Chapter 6

Methodologies for the Assessment of Environmental Flows

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INTRODUCTION

The previous chapter discussed the emergence of concerns for diminishing flows in rivers during the 1950s in the USA and the consequential evolution of the concept of environmental flows. Parallel developments occurred worldwide in the understanding of river ecosystems (see chapter 2) and the impacts of flow regulation on ecosystem components other than fish (chapter 4). Accordingly, the methodologies for the assessment of flow requirements in the rivers were also developed to meet the gradually widening scope of the subject. During the past four decades, hundreds of studies were made across the world to develop, apply and adapt numerous methods of environmental flow assessments (EFAs). These methods have been critiqued, evaluated and reviewed frequently in a variety of publications (Stalnaker and Arnette 1976, Jowett 1997, Dunbar et al. 1998, Annear et al. 2002, Arthington 2012, Hatfield et al. 2013, Linnansaari et al. 2013). Most reports on the studies of environmental flows start with a review which usually covers similar ground. The geographical spread and use of different methods around the world has been reviewed by Tharme (2003). This chapter provides another overview of developments in a historical perspective describing briefly the more important methods, with some comments on their limitations and advantages.

Development of EFA Methods

The development of a methodologies for environmental flows assessment (EFA) started with the investigations by fish biologists of the instream flow needs of fish below the federally-funded hydroelectric and irrigation dams on large rivers (Trihey and Stalnaker 1985) with the objective of setting minimum flow "standards" for the low flow periods (Leathe and Nelson 1986). Starting with Oregon in 1955, instream flow programs soon proliferated across the USA and Canada but differed in their scope and approach depending upon the States' legal requirements, water availability, and the characteristics of aquatic resources. By the middle of the 1970s, three significant events occurred that greatly influenced the future development of instream flow studies. The American Fisheries Society published the Proceedings of a broad-based conference organised a year earlier in Idaho to discuss the legal, social and biological aspects of the instream flow issue (Orsborn and Allman 1976). In the same year, Stalnaker and Arnette (1976) published a comprehensive compilation and critical evaluation of the methods available until then. The U.S. Fish and Wildlife Service at Fort Collins, Colorado, then set up the Cooperative Instream Flow Service Group (CIFSG) for advancing the activities related to instream flow assessments (see Leathe and Nelson 1986).

In the 1970s, the focus was on determining flows necessary to preserve charismatic aquatic species like salmon or trout. Later, environmental flows assessments evolved with the inclusion of additional consideration of (a) a broader spectrum of organisms and communities (more fish species, macroinvertebrates and macrophytes), (b) finer analysis of stream hydrology (from average annual flow through its distribution over the year to the entire spectrum of variability in the flow regime), (c) fluvial geomorphology (from channel area under water to nature of the bed material, macro- and microhabitats, and river types), (d) diversity of habitats (from channel only to the inclusion of the riparian zone and floodplains and now to the entire river system), (e) socioeconomic aspects, and finally (f) ecosystem services. Various evolving methods undergo adaptation to suit the needs of diverse situations in different countries. Tharme and Smakhtin (2003) observed that regardless of the type of the EFA methods, all of them have been designed and/or applied in a developed country context. These therefore reflect distinct gaps in environmental flow knowledge and practice in almost all developing countries, most of which lack the technical and institutional capacity to establish environmental water allocation practices.

As pointed out in the previous chapter, environmental flows "***are required to sustain freshwater ecosystems***" and the livelihoods and well-being of human populations dependent upon them. Most publications refer to the need for maintaining the 'ecological integrity' of the rivers. However, the goals and objectives of EFAs have often been confined to a single component such as particular tax of fish other fauna or macrophytes, riparian habitat, floodplain connectivity, protection of estuarine systems (including mangroves), recreation, or some cultural activity. While methods have been developed or modified for such narrow objectives, they cannot be and should not be considered as environmental flows assessments. It is well recognised that a considerable degree of compatibility exists amongst many instream uses and downstream delivery requirements for offstream or consumptive uses except that both the timing and the magnitude of the demands being placed on the stream system need due consideration (Stalnaker 1990).

Overall, EFA methods have evolved from very simple single statistic to complex modeling, reflecting also the change in the capability of scientists and water managers to define flows required to maintain a full spectrum of riverine species, processes, and services.

