RESEARCH REPORT

89

Planning for Environmental Water Allocations

An Example of Hydrology-based Assessment in the East Rapti River, Nepal

V. U. Smakhtin and R. L. Shilpakar

IWMI
International
Water Management
Institute

FUTURE HARVEST
IWMI is a Future Harvest Center
supported by the CGIAR

Research Reports

IWMI's mission is to improve water and land resources management for food, livelihoods and nature. In serving this mission, IWMI concentrates on the integration of policies, technologies and management systems to achieve workable solutions to real problems—practical, relevant results in the field of irrigation and water and land resources.

The publications in this series cover a wide range of subjects—from computer modeling to experience with water user associations—and vary in content from directly applicable research to more basic studies, on which applied work ultimately depends. Some research reports are narrowly focused, analytical and detailed empirical studies; others are wide-ranging and synthetic overviews of generic problems.

Although most of the reports are published by IWMI staff and their collaborators, we welcome contributions from others. Each report is reviewed internally by IWMI's own staff and Fellows, and by external reviewers. The reports are published and distributed both in hard copy and electronically (www.iwmi.org) and where possible all data and analyses will be available as separate downloadable files. Reports may be copied freely and cited with due acknowledgment.

Research Report 89

Planning for Environmental Water Allocations: An Example of Hydrology-based Assessment in the East Rapti River, Nepal

V. U. Smakhtin and R. L. Shilpakar

International Water Management Institute
P O Box 2075, Colombo, Sri Lanka

IWMI receives its principal funding from 58 governments, private foundations, and international and regional organizations known as the Consultative Group on International Agricultural Research (CGIAR). Support is also given by the Governments of Ghana, Pakistan, South Africa, Sri Lanka and Thailand.

Authors: Vladimir Smakhtin is a Principal Scientist in Hydrology and Water Resources at the International Water Management Institute (IWMI), Colombo, Sri Lanka (v.smakhtin@cgiar.org) and Rajendra Shilpakar is an Assistant Coordinator of the South Asia Water Analysis Network (SAWAN) project of the Water, Hazard and Environmental Management Programme, at the International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal (rshilpakar@icimod.org.np).

Acknowledgements: This study was supported by core funds of the IWMI Theme, Water for Health and Environment and by the CGIAR-wide research program, Comprehensive Assessment of Water Management in Agriculture. The authors gratefully acknowledge the assistance with data provision from Mr. Vijay Shanker Mishra (Irrigation Engineer of the Department of Irrigation, Nepal) and the valuable comments on issues related to data quality and hydrological simulation from Mr. Bhakta Lal Manandar, Dr. Dilip Gautam (Department of Hydrology and Meteorology, His Majesty's Government of Nepal) and Dr. Gwyn Rees (Centre for Ecology and Hydrology, Wallingford, UK). Thanks are due to Mr. Sujeewa Piyankarage (IWMI, Colombo) for his help with the preliminary screening and formatting of hydrological data and to Dr. Dhruba Pant (IWMI, Kathmandu) and Ms. Mandira Shrestha (ICIMOD, Kathmandu) for the provision of documentation and fruitful discussions during the course of the study. Two reviewers provided valuable and valid comments on the report.

Smakhtin, V. U.; Shilpakar, R. L. 2005. *Planning for environmental water allocations: An example of hydrology-based assessment in the East Rapti River, Nepal*. Research Report 89. Colombo, Sri Lanka: International Water Management Institute.

/ water allocation / hydrology / assessment / flow / planning / simulation / water use / rivers / Nepal /

ISSN 1026-0862
ISBN 92-9090-594-8

Cover photo by Rajendra Shilpakar shows Lothar khola, a tributary of the East Rapti River.

Please send inquiries and comments to: iwmi@cgiar.org

Contents

Acronyms

AMSL	above mean sea level
BB	Building Blocks
BBM	Building Block Methodology
DEM	digital elevation model
DHM	Department of Hydrology and Meteorology (Nepal)
DM	Desktop Model
EF	environmental flow
EFA	environmental flow assessment
EIA	environmental impact assessment
ELEV	mean catchment elevation
FDC	flow duration curve
MAP	mean annual precipitation
MAR	mean annual runoff
RCNP	Royal Chitwan National Park
RVA	Range of Variability Approach
SD	standard deviation
SS	source site

Summary

The protection of the aquatic environment is high on the world water resources agenda. Most developing countries, however, still lack the technical and institutional capacity to establish environmental water allocation practices and policies. The existing methods of assessment of environmental water allocations are either complex and resource-intensive (comprehensive holistic approaches) or not tailor made for the specific conditions of a particular country, region or basin (desktop methods). Detailed quantification of natural and present-day hydrology for such assessments in river basins in developing countries is also lacking. To promote emerging concepts of environmental flow assessment and management, it is important, among others, to change the dominating perception that environmental demand is the least important, create awareness among responsible authorities about the existing methodologies and processes that should be followed, and illustrate the applicability of these approaches through relevant case studies.

This report addresses these issues in the specific context of Nepal, where establishing a program of environmental water management is important to safeguard the beauty of the country and livelihoods of rural populations. The study uses the East Rapti River basin as an example. This basin includes one of the main tourist attractions in the country, the Royal Chitwan National Park. A hydrological simulation is first performed by a simplified data generation procedure, which works in data-poor regions. This is followed by the application of two hydrology-based environmental flow assessment techniques, the Tennant method and the Range of Variability Approach (RVA). The report also examines the possibility of using a more advanced hydrology-based method, the South African Desktop model. Some of these techniques are modified, following a discussion of their limitations. It is indicated that hydrology-based, desktop methods of environmental flow assessment represent a necessary first step in planning for environmental allocations in developing countries. It is shown that use can be made of complementary features of existing techniques to arrive at justified environmental water needs estimates even in conditions of limited, basin-specific, eco-hydrological knowledge.

Planning for Environmental Water Allocations: An Example of Hydrology-based Assessment in the East Rapti River, Nepal

V. U. Smakhtin and R. L. Shilpakar

Introduction

In Nepal, rivers are important sources of drinking and irrigation water, mechanical and hydroelectric power and economic aquatic resources (such as fish, sand, etc.). Recognizing the indispensable role of rivers in national economic development and establishing environmentally adequate and socially acceptable limits of their exploitation are of utmost importance. Nepal also boasts of extraordinary natural beauty, which stimulates tourism. Maintaining a healthy aquatic environment is therefore important from this perspective as well.

Nepalese hydrology has some distinctive features, which make the design and implementation of a national environmental flow management program interesting and challenging. Most of the rivers have steep gradients and are often fed, at least partially, by glaciers. Yet the climate is monsoon-driven and this ensures a high seasonal variability of rainfall and runoff (Kansakar et al. 2002).

The primary focus of water development projects in Nepal has been hydropower and irrigation. To date, there has been no consideration of environmental flow requirements downstream of these developments. The need to minimize adverse environmental and social impacts of projects, such as hydropower and irrigation development, is rising high on the international agenda (ADB 2000; UNEP 2001), and has implications for Nepal as well. The country's environmental policy and legislation are in their infancy at present (Bhandari 2001) and do not specify nor even mention ecologically acceptable limits of water withdrawals (MoWR 1992). The new hydropower development policy (MoWR 2001) has, however, stipulated the need for maintaining a minimum flow in rivers, downstream of hydropower plants. Such a maintenance flow is to be set either at 10 percent of the minimum monthly average discharge or equal to the discharge— determined as part of an associated Environmental Impact Assessment (EIA) study—whichever is the greater. However, such recommendations remain arbitrary and minimal. The described situation is typical of many other developing countries, which have not yet been exposed to the principles of environmental flow assessment and management.

At the same time, an expanding field of environmental flow assessment (EFA) has emerged internationally, primarily during the past two decades, stimulated by the ongoing conflict between water resources development and the maintenance of associated ecosystems on which local livelihoods often depend. EFA may be conducted using multiple techniques, which differ significantly in the level of accuracy and input information required (e.g., Tharme 2003). Different EFA methodologies should be and are used for different purposes—from general water resources planning to the setting up of detailed plans for managed dam releases. In some developed countries, there is a move towards hierarchical, two-tier frameworks to guide EFA over a range of spatial scales, driven by the availability or access to resources, including data, time, technical capacity and finances (e.g., Dyson et al. 2003). These tiers include:

- Comprehensive assessment, using primarily holistic methodologies.
- Planning-type desktop assessment, using primarily ecologically relevant hydrological characteristics (indices) or analysis of hydrological time series.

The former (comprehensive assessment) adopts a whole-ecosystem view in assessing environmental flow needs, whereby ecologically and/or socially important flow events are identified and an ecologically acceptable flow regime is defined by a multidisciplinary panel of experts. These methods require substantial amounts of fieldwork and may take significant amounts of time and resources to complete for a single river basin.

The latter (desktop assessment) is suitable for initial, reconnaissance-level assessments of environmental flow needs in unregulated river basins and/or river basins where the pressure on water resources is not yet extreme, but starting to grow. Many river basins in Nepal still fall into this category. It is therefore important that the movement towards environmentally and socially sustainable water resources management starts at this point. Once the developments have occurred and adverse impacts have manifested themselves, it is much more difficult to reverse the environmental damage done to rivers. While comprehensive EFAs with holistic methodologies are certainly preferable, in countries like Nepal the use of simple and quick, planning-type methods may be seen as the starting point. While such methods provide estimates of low confidence, they may be used to set the feasible limits for future water resources exploitation and change the commonly existing perceptions about insignificance of environmental water allocations in basin planning and about the nature of such allocations.

