	Finchaa	2,395	1971	Hydropower production (installed capacity 134 MW) Sugarcane irrigation (8,145 ha)
Koga	Koga	83	2008	Smallholder irrigation (7,200 ha)

Modified from Awulachew et al. (2008) and McCartney et al. (2009).

required for the means of living of the rural population. Rainfed and floodplain agriculture, agro-pastoralism and artisanal fisheries play the most important role. The high percentage of 84% out of the total 77 million Ethiopians (2008 census) living in a rural setting (AFP, 2008) and therefore being dependent on the natural resource base, gives a measure of the importance of water resources and the related ecosystem services for subsistence-based livelihoods in Ethiopia.

In the context of a lack of significant fossil fuel reserves (Larson and Larson, 2007), presumed national water abundance, and an urgency to harness these resources to increase the national level of development and alleviate poverty the Ethiopian government has developed comprehensive Development Master Plans for all of the major river basins (Yohannes, 2008). The Abay River Master Plan (1998) identified various potential sites for future "modern" irrigation schemes. The currently planned projects will cover approximately 174,000 ha, corresponding to 21% of the total 815,581 ha that are estimated to be suitable for irrigated agriculture in the basin. Furthermore, over 120 potential sites for hydropower schemes have been identified within the Abay catchment area with a total potential capacity of over 30,000 MW (Larson and Larson, 2007). Of these 26 were investigated in detail during the preparation of the Abay River Basin Master Plan and several have now advanced to the stage of feasibility studies.

The growing demand for power and irrigation will certainly increase the pressure on water resources and related ecosystems in the Blue Nile basin in the near future. Accelerating population growth rates and development-related water needs in Ethiopia as well as downstream in Sudan, where there are plans to increase substantially the already high levels of irrigation (McCartney et al., 2009), will further aggravate this trend.

17.4.3 Water Resources Management Policy

With the water resources development sector on the rise, in 1999 the Ethiopian Government prepared a Water Resources Management Policy in order to enhance economic growth and to optimize the use of the country's resources. The officially stated goal of the Policy is:

> ... to enhance and promote all national efforts towards the efficient, equitable and optimum utilization of the available water resources of Ethiopia for significant socio-economic development on sustainable basis (MoWR, 1999).

In five subsections the Policy addresses fundamental management principles regarding general water resources, water supply and sanitation, irrigation, hydropower, and institutional arrangements. A series of highly relevant and progressive ideas, founded upon the Integrated Water Resources Management (IWRM) concept, are incorporated. In general terms, the policy marks a shift away from purely supply side management and the prioritizing of industrial and urban users. With regard to water allocation, the Policy recognizes basic human and livestock needs as well as the environmental reserve as highest priority users. Water allocation plans have to be built around these key requirements. By using the term "environmental reserve" the Policy shows strong parallels with the water management philosophy adopted in South Africa, where ecological water requirements have to be determined before any flow alteration takes place. Consequently, only the difference between the total available water resource (natural flow regime) and the environmental reserve can be considered available for other uses.

In addition, the Policy calls for the minimization or mitigation of adverse environmental impacts and identifies Environmental Impact Assessments (EIA) as critical parts of any water resources project.

Despite the overall progressive nature of the Water Policy, there are numerous problems related to its implementation. On the ground practices deviate a lot from the written policy. There tends to be a lack of coordination between the various implementing agencies and in many cases requirements stipulated in the policy are neglected (Haileselassie et al., 2008). Often EIAs (including EFA) are either not conducted at all or insufficient resources and attention are given to them. Environmental standards regarding water quality as well as quantity are not acted upon due to a lack of monitoring and enforcement mechanisms. Hence, despite a modern legal framework, it is clear that environmental considerations are currently of relatively low priority in Ethiopian water resources planning and development.

17.4.4 Environmental Flow Assessment

17.4.4.1 Selection of Key Locations

As discussed above, significant hydraulic development is planned in the Abay basin. The sites of potential future flow alteration present focal points for EFAs. In addition to proposed dam sites on the main stem of the river, those on major tributaries are also sites of interest since these rives contribute significant amounts of water to the main stem and so influence its hydrological characteristics.

