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Water Resources and Environment Technical Note C.1

Environmental Flows: Concepts and Methods

Series Editors
Richard Davis
Rafik Hirji

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WATER RESOURCES AND ENVIRONMENT

TECHNICAL NOTE C.1

Environmental Flows: Concepts and Methods

SERIES EDITORS
RICHARD DAVIS, RAFIK HIRJI



The World Bank
Washington, D.C.

Water Resources and Environment Technical Notes

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FOREWORD

The environmentally sustainable development and management of water resources is a critical and complex issue for both rich and poor countries. It is technically challenging and often entails difficult trade-offs among social, economic, and political considerations. Typically, the environment is treated as a marginal issue when it is actually key to sustainable water management.

According to the World Bank's recently approved Water Resources Sector Strategy, "the environment is a special 'water-using sector' in that most environmental concerns are a central part of overall water resources management, and not just a part of a distinct water-using sector" (World Bank 2003: 28). Being integral to overall water resources management, the environment is "voiceless" when other water using sectors have distinct voices. As a consequence, representatives of these other water using sectors need to be fully aware of the importance of environmental aspects of water resources management for the development of their sectoral interests.

For us in the World Bank, water resources management—including the development of surface and groundwater resources for urban, rural, agriculture, energy, mining, and industrial uses, as well as the protection of surface and groundwater sources, pollution control, watershed management, control of water weeds, and restoration of degraded ecosystems such as lakes and wetlands—is an important element of our lending, supporting one of the essential building blocks for sustaining livelihoods and for social and economic development in general. Prior to 1993, environmental considerations of such investments were addressed reactively and primarily through the Bank's safeguard policies. The 1993 Water Resources Management Policy Paper broadened the development focus to include the protection and management of water resources in an environmentally sustainable, socially acceptable, and economically efficient manner as an emerging

priority in Bank lending. Many lessons have been learned, and these have contributed to changing attitudes and practices in World Bank operations.

Water resources management is also a critical development issue because of its many links to poverty reduction, including health, agricultural productivity, industrial and energy development, and sustainable growth in downstream communities. But strategies to reduce poverty should not lead to further degradation of water resources or ecological services. Finding a balance between these objectives is an important aspect of the Bank's interest in sustainable development. The 2001 Environment Strategy underscores the linkages among water resources management, environmental sustainability, and poverty, and shows how the 2003 Water Resources Sector Strategy's call for using water as a vehicle for increasing growth and reducing poverty can be carried out in a socially and environmentally responsible manner.

Over the past few decades, many nations have been subjected to the ravages of either droughts or floods. Unsustainable land and water use practices have contributed to the degradation of the water resources base and are undermining the primary investments in water supply, energy and irrigation infrastructure, often also contributing to loss of biodiversity. In response, new policy and institutional reforms are being developed to ensure responsible and sustainable practices are put in place, and new predictive and forecasting techniques are being developed that can help to reduce the impacts and manage the consequences of such events. The Environment and Water Resources Sector Strategies make it clear that water must be treated as a resource that spans multiple uses in a river basin, particularly to maintain sufficient flows of sufficient quality at the appropriate times to offset upstream abstraction and pollution and sustain the downstream social, ecological, and hydrological functions of watersheds and wetlands.

With the support of the Government of the Netherlands, the Environment Department has prepared an initial series of Water Resources and Environment Technical Notes to improve the knowledge base about applying environmental management principles to water resources management. The Technical Note series supports the implementation of the World Bank 1993 Water Resources Management Policy, 2001 Environment Strategy, and 2003 Water Resources Sector Strategy, as well as the implementation of the Bank's safeguard policies. The Notes are also consistent with the Millennium Development Goal objectives related to environmental sustainability of water resources.

The Notes are intended for use by those without specific training in water resources management such as technical specialists, policymakers and managers working on water sector related investments within the Bank; practitioners from bilateral, multilateral, and nongovernmental organizations; and public and private sector specialists interested in environmentally sustainable water resources management. These people may have been trained as environmental, municipal, water resources, irrigation, power, or mining engineers; or as economists, lawyers, sociologists, natural resources specialists, urban planners, environmental planners, or ecologists.

The Notes are in eight categories: environmental issues and lessons; institutional and regulatory issues; environmental flow assessment; water quality management; irrigation and drainage; water conservation (demand management); waterbody management; and selected topics. The series may be expanded in the future to include other relevant categories or topics. Not all topics will be of interest to all specialists. Some will find the review of past environmental practices in the water sector useful for learning and improving their performance; others may find their suggestions for further, more detailed information to be valuable; while still others will find them useful as a reference on emerging topics such as environmental flow assessment, environmental regulations for private water utilities, inter-basin water transfers, and climate variability and climate change. The latter topics are likely to be of increasing importance as the World Bank implements its environment and water resources sector strategies and supports the next generation of water resources and environmental policy and institutional reforms.

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INTRODUCTION

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

The recognition that modifications to river flows are an important source of riverine, floodplain, and in some cases estuarine degradation is relatively recent. The methodology linking downstream resource degradation and their social consequences is also in its early stages of development. The World Bank acknowledged the issue in its 1993 Water Resources Management Policy, which included as an objective that “the water supply needs of rivers, wetlands, and fish-

eries will be considered in decisions concerning the operation of reservoirs and the allocation of water.” The World Bank's environmental assessment policy (Operational Policy 4.01) is triggered if modifications to river flows lead to adverse environmental risks and impacts. If changes in flow have the potential to cause significant loss or degradation of natural habitats, borrowers must also comply with the Bank's natural habitats policy (Operational Policy 4.04) in order for a loan to be approved.

Technical Notes C.1 to C.4 deal with environmental flows. Although changes in flow will affect water quality—for example, by increasing or decreasing turbidity—the focus in these notes is primarily on the direct effects of flow on the ecological functioning of rivers and the management of water quantity. Note C.1 introduces concepts and methods for determining environmental flow requirements for rivers, including a description of how different sorts of river flows contribute to the maintenance of rivers, the practicalities of undertaking a flow assessment, the need for balancing environmental and offstream demands for water, and the challenges faced in implementing environmental flows. Note

C.2 reviews some important case histories. Note C.3 describes the reinstatement of flood releases from reservoirs for floodplain inundation. Note C.4 addresses the downstream social issues arising from changes in flows.



Photo by Curt Camermark, World Bank

River crossing agricultural fields, Nepal

ENVIRONMENTAL FLOWS AND RIVER MANAGEMENT

Environmental flows are the water that is left in a river ecosystem, or released into it, for the specific purpose of managing the condition of that ecosystem (Box 1).

The failure to maintain such flows has led to a decline in the health of many of the world's water-dependent ecosystems, largely as a result of increasing pressure from water and catchment developments. These ecosystems include not just in-river fauna and flora, but also the floodplains and wetlands watered by floods, groundwater-dependent ecosystems replenished through river seepage, and estuaries.

Not only does the decline in water-dependent ecosystems threaten environmental values such as maintenance of biodiversity and protection of threatened species, but it directly affects many economic sectors that rely on such ecosystems. In many parts of the world, people depend on properly functioning rivers and estuaries for fish and navigation; floodplain vegetation for grazing, fiber, and food; and wetlands for sediment trapping and pollution removal. Biophysical changes impact livelihoods.

The understanding that flows are critical for maintaining ecosystems has triggered an international move to understand and describe the links between

flows and ecosystem functioning, so that environmental flows can be specified that will halt or reverse this decline, and to help minimize the loss of valued ecosystem features (Box 2). This understanding can be used to describe flows for a river that will:

- minimize or mitigate the impacts of new water-resource developments
- rehabilitate systems impacted by past developments
- allow calculation of the costs of compensating people for such impacts.