None of the existing desktop methods has been developed or tested in Nepal, or even illustrated using data from any Nepalese river basin. This report presents some of these approaches and illustrates their applicability in the specific context of the East Rapti River basin, which features one of the main tourist attractions of Nepal, the Royal Chitwan National Park.

Study Basin

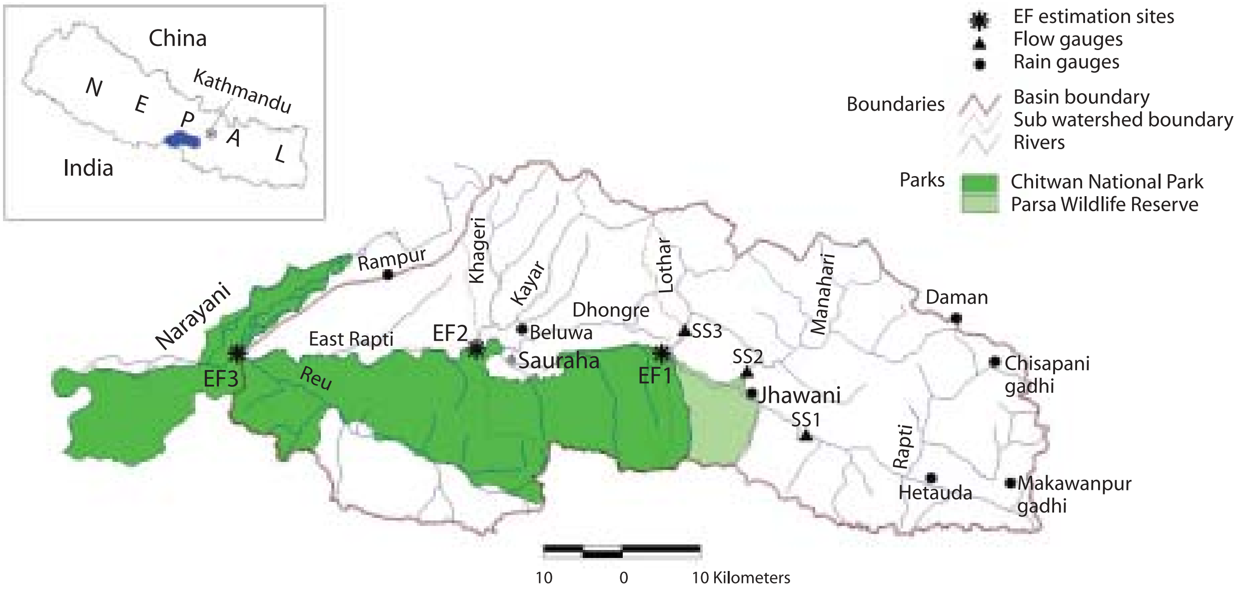
General Features

The East Rapti River originates in the Mahabharat mountain range about 25 km southwest of Kathmandu (figure 1) and approximately 2,000 m above mean sea level (AMSL). It joins the Narayani River, one of the four major rivers in Nepal, after flowing for 122 km (IWMI 2000a). The catchment area above the confluence of East Rapti with Narayani is 3,084 km^2.

The northeastern part of the basin is mountainous, with maximum elevations reaching almost 2,600 m, while in the downstream western parts the elevations do not normally exceed 300 m AMSL (figure 2). The East Rapti River joins the Narayani River at an altitude of 140 m.

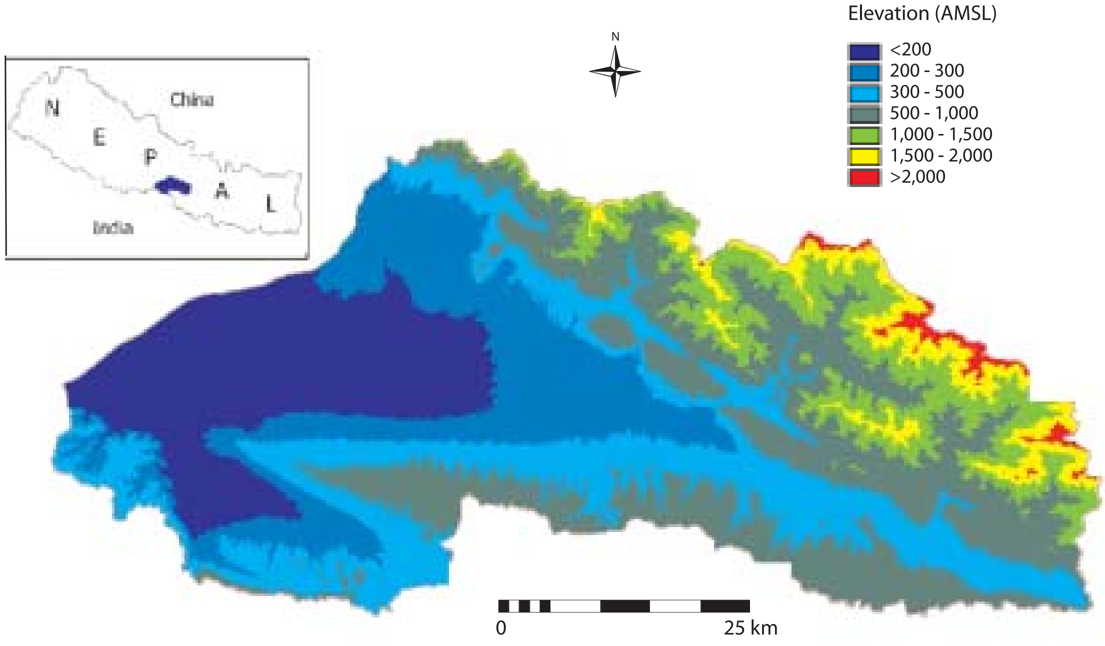
The mean basin elevation is about 570 m AMSL. The Mean Annual Precipitation (MAP) in the basin is approximately 2,000 mm (Shilpakar 2003). About 90 percent of the total annual rainfall occurs during the period from May to October. Approximately 65 percent of the basin area is covered by forest and another 27 percent by cultivated agriculture (primarily rice, wheat and maize).

FIGURE 1.
A schematic map of the East Rapti River basin showing major tributaries, location of existing flow and rainfall stations and the area of the Royal Chitwan National Park.



Note: EF1, etc. = environmental flow estimation site; SS = source site (flow gauge).

FIGURE 2.
A digital elevation model for the East Rapti River basin, with a resolution of 30 m.



Royal Chitwan National Park

The primary feature of the river basin is the Royal Chitwan National Park (RCNP), which was established in 1973 and designated as a World Heritage Site in 1984 (figure 1). The RCNP covers an area of 923 km^2, out of which 710 km^2 falls within the East Rapti basin (approximately 23% of the basin area).

The RCNP has an important role in the socioeconomic, ecological and institutional environments of the basin. The park contains Siwalik Hills and oxbow lakes and flood plains of the East Rapti and Narayani rivers. The vegetation of the RCNP can be classified into three main types. About 70 percent of its area is covered by Sal forest that grows in pure stands or in association with other tree species. The understory of a Sal forest consists of tall grasses or a sparse growth of shrubs. Grasslands cover about 20 percent of the park area. About 7 percent of the RCNP area along rivers, oxbow lakes and on islands in the rivers is covered by riverine forest. The RCNP also harbors endangered plant species like *Cyathea spinulosa* (a tree fern), Cycas (*Cycas pentinata)* and several orchids (KMTNC 1996).

There are more than 40 species of mammals, a total of 486 species of birds, and about 49 species of amphibians and reptiles in the park. The park is renowned for its endangered one-horned rhinoceros, tigers and gharial crocodiles. The oxbow lakes and flood plains covered by grassland and riverine forest are the main habitats of the one-horned rhino. Other endangered species found in the park include the sloth bear, gaur, leopard, wild elephant, four-horned antelope, Gangetic dolphin, spotted lingsang, Bengal florican, giant hornbill, black stork, white stork, sarus crane, lesser florican and python. The river systems contain a wide variety of aquatic fauna and flora. In addition, the shallow lakes and rivers support several endangered and threatened species like fishing eagles, osprey, fish-owls, storks, cormorants, several species of waders including ibises, and waterfowls (KMTNC 1996).

Social and Water-use Issues

A socioeconomic study (Ghimire et al. 2000) reported that the main occupation of the people in the basin is agriculture and that the majority of the farmers (46%) own less than 0.5 ha of land. This figure indicates the subsistence nature of agriculture and may, as well, point to the importance of irrigation to the farmers for their livelihood. The *Bote* and *Danuwar*, the most unprivileged and predominantly illiterate tribes who hardly have any access to agricultural land and other alternative jobs, depend heavily on fishing (Kayastha and Pant 2001). At the same time, livelihoods in the area also depend on natural forest resources. This dependency often leads to conflicts between the people and the park. In order to conserve the biodiversity of the park area through community participation and to ensure the socioeconomic development of the people living near the park, the government introduced the People and Park Project in 1993. The project established a 750-km^2 buffer zone in 1996 and started implementing various income generating and infrastructure development activities for people living in the buffer zone (Straede and Helles 2000). It supported 18 user groups for the implementation of irrigation activities benefiting 850 households as part of its productive investment (HMGN and UNDP 2000). As a result, irrigation to 294 ha of land was improved. It is believed that the households were able to increase food production with better irrigation facilities, which in turn is expected to help in reducing forest encroachment for food and firewood. At the same time, irrigation development increases the pressure on river water resources, which are also needed for the conservation of the park.