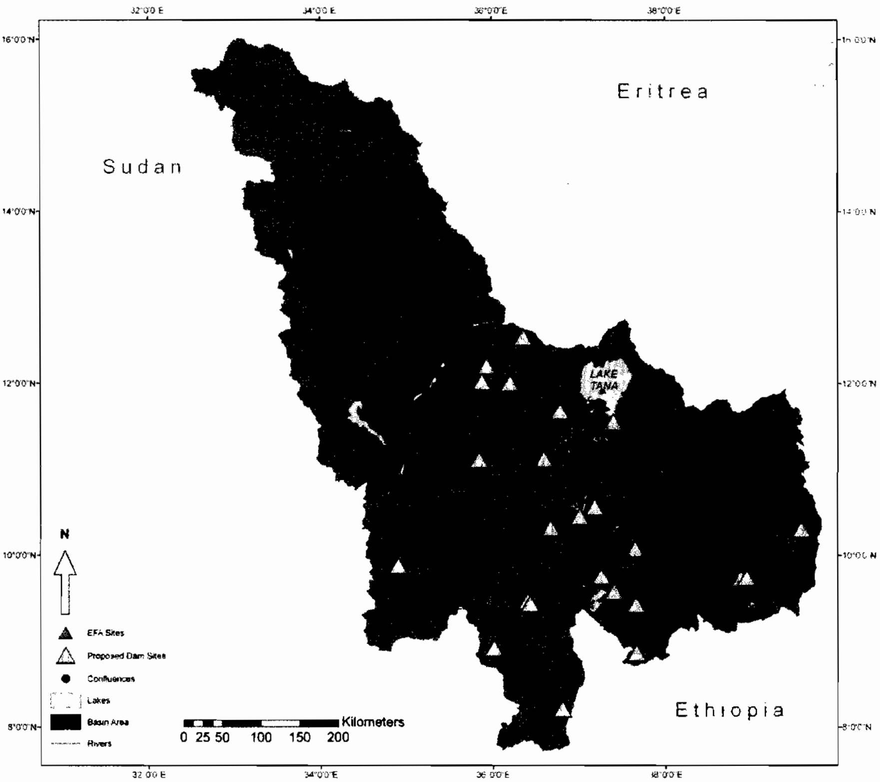

Fig. 17.2 Location of sites of interest for EFA (proposed dam sites, major confluences) and the three EFA sites selected for this study

Within the Abay 33 locations of interest for EFA can be identified (19 proposed dam sites; 14 major confluences) (Fig. 17.2). From these locations of interest, three key sites were selected for this study. These were selected based principally on their significance in terms of the dimension of the dam planned or the size of the joining river branch.

Two of the selected study sites are situated on the main stem of the Abay. The first at Karadobi and the second near the Sudanese border. Both are planned locations for large hydropower dams.

The Karadobi scheme will be located roughly two kilometers downstream of the confluence with the Guder tributary approximately 300 km downstream of Lake Tana (Norconsult, 2006). With an intended dam height of 250 m and an anticipated total reservoir volume of 40,220 Mm^3, the Karadobi scheme is the biggest of the currently planned dams in the Abay basin.

The Border dam will be located approximately 21 km upstream of the border with Sudan (Block et al., 2007). The dam planned for this site will have a height of approximately 90 m and a total storage capacity of 11,100 Mm^3.

The third site chosen is situated on the lower Didessa River close to its confluence with the Abay. The Didessa River is the largest tributary of the Abay. A hydropower scheme is planned on the Lower Didessa, which if constructed could impact significantly the flow regime of the main stem of the river.

17.4.4.2 Availability of Hydrological and Ecological Data

A data inventory for the Blue Nile basin revealed constraints in the availability of both hydrological and ecological data. Hydrological data are only available at a few locations and are limited to discontinuous records.

For the EFA sites at Karadobi and near the Sudanese border, flow data were obtained from Norconsult (2006). These data records were created in the course of a pre-feasibility study for the Karadobi dam. Using the incomplete time series available, all records were in-filled and extended over a 50-year period (1954–2003) with a monthly time step by applying multi-site, multiple regression procedures (Norconsult, 2006).

There are no streamflow data for the EFA site on the Lower Didessa River because there is no flow gauge located close to the confluence. However, monthly time-step estimates of the flow were derived for the Abay River Basin Master Plan based on rainfall-runoff modelling (BCEOM, 1998). These data were used in the current study. However, the length of record only covers the period from 1960 to 1992 (33 years). Thus, time-coincident data from both sources (MoWR and BCEOM) for these 33 years were used for the environmental flow assessments.

Despite the notion of rich biodiversity and high endemism in the basin, site-specific data on local ecology or habitat requirements for target biota are non-existent. This limited the EFA method applied to those which do not require ecological data.