These flow descriptions can be as simple as the specification of a water depth to provide wetted habitat for a fish species, or as complex as a description of a completely modified flow regime to maintain a whole river and floodplain ecosystem. Armed with this knowledge, decisionmakers are better equipped to achieve a satisfactory balance between consumptive uses and ecosystem uses of the water resource. Of course, environmental flows alone are seldom a sufficient prescription for healthy rivers. Environmental flow allocations should be considered in combination with other complementary mitigation measures—such as water quality improvements—in order to achieve a cost-effective combination of management interventions (see Skagit River Case Study in Note C.2).

Box 1. TERMINOLOGY

Several terms are used to describe flows for ecological maintenance of rivers. “Environmental flows” is a comprehensive term that encompasses all components of the river, is dynamic over time, takes cognizance of the need for natural flow variability, and addresses social and economic issues as well as biophysical ones. Other terms include:

- Instream flow requirements (IFRs): an earlier, less-comprehensive term for environmental flows, usually focused on flows for fish.
- Maintenance IFR: a flow regime required to maintain all river ecosystem functions, and to provide sufficient access to water to allow plants and animals to reproduce in most years.

- Drought IFR: a drastically reduced flow regime for recognized drought years that is sufficient to maintain species in a system without necessarily supporting reproduction.

- Minimum flow: a general term used to describe a flow required to maintain some feature of a river ecosystem. The concept of minimum flow originated in the United States as a streamflow standard to limit the abstraction of water during the dry season, and may not be relevant in arid and semi-arid regions.

All of the above terms describe the maintenance of healthy conditions in a river.

Box 2.

EXAMPLES OF VALUED FEATURES OF RIVERS THAT COULD BE PROTECTED THROUGH ENVIRONMENTAL FLOWS

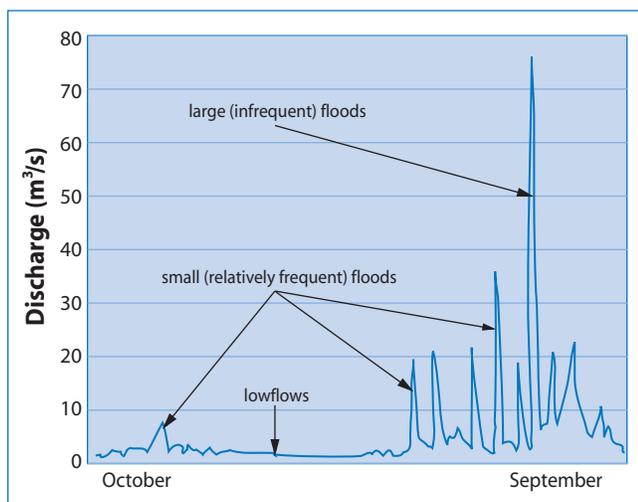
Feature	Explanation of value	Examples of environmental flows required
Aquatic animals	Freshwater fish are a valuable source of protein for rural people. Other valued fauna include: angling fish, rare water birds, or the small aquatic life that forms the base of the food chain.	<ul style="list-style-type: none"> ■ flows to maintain the physical habitat; ■ flows to maintain suitable water quality; ■ flows to allow passage for migratory fish; ■ small floods to trigger life-cycle cues such as spawning or egg-laying.
Riparian vegetation	Stabilizes river banks, provides food and firewood for rural people and habitat for animals, and buffers the river against nutrient and sediment losses from human activities in the catchment.	<ul style="list-style-type: none"> ■ flows that maintain soil-moisture levels in the banks; ■ high flows to deposit nutrients on the banks and distribute seeds.
River sand	Used for building.	<ul style="list-style-type: none"> ■ flows to transport sand and to separate it from finer particles.
Estuaries	Provide nursery areas for marine fish.	<ul style="list-style-type: none"> ■ flows that maintain the required salt/freshwater balance and ocean connection to estuary.
Aquifers and groundwater	Maintain the perennial nature of rivers acting as sources of water during the dry season.	<ul style="list-style-type: none"> ■ flows to recharge the aquifers.
Floodplains	Support fisheries and flood-recession agriculture for rural people.	<ul style="list-style-type: none"> ■ floods that inundate the floodplain at the appropriate time of the year.
Aesthetics	The sound of water running over rocks, the smells and sights of a river with trees, birds, and fish.	<ul style="list-style-type: none"> ■ sufficient flow to maximize natural aesthetic features, including many of the flows mentioned above.
Recreational and cultural features	Clean water and rapids for river rafting or clean pools for baptism ceremonies or bathing. Also features valued by anglers, birdwatchers, and photographers.	<ul style="list-style-type: none"> ■ flows that flush sediments and algae, and that maintain water quality – see also aquatic animals.
Ecosystem services	Maintain the capacity of aquatic ecosystems to regulate essential ecological processes, for instance to purify water, attenuate floods, or control pests.	<ul style="list-style-type: none"> ■ flows that maintain biodiversity and ecosystem functioning.
Overall environmental protection	A wish to minimize human impacts and conserve natural systems for future generations.	<ul style="list-style-type: none"> ■ some or all of the above types of flows.

THE SIGNIFICANCE OF DIFFERENT FLOWS

In general, the closer decisionmakers want the aquatic system to be to natural, the greater the volume of the original flow regime that will be required as an environmental flow. However, the pattern of flow over time is as important as the overall quantity.

The flow regime of a river can be divided into base flows (low flows), small floods that occur every year, and occasional large floods that spread out onto floodplains (Figure 1). Different components maintain different parts of aquatic ecosystems (Box 3). The loss or degradation of one component of a flow regime will affect a system differently than the loss of some other component. Identifying these flow components—and understanding the ecosystem consequences of their loss or modification—is central to a flow assessment. The timing of these flow components within a year is also important, since temperature and other temporal cues play an important part in ecosystem functioning. However, these cues can often depend on real-time conditions that are not exactly fixed by calendar day or month. Consequently, some environmental flow prescriptions allow river operators to exercise discretion, within specified rules, to ensure that the flows are effective.

FIGURE 1.
AN ANNUAL HYDROGRAPH OF DAILY FLOWS IN A RIVER, BEGINNING IN OCTOBER OF ONE YEAR AND CONCLUDING IN SEPTEMBER OF THE FOLLOWING YEAR. THIS IS CALLED A FLOW REGIME.



The temporal characteristics of the flow regime also have an important influence on the overall character of a river ecosystem. Fluctuations between low flows and small and large floods change conditions through each day and season, creating mosaics of areas inundated and exposed for different lengths of time. The more diverse the physical conditions, the higher the biodiversity and the greater the resilience of the ecosystem to disturbance.

Box 3. EFFECTS OF DIFFERENT COMPONENTS OF A FLOW REGIME ON RIVERS

Flows	Importance to river ecosystem
Low flows: their range in dry and wet seasons	Low flows occur when the river is not in flood. They are larger and more varied in the wet season than in the dry, and define whether the river flows all year, only during the wet season, or just after rains. They create different conditions in different seasons, dictating which (and how many) biotic species occur at any time of the year.
Small floods: size, number per year, and timing	Small floods stimulate spawning in fish, flush out poor-quality water, cleanse the riverbed, and sort the river stones by size, thereby creating different kinds of habitat. They trigger and synchronize activities as varied as upstream migrations of fish and germination of seedlings on riverbanks.
Large floods: size and timing	Large floods trigger the same in-river responses as small ones, but also provide scouring flows that shape the channel. They move and cleanse cobbles and boulders on the riverbed, and deposit silt, nutrients, eggs, and seeds on floodplains. They re-charge soil moisture levels in the banks, enabling seedlings of riparian trees to grow, and maintain links with the sea by scouring estuaries. These floods inundate backwaters, secondary channels, and floodplains. They trigger bursts of growth in many floodplain species, including waterbirds such as ibis. Note C.3 describes the release of water for large floods.