Apart from the park needs and irrigation (which is by far the largest water user in the basin), the East Rapti River water is used for domestic needs, industry, fisheries and recreation (IWMI 2000a). There are no major water regulating structures in the basin. Small irrigation systems in the upstream part of the basin tap water from seasonal streams and tributaries of the East Rapti River. The middle reaches of the basin known as East Chitwan are intensively used for irrigation. There are 94 irrigation systems here that irrigate about 9,500 ha. Out of these, 9 irrigation systems, irrigating 2,200 ha, abstract water directly from the East Rapti River (IWMI 2000a). Water to other systems is supplied from the tributaries of the East Rapti, mainly Dhongre khola (river/stream), Kayar khola and Khageri khola (figure 1). In the most downstream part of the basin (West Chitwan), water for irrigation is supplied from the Khageri khola and the Narayani River and no irrigation abstractions take place from the East Rapti River (IWMI 2000b).

There are also a few water quality issues of concern in the basin. These include untreated discharges from the Hetauda municipality and the Hetauda industrial district, wastewater from the Sauraha tourist area, occasional use of explosives and poisons for fishing, etc. However, there are no major complaints or conflicts concerning water pollution at present. This could partially be due to the ignorance of the downstream communities regarding water pollution and its adverse effects and partially because water quality still remains reasonably good (Manandhar 2002). As the area is rapidly undergoing urbanization, the issue of safe disposal of industrial effluents and wastewater from major settlements needs to be addressed before adverse impacts on the river ecosystem occur.

Simulating River Hydrology

Planning-type environmental flow assessment (EFA) methodologies, which are considered in this report, are normally hydrology-driven. This implies that hydrological data have to be available for those sites along the river where EFA is attempted. It is also agreed now in eco-hydrology that environmentally acceptable flow regimes shall mimic natural (or at least unregulated) patterns of flow *variability* in a river (Petts 1996; Poff et al. 1997; Hughes and Hannart 2003). High flows of different frequency are important for channel maintenance, bird breeding, wetland flooding and maintenance of riparian vegetation. Flows in a moderate range may be critical for cycling of organic matter from river banks and for fish migration. Low flows of different magnitude are important for algae control, water quality maintenance, use of the river by local people, etc.

Maintenance of flow *variability* is an important assertion, given the still dominant view that environmental allocations should be specified as a “minimum flow.” For example, the new hydropower development policy of Nepal (MoWR 2001) suggests that a minimum flow downstream of hydropower plants shall be ensured and set to an approximate constant level of 10 percent of the minimum monthly average discharge. This contradicts the need to maintain flow *variability* in a river.

Natural flow variability is best described by daily discharge time series. These time series have to be simulated for each selected estimation site. The environmentally acceptable flow regimes are to be established at each such site, using the simulated time series. These sites are referred to in this report as “environmental flow” (EF) estimation sites.

Selection of EF Sites

EF sites were selected using maps, although field visits would normally be required by more comprehensive EFA methods. The selection was based primarily on their location relative to the RCNP and major basin water developments, as described below.

Site 1 (EF1) is located at the confluence of the Lothar and the East Rapti rivers (figure 1). This point was selected considering that most of the irrigated agricultural areas are located downstream of this confluence and that the boundary of the RCNP begins here. Also, there is very little potential for further development of water resources upstream of this point.

Site 2 (EF2) is located at the confluence of Khageri khola and the East Rapti river, about 2 km downstream of Sauraha, one of the main entry points to the RCNP. The main tourist activities start downstream of this point and, in addition to the ecological requirement, a minimum flow in the river has to be maintained from this point downstream for the operation of ferries and boats.

Site 3 (EF3) is the basin outlet, i.e., a confluence of the East Rapti River and the Narayani River (known as Gandak River in Indian territory).

While the hydrological time series are simulated for all three sites in this study, most of the examples given in this report are for EF2, where some arbitrary "estimates" of environmental flows were available from previous reconnaissance studies (IWMI 2000a and Shilpakar 2003). The other two EF sites were used primarily for soft validation of simulations through discussion with specialists of the Department of Hydrology and Meteorology (DHM) who are knowledgeable about the river hydrology. In the condition of an inherent lack of observed data in this specific basin (and typically in basins of many Asian countries), such soft validation often appears to be the only working alternative (Smakhtin et al. 2004). The details of the estimation sites are summarized in table 1.

Available Observed Flow Data

Six river stations (flow gauges) measure (or measured) flow in the basin. Five of them are located on different tributaries whereas the Rajaiya station is on the East Rapti River itself. Three of the stations had records covering only a short period of time or unreliable records that could not be used. The locations of the remaining three stations are shown in figure 1 and their details are summarized in table 1. Flows at these stations are measured using calibrated gauges. The main problem at these stations is siltation during the monsoon. The rating curves developed

TABLE 1.
Observation points and estimation sites in the East Rapti River basin.

River	Site code	Location	Catchment area (km^2)	% of the area
East Rapti	SS1	Rajaiya	576	19
Manahari	SS2	Manahari	427	14
Lothar	SS3	Lothar	172	6
East Rapti	EF1	Downstream of the confluence of East Rapti and Lothar rivers; at RCNP border	1,417	46
East Rapti	EF2	Downstream of the confluence of the East Rapti River and Khageri khola; near Sauraha, main entry point to RCNP	2,219	72
East Rapti	EF3	Confluence of Narayani and East Rapti rivers; basin outlet	3,084	100

Note: SS = source site (flow gauge); EF1, etc. = environmental flow estimation sites.

by the DHM are updated and verified annually after the rainy season. The DHM made available to the authors the observed flow data for the 30-year period from 1965 to 1995, which is sufficiently long for this study.

Previous analysis of data had concluded that the observed flow records at the three stations are stationary (Tahal Consulting Engineers 2002). The quality of data at the Rajaiya station was found to be the best in the basin and was rated as “reasonably good.” Some constant, daily flow values of the dry period point to data inaccuracies and are less reliable. They are likely to be related to false “measurements” by technicians who made the observations. These suspect measurements however are infrequent.

Generating Representative Daily Flow Sequences for EF Sites

No study has been conducted to date on simulating *daily flows* at ungauged locations in the East Rapti basin. This report therefore presents the first attempt to do this. Representative daily flow time series for ungauged EF sites have been generated in this study using a spatial interpolation technique described by Hughes and Smakhtin (1996). The technique is based on typical flow duration curves for each calendar month of the year. A flow duration curve (FDC) is a cumulative distribution of daily flows at a site. The main assumption of the spatial interpolation technique is that flows occurring simultaneously at sites in reasonably close proximity to each other correspond to similar percentage points on their respective FDCs. Continuous FDCs are presented in this technique by FDC tables with 17 discharge values for 17 fixed percentage points (0.01, 0.1, 1, 5, 10, 20, 30, 40, 40, 50, 60, 70, 70, 80, 90, 95, 99, 99.9, and 99.99 percent). The site at which streamflow time series is generated is called a destination site. The site with recorded time series, which is used for generation, is called a source site (SS). In essence, the procedure is to transfer the streamflow time series from the location where the data are available (gauged [source] sites; see table 1) to another location where the time series is needed (EF sites in table 1). The generation technique may be presented in two steps: (i) generation of FDC tables for source sites and EF sites for each month of the year and (ii) actual simulation of the time series using established FDCs for the EF sites. Both steps are briefly described below.

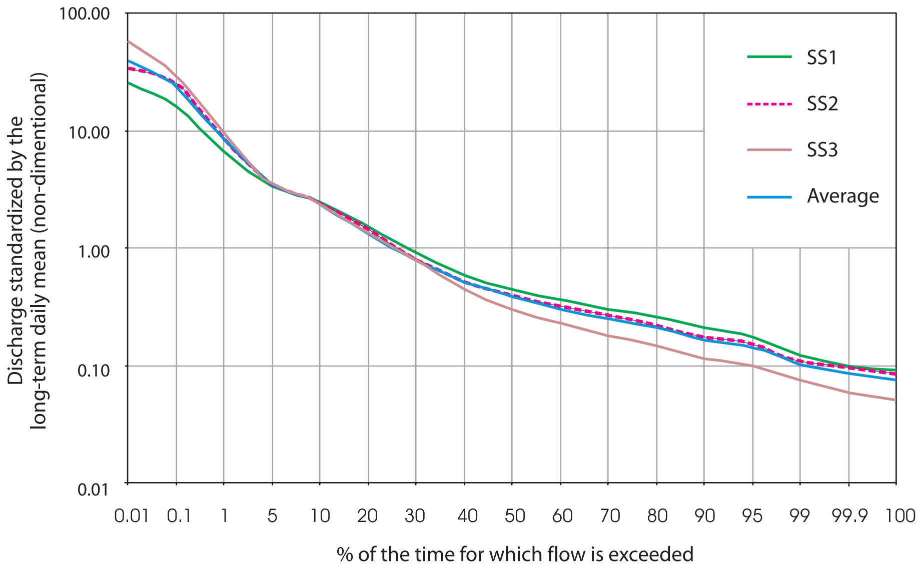
Generating FDC tables

Generation of FDC tables for source sites may be done directly using their observed records. For ungauged EF sites, there exists a variety of ways to approach this problem (e.g., using either the averaged/regional flow duration curve or the curve from the nearest gauge, etc.). The existing experience (Smakhtin 2000) suggests that all these approaches normally result in time series that are very similar. The approach adopted in this study was to construct the regional non-dimensional FDC first and then use it to calculate actual FDCs at selected EF sites. To construct a regional FDC, each of the three FDCs constructed from available observed data sets were normalized by their corresponding long-term mean flows, and their ordinates for 17 fixed percentage points were then averaged (figure 3). The approach is also explained in detail by Smakhtin et al. (1997).