17.4.4.3 EFA Method Selection

Choosing the right EFA method from the plethora of methods available is not straightforward. Each method has advantages and disadvantages. Essentially, the choice for an appropriate approach depends on the data and resources available and the type of issue to be addressed (Dyson et al., 2003).

In common with the situation in many other developing countries, environmental flow initiatives in Ethiopia are still in their infancy. Country-specific EFA methods have not been developed, nor have existing methods been adapted to Ethiopian conditions (compare Tharme, 2003).

Based on a literature survey and the data availability three hydrologic index EFA methods were selected for the current study. Specifically, these were the Global Environmental Flow Calculator (GEFC), the Desktop Reserve Model (DRM) and the Tennant Method.

The GEFC was selected due to its fast and straightforward applicability, and the additional option to use its internal flow database in comparison to user-defined data. In contrast to this first, very simple model, the DRM was chosen because it is considered to be the most advanced hydrology-based desktop method to date (Smakhtin and Shilpakar, 2005). In addition, the Tennant Method was applied, since it is the most commonly applied hydrologic index method worldwide (Tharme, 2003). Further details and underlying principles of each of the methods are given below.

Global Environmental Flow Calculator

The Global Environmental Flow Calculator (GEFC) is a software package complemented by a global database of simulated flow time series. The EFA technique incorporated in the GEFC involves a number of successive steps and essentially relies on flow duration curves (FDCs) – cumulative probability distribution functions of flows – that reflect the natural, unregulated flow pattern based on flow time series with a monthly time step. FDCs in the GEFC can be created by accessing either the default simulated flow time series from the package's internal global database or by importing a user defined file containing observed or otherwise simulated flow records. In the case of site-specific assessments user-defined flow data records should greatly improve the precision of the results and – if available – should always be chosen as the preferred option. For a detailed description of the computation procedures applied in the preparation of the global default data refer to Smakhtin and Eriyagama (2008).

FDCs show the percentage of time that a certain flow rate is equaled or exceeded. In the GEFC, 17 fixed percentiles are used (0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99%) to adequately cover the whole range of flow variability and to ease further application in the context of the subsequent steps (Smakhtin and Eriyagama, 2008).

The GEFC incorporates six environmental management classes (EMCs). EMCs relate to the desired ecological condition of the river. The six classes range from "unmodified and largely natural" rivers (classes A and B) where future developments should be restricted to "seriously and critically modified" rivers (classes E and F). Classes E and F are deemed ecologically unsustainable so class D (i.e. "largely modified") is usually set as the lowest allowed management "target" for future status. The higher the class, the more water is allocated for ecosystem maintenance and the greater the range of flow variability preserved (Smakhtin and Eriyagama, 2008).

In GEFC, unique FDCs can be generated and subsequently translated into more tangible, physical data (e.g. monthly flow time series in m^3/s) for each of the six EMCs based on site-specific natural flow records. Details of the lateral shifting method for the estimation of environmental FDCs for different EMCs can be found in Smakhtin and Anputhas (2006) and Smakhtin and Eriyagama (2008). The spatial interpolation procedure applied in the computation of the associated simulated monthly time series is explained in Hughes and Smakhtin (1996).

Desktop Reserve Model

The Desktop Reserve Model (DRM) is a hydrology-based method using monthly natural flow records, which has been developed by Hughes and Münster (2000) and further refined by Hughes and Hannart (2003) to provide a method for generating low-confidence, initial environmental flow requirements for rivers in South Africa.

The DRM is based on the principles of the Building Block Methodology (BBM) (King et al., 2000). The BBM is underpinned by the concept that different components of a river's natural flow regime are essential for the creation of an ecologically acceptable, modified flow regime. These so-called "Building Blocks" (BBs) of the flow regime are low or base flows, small increases in flow (freshets) and high flow or flood events, which are required for channel maintenance (Hughes et al., 1997). In this context, flow variations between normal ("maintenance") and dry ("drought") years play a fundamental role and are defined individually. As a result, four BBs of the natural flow regime are defined in the model output for each of the 12 calendar months:

- Maintenance base flows;
- Drought base flows;
- Maintenance high flows and freshets;
- Drought high flows and freshets.