Different developments will affect different components of the flow regime and, in turn, elicit various responses from the aquatic ecosystem. However, not all changes to the flow regime arise from direct manipulations of flows. For instance, deforestation of an upland catchment can significantly increase the energy of floods, resulting in changes to the form of the riverbed as well as deposition of excessive sediment on floodplains. Box 4 summarizes typical develop-

ments, the components of the flow regime most commonly affected, and examples of the consequences for aquatic ecosystems. These consequences have a direct impact on human populations dependent on these ecosystems. Thus, the reduction in small-to-medium-sized floods following the building of a large dam can remove cues needed for fish breeding, and so affect the livelihoods of downstream water-dependent communities.

Box 4.

ACTIONS THAT IMPACT FLOW AND CONSEQUENCES FOR AQUATIC ECOSYSTEMS

Management actions	Example of the impact on flow	Examples of ecosystem consequences
Irrigation flows (using the river as a conduit)	Dry-season lowflows increased, and seasonal variability reduced.	<ul style="list-style-type: none"> Can result in higher flows in the dry than in the wet season. Hydraulic and thermal conditions, in particular, can become mismatched with life-cycle requirements, causing species to decrease in numbers and abundance. Pests are often able to take advantage of such environmental conditions and increase in abundance.
Run-of-river diversion	Wet and dry season lowflows reduced.	<ul style="list-style-type: none"> Reduces habitat availability and restricts movement of aquatic animals, thus increasing competition for space and vulnerability to predation. Increases diurnal temperature fluctuations, concentrates effluents, and can lead to toxic algal blooms.
Large dams	Frequency and duration of floods reduced.	<ul style="list-style-type: none"> Flood cues that trigger fish spawning or seed germination may occur at the wrong time of the year or not at all, resulting in a failure to produce new generations of individuals. Reduced wetting of banks stresses riparian vegetation and reduces establishment of seedlings. Bank stability is weakened and soil erosion increases. Reduced flows into estuaries reduces access for marine fish using estuaries as nursery areas. Reduced flooding of riparian wetlands and floodplains causes loss of fisheries and other attributes. <p>See Lesotho Highlands Water Project in Note C.2.</p>
Hydropower stations	Timing and distribution of flows altered. Rate of change between high and low flows decreased.	<ul style="list-style-type: none"> Mismatched flows and abnormal flow fluctuations impact life-cycle stages of many animals and plants. See Skagit River case study in Note C.2.
Afforestation of catchment	Wet and dry season lowflows reduced and small floods attenuated.	<ul style="list-style-type: none"> Reduces flood cues that trigger fish spawning or seed germination, and decreases wetted habitat through the year.
Deforestation of catchment	Energy of medium-large floods increased; dry season flows increased.	<ul style="list-style-type: none"> Increases bank and bed erosion, which alters the available habitat for aquatic species. Reduces habitat availability in the dry season. Increases the risk of animals being washed away.

Box 5.
INSTREAM FLOWS THAT ARE NOT ENVIRONMENTAL FLOWS

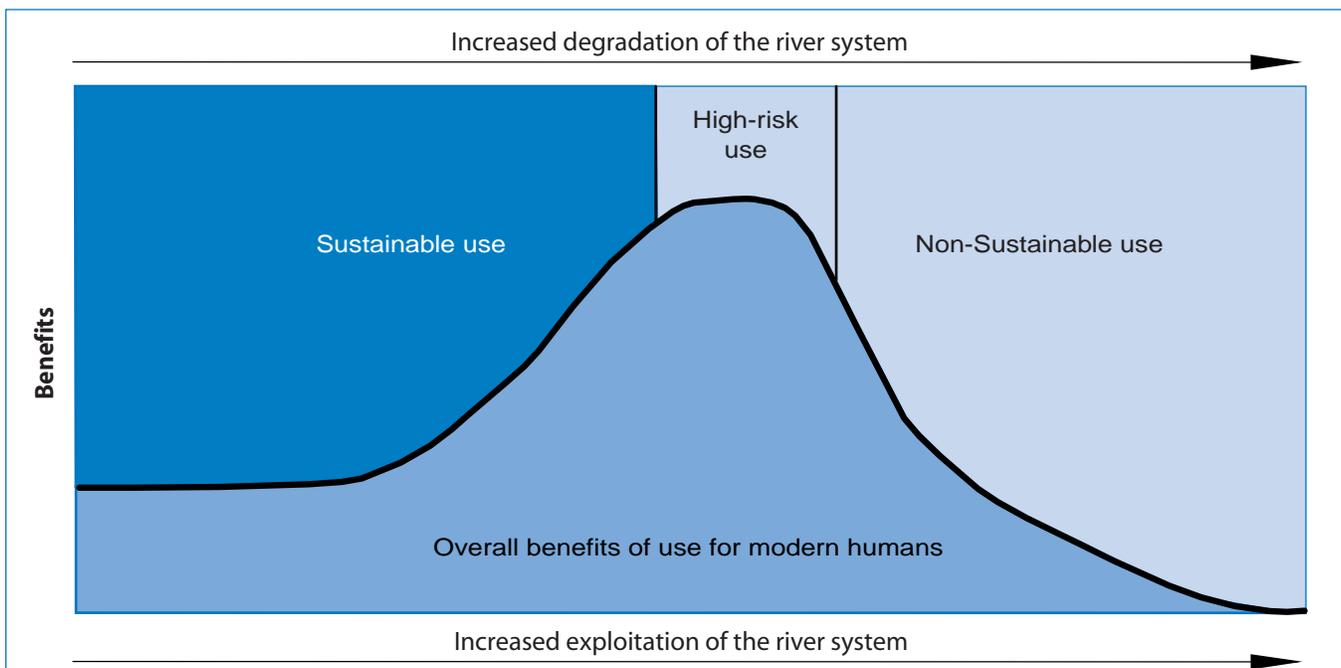
Hydropower releases	Water released to generate hydroelectricity creates wide fluctuations in downstream river flow, flooding, and drying out habitat for aquatic species such as fish (see Note C.2). To some extent, such flow surges can be controlled to mitigate their impact on the downstream river.
Irrigation releases	Irrigation water releases can cause seasonal reversal of the flow regime, with flows that are higher in the dry season than in the wet. Life-cycle cues for aquatic species, provided by the flow, become mismatched with temperature and other required conditions, causing loss of species and other ecosystem imbalances.
Navigation	Unnaturally high flows for navigation can cause bank and bed erosion, and can also dampen or remove flow variability (Box 3).
Dilution of pollution	Diluting pollutants as a way to improve water quality is poor management. If pollutants are controlled at the source and not through high dilution flows, more water is available for other uses.
Release of wastewater	Same as for navigation, but with added pollution impact.
Interbasin transfers	Water moved from one catchment to another can have many of the above effects. It can also impact on biodiversity through the introduction to a catchment of competitive or alien species.

Water released down a river for nonenvironmental purposes (Box 5) may damage the aquatic environment. Any flow assessment that is part of a development proposal should include the ecosystem impacts of nonenvironmental flows.

Balancing the multiple and competing demands for water is one of the greatest challenges facing water

managers. In the past, some development costs, particularly those affecting the environment and borne by economically weak communities, have been ignored. As a general rule, the overall benefits from exploitation of water resources increase to a point beyond which use is no longer sustainable, as the systems degrade with exploitation and the costs eventually outweigh the benefits (Figure 2).