While the use of only three individual FDCs (all located in the upstream parts of the basin) to estimate the “regional” curve may be seen as the limitation of this approach, it is effectively the only possible solution given the available observed flow data. At the same time, Smakhtin et al. (1997) have shown that catchments of different size may display similar standardized FDCs. Also, the similarity between FDCs in upstream and downstream parts of the same river basin is likely to be higher in humid regions, dominated by the monsoon, which extends over large areas. More research is needed to quantitatively characterize how the shape of a FDC depends on the physiography, climate and size of a particular river basin (Smakhtin 2000).

The established, regional, non-dimensional FDC may then be used to calculate the actual

FIGURE 3.
Normalized flow duration curves at gauged (source) sites in the East Rapti River basin.



Note: SS = source site.

FDC at an ungauged site by multiplying the ordinates of the regional curve by the estimate of mean flow at an ungauged site. Mean flow may be calculated using relevant regional regression models. The regression equation relating mean flow with measurable physiographic parameters was derived for Nepal by Rees et al. (2002). It is re-written here in the form:

$$MAR = MAP + (0.187*ELEV) - 764.712 \qquad (1)$$
$R^2 = 0.73$; SE = 390 mm

where MAR is mean annual runoff and MAP is mean annual precipitation (both are in *mm)* and ELEV (mean catchment elevation) is in *m AMSL*.

The above regression model is the only one available at present for the MAR estimation in ungauged basins in Nepal. A Digital Elevation Model (DEM) constructed by Shilpakar (2003) was used to calculate ELEV for catchments upstream of the three EF sites. The DEM was prepared using digital contour data of 20 m interval in mountain areas and 5-10 m interval in plains. The computed ELEV values (table 2) are the simple averages of catchment elevations of all cells within EF catchments and have a spatial resolution of 30 m.

To calculate MAPs for input into equation (1), the data from seven rainfall stations in and around the East Rapti River basin were used (figure 1). These stations are operated by the DHM. Out of the seven stations, Daman, Chisapani Gadhi, Makawanpur Gadhi and Hetauda are located in the upper, mountainous part of the basin. The other three stations, Beluwa, Jhawani and Rampur, are located in the flat, lower valley part of the basin. The MAPs for all these stations were calculated from their data recorded during the period 1976-2001 and used in Thiessen polygon analysis to derive the MAP for each of the three ungauged EF catchments. ELEV and MAP values were then used as input to equation (1) to calculate mean annual runoff depth (MAR) and subsequently the long-term mean discharge (table 2), which in turn was used to scale the regional FDCs for the ungauged EF sites.

TABLE 2.
Parameters used in MAR calculations and calculated MAR values for EF sites.

Site code	Location	Catchment area (km^2)	MAP (mm)	ELEV (m)	MAR (mm)	Long-term mean discharge (m^3 s^{-1})
EF1	Pratappur	1,417	2,025	878	1,424	64.01
EF2	Sauraha	2,219	1,984	692	1,349	94.90
EF3	Megauli	3,084	1,970	574	1,313	128.37

Note: MAR = mean annual runoff; MAP = mean annual precipitation; ELEV = mean catchment elevation.

Simulating continuous daily time series at EF sites

Actual simulation of the time series using established FDCs for the EF sites includes selection of the source site, from which the information will be transferred (to the destination sites), and assigning a weighting factor (to each source site) associated with the degree of similarity between the flow regimes of source and destination sites. The degree of similarity (and the corresponding weighting factor) is high if a source site and a destination site display sequentially similar flow regimes (i.e., if there is a peak flow at the source site, there will also be a peak flow at the destination site). This may be ensured if the source sites are in close proximity to the destination sites, or if they are representative of hydrological variability in the surrounding region. The examples include two sites (gauged and ungauged) on the same river or two sites in adjacent, similarly sized catchments.

After the source sites are selected and weighting factors are assigned, the procedure is as follows. For each day: (i) identify the percentage point position of the source site's streamflow on the source site's FDC (for the relevant month) and (ii) read off the flow value for the equivalent percentage point from the destination site's flow duration curve (figure 4). If more than one source site was used, the final step is to calculate the weighted average of the estimated destination site flow values. This is assumed to be a final destination site flow value for this day. More details of this procedure can be found in Hughes and Smakhtin (1996).

It is normally recommended to use more than one source site where possible. The use of several source sites is an attempt to account for the fact that an EF (destination) site time series may be the result of several influences, which may not be reflected in a single source site time series. Also, part of an individual source site time series may be missing and the use of several should decrease the number of missing values in the resultant time series at the EF site. Three available source sites (SS1, SS2 and SS3) were used in the simulations. Weighting factors were assigned to each of them based primarily on the size of their catchment areas. SS1 has the largest area of 576 km^2 and it could be assumed that its flow will be most similar to the flow at EF stations downstream. The other two stations with upstream areas of 472 km^2 and 172 km^2 (table 1) have proportionally smaller impacts on the resultant flow time series. The weights assigned to SS1, SS2 and SS3 were 0.5, 0.4 and 0.1, respectively.

An extract from the simulated time series at the Park site (EF2; figure 1) is shown in figure 5 along with the concurrent observed flow record at the upstream flow gauge on the same river (Rajaiya gauge, SS1; figure 1). Although no direct comparison is possible in this case, the pattern of flow variability at both sites is obviously similar, as the resultant flow time series at the downstream destination EF2 site represents a non-linear scaled combination of the flows on upstream flow gauges. The results were also rated as "satisfactory" in discussions with the representatives of the DHM (D. Gautam, DHM, personal communication).

FIGURE 4.
Illustration of streamflow generation procedure by spatial interpolation.

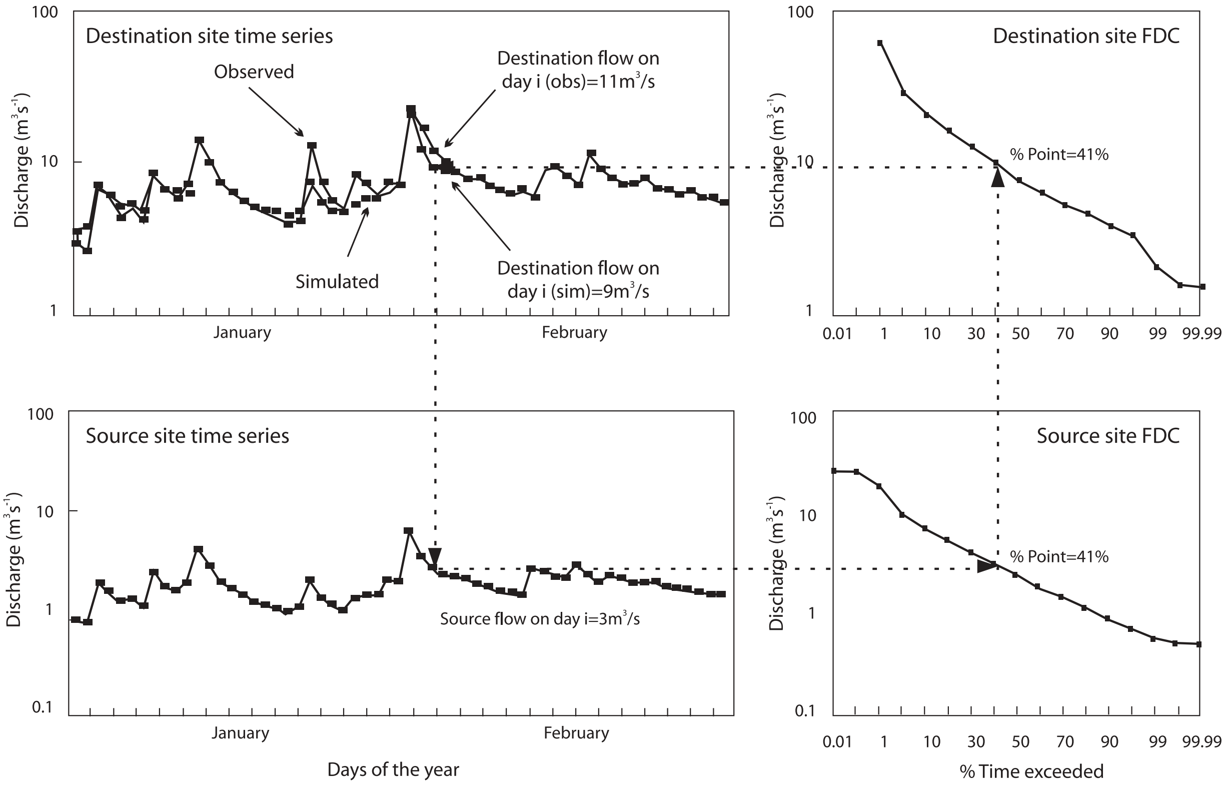
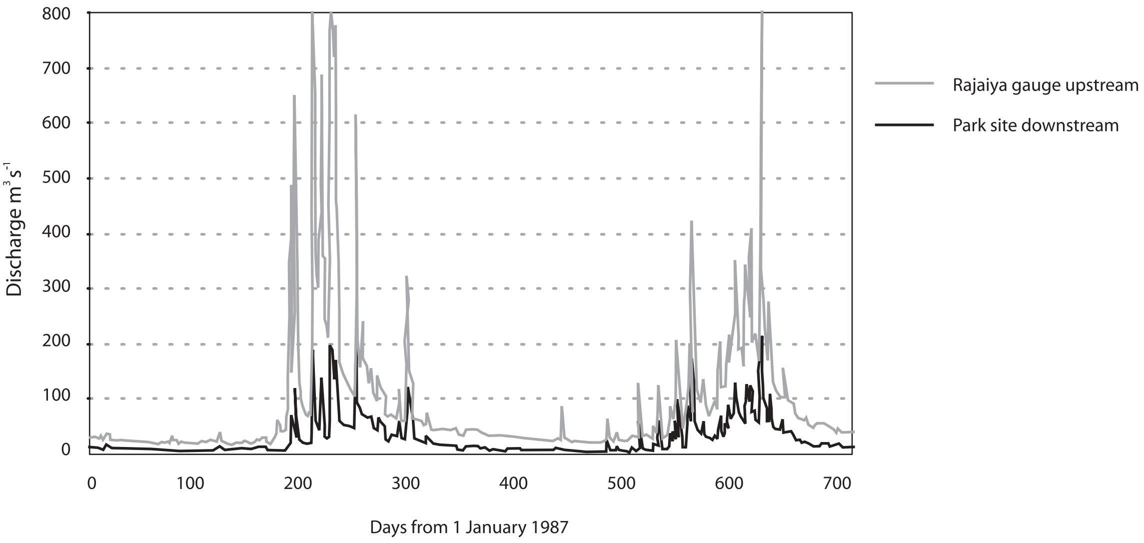