In addition to this table of monthly requirements for maintenance and drought flows, the model also combines these parameters to monthly assurance or frequency curves. The DRM includes parameters for 21 regionalized assurance curves (e.g. Cape, Karoo, Drakensburg, Zululand, etc. regions), which were established for the natural flow regimes of 1,946 quaternary catchments in South Africa (Hughes and Hannart, 2003). These assurance rules define the frequency with which maintenance and drought years occur in specific regions and principally depend on the prevailing climatic conditions. Consequently, maintenance years dominate (60–70%) in wetter areas with rivers comprising a stable flow regime, whereas they are less common ($\leq$ 20%) in semi-arid and arid rivers (Kashaigili et al., 2006).

Similar to the GEFC, the DRM uses the classification of management targets divided into EMCs for the computation of suitable environmental flows. However, the DRM incorporates only four possible EMCs (A–D), because classes E and F are not regarded as acceptable management goals. In addition, the DRM offers the possibility of opting for transitional EMC categories (e.g. A/B, B/C), which increases the range of possible management scenarios within the model.

Tennant Method

The Tennant Method was developed in the United States by Tennant (1976) together with the US Fish and Wildlife Service. Environmental flow recommendations resulting from this method are based on specific percentages of the average annual runoff (MAR) related to qualitative fish habitat, as well as to recreational, wildlife and other environmental resources attributes. The impacts of changing discharge rates on stream width, depth, velocity, temperature, substrate, etc., were determined empirically for 11 streams in Montana, Wyoming and Nebraska and translated into an easy to use look-up table (Table 17.3) that suggests the quality of flow-related

Table 17.3 Environmental flow requirements for fish, wildlife, and recreation

	Percentage of MAR	
Description of flows	Dry season	Wet season
Flushing or maximum	200	
Optimum range	60–100	
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair or degrading	10	30
Poor or minimum	10	10
Severe degradation	0–10	

From Tennant (1976).

ecosystem conditions on a seasonal basis (i.e. wet and dry season flow requirements). For example, it was found that below the critical dry season flow rate of 10% of MAR water depth was insufficient for fish migration leading to a decline in or loss of sensitive species, whereas flow rates of roughly 30% of MAR sustained satisfactory width, depth and velocity to allow for migration (Gordon et al., 2004).

17.4.4.4 Comparison of EFA Methodologies

The environmental flow recommendations for the three key EFA sites were calculated using the three hydrologic index methods, i.e. the GEFC, DRM and Tennant Method. Their similarities and differences were examined and their applicability in a developing country context with severe data constraints was assessed.

For an unbiased comparison, the EMC used in GEFC and DRM, and the Tennant quality category respectively, had to be set to an equivalent management target. Based on a scoring chart that utilizes aggregate environmental indicators to assess the ecological condition of a river (Smakhtin et al., 2007), the most realistic environmental status of the Blue Nile and its tributaries was assessed as EMC C/D (i.e., moderately to largely modified). This reflects the need to balance socio-economic development needs in Ethiopia with the requirement to protect basic ecological services. It means that the flow regime should be allowed to 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).

As the GEFC does not allow for transitional management classes the average flow value for EMC C and D was calculated and used for comparison. In case of the DRM, the direct simulation of a monthly flow series for EMC C/D was possible and was used accordingly. For the Tennant Method the environmental quality category "fair or degrading" was assumed to be most comparable to EMC C/D and the respective thresholds (10% of MAR as dry season flow and 30% of MAR as wet season flow) were used for the generation of a monthly environmental flow series for further evaluation and comparison.

17.4.4.5 Model Adjustments

As the three hydrologic index methods applied were developed for other regions, initially a reconfiguration of internal model parameters was undertaken to make the models more applicable to the conditions in the Blue Nile basin.

Within the DRM the estimations of the annual totals of the BBs are based on a fixed-internal setting regarding the seasonal distribution of high and low flows, which was determined according to the prevailing flow patterns of South African rivers (c.f. Midgley et al., 1994). The primary dry season is defined as occurring from June to August and the wet season months are January to March. However, the Blue Nile basin is characterized by a different climatic pattern, with the wet season primarily concentrated from July to October and the key dry season flow from February to April. Therefore, the input flow series was shifted by 6 months (i.e. January became July, February became August, etc.). The output time series was then corrected accordingly in order to assign the flow values to the appropriate months. The assurance parameters chosen were those attuned to the conditions in the Drakensburg region of South Africa as its natural flow regime was most comparable to that of the Blue Nile basin due to similar climatic and geological characteristics.