FIGURE 2.
HYPOTHETICAL SCHEMATIC ILLUSTRATING THE GENERAL RELATIONSHIPS BETWEEN ECOSYSTEM USE AND CONDITION



METHODS FOR QUANTIFYING ENVIRONMENTAL FLOWS

Many methods have been developed over the last 20 years—primarily in Europe, the United States, South Africa, and Australia—to establish environmental flows. Some techniques were developed for protection of specific (often threatened) species, while others were developed for broader ecosystem protection. These techniques have now been applied in over 25 countries, resulting in a considerable body of experience for temperate and semi-arid rivers, but only limited experience in the application of these methods to tropical rivers.

Environmental flow assessment methods fall into two categories, prescriptive and interactive (Box 6). Methods based on the prescriptive approach usually address a narrow and specific objective and result in a recommendation for a single flow value or single component of the flow regime. Their outcomes tend not to lend themselves to negotiation, because effort is mostly directed to justifying the single value, and insufficient information is supplied on the implications of *not* meeting the recommended value to allow an informed compromise. Interactive approaches, on the other hand, focus on the relationships between changes in river flow and one or more aspects of the river. Once these relationships are established, the outcome is no longer restricted to a single interpretation of what the resulting river condition would be. Methods based on the interactive approach are thus better suited for use in negotiations. They do tend to be more complex, however, and have more onerous data and time requirements, than do prescriptive approaches. Several methods have been developed in each category.

The methods presented in this Note are chosen to illustrate different degrees of data and time requirements, as well as the reliability of the results and the level of experience required to apply the method (Table 1).

PRESCRIPTIVE APPROACHES

These can be divided into four broad categories:

- Hydrological index methods are mainly desktop approaches relying primarily on historical flow records to make flow recommendations for the future. Little, if any, attention is given to the specific nature of the considered river or its biota.
- Hydraulic rating methods use the relationship between the flow of the river (discharge) and simple hydraulic characteristics such as water depth, velocity, or wetted perimeter to calculate an acceptable flow. These methods are an improvement on hydrological index methods, since they require measurements of the river channel, and so are more sensitive than the desktop approaches to differences between rivers. However, judgment of an acceptable flow is still based more on the physical features of the river rather than on known flow-related needs of the biota.
- Expert panels use a team of experts to make judgments on the flow needs of different aquatic biota.
- Prescriptive holistic approaches require collection of considerable river-specific data and make

Box 6.

FEATURES OF PRESCRIPTIVE AND INTERACTIVE METHODOLOGIES

Prescriptive	Interactive
Often provide a single flow regime to maintain a single objective (river condition).	Provide a range of flow regimes, each linked to a different river condition.
Motivate for the inclusion of specific parts of the flow regime.	Explain the consequences of flow manipulations.
Not conducive to exploring options.	Conducive to exploring options.
Suited for application where objectives are clear and the chance of conflict is small.	Suited for application where the eventual environmental flow is an outcome of negotiations with other users.

TABLE 1.
RELATIVE DATA AND TIME REQUIREMENTS OF SELECTED FLOW ASSESSMENT METHODS

Output	Method	Data and time requirements	Approximate duration of assessment	Relative confidence in output	Level of Experience
Prescriptive	Tennant Method	Moderate to low	Two weeks	Low	USA/extensive
	Wetted-Perimeter Method	Moderate	2-4 months	Low	USA/extensive
	Expert Panels	Moderate to low	1-2 months	Medium	South Africa, Australia/ extensive
	Holistic Method	Moderate to high	6-18 months	Medium	Australia/ very limited
Interactive	IFIM	Very high	2-5 years	High	USA, UK/extensive
	DRIFT	High to very high	1-3 years	High	Lesotho, South Africa/very limited

structured links between flow characteristics of the river and the flow needs of the main biotic groups (fish, vegetation, invertebrates). Two examples are included here.

Hydrological index methods. The Tennant (or Montana) Method is a desk-top approach that is relatively inexpensive, quick, and easy to apply. Its development required considerable research and

input from experts. The results compare relatively well with those from data-intensive techniques. The approach is based on trends derived from field observations in the United States of the relationship among river condition, the amount of flow in the river, and the resultant fish habitat. These are used to recommend environmental flows for the maintenance of fish, wildlife, recreation, and related resources (Table 2). For example, if the average annual

TABLE 2.
TENNANT METHOD: PERCENTAGE OF AVERAGE ANNUAL FLOW (AAF) REQUIRED TO ACHIEVE DIFFERENT OBJECTIVES (AAF EXPRESSED AS INSTANTANEOUS FLOW)

Objective	Recommended percentage of AAF	
	Autumn-Winter	Spring-Summer
Flushing or maximum flows	200	200
Optimum range of AAF	60-100	60-100
Percentage AAF required to maintain a required river condition		
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair or degrading	10	30
Poor or minimum	10	10
Severe degradation	10-zero flow	10-zero flow

flow (AAF) in a river is 100×10^6 cubic meters per annum (m^3a^{-1}), then for an “outstanding” river condition, the flow in the river in Autumn-Winter would need to be 40 percent of the average instantaneous flow, or 1.5 cubic meters per second (m^3s^{-1}). The method is claimed to be applicable to a wide range of river types and sizes, and the general approach, at least, may be applicable in many parts of the world. Once the initial relationship between river condition and flow has been established for a region, the data requirements of the method are moderate, requiring measured or easily simulated monthly hydrological data.

As with all rapid assessment methods, the Tennant Method is most suited to the region—in this case, the western United States—where it was developed, where the hydrological and ecological characteristic of the rivers are well-studied and well-understood. It was designed principally for managing trout habitat, which may limit its applicability to other biota in other parts of the world.

In new regions where time is a major constraint, a specially tailored Tennant approach, based on field observations of the habitat responses of the biota of interest in that region, would provide a good medium-resolution technique for determining environmental flows. The outcome of such a “Tailored Tennant” approach would be a table similar to that in Table 2, but based on empirical observations that are relevant to the country where they were taken.

Other examples of hydrological index methods include the Flow Duration Curve Analysis, Range of Variability Approach, and the Desktop Method.

Hydraulic rating methods. Like hydrological index methods, hydraulic rating methods also use the hydrological record. However, they link this to simple cross-section data collected in the river of interest. The Wetted-Perimeter Method is a low-resolution, river-specific method that is used for determining seasonal flows required to maintain fish populations. It is relatively quick and cost-effective. The number of measurements taken and field visits made will depend on the level of confidence required for the study. It is useful as a planning method at

catchment scale or greater. Because it is widely used in the United States, there is a great deal of expertise and experience to draw upon.

The method is based on the assumption that fish-rearing is related to food production, which in turn is related to how much of the river bed is wet. It uses relationships between wetted perimeter and discharge, depth, and velocity to set minimum discharges for fish food production and rearing (including spawning). The relationships are constructed from measuring the length of the wetted perimeter at different discharges in the river of interest. The resulting recommended discharges are based on inflection points on the wetted-perimeter/discharge curve, which are assumed to represent the maximum habitat for minimum flow before the next inflection point (Figure 3).