Classification of Methods

The large number of methods have been categorized in different ways (Table 1). Stalnaker (1990) categorised them as “standard setting” or “incremental”. He defined Standard Setting Methodologies as “those measurements and interpretive techniques designed to generate a flow value (or values) intended to maintain the fishery or recreational use at some acceptable level (usually dictated by policy)” and Incremental methodologies as “organized and repeatable processes by which (1) a fishery habitat-stream flow relation and the hydrology of the stream are transformed into a baseline habitat time series, (2) proposed water management alternatives are simulated and compared with the baseline, and (3) project operating rules are negotiated”.

Dunbar et al. (1998) retained these categories but called the Incremental Moethodologies as Empirical Methods. According to them, Standard Setting Methods (sometimes called desktop methods), are primarily office-based scoping exercises that make use of existing information to predict an appropriate schedule of instream flow requirements. Often these are explicitly conservative (i.e., biased in favour of environmental protection) to account for uncertainty in predicted effects. On the other hand, Empirical Methods are based on biological and physical data collected in the field that are used to determine a schedule of flow requirements, often in a negotiation context. It is however possible to assess flow regime requirements by combining easily obtained information with detailed, site-specific studies. In general, studies that move away from standard setting and towards an incremental approach (i.e., quantification of instream requirements), enable various management options to be assessed (Dunbar et al. 1998).

Dyson et al. (2003) made a distinction between Methods, Appoaches and Frameworks by elaborating that the Methods typically deal with specific assessments of the ecological requirement; Approaches are ways of working to derive the assessments, e.g. through expert teams; and Frameworks for flow management provide a broader strategy for environmental flow assessment by making use of one or more specific methods and applying a certain approach.

King and Brown (2003) distinguish between methods based on the Prescriptive and Interactive approaches. The methods based on a prescriptive approach usually address a specific objective and lead to the recommendation of a single flow value or single component of the flow regime. Methods based on Interactive approaches focus on the relationships between changes in flow and some aspect of the river that are used for setting the flow based on the desired river condition (Table 2).

Tharme (2003) and Tharme and Smakhtin (2003) prefer to categorise the methods into four groups namely, hydrological, hydraulic, habitat-simulation (or habitat rating) and holistic methods. This categoraisation has been widely followed and is used here to descrive the more important methods of each category.

Table 1. Three scheme for classifying Environment Flows Assessment methods

Organisation	Categorization of Methods	Sub-category	Examples
IUCN (Dyson et al. 2003)	Methods	Look-up tables	Hydrological (e.g. Q95 Index)
			Ecological (e.g. Tennant Method)
		Desk-top analyses	Hydrological (e.g. Richter Method)
			Hydraulic (e.g. Wetted Perimeter Method)
			Ecological
		Functional analyses	BBM, Expert Panel Assessment
			Method, Benchmarking Methodology
		Habitat modelling	PHABSIM
	Approaches		Expert Team Approach
			Stakeholder Approach (expert and non-expert)
	Frameworks		IFIM, DRIFT
World Bank (King and Brown 2003)	Prescriptive approaches	Hydrological Index Methods	Tennant Method
		Hydraulic Rating Methods	Wetted Perimeter Method
		Expert Panels	
		Holistic Approaches	BBM
	Interactive approaches		IFIM, DRIFT
IWMI (Tharme 2003)	Hydrological index methods		Tennant Method
	Hydraulic rating methods		Wetted Perimeter Method
	Habitat simulation methodologies		IFIM
	Holistic methodologies		BBM, DRIFT, Expert Panels, Benchmarking Methodology

Table 2. Features of Prescriptive and Interactive Methodologies (from King and Brown 2003)

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

More recently, the Nature Conservancy has distinguished three levels in a hierachical framework of development of environmental flow methodologies. Level 1 includes hydrological, hydraulic and habitat simulation methodologies. At Level 2, initial flow recommendations rely primarily on the judgment of multidisciplinary expert panels which builds on the basic approach from Level 1. At Level 3, the process is characterized by greater up-front investment in more sophisticated methods for examining tradeoffs and predicting results of operational changes. It is appropriate for situations that require a high degree of certainty before making operational changes. For details, see http://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/Pages/environmental-flows.aspx

HYDROLOGICAL METHODS

Hydrological methods utilise long-term time series data (usually for the past 30 to 50 years) on the river flows (discharge as cumec, $m^3 s^{-1}$) measured (or estimated from various modeling techniques) at several points along the stream. Because of the reliance on past flow data, these methods are also called Historical Flow methods. The data may be averaged daily, weekly, 10-daily, or monthly. The method involves an expert assessment, based on the available knowledge of hydrology, river characteristics and some fish species of primary interest, and of the level of flow that would maintain the stream/river ecosystem at an acceptable or desired level. Hydrological methods assume a relationship between flow and specific biological parameters. This flow level can vary from a single fixed value to a number of variable values, expressed as percentage of natural flow values. Flow data may also be analysed statistically to arrive at an index value. In general, these methods do not involve consultation with stakeholders.