The Tennant Method was developed for the climatic conditions in the western United States with low streamflows in fall and early winter (October to March) and high flows in summer (April–September) (Tennant, 1976). Therefore, similar to the procedure with the DRM, the timing of occurrence for the wet and dry season was altered to December to May (dry season) and June to November (wet season). Additionally, in contrast to the other two EFA methods applied, the Tennant method only yields a point value (MAR) for each environmental quality category. In order to link the Tennant MAR categories with flow variability, its environmental flow recommendations were applied and examined in relation to the monthly streamflow series in a so-called "extended" version of Tennant's original concept (Smakhtin and Shilpakar, 2005). Thereby, the natural flow record itself provides for the maintenance of characteristic elements of the hydrograph, whilst Tennant provides the percentage of acceptable flow reduction for each month. Furthermore, a prerequisite for successful application of the Tennant Method in an area different from that for which it was originally developed, is the morphologic similarity (e.g. width, depth, velocity) of the streams (Gordon et al., 2004). Since no morphologic data were available for the Blue Nile basin, the direct transfer of the method without additional field investigations and revaluation of Tennant's original measurements was necessary, but means that results must be treated with extra caution.

In case of the GEFC no site-specific model adjustments were made.

17.4.4.6 EFA Results

The application of the GEF, DRM and Tennant Method to the three study sites in the Blue Nile basin resulted in three different environmental flow time series for each site.

Table 17.4 shows the monthly averages of the three environmental flow series for each EFA site. The annual average values indicate that the maintenance of EMC C/D or "fair or degrading" conditions would require roughly 28, 24 or 21% of the observed MAR according to Tennant, GEFC and DRM, respectively. Furthermore, it can be seen that the DRM consistently results in the lowest flow recommendations, which are approximately 25% lower than the flow recommendations from the Tennant Method (which suggests the highest annual flows) for all three EFA sites. The GEFC computes intermediate annual flow recommendations that are 4, 22 and 16% below Tennant's flows for the EFA sites Karadobi, Lower Didessa and Border, respectively.

In a month-by-month analysis it can be seen that the environmental flow series derived from the Tennant Method exhibits the largest seasonal flow variations. It shows the lowest values for recommended monthly flows in the dry season (December–May) for all three study sites, where the suggested flows are up to 80% lower than the environmental flows recommended by the two other methods. On the other hand, the recommended flows during the wet season (June to November) exceed the environmental flow series derived from GEFC and DRM by up to 60%.

The differences and similarities of the results from the three individual methods for each of the sites under investigation are illustrated in Fig. 17.3.

17.4.5 Conclusions and the Way Forward

The maintenance of natural hydrological regimes is highly relevant in developing countries, such as Ethiopia, where the livelihood security of a large part of the population is strongly dependent on environmental goods and services. At the

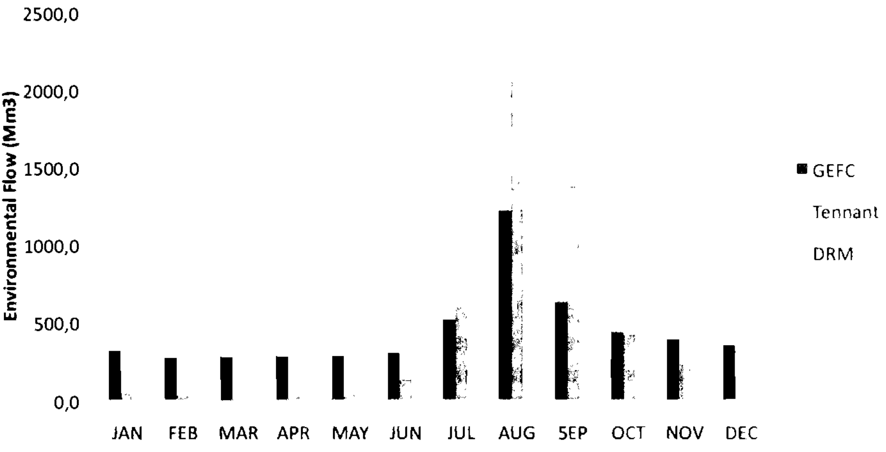

Fig. 17.3 Comparison of results (mean monthly flow requirements in Mm^3 for EMC C/D or "fair"conditions) from different environmental flow assessment (EFA) methods for the EFA site at **a** Karadobi, **b** Lower Didessa and **c** near the Sudanese border

Table 17.4 Monthly averages of observed flows and environmental flow time series ensuring EMC C/D or Tennant's ecological category "fair or degrading", which were generated for the three key EFA sites in the Blue Nile basin