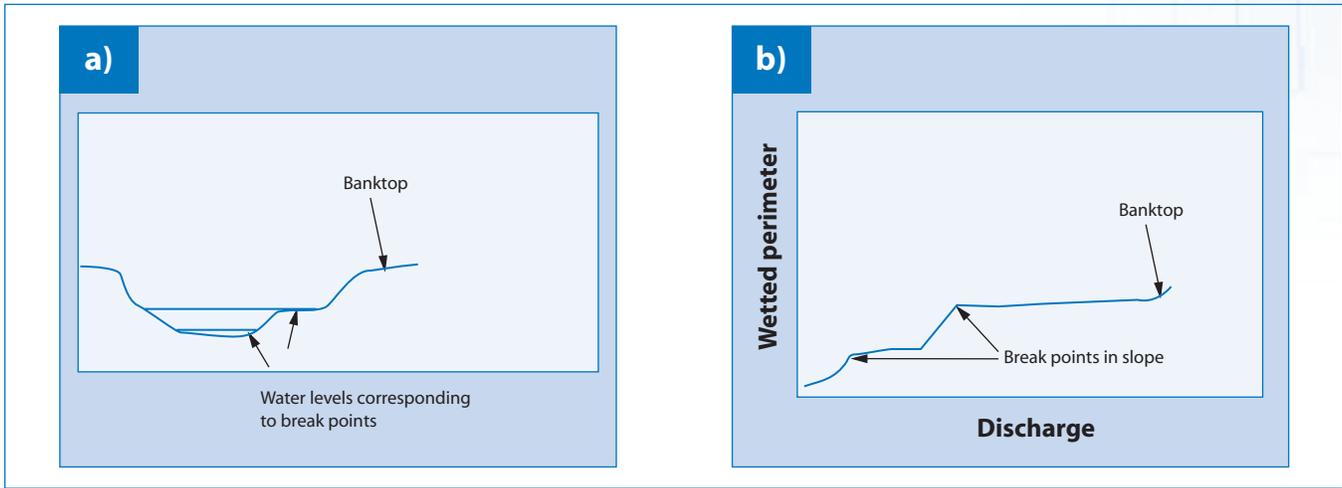
The disadvantage of the method is that the observed relationships between wetted-perimeter and discharge used to recommend suitable habitat for fish are based on general principles, and are not proven to be relevant to the fish of a particular river. To remedy this, detailed studies have to be undertaken on the relationship between wetted perimeter and the survival and reproduction of particular fish species. Although these studies increase the reliability of the results, they also add considerably to the time required and the costs of the method.

Expert panel. The family of expert-based methods described here have the common feature that they use a team of experts to make judgments on the flow needs of different aquatic biota. The composition of the panel will depend on the specific environmental and social features of the river in question, but typically includes a hydrologist, geomorphologist, aquatic botanist, and fish biologist. In many cases, one or more community representatives will join the panel. The collective experience of the panel members is used in the absence of reliable, predictive flow-ecology models. By putting these experts on a panel, rather than employing them independently, it is expected that an integrated assessment of flow needs will emerge.

Although the procedure varies from panel to panel, it is usual for the panel to undertake field inspec-

FIGURE 3.

WETTED-PERIMETER METHOD: (A) HYPOTHETICAL CHANNEL CROSS-SECTION AND (B) GRAPH OF WETTED PERIMETER VERSUS DISCHARGE. BREAKPOINTS IN SLOPE INDICATE THE MAXIMUM AVAILABLE FISH HABITAT FOR THE LEAST AMOUNT OF WATER, UNTIL THE NEXT BREAKPOINT.



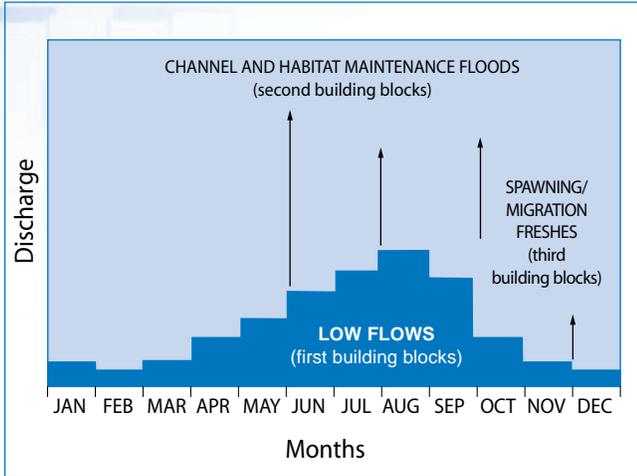
tions at different points in the river. If the river has upstream impoundments, it is also common for different-sized flows to be released during these field visits so that the experts can see the extent of inundation and, in some cases, the response of ecological compartments to these different flows. The panel meets with stakeholders during the course of the field visits to understand the water use requirements of different communities along the river. The panel also has access to the hydrological records for the river as well as ecological data and reports. Based on this array of information, the panel produces a draft report describing the likely ecological responses of the river biota to different flow regimes, including low, medium, and high flows. The report is discussed at one or more workshops attended by stakeholders and managers before being finalized.

The method has been widely applied in the eastern states of Australia with considerable success. Its advantages are its rapidity, ability to effectively capture and integrate the knowledge of different experts, and its flexibility. It does not rely on the existence of models (although models can be employed if available). However, the results are site-specific and non-reproducible, and therefore more open to challenge than traditional data-intensive/modeling approaches.

Holistic approaches. Holistic approaches are essentially ways of organizing and using flow-related data and knowledge. They often incorporate some of the methods described above, particularly the expert panel methods. They are better described as *methodologies*, which implies the linking of several distinct procedures or methods to produce an output that none could have produced alone. They were developed in the southern hemisphere, mainly because northern hemisphere methods, which tend to target individual (often commercially valuable) species, were too limited when the aim was to manage the health of the whole river ecosystem.

The Holistic Method in Australia and the Building Block Methodology (BBM) in South Africa were developed in collaboration and share the same basic tenets and assumptions. Both require early identification of the future desired condition of the river. An environmental flow regime is then constructed—on a month-by-month basis, through separate consideration of different components of the flow regime (Figure 4)—to achieve and maintain this condition. Each flow component is intended to achieve a particular ecological, geomorphological, or water-quality objective. Given the similarities between the two methodologies, only the BBM is discussed further here.

FIGURE 4.
THE “BUILDING BLOCKS” OF THE MODIFIED FLOW REGIME
CREATED USING THE BBM.



The BBM was designed to address the southern-African realities of limited data, money, and time. It depends on available knowledge, expert opinion, and limited new data, which are used in a structured set of activities to describe an environmental flow. The major components of a river ecosystem, both physical (hydrology, physical habitat, and chemical water quality) and biological (vegetation, fish and macro-invertebrates), are considered, as is subsistence use of the river by riparian people. For each of these disciplines, all available data are synthesized and new data collected where necessary. Field measurements always include the sur-

veying of cross-sections at representative sites along the river, and development of the relationship between flow and water depth, velocity, and area of inundation. The biological specialists also conduct field studies, from which they develop an understanding of the links between aquatic species and the flow in the river at different times. After data collection, a desired future condition for the river is described in a specialist workshop.

The specialists then reach consensus on a modified flow regime that would help achieve the desired condition.

The strength of the BBM lies in its ability to incorporate any relevant knowledge, and to be used in both data-rich and data-poor situations. It addresses a wide range of ecosystem components, and the final environmental flow is arrived at through consensus by the full BBM team of river specialists. It is well documented and is widely used in South Africa. Holistic approaches are new, however, and judging their effectiveness will take time.

INTERACTIVE APPROACHES

Flow-assessment methods that use an interactive approach tend to be more complex than prescriptive methods and are predominantly limited to two broad types: the habitat simulation and holistic methodologies. They are illustrated here by one of the oldest—the Instream Flow Incremental Methodology (IFIM)—and one of the newest—Downstream Response to Imposed Flow Transformations (DRIFT).

Both are essentially problem-solving tools with similar approaches (Table 3). The output is a set of options—alternatives in IFIM terminology, or scenarios in DRIFT terminology. Each option quantitatively describes:

- a modified flow regime
- the resulting condition of the river, or species, whichever is being addressed
- the effect on yield for offstream users
- the direct economic costs and benefits.



Kihansi Gorge, Tanzania

Photo by Peter Dewees, World Bank

DRIFT also addresses the social costs and benefits of changing river conditions, particularly for downstream riparian users (the population at risk) of river resources. Neither methodology provides a recommended environmental flow. Rather, each seeks to

provide objective, scientifically based input on the consequences for rivers of a range of flow manipulations. These allow water managers to make more informed decisions on the equitable use of water.