Hydrological methods were the first to be developed and still continue to be developed further and used widely. About 30% of all methods belong to this category, make relatively little use of morphological and biological information on rivers and are usually region-specific (Tharme 2003). Olden and Poff (2003) have reviewed more than 170 of these indices and highlighted patterns of redundancy among them. They provided several statistically and ecologically-based recommendations for the selection of a few indices which can be used to adequately characterize flow regimes in a non-redundant manner.

Tennant Method

The Tennant Method (Tennant 1975, 1976a,b), also known as the Montana Method, is one of the oldest methods developed specifically for the needs of fish. It was based on Tennant's 17 years of experience on hundreds of streams, and testing in the field on 11 streams (58 cross sections, 38 different flows) in Nebraska, Wyoming, and Montana. Tennant used empirical hydraulic data from cross-channel transects combined with subjective assessments of habitat quality to define relationships between flow and aquatic habitat suitability. Tennant assumed that a proportion of the mean flow is needed to maintain a healthy stream environment. He observed that the stream width, water velocity and depth increased from no flow to 10% of the mean flow and decreased thereafter (Figure 1). Tennant considered only the suitability of the physical habitat that was related to the flow. He considered an average depth of 0.3m and velocity 0.25 m/s to be the lower limit (for short-term survival) and an average depth of 0.45 to 0.6m and velocities of 0.45 to 0.6 m/s to be optimal for fish. These levels were obtained at 10% and 30% of the mean annual discharge respectively, in the streams studied by him. The stream flow recommendations were based on percentages of mean annual discharge (= average annual flow) (Table 3). Only low flow (October-March) and high flow (April-September) periods were identified

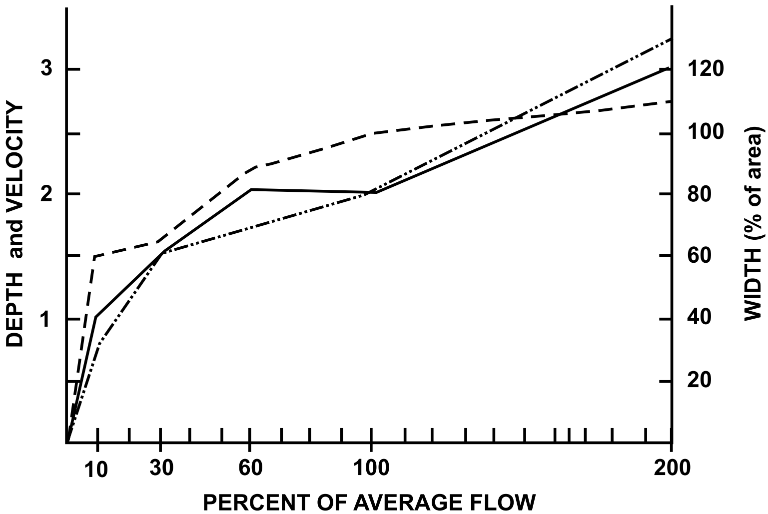

Figure 1. Relationship of flow (%) with channel width, depth and flow velocity (redrawn from Tennant 1976)

Modifications of the Tennant Methods

The Tennant Method is simple as it requires no field work and is based on a single hydrologic statistic (Mean Annual Discharge). It has influenced numerous studies in the USA and has been applied in many countries (Reiser et al. 1989, Jowett 1997). In eastern Canada, a fixed percentage of Mean Annual Flow (25 or 30%) had been recommended and followed for long (Annear and Conder 1983).

Table 3. Instream flow regimes for fish, wildlife, recreation and related environmental resources, as described in Tennant (1976). Flows are expressed as percentages of mean annual discharge (MAD).