FIGURE 5.
Observed (Rajaiya gauging station, SS1) and simulated (Park site, EF2) hydrographs in the East Rapti River.



Desktop Environmental Flow Assessments

Previous Recommendations and Their Hydrological Interpretation

Only one previous attempt to approach the issue of environmental flow needs in the basin is known to the authors (IWMI 2000a). The focus was on the minimum discharge and depth of water in the river. Minimum flow maintenance was deemed necessary in the East Rapti River at the RCNP border (EF2; table 1) primarily to cater for the needs of tourist activities (i.e., boat or ferry passage). It was also presumed that once such a minimum flow is set, it will contribute positively to the maintenance of the flora and fauna in the riverine forest and flood plains of the park, which will ensure the means of livelihood of people resettled in the buffer zone from the park area. However, there was no real scientific basis on which to decide how much water is really necessary to manage the park and sustain its environment, and it was arbitrarily assumed that at least 15 m^3 s^{-1} had to be left in a river at EF2 at all times. This flow ensures a width of at least 50 m at the site with a mean depth of approximately 1 m and a velocity of 0.3 m s^{-1}. The depth of 1 m was deemed necessary for ferry operation but no ecological or other motivation for the flow was suggested. This "assessment" did not use any of the existing (even simple) environmental flow methods. Effectively, only a quantitative "statement of perceptions" was made and a need for "further research" in this area was emphasized.

The flow of 15 m^3 s^{-1} is difficult to interpret even in the context of the MAR at the site, since no MAR was estimated at the time. However, with the daily time series, which have been simulated in this study, this flow value could be interpreted. Using the generated time series at EF2, it is possible, for example, to estimate the exceedence value of the recommended 15 m^3 s^{-1}. It was found to be exceeded approximately 95 percent of the time. Such a "flow requirement" may only be seen as unrealistically low. It is, however, higher than the value of 10 percent of the minimum monthly average flow (as per hydropower development policy; MoWR 2001), which is 2 m^3 s^{-1} (10% of the minimum monthly average flow at EF2, that is 19.9 m^3 s^{-1} in March). The latter value suggests that MoWR "standards" are unrealistically low, because such a low flow has never occurred in the simulated time series. In addition, a constant flow of 2 m^3 s^{-1} or 15 m^3 s^{-1} or even higher does not take into account hydrological variability and therefore is in conflict with the whole concept of environmental flow allocation.

Linking Flow Variability and Tennant Method

The most straightforward approach of bringing hydrological variability into the picture could be the combination of the lookup flows suggested by Tennant (1976) with a typical FDC and/or hydrographs generated at EF sites. The Tennant method attempts to separate *a priori* the MAR range into several ecologically important classes. All suggested classes correspond to different levels of aquatic habitat maintenance or degradation. A threshold of 10 percent of the MAR reserved for the aquatic ecosystem was considered to be the lowest limit for environmental flow recommendations (corresponding to severe degradation of a system). Fair or good habitat conditions could be ensured if 35 percent of the MAR is allocated for environmental purposes. Allocations in the range of 60 to 100 percent of the MAR represent an environmental optimum. This technique is still widely used in North America (Tharme 2003).

The Tennant MAR classes may, in principle, be linked with flow variability. Once the "ecological" MAR target is set according to Tennant thresholds (e.g., "maintain good aquatic habitat at 40 percent of the MAR"), the natural variability of flows may be subsequently mimicked by using a streamflow time series or its FDC, representing natural flow at the site. Such a time series may be simulated as described above. Expert input would only be necessary to define the environmental MAR target, while the variability of environmental flows would be defined by the representative streamflow time series. Such an approach may be seen as an extension of the Tennant method, but both remain scientifically weak. The threshold selection (percent of the MAR) remains arbitrary, while the attempt to apply this threshold to the actual hydrograph at any EF site will lead to equal scaling down of all naturally occurring flows, high and low. Such scaling is not justified ecologically.

One positive aspect, which may, however, come from the Tennant approach, is the awareness that 10 percent of the MAR may be considered the lowest and highly undesirable threshold for environmental flow allocations and that *at least* some 30 percent of the total natural MAR (coupled with the maintenance of elements of natural flow variability) may need to be retained in the river throughout the basin to ensure fair conditions of riverine ecosystems.

Modified Range of Variability Approach

One way of maintaining flow variability across the full flow regime is to protect the flow across the entire flow duration curve. Some of the earlier suggested EFA methods may be interpreted from this angle. Richter et al. (1997) suggested a Range of Variability Approach (RVA) for the estimation of an environmentally acceptable flow regime. RVA is an excellent example of a technique where the role of hydrological variability in structuring and maintenance of a freshwater dependent ecosystem is raised to the highest level. Thirty-two hydrological characteristics (parameters), which jointly reflect different aspects of flow variability (magnitude, timing, frequency, duration and rate of change) were suggested (table 3). To estimate these characteristics, the method uses a reference, daily time step, streamflow time series at a site of interest. This time series is representative of natural (undisturbed) flow conditions in an upstream river catchment. It is further suggested that in a modified flow regime, all 32 parameters should be maintained within the limits of their

FIGURE 6.
Distribution of low-flow discharges with different averaging intervals (four RVA parameters) at the Rajaiya gauging station.

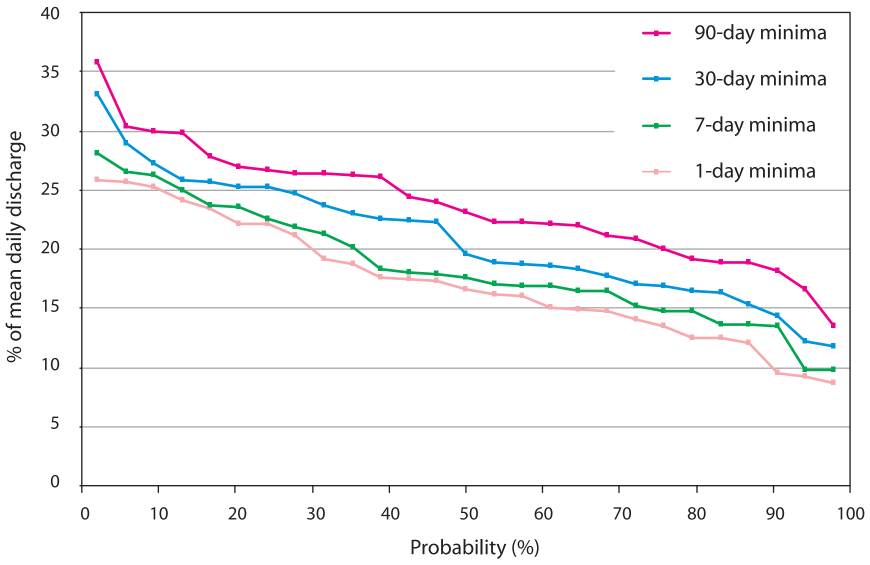


TABLE 3.
Original RVA flow parameters and RVA parameters used in this study.