TABLE 3.
PHASES OF IFIM AND DRIFT

PHASES	IFIM	DRIFT
Problem identification or issues assessment	<ul style="list-style-type: none"> ■ Identification of interested and affected parties, their concerns, information needs and relative influence or power. ■ Identification of the broad study area, and the extent of probable impacts. 	<ul style="list-style-type: none"> ■ Identification of the main components of the project and the interested and affected parties. ■ Identification of the population at risk. ■ Identification of the broad study area, and the extent of probable impacts. ■ Identification of social concerns (local, national, and international) to be addressed in the biophysical studies.
Study planning	<p><i>Both approaches require:</i></p> <ul style="list-style-type: none"> ■ Assessment of existing biophysical, social, and economic data, and evaluation of the need for further data. ■ Selection of representative river reaches. ■ Design of data collection procedures. ■ Identification of key data collection sites. <p>Interdisciplinary integration of site selection and data collection avoids overlaps and gaps, and maximizes the usefulness of the data.</p>	
		<p>Addition of social considerations in selection of study area and sites. In particular, compatibility ensured between biophysical data (collected at river sites) and social data (collected in rural villages).</p>
Study implementation	<ul style="list-style-type: none"> ■ Collection of hydraulic and biotic data. ■ Calibration of habitat model. 	<ul style="list-style-type: none"> ■ Collection of hydraulic, chemical, geomorphological, thermal and biotic data, and analyses to develop predictive capacity on how flow changes will affect each. ■ Multidisciplinary workshop to compile a database of biophysical consequences of a range of flow manipulations.
Options analysis	<p><i>Both approaches require:</i></p> <ul style="list-style-type: none"> ■ Development of environmental flow alternatives or scenarios, each describing a possible future flow regime and the resulting river condition. ■ Yield analysis of water available for development with each scenario. 	
	<ul style="list-style-type: none"> ■ Determination of the direct costs and benefits of the alternatives 	<ul style="list-style-type: none"> ■ Determination of the direct costs and benefits of each scenario. ■ Additionally, for each scenario, determination of the social impacts and costs to the population at risk of changing river condition.
Problem resolution	<p><i>Both approaches require:</i></p> <ul style="list-style-type: none"> ■ Assessment of the bigger picture (for example, data on other costs/benefits of the water-resource development). ■ Negotiation with offstream water users. ■ Public participation ■ Transparent decisionmaking processes. 	

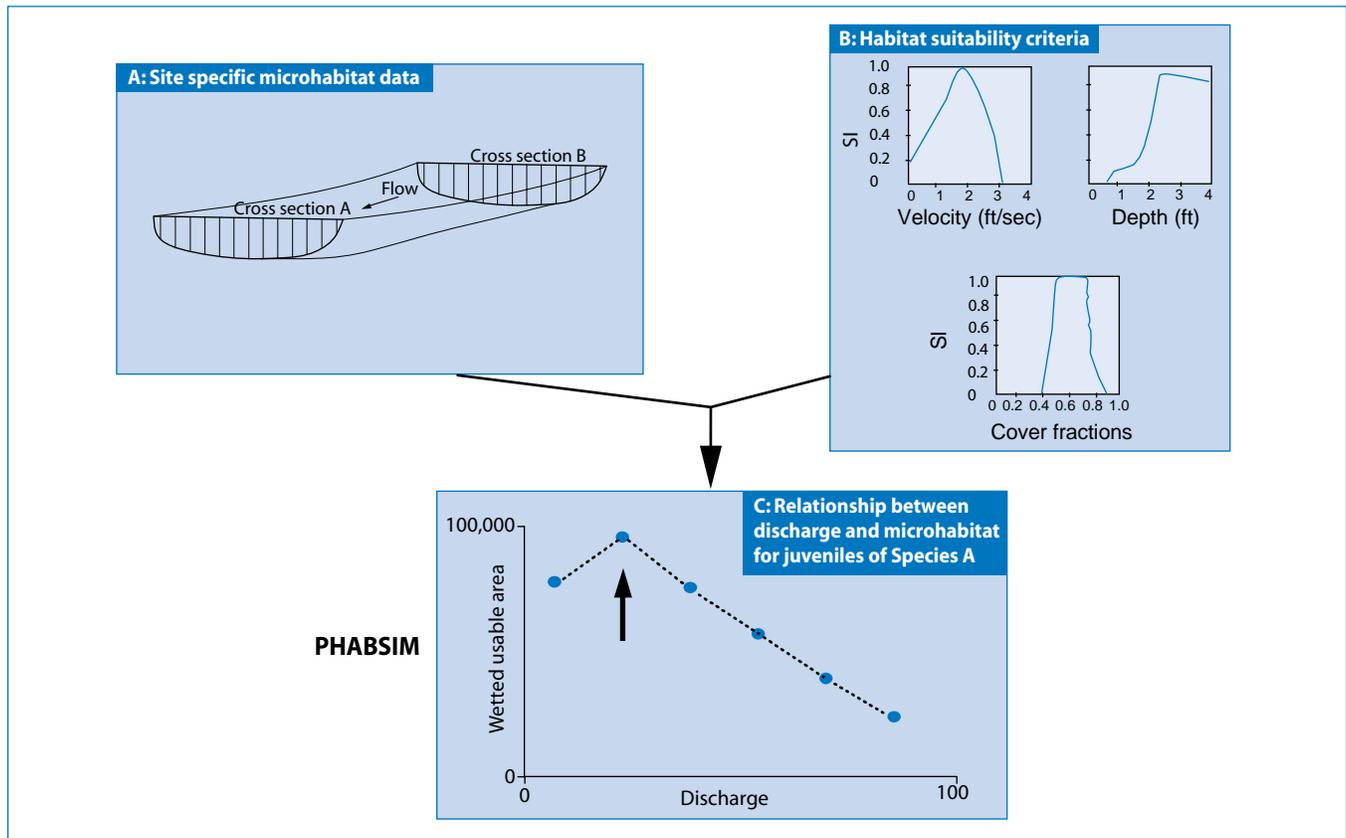
Habitat simulation methodologies: the Instream Flow Incremental Methodology (IFIM). IFIM is the most commonly used flow assessment method worldwide and the best-documented method currently available. It was developed by the U.S. Fish and Wildlife Service’s Instream Flow Group in the late 1970s. It is founded on a basic understanding and description of the water supply and habitats within river reaches of concern.

IFIM is used to evaluate the effects of incremental changes in discharge on channel structure, water quality, temperature, and availability of suitable microhabitat for selected target aquatic species. Both macrohabitat and microhabitat, as described below, are assessed for key species. These species are chosen either because they are the major species of

concern, or because they are deemed to represent the species and the general river condition desired.

Microhabitat is the small physical area in any place in a river that is directly relevant to the species being studied. The availability of suitable microhabitat over a range of flows is modeled using PHABSIM II (Physical Habitat Simulation Model). This model predicts how the water depth, water velocity, and riverbed features change with changing flow, and thus their changing suitability for the chosen species (Figure 5). The model was designed for, and is usually applied to, fish habitat. The model requires extensive field data and considerable understanding to apply. It also requires a fairly detailed understanding of the habitat preferences of the chosen species during their different life stages. For ex-

FIGURE 5. CONCEPTUALIZATION OF HOW PHABSIM CALCULATES HABITAT VALUES AS A FUNCTION OF FLOW. (A) FIRST, DEPTH, VELOCITY, COVER CONDITIONS, AND AREA ARE MEASURED OR SIMULATED FOR A GRID OF CELLS OVER A RANGE OF FLOWS. (B) SUITABILITY INDEX (SI) CRITERIA ARE USED TO WEIGHT THE SUITABILITY OF EACH CELL AS HABITAT FOR EACH SELECTED SPECIES OVER THE SAME RANGE OF FLOWS. THE HABITAT VALUES FOR ALL CELLS IN THE STUDY REACH ARE SUMMED TO OBTAIN A SINGLE HABITAT VALUE FOR EACH FLOW (C). THE OPTIMUM MICROHABITAT FOR JUVENILES OF SPECIES A IS NOTED WITH AN ARROW.



ample, some fish species require attached vegetation for egg laying, others need clean pebble beds; some require reeds or grasses for refuge, others need large woody debris. In spite of these data and knowledge demands, some of the PHABSIM programs can be used with limited field data for reconnaissance or area-wide planning studies.