	Environmental flow requirements (Mm^3)											
EFA site/method	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Karadobi												
Observed	449.1	376.2	398.6	380.8	397.6	432.9	3,061.1	7,241.8	4,583.5	1,399.5	762.4	553.7
GEFC	317.1	270.9	278.2	279.7	282.2	301.5	514.8	1,218.3	629.3	435.2	388.1	350.8
DRM	179.5	157.6	159.2	153.5	155.2	319.4	357.4	1,330.9	541.6	378.5	268.4	211.3
Tennant	44.9	36.7	39.9	38.1	39.8	129.9	918.3	2,172.5	1,375.1	419.9	228.7	55.4
Didessa												
Observed	109.8	63.8	52.6	56.5	95.9	289.4	954.8	1,810.1	1,774.3	1,111.9	355.0	185.8
GEFC	28.0	15.0	13.4	14.5	23.8	69.6	150.9	444.8	409.6	214.2	80.5	48.4
DRM	51.7	34.2	29.4	27.6	33.2	110.1	123.7	381.6	220.9	221.3	129.1	83.1
Tennant	11.0	6.4	5.3	5.7	9.6	86.8	286.4	543.0	532.3	333.6	106.5	18.6
Border												
Observed	511.1	351.4	301.8	284.9	337.2	888.1	1,215.5	3,190.5	1964	1,623.4	1,169.2	757.4
GEFC	318.4	215.2	188.9	180.3	241.0	476.3	1,313.3	3,707.6	2,196.4	1,066.7	609.0	403.2
DRM	420.5	283.4	244.3	225.6	259.0	740.8	917.5	2,657.0	1,477.9	1,370.4	946.7	614.1
Tennant	84.9	51.0	41.6	39.0	59.2	538.1	2,227.4	3,880.2	3,321.5	1,871.2	795.7	132.7

same time it is recognized that the implementation of environmental flows can also involve some costs related to reduced hydropower and irrigation supply, which is in high demand and essential for national socio-economic development. Despite the national benefits of water resources development, hydraulic structures and related flow alterations also pose an equity problem as the part of the population that is mainly affected and pays the price of such developments (due to lost ecosystem services and displacement) rarely benefit from the supply of electricity. These conflicting interests should be thoroughly evaluated prior to finalizing the planning and design of the numerous water resource developments, proposed for the Abay basin.

In order to achieve compliance with the Ethiopian Water Resources Management Policy potential adverse environmental and socio-economic impacts from hydraulic structures and other water uses have to be minimized or mitigated. Thus, the concept of environmental flows is a pre-requisite for finding a compromise between environmental, economic and social demands on the available water resources.

This study attempted the quantification of a full range of environmental flows (i.e. both high and low flows) using three desktop hydrological methods in the Abay basin. It demonstrated that, in the absence of ecological information, hydrological data can be used to produce coarse, initial estimates of environmental flow requirements. The different approaches produced broadly similar results. Nevertheless all the model results must be treated with caution and they should not be used for anything more than very preliminary planning. Much more detailed studies, including ecological surveys are necessary to provide estimates which can be accepted with more confidence. As indicated by the overassessd flow recommendations from the DRM, such information is essential to recalibrate the models for the monsoon-driven flow regime of the Blue Nile. Further studies and the development of region-specific model parameters are required to improve the accuracy of the first estimates derived from this study.

Furthermore, the calculation of environmental flows based purely on hydrologic indices has to be restricted to preliminary assessments. Links between flow regime and ecological response are merely assumed, whereas links between flow regime and social impacts are not considered at all. Because of the high proportion of the Ethiopian population living in a rural setting and dependent on subsistence livelihoods, the reliance of these communities upon river flows and related ecosystems has to be assessed. While in the short term hydrology-driven methods provide quick estimates for initial planning, they have to be supported by more comprehensive approaches (e.g. holistic methods) in order to achieve more accurate and (legally) defensible results in the longer term.

Ethiopia's progressive Water Resources Management Policy provides an enabling foundation for sustainable water resources management including the implementation of environmental flows. As basic human and environmental needs are recognized as the highest priority users, in principle further data acquisition relating to these aspects should be promoted. However, a lack of effective monitoring and enforcement mechanisms, as well as the general perception that environmental considerations hamper development, still pose major constraints for the success of environmental flow assessments in Ethiopia and other developing countries.

In future, as more dams are constructed, difficult choices will need to be made. Informed decisions are only possible with at least a basic understanding of the requirements of all the components of the water system. Greater understanding of flow-ecology-livelihood linkages is essential if water resources are to be used in a sustainable and equitable manner.

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