	October-March	April-September
Flushing or Maximum	200%	200%
Optimum Range	60-100%	60-100%
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or Degrading	10%	30%
Poor or Minimum	10%	10%
Severe Degradation	0-10%	0-10%

However, from the very beginning, many researchers in North America pointed out that the method is not applicable to other geographical regions and other streams with different flow patterns. Tennant Method was developed for the region where the streams have similar hydrologic regimes and therefore the same %MAD statistic could be used for all of them but with different streamflow patterns, it is not applicable. Recently, Mann (2006) observed that Tennant's original dataset represented low gradient streams (<1% slope), and hence was not applicable to high gradient streams even in the western USA (>1 % slope). Many modifications were suggested. In Texas, Matthews and Bao (1991) found that the flow regimes of rivers varied so that the fixed proportions of annual mean flow were not suitable for fish. They recommended modifications to account for the flashy stream flows and used median annual discharge (MedAD) in place of MAD considering the life cycle requirements of fish. In Oklahoma, a shift in the periods of low and high flows was suggested (July to December and January to June (Orth and Maughan 1981). Fraser (1978) suggested that the Tennant method could be extended to incorporate seasonal variation by specifying minimum flows for each month as a percentage of mean monthly flows.

Tessman (1980) followed it up by considering natural variations in flow on a monthly basis to determine the flow thresholds. The Tessman rule recommends minimum flow guidelines which require the flow to vary each month. The flow for each month is determined by considering the following rule :

1) MMF, if MMF < 40 % MAF;
2) 40 % of MAF, if 40 % MAF < MMF < 100% MAF; and,
3) 40 % of MMF, if MMF > MAF.

where MAF is mean annual flow and MMF is mean monthly flow. Further, a 14-day period of 200% MAF is required during the month of highest flow for channel maintenance.

This modification has been more widely applied to regions with different hydrological and biological cycles (e.g., Estes 1995 and Locke 1999).

In British Columbia (Canada), the Ministry of Environment developed a modified Tennant Method by explicitly accounting for the biological and physical information (Table 4). The timing for each flow threshold were specified to meet the requirements at different stages in the fish life cycle (spawning, incubation, migration, active rearing, overwintering) along with the geomorphological features of the target stream (Ptolemy and Lewis 2002). Flow levels were recommended in weekly time blocks considering species periodicity and natural flow, and a higher value is selected in case of two or more conflicting requirements at the same time.

This method is also based on a single hydrological statistic but requires good quality information on fish biology and stream features. The water resource managers may find its implementation somewhat difficult because of weekly time blocks.

The BC-Instream Flow Threshold

To meet the needs of regulations governing water diversion, particularly in small hydropower projects in British Columbia, Hatfield et al. (2003) developed a hydrological method based on historic flow data. The method requires an assessment of fish presence or absence and an adequate time series (20 years continuous data) of mean daily flows. Two thresholds were recommended:

Table 4. Summary of recommended flows according to modified Tennant method developed for streams in British Columbia (from Hatfield et al. 2003)

Biological or Physical Requirement	% MAD	Duration per annum
Short-term biological maintenance	10	Days
Juvenile summer to fall rearing	20	Months
Over-wintering	20	Months
Riffle optimization	20	months
Incubation .	20	Months
Kokanee spawning	20	days-weeks
Smolt emigration	50	Weeks
Gamefish passage at partial barriers	50 to 100	Days
Large fish spawning/migration	148^{*} $MAD^{0.36}$	days weeks
Off-channel connectivity/riparian function	100	Weeks
Channel geomorphology/sediment flushing	>400	1 to 2 days

(i) for streams without fish, a minimum flow release equivalent to the median monthly flow during the low flow months; and

(ii) for streams with fisheries, a seasonally-adjusted threshold calculated as percentiles of mean natural daily flows for each calendar month. These percentiles varied through the year (on a sliding scale from 20% during the month of highest median flow to 90% during the month of lowest median flow) to ensure higher protection during low flow months rather than during high flow months.

This method takes care of the different stream flow patterns and has been approved by the Ministry of Environment and the Department of Fisheries and Oceans in British Columbia. However, doubts remain about its applicability to all stream types and in situations where water is abstracted for consumptive uses.