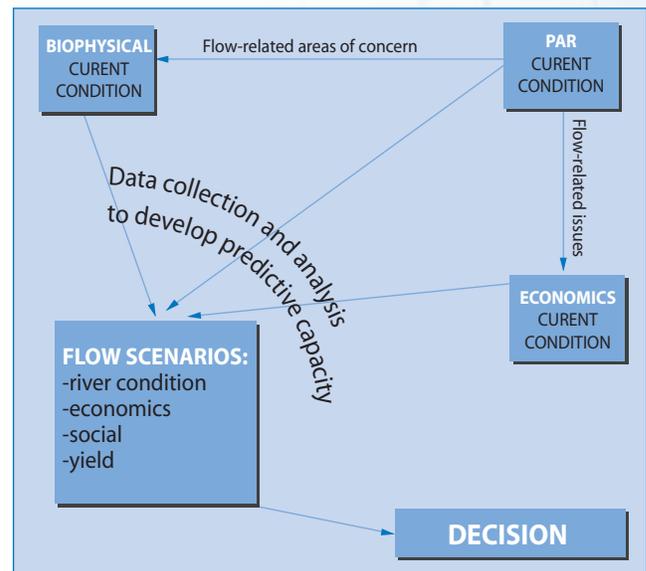
The suitability of microhabitat is qualified, in the macrohabitat component, by the suitability of water quality and temperature. Thus, even if the physical microhabitat requirements are met, some fish species will not breed if the correct water temperature and flow cues are absent. The results are a time series of suitable habitat for a particular species over a period of changing flows (Figure 5).

IFIM has been subjected to extensive scientific critique, but this is more a product of its widespread use in flow assessments than an indication of its merits relative to other methods. Its main drawbacks lie in its complexity, difficulty of use, its extensive field data demands, requirements for good understanding of target species needs, and questionable applicability outside its area of development. Its authors suggest that its strong scientific basis make it appropriate for the most controversial project assessments and that other less onerous methods are better employed for other projects.

Downstream Response to Imposed Flow Transformations (DRIFT). DRIFT was developed for the assessment of environmental flows for the Lesotho Highlands Water Project (see Note C.2). DRIFT culminates in one or more multidisciplinary workshops that are designed to produce an agreed number of biophysical and socioeconomic scenarios.

Specialists use methods that are specific to different components of the flow regime to collect data and then, within the DRIFT structure, to predict the consequences of flow changes. For instance, PHABSIM II could be used by the fish biologists to model changes in fish habitat arising from medium-level floods that affect in-stream fish habitat. DRIFT also uses data on cultural and subsistence use of the river to predict the socioeconomic implications of river change (Figure 6, Table 3, and Box 7).

FIGURE 6.
BASIC COMPONENTS OF A DRIFT ASSESSMENT



DRIFT is essentially a system for managing data and knowledge in a structured way, following five main steps.

- Identification and isolation of wet-season and dry-season low flows, and small and large floods from the long-term hydrological record.
- Description of the consequences for the river of partial or complete removal of each of these flow components (Box 3).
- Creation of a biophysical database detailing the consequences of flow alterations.

Box 7.
INCORPORATION OF SOCIAL DATA INTO FLOW ASSESSMENTS

In regions such as Africa, South America, and Asia, where large numbers of poor people rely directly on rivers for subsistence, flow assessments should include consideration of the social and economic implications of changes in river flow. In some cases these will be obvious, such as loss of a food fish or plant, deterioration in the quality of potable water, or filling in of a pool used for ceremonies. In others, the impacts will be less obvious. Vitamins and minerals supplied by riparian plants may contribute to the overall health of a community, or certain levels of flow may dilute or aid decomposition of wastes entering the river, so that the water can be drunk without incurring health risks. So often externalized in water-resource planning, these indirect costs of deteriorating river condition are usually borne by the poorest members of society.

- Use of the database to describe how river condition will change with any future combination of high and low flows.
- Description of the socioeconomic implications of the changes in river condition. This, together with the previous step, constitutes the creation of environmental flow scenarios.

CHOOSING THE RIGHT TECHNIQUE

The purpose of a flow assessment and the intended use of the results should guide the selection of the assessment method. Project-specific flow assessments for large or controversial projects, which are likely to call for considerable negotiation and tradeoffs between environment and development issues, require a more comprehensive approach than do flow assessments for coarse-scale

planning studies, where a single number might suffice.

Within either category, the flow assessment method eventually chosen will depend on technical considerations such as the quality and availability of data on the study rivers, the location and extent of the study area, the prevailing time and financial constraints, and the level of confidence required in the final output. Eco-hydrology is a relatively new scientific field, so there is only limited understanding and very few models of species responses to varying hydrologic conditions. Most of the data and understanding required for interactive approaches have to be acquired on a site-by-site basis, considerably adding to the time, funding, and expertise required for a flow assessment. Probably because of this, most applications have used a prescriptive approach.

ENVIRONMENTAL FLOWS IN THE DECISIONMAKING PROCESS

ENVIRONMENTAL ASSESSMENT AND ENVIRONMENTAL FLOW ASSESSMENT

Environmental Assessment (EA) is the integrative process of identifying and evaluating the likely biophysical, social, and other relevant effects of development proposals prior to major decisions being made. Mitigation measures are sometimes included in EA and sometimes described in separate Environmental Management Plans (EMPs).

In the case of water development projects, a flow assessment should be an essential component of an EA. Impacts arising from alteration of a river's flow regime will always have the potential to be severe. These impacts can often be mitigated through the design of environmental flows or compensated through resource substitution or community development programs, and this can be shown in an EMP.

ALLOCATING WATER

Increasingly, flow assessments are seen as tools in water-resource management that display the wider

costs as well as the benefits of development, allowing more informed tradeoffs to be made.

Water policy and legislation can provide a vital support and guide to decisionmakers. Where policy and legislation define the need and objectives for environmental flows within the realm of sustainable utilization, flow assessments need only determine the volume and temporal distribution of an environmental flow. Without such a framework, they have the burden of not only defining environmental flows but also of giving legitimacy to them.

With such legal support, a structured, transparent, and widely accepted decisionmaking process can address the results of engineering, economic, and environmental studies, including flow assessments. From this, an agreed decision can emerge on whether, and in what way, to proceed with a water resource development. In the event such a development is pursued, agreement on the desired future river condition and the flow allocations required to maintain that condition will provide the legitimacy for environmental flow allocations.

Flow-related effects that are not easily expressed in monetary terms need to be included in this decision process. If not, effects of development arising from changes in flow regime—such as the loss of a fish species, or the declining quality of life of ri-

IMPLEMENTATION

Environmental flows should be only one part of an integrated set of environmentally sensitive features. Complementary mitigation (biophysical) features that could be considered include fish ladders; multiple-level releases in reservoirs; water-chemistry and temperature sensors at the different off-take structures; outlet pipes able to take the volume from all the off-takes simultaneously if necessary; structures that minimize anticipated water-quality conditions such as anoxic or super-saturated water; and a facility for passing sediments through reservoirs and past the dam walls or weirs.