Original RVA number	RVA streamflow parameter	New number
1	Mean daily discharge: January	1
2	Mean daily discharge: February	2
3	Mean daily discharge: March	3
4	Mean daily discharge: April	4
5	Mean daily discharge: May	5
6	Mean daily discharge: June	6
7	Mean daily discharge: July	7
8	Mean daily discharge: August	8
9	Mean daily discharge: September	9
10	Mean daily discharge: October	10
11	Mean daily discharge: November	11
12	Mean daily discharge: December	12
13	Annual minima: 1-day means	13
14	Annual maxima: 1-day means	14
15	Annual minima: 3-day means	
16	Annual maxima: 3-day means	
17	Annual minima: 7-day means	
18	Annual maxima: 7-day means	
19	Annual minima: 30-day means	15
20	Annual maxima: 30-day means	16
21	Annual minima: 90-day means	
22	Annual maxima: 90-day means	
23	Julian date of each annual 1-day maximum discharge	
24	Julian date of each annual 1-day minimum discharge	
25	Number of high pulses each year	
26	Number of low pulses each year	
27	Mean duration of high pulses within each year (days)	
28	Mean duration of low pulses within each year (days)	
29	Means of all positive differences between consecutive daily values	
30	Means of all negative differences between consecutive daily values	
31	Number of rises	
32	Number of falls	

natural variability. For each parameter, a threshold of 1 standard deviation (SD) from the mean is suggested for use as a default arbitrary limit for setting environmental flow targets in the absence of other supporting ecological information.

Despite the relatively advanced nature of the RVA, there are two important issues that need to be considered. First, the number of parameters used is too large for the level of subjectivity associated with their selection. The choice of parameters is subjective despite the fact that an attempt was obviously made to make the parameter list comprehensive and scientifically sound. In addition, many of the selected parameters are either likely to be correlated with each other, or there is little difference between their values. Figure 6 illustrates the distribution of four RVA parameters extracted from the simulated 27-year long discharge time series at EF2. These parameters are listed as “original RVA parameters” 13, 17, 19 and 21 in table 3. It can be seen that even the difference between 1-day and 90-day average minimum flow values is relatively small and equals approximately 6 percent of the mean flow throughout the entire range of extracted flow minima. The differences between flow minima of other averaging intervals are even less. A similar situation occurs at the “top end” of the flow range where high flows of different averaging intervals (original RVA parameters 14, 16, 18, 20 and 22 in table 3) are calculated. This suggests that the full list of RVA parameters is excessive and points to the possibility of rationalizing the technique.

Second, although the RVA stems from a general aquatic ecology theory, the relationships and links between the RVA parameters, describing hydrological variability on one hand and ecological characteristics and processes of a river on the other, remain largely uncertain. Some good examples of possible ecosystem impacts associated with RVA flow parameters are given on www.epa.gov/watertrain/river/table1.html. These examples, however, are *qualitative* (e.g., “annual minima and maxima affect the balance of competitive, ruderal and stress-tolerant organisms”). They contribute little to the

FIGURE 6

quantitative definition of ecological thresholds, which could have been built into the RVA, and, again, hardly justify the selection of the 32 parameters listed. A lack of *quantitative* knowledge on hydro-ecological processes and links is also apparent from the recommendation to use an arbitrary threshold of 1 SD to set the limits in which the RVA parameters should fluctuate in a modified flow regime. On the other hand, this pragmatic approach allows RVA to be applied as a desktop tool, ensures that sufficient water is available for human uses and accepts that it will not be possible to maintain the full range of natural streamflow variability in regulated or otherwise affected river systems.

The approach adopted here was to reduce the number of flow parameters, express them as flows on the FDC and, following the RVA default threshold, assume that the attained annual value of each selected parameter should be:

$$(\text{mean} - 1\ \text{SD}) \leq \text{parameter} \leq (\text{mean} + 1\ \text{SD}) \quad (2)$$

Out of 32 original RVA parameters only 16 were selected (tables 3 and 4). Twelve monthly means are required as they jointly capture one primary aspect of flow variability—seasonal flow distribution—and also reflect to a certain degree both the timing of flow events and their magnitude. These flows, however, do not reflect the variability of flows at the top and low ends of the flow range. They have therefore been supplemented by 1-day and 30-day annual maxima means and 1-day and 30-day annual minima means. This brings the number of flow parameters down to 16 (table 3).

The 16 selected parameters (flows) for each EF site may be located on the annual, period-of-record flow duration curve corresponding to each site. The percentage of time that each of these flows is exceeded is then estimated directly from the curve. Table 4 summarizes the results of this analysis for the EF2 site.

Given that the most likely future scenario in the East Rapti basin (like in most impacted river

TABLE 4.

Analysis of selected RVA parameter for the EF2 site (Park site) on the East Rapti River.

	Mean ($m^3\ s^{-1}$)	% time flow exceeded	SD ($m^3\ s^{-1}$)	Low (Mean – 1 SD) ($m^3\ s^{-1}$)	High (Mean + 1 SD) ($m^3\ s^{-1}$)
January	27.2	63.2	4.6	22.6	31.8
February	22.9	73.3	3.7	19.2	26.6
March	19.9	82.3	4.0	15.9	23.9
April	20.2	81.3	6.5	13.8	26.7
May	24.3	69.7	9.5	14.8	33.8
June	68.8	33.4	48.1	20.6	116.9
July	227.6	9.67	100.1	127.4	327.7
August	287.6	5.96	152.4	135.2	440.0
September	240.0	8.64	88.8	151.2	328.7
October	99.9	27.2	29.0	70.9	128.8
November	49.2	40.0	9.4	39.9	58.6
December	33.2	53.3	4.3	28.9	37.5
1-day minimum	14.3	95.3	3.5	10.8	17.8
30-day minimum	17.0	89.1	3.6	13.4	20.7
1-day maximum	1,451.1	0.33	733.5	717.6	2,184.6
30-day maximum	340.8	4.15	145.3	195.5	486.0

systems) is the overall reduction of different flows, it is the first part of equation (2) above that is of primary importance. This is a low-threshold condition: (mean – 1 SD) ≤ parameter. The assumption used to construct a FDC corresponding to this condition is that the 16 low-threshold flow parameters (table 4, column 5) are exceeded the same amount of time in the modified (target) flow time series as the 16 original parameters in the natural flow time series (table 4, column 2). Therefore, each flow in column 5 is plotted against its corresponding time of exceedence (column 3, table 4). The resultant FDC (red curve of figure 7) represents the summary of an environmental flow regime in which the selected 16 flow parameters are at their lowest acceptable RVA limit of (mean – 1 SD). Figure 7 also displays the original FDC, representing the natural flow regime at the site. Markers on original (green) and modified (red) curves indicate the flows listed in table 4 (columns 2 and 5, respectively).

Now this FDC can also be converted into a complete time series of environmental flows. The conversion could be easily done by using the same spatial interpolation approach described earlier and illustrated by figure 4. The interpretation of this approach needs only a minor change. The destination site now is the site EF2 with the FDC representing the environmental flow regime (red curve of figure 7). The source sites and weights are the same as those used for the generation of the natural flow at EF2.

The hydrographs of figure 8 are shown at logarithmic scale for better illustration of flow differences at both high and low flows. The "environmental" hydrograph represents the regime calculated using the modified RVA method and may be interpreted as "environmental water demand." It retains most of the features of natural flow variability. The differences between the natural and "environmental" hydrographs at any particular time should ideally be considered as water available for other uses.

The total environmental, long-term, mean annual flow requirement estimated by this method amounts to 56 percent of the total natural MAR. This may be perceived as a high requirement for the default minimum acceptable threshold (1 SD) used in calculations in the absence of basin-specific ecological information. On the other hand, it is lower than Tennant's optimal range threshold of 60 percent of the natural MAR. In this context, the value obtained from RVA may be

FIGURE 7.
Annual flow duration curves at EF2 site showing the location of 16 parameters in original (natural) and modified (target) environmental flow time series.

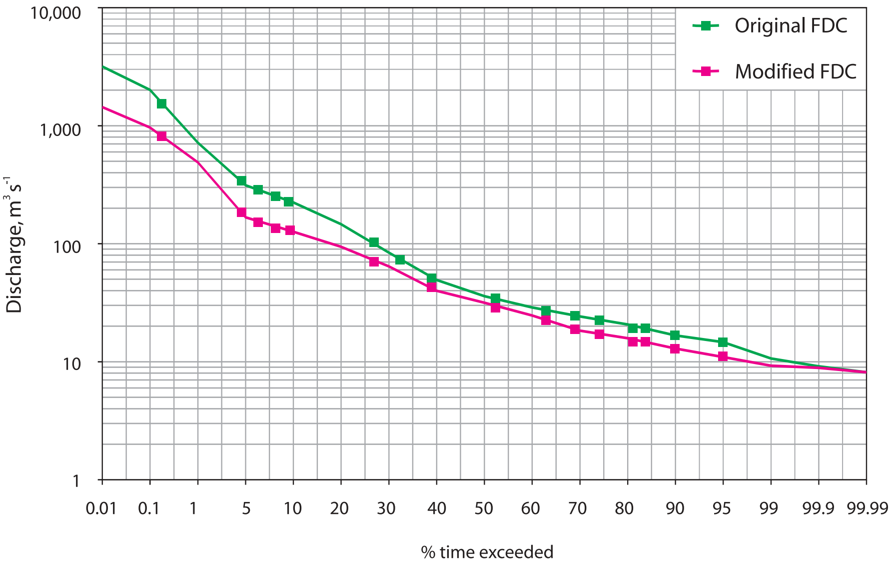
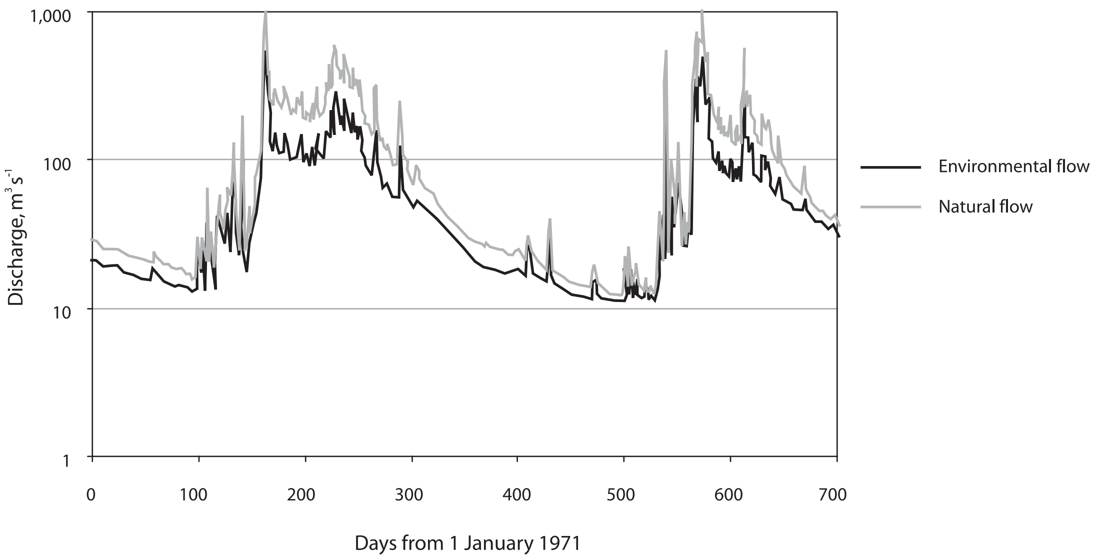


FIGURE 8.
Simulated natural and environmental flow hydrographs at the Park site, EF2.



seen as an estimate of the lowest, acceptable environmental flow allocation, given the high conservation priority of the river.

A South African "Desktop Model" for Determination of Ecological Reserve

The original RVA approach is certainly well motivated, but it still requires a great deal of hydrological and ecological data plus understanding to apply successfully. Given the current limited understanding of eco-hydrological relationships for rivers, RVA modifications similar to the one illustrated above are justified. They can make the technique much easier to apply, while preserving its original concepts, although they do not take away the issue of arbitrary threshold setting.

Another hydrology-based, planning-type EFA methodology was developed by Hughes and Münster (2000) and further refined by Hughes and Hannart (2003). It is known as the "Desktop Model" (DM) and it emerged from the results of many *comprehensive* assessments of Ecological Reserve of South African rivers. The "Ecological Reserve for rivers" is effectively a South African term for "environmental flows." Quantifying Ecological Reserve involves determining the water volumes and flow rates that will sustain a river in a predetermined condition. The latter is referred to as an "environmental management class" and is related to the extent to which this condition deviates from the natural. There are four environmental management classes (A, B, C and D) where class A rivers are largely natural and class D rivers are largely modified.

The DM originates from the Building Block Methodology (BBM; King and Louw 1998). "Building Blocks" (BBs) are environmental flows, which jointly comprise the ecologically acceptable, modified flow regime. The major BBs are low flows (baseflows), small increases in flow (freshes) and larger high flows, which are required for river channel maintenance. BBs are defined for each of the 12 calendar months and differ between "normal years" and "drought years." The first are referred to as "maintenance requirements" and the second as "drought requirements." The set of BBs, therefore, includes maintenance low flows, maintenance high flows, drought low flows and drought high flows.

Hughes and Münster (2000) analyzed the results of previous comprehensive environmental flow assessments of South African rivers in the context of hydrological variability of these rivers and developed the empirical relationships, which related the above BBs to flow variability. These relationships allow the environmental flows for an ungauged site to be estimated, if hydrology for this site is available or can be generated, as in the case of the East Rapti River.

The major assumption of the DM, which emerged from the analysis of comprehensive Ecological Reserve estimates, is that the rivers with more stable flow regimes (a higher proportion of their flow occurs as baseflow) may be expected to have relatively higher low-flow requirements in normal years ("maintenance low flow requirements" in Ecological Reserve terminology). Rivers with more variable flow regimes would be expected, from the purely hydrological perspective, to have relatively lower maintenance low-flow requirements and/or lower levels of assurance associated with them. The consequence of these assumptions is that the long-term mean environmental requirement would be lower for rivers with more variable flow regimes. The DM, therefore, explicitly introduced the principle of "assurance of supply" for "environmental water demand."

Technically, the DM (and corresponding software) allows the estimation of low and high flows of maintenance and drought, and the establishment of assurance rules. The underlying concepts of the DM are attractive and, to an extent, ecologically justified (as they emerge from the results of comprehensive assessments, which involve a variety of ecological disciplines). One stumbling block for DM applications in Nepal or other countries at present is that parameters of the DM relationships were estimated on the basis of South African case studies. At the same time, DM is, perhaps, the most advanced desktop method to date, which can be further developed/ applied to different physiographic and ecological conditions. The application of a DM for the East Rapti River is currently in progress and the subject of a different study. One advantage of the DM is that it is based on flow data of monthly resolution—data that are more readily available/ accessible in developing countries.

Smakhtin et al. (2004) attempted to use the concepts behind DM to evaluate the total environmental water requirements of the world's rivers. The assessment was done based on the assumption that rivers have to be maintained *at least* in environmental management class C, which represents the "fair" condition of an ecosystem. From this preliminary assessment, most rivers in Nepal were found to have an environmental requirement of 20-25 percent of natural MAR. This is less than half the environmental flow requirement determined by the modified RVA method (56 percent) and should be seen as the bare survival minimum for the East Rapti River

Conclusions

This study attempts to interpret several hydrology-based, desktop environmental flow assessment methods in the Nepalese context, using the East Rapti River as an example. It is shown that none of the currently existing desktop techniques is directly suitable for immediate application. Some of them are too simplistic and do not take into account the recent hydro-ecological theories (e.g., Tennant method). Others are too elaborate for the level of subjectivity associated with them (e.g., RVA). Yet others are developed for a specific country/region (e.g., DM) and need to be re-calibrated/tested in a different physiographic environment (like the monsoon and ice-melt driven flow regimes of Nepal) before they can be reliably applied. There is therefore a need to further develop/modify and test existing methods in specific river basins.

The study also illustrates how the required hydrological information can be generated for the locations where EFA is intended—quickly and in conditions of limited observed data, which is the typical case in most of the developing world. This hydrological information (natural flow time series) is necessary, regardless of the type of EFA method chosen, and can also be used for different engineering applications.

The study illustrates how an existing hydrology-based technique (RVA) can be modified to simplify the process of EFA in the absence of local eco-hydrological knowledge and expertise and yet preserve the principles of flow variability in the estimation process.

One of the major problems in environmental flow assessments, effectively reflected in all methods used (and also in-built in some comprehensive techniques), is the elusive search for environmentally acceptable thresholds, below which there is some significant change in the system. In reality, the relationships between river flows and river ecology variables, when illustrated graphically, often tend to be smoothly curving lines. This suggests a consistent decline in ecosystem health with reduced water availability. In the absence of clear thresholds, setting environmental flows becomes a matter of a "dialog" between social preferences and eco-hydrological science. Linking the two is the challenge for the future, particularly in developing countries like Nepal. This could lead to the development of new field of work like, for example, "socio- hydrology" or "socio-ecology."

Linked to the above, similar to many other low-income Asian countries, is the high rural population (86 percent of total) of Nepal with a predominantly subsistence livelihood. It is essential that in such countries programs for establishing environmentally acceptable limits for water resources exploitation consider not only the relationship between flow and the river ecosystem, but also the interaction of rural communities with the river flow and ecosystem. In the East Rapti River basin, as indicated earlier, Bote and Danuwar communities are highly dependent on the river resources for fishing, timber collection during floods, subsistence farming, washing, bathing, swimming and other activities. None of the environmental flow assessment methods demonstrated above explicitly take into account these interactions. To identify the importance of different levels of flow regime to sustain rural livelihood in the area, methods like participatory rural appraisal should be carried out. This may only be done as part of the comprehensive environmental flow assessment, which brings together many disciplines and produces the results of higher confidence.

While such assessments certainly represent the direction that should be followed in principle, in planning for environmental allocations in developing countries, low-confidence methods need to be used as the first step to safeguard, albeit implicitly, at least some of the environmentally and socially important riverine functions.

Literature Cited

ADB (Asian Development Bank). 2000. *Energy 2000 - Review of the energy policy of the Asian Development Bank*. Manila, Philippines: ADB. 101 pp.

Bhandari, V. 2001. The relevance of Nepalese environment protection act and rules on old hydropower plants. *A Journal of the Environment* 6(7).

Dyson, M.; Bergkamp, G.; and Scanlon, J., eds. 2003. *Flow: The essentials of environmental flows*. Gland, Switzerland and Cambridge, UK: The World Conservation Union (IUCN). xiv + 118 pp.

Ghimire, D .P.; Dutta, J. P.; Poudel, R.; Khatri-Chhetri, T. B.; Adhikari, K. R.; Shukla, A.; Uprety, G.; and Devkota, B. 2000. Socioeconomic and stakeholders analysis in the East Rapti River basin of Nepal. Kathmandu, Nepal: Water Management Study Program, Institute of Agriculture and Animal Sciences (IAAS) and International Water Management Institute. Unpublished report. 39 pp.