Compensation and mitigation programs should be developed on the basis of specific consideration of downstream issues, which are often different than upstream issues. Downstream impacts relate not only to the reduction in water flows, but also the associated transformation from an aquatic environment to a terrestrial environment. Downstream issues that may form part of the compensation and mitigation programs for riverine resource losses may include reduction in fish, vegetables, plants, animal forage, firewood, timber for other uses and water supply for people, livestock and other uses from direct and indirect changes in the amount, quality, and timing of flows. The methodologies for addressing downstream social issues has not been well established and the practice is still evolving.

Experience in a number of countries has shown that recommendations arising from environmental flow assessments are not always implemented. The features that are likely to lead to successful implementation are summarized in Box 8. These features are extensive; few projects would be able to satisfy all of them. Nevertheless, the box provides a checklist

parian people—will be undervalued and lead to disproportionate costs being borne by those groups in society who are not fully integrated into a market economy, or fully represented in the decisionmaking process.

that a project manager may want to consider when embarking on the implementation of an environmental flows assessment.

Conversely, some of the common reasons for the failure to implement assessments are:

- the perception among engineers and water managers that “too much” water was requested
- lack of flow-related biological data that can be used to justify the environmental flows, resulting in a heavy reliance on expert opinion
- unwillingness or inability to incorporate innovative, and possibly more expensive, release mechanisms into dams for environmental releases
- lack of political or legislative pressure to implement the environmental flows (usually because other demands were seen as more important)
- “last minute” or post-hoc flow assessments that are commissioned after most (if not all) the major decisions about the design and cost of the development, and the allocation of water, have already been made
- reluctance to move away from established practices.

A monitoring program is particularly important given the generally poor understanding of the links between flow and ecological response. The implementation of an agreed flow regime should allow for adaptive management based on the monitoring. The monitoring program should be designed to provide essential feedback on whether:

- the agreed-upon flow is being released
- the overall objective (desired river condition) is being achieved

- the objectives for different components of the flow regime are being met
- the environmental flow allocation needs to be modified in the light of the observed responses.

The monitoring program should be designed to allow the effects of environmental flows on different

biota to be separated from the effects of other interventions—for example, improved water quality from sewage treatment plants—and from climatically induced variations in river flows. In practice, this is extremely difficult to do, and the interpretation of any monitoring program will always rely on the experience of the hydrologists and ecologists involved.

Box 8.

DESIRABLE FEATURES FOR A SUCCESSFUL ENVIRONMENTAL FLOWS IMPLEMENTATION.

<p>Political will, legislation, and management strategies</p>	<ul style="list-style-type: none"> ■ Recognition of tangible and intangible national costs of degraded rivers. ■ Acceptance of flow assessments as a tool for use in integrated river-basin management. ■ Supporting legislation to empower water managers to manage river flows according to recommendations. ■ The necessary tools to implement and enforce legislation. ■ A structured and transparent decisionmaking process, whereby the results of engineering and economic studies, environmental flow assessments, and stakeholder input are jointly used to decide on future flow allocations and river condition. ■ Ethical, moral, and other intangible considerations form important inputs to the final decisionmaking process. ■ Commitment of politicians, developers, and water resource managers to adhere to agreed-upon environmental flow objectives.
<p>Data and tools</p>	<ul style="list-style-type: none"> ■ Long-term accurate hydrological data. ■ Hydrological models with daily time-steps. ■ Linked surface and groundwater models for intermittent rivers. ■ Long-term water chemistry records for rivers (and groundwater, where necessary), preferably linked to hydrographs. ■ Appropriate flow assessment methodologies. ■ Comprehensive data on the distribution, life histories, and flow-related habitat requirements of riverine species in the rivers of concern. Similar data for the abiotic aspects of rivers and, where relevant, for estuaries and coastal marine environments. Data on the tolerance ranges of riverine biota to physical and chemical variables. ■ A well-structured link between river and estuary flow assessments where appropriate.
<p>Specialist expertise</p>	<ul style="list-style-type: none"> ■ Senior specialists, with first-hand knowledge of the rivers of concern, in the flow-related aspects of the following disciplines: hydrology, geohydrology, hydraulics, geomorphology, sedimentology, water chemistry, biotic integrity, physical habitat, riparian and instream vegetation, fish, invertebrates, and possibly herpetofauna and terrestrial wildlife. ■ If socioeconomic aspects are to be included in the assessment, specialists in the following disciplines may be required: sociology, human geography, anthropology, public health, domestic-stock health, resource and project economics, and public participation procedures. Also required are specialists with knowledge of the flow-related aspects of waterborne diseases, and those of parasites and/or their hosts.
<p>Funds</p>	<ul style="list-style-type: none"> ■ Recognition that ecological and socioeconomic aspects of water resource development are as important as engineering and direct economic aspects. ■ Sufficient planning to provide adequate funds for flow assessments.
<p>Time management</p>	<ul style="list-style-type: none"> ■ Suitable planning horizons for flow-related investigations

CONCLUSION

Provision for environmental flows is central to integrated water resources management. EFA methods are still evolving and World Bank experience in addressing downstream biophysical and social impacts is limited, but developing. A recent review of the impact of dams on ecosystem function for the World Commission on Dams concluded that there were four principle approaches to limiting the impacts of dams on natural resources: avoidance; mitigation; compensation; and restoration.

Successful mitigation, compensation, and restoration of downstream effects are more likely if a thorough flow assessment has been undertaken.

This Technical Note has outlined the principles behind environmental flow assessments, provided a description of the methods that have been used to assist with such assessments, and highlighted the

features that will enhance the chance of successful implementation of environmental flows.

Although the theory has developed rapidly in the last three decades, the practical application of environmental flows has been retarded by a lack of data and understanding of hydrology-ecology linkages; a lack of specialists in developing countries; a lack of legislative support; and a reluctance on the part of water resource developers, designers, builders, and operators to move away from past practices. Provision of water for the environment will bring with it legal challenges from other potential users of the water, yet the scientific knowledge base needed to defend environmental flows against such challenges remains poor. Much of this is changing, however, and flow assessments are becoming integrated with other tools such as EA and water allocation planning for guiding decisions on water resource developments.

FURTHER INFORMATION

The following reports provide contextual information on environmental flows :

- Bergkamp, G., M. McCartney P. Dugan, J. McNeely and M. Acreman. 2000. "Dams, ecosystem functions and environmental restoration." Contributing paper to World Commission on Dams Thematic Review. Environmental Issues I I. New York: UNEP. Downloadable from www.dams.org or on CD from Earthscan, London, www.earthscan.co.uk
- Bizer, J.R. (2000). "International mechanisms for avoiding, mitigating and compensating the impacts of large dams on aquatic and related ecosystems and species." Submission E NV249 to World Commission on Dams. New York: UNEP. Downloadable from www.dams.org or on CD from Earthscan, London, www.earthscan.co.uk
- Harper, D.M., and A.J.D. Ferguson, eds. 1995. *The Ecological Basis for River Management*. Chichester, UK: John Wiley and Sons.

The following three documents provide comparative descriptions of environmental flow techniques:

- Arthington, A. H., and J.M. Zalucki, eds. 1998. "Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods." Occasional Paper No 27/98. Canberra, Australia: Land and Water Resources Research and Development Corporation.
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Tharme, R.E. 1996. "Review of the international methodologies for the quantification of the instream flow requirements of rivers." Water law review final report for policy development for the Department of Water Affairs and Forestry, Pretoria. Cape Town: Fresh water Research Unit, University of Cape Town, Cape Town, South Africa.

Information on specific techniques described in this Technical Note can be obtained from:

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