Hughes, D. A.; and Hannart, P. 2003. A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. *Journal of Hydrology* 270: 167-181.

Hughes, D. A.; and Münster, F. 2000. Hydrological information and techniques to support the determination of the water quantity component of the ecological reserve. *Water Research Commission Report TT 137/00*, Pretoria, South Africa. 91 pp.

Hughes, D. A.; and Smakhtin, V. U. 1996. Daily flow time series patching or extension: A spatial interpolation approach based on flow duration curves. *Hydrological Sciences Journal* 41(6): 851- 871.

IWMI (International Water Management Institute). 2000a. Water accounting for East Rapti River basin. Kathmandu, Nepal: IWMI. Unpublished Report. 29 pp.

IWMI. 2000b. Initial assessment of the existing physical resource base and institutional arrangements in East Rapti River basin. Kathmandu, Nepal: IWMI. Unpublished Report. 19 pp.

Kansakar, S. R.; Hannah, D. M.; Gerrard, J.; and Rees, G. 2002. Flow regime characteristics of Himalayan river basins in Nepal. In *FRIEND 2002 - Regional Hydrology: Bridging the gap between research and practice*, eds. H. A. J. van Lannen and S. Demuth. International Association of Hydrological Sciences (IAHS) Publication No. 274: 425-432.

Kayastha, R. N.; and Pant, D. 2001. Existing arrangement for water management in East Rapti River basin: Institutional issues. In *Integrated development and management of water resources: A case of Indrawati River basin, Nepal. Proceedings of a workshop held in Kathmandu, Nepal, April 2001*, eds. R. N. Kayastha, U. Prajuli, D. Pant and C. Sharma. Kathmandu, Nepal: Water and Energy Commission Secretariat (WECS) and International Water Management Institute.

King, J.; and Louw, D. 1998. Instream flow assessments for regulated rivers in South Africa using Building Block Methodology. *Aquatic Ecosystems Health and Management* 1:109-124.

KMTNC (King Mahendra Trust for Nature Conservation). 1996. *Royal Chitwan National Park after twenty years: An assessment of values, threats and opportunities.* Kathmandu, Nepal: KMTNC.

Manandhar, A. 2002. *The South Asian Transboundary Water Quality Monitoring Programme. Environment and Public Health Organization (ENPHO)*. www.enpho.org. Downloaded on 04 January 2004.

MoWR (Ministry of Water Resources). 1992. Water Resources Act (1992). In *Nepalese Legal Provisions on Hydropower Development*. Kathmandu, Nepal: Electricity Development Centre (currently known as Department for Electricity Development), Ministry of Water Resources, His Majesty's Government of Nepal. 175 pp.

MoWR. 2001. Hydropower Development Policy 2058 (2001): Approved by His Majesty's Government of Nepal on 15 October 2001. (In Nepali). Kathmandu, Nepal: Ministry of Water Resources, His Majesty's Government of Nepal. 34 pp.

Petts, G. E. 1996. Water allocation to protect river ecosystems. *Regulated Rivers: Research and management* 12: 353-365.

Poff, N. L; Allan, J. D.; Bain, M. B.; Karr, J. R.; Prestegaard, K. L.; Richter, B. D.; Sparks, R. E.; and Stromberg, J. C. 1997. The natural flow regime: A paradigm for river conservation and restoration. *Bioscience* 47: 769-784.

HMGN and UNDP (His Majesty's Government of Nepal and United Nations Development Programme). 2000. *Park People Programme annual report 2000: Consolidating conservation through people's participation*. Kathmandu, Nepal: Department of National Park and Wildlife Conversation, HMGN and UNDP. 57 pp.

Rees, G.; Crocer, K.; Zaidman, M.; Cole, G.; Kansakar, S.; Chalise, S.; Kumar, A.; Safar, A.; and Singhal, M. 2002. Application of the regional flow estimation method in the Himalayan region. In *FRIEND 2002- Regional Hydrology: Bridging the gap between research and practice*, eds. H. A. J. van Lannen and S. Demuth. International Association of Hydrological Sciences (IAHS) Publication No. 274: 433 –440.

Richter, B. D.; Baumgartner, J. V.; Wigington, R.; and Braun, D. P. 1997. How much water does a river need? *Freshwater Biology* 37: 231-249.

Shilpakar, R. L. 2003. Geo-information procedures for water accounting: A case of the East Rapti River basin, Nepal. M. Sc. Thesis. Enschede, The Netherlands: International Institute for Geo-Information Science and Earth Observation (ITC). 59 pp.

Smakhtin, V. U. 2000. Simple methods of hydrological data provision. *Water Research Commission Report* No 867/1/00, Pretoria, South Africa. 86 pp.

Smakhtin, V. U.; Creuse-Naudine, E.; and Hughes, D. A. 1997. Regionalisation of daily flow characteristics in part of the Eastern Cape, South Africa. *Hydrological Sciences Journal,* 42: 919-936.

Smakhtin, V. U.; Revenga, C.; and Döll, P. 2004. Taking into account environmental water requirements in global-scale water resources assessments. Comprehensive Assessment Research Report 2. Colombo, Sri Lanka: Comprehensive Assessment Secretariat. www.iwmi.org/assessment.

Straede, S.; and Helles, F. 2000. Park-people conflict resolution in Royal Chitwan National Park, Nepal: Buying time at high cost? *Environmental Conservation* 27: 368-381.

Tahal Consulting Engineers Ltd. 2002*. Institutional development of Department of Hydrology and Meteorology, Final Report*. Technical Report No. 7: Basin Study. Kathmandu, Nepal: Tahal Consulting Engineers Ltd.

Tharme, R. E. 2003. A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* 19: 1-45.

Tennant, D. L. 1976. Instream flow regimens for fish, wildlife, recreation and related environmental resources. *Fisheries* 1: 6–10.

UNEP (United Nations Environmental Programme). 2001. *Nepal: State of the environment 2001*. Kathmandu, Nepal: UNEP in collaboration with Ministry of Population and Environment (MOPE), His Majesty's Government of Nepal (HMGN), International Centre for Integrated Mountain Development (ICIMOD), South Asia Co-operative Environment Programme (SACEP), and Norwegian Agency for Cooperation and Development (NORAD). 210 pp.

Research Reports

76. *Small Dams and Social Capital in Yemen: How Assistance Strategies Affect Local Investments and Institutions.* Douglas L. Vermillion and Said Al-Shaybani. 2004.

77. *Simulating the Hydrology of Small Coastal Ecosystems in Conditions of Limited Data.* V. U. Smakhtin, S. C. Piyankarage, P. Stanzel and E. Boelee. 2004.

78. *Irrigation Kuznets Curve, Governance and Dynamics of Irrigation Development: A Global Cross-Country Analysis from 1972 to 1991.* Madhusudan Bhattarai. 2004.

79. *Strategic Analysis of Water Institutions in India: Application of a New Research Paradigm.* R. Maria Saleth. 2004.

80. *Robbing Yadullah's Water to Irrigate Saeid's Garden: Hydrology and Water Rights in a Village of Central Iran.* François Molle, Alireza Mamanpoush and Mokhtar Miranzadeh. 2004.

81. *Inadequacies in the Water Reforms in the Kyrgyz Republic: An Institutional Analysis.* Mehmood Ul Hassan, Ralf Starkloff and Nargiza Nizamedinkhodjaeva. 2004.

82. *Valuing Nutrients in Soil and Water: Concepts and Techniques with Examples from IWMI Studies.* Pay Drechsel, Mark Giordano and Lucy Gyiele. 2004.

83. *Spatial Variation in Water Supply and Demand Across River Basins of India.* Upali A. Amarasinghe, Bharat R. Sharma, Noel Aloysius, Christopher Scott, Vladimir Smakhtin and Charlotte de Fraiture. 2004.

84. *An Assessment of Small-scale Users' Inclusion in Large-scale Water User Associations of South Africa.* Nicolas Faysse. 2004.

85. *The Use of Remote-Sensing Data for Drought Assessment and Monitoring in Southwest Asia.* P. S. Thenkabail, M. S. D. N. Gamage and V. U. Smakhtin, 2004.

86. *Strategies for the Management of Conjuctive use of Surface Water and Groundwater Resources in Semi-arid Areas: A Case Study from Pakistan.* Asad Sarwar Qureshi, Hugh Turral and Ilyas Masih. 2004.

87. *Economics and Politics of Water Resources Development: Uda Walawe Irrigation Project, Sri Lanka.* François Molle and Mary Renwick. 2005.

88. *"Bright Spots" in Uzbekistan, Reversing Land and Water Degradation While Improving Livelihoods: Key Developments and Sustaining Ingredients for Transition Economies of the former Soviet Union.* Andrew Noble, Mohammed ul Hassan and Jusipbek Kazbekov. 2005.

89. *Planning for Environmental Water Allocations: An Example of Hydrology-based Assessment in the East Rapti River, Nepal.* V. U. Smakhtin and R. L. Shilpakar. 2005.

Postal Address:
P O Box 2075
Colombo
Sri Lanka

Location:
127, Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Tel:
+94-11-2787404

Fax:
+94-11-2786854

E-mail:
iwmi@cgiar.org

Website:
http://www.iwmi.org

IWMI
International
Water Management
Institute

FUTURE HARVEST
IWMI is a Future Harvest Center
supported by the CGIAR

ISSN 1026-0862
ISBN 92-9090-594-8