Alberta Desktop Method

Recently, the Government of Alberta (Canada) adopted a strategy for sustainable water resources management which, inter alia, calls for "... science-based methods for determining the ecological requirements for a healthy aquatic environment." Accordingly, Locke and Paul (2011) developed another Desktop method based on natural historic stream flows (observed or modeled daily flows over a long period) with the objective of providing "full protection of the riverine environment, in the absence of site-specific studies" that meant "no measurable environmental decline over the long term due to human changes in the flow regime". Essentially, the method recommends the limits of abstraction of water from streams by explicitly supporting the maintenance of instream and riparian habitats. The method recommends "15 percent instantaneous reduction from natural flow or, the lesser of either the natural flow or the 80 percent exceedance natural flow based on a weekly or monthly (depending on the availability of hydrology data) time step". Hatfield et al. (2013) pointed out the limitations of the method inasmuch as the recommended flows do not take into account stream size/type and issues of lateral connectivity. In some other provinces of Canada and also in some European countries, similar Percentage of Flow (POF) methods have been used to recommend the upper limit of abstraction as percentages of current natural flow. The proportions of natural flow therefore vary depending on different river types (see Linnansaari et al. 2012).

Flow Duration Curve Methods

The flow-duration curve (FDC) is a cumulative frequency curve representing the percent of time during which the average discharge (flow rate) equaled or exceeded a particular value at a given location (Figure 2). The FDC may be based on daily, weekly or monthly values of discharge. It is a measure of the range and variability of a stream's flow which is best projected when daily discharge data are used for its preparation. The discharge data are usually plotted on a logarithmic scale or as percentages of total discharge. However, the FDC totally disregards the chronological sequence of events. The FDC when prepared for long-term data (10-50 years) is useful in assessing the availability of water at a particular

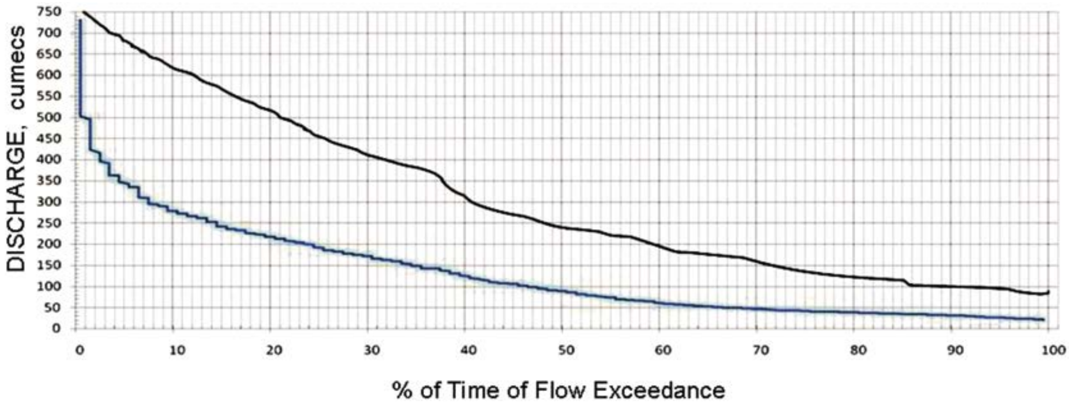

Figure 2. Flow duration curves for two Himalayan rivers

location but is of limited advantage from biological viewpoint because the biota are also significantly affected by the time of the year when they experience a particular flow volume and velocity.

A large number of hydrological indices have been suggested on the basis of Flow Duration Curves by specifying the exceedance percentile or the period of a particular flow level observed over a number of years (see Olden and Poff 2003, Pyrce 2004). Many of these indices were developed keeping in mind the low flow thresholds for allowing surface water abstraction for different uses, especially hydropower, and also for the assessment of effluent discharge limits in receiving streams (Smakhtin and Toulouse 1998). Low flow indices were interpreted later as environmental flows for protecting the fish or other biota. The low-flow indices are based on more than 50% exceedance obtained from FDC for daily discharge data. Interestingly, Smakhtin and Toulouse (1998) have demonstrated that many low-flow characteristics are strongly correlated and that one low-flow index may often be derived from another by means of regression relationships. For a discussion of low flow indices, see Smakhtin 2001, Pyrce 2004).

One of the most commonly referred hydrological index is the 7Q10. It defines the lowest flow recorded for seven consecutive days within a 10-year return period. Despite its popularity (Tharme 2003, Caissie et al. 2007, Richter et al. 2011), 7Q10 does not represent an environmental flow method. This hydrologic statistic was developed to protect water quality under the USA Federal Clean Water Act. It denotes the minimum volume of water needed in the river to meet point discharge water quality thresholds. A variant of 7Q10 is 7Q2 which was earlier used in Quebec (Canada). The 7Q2 uses a 2 year return period for 7 day low flows and therefore, provides a slightly higher flow threshold. It represented about 33% of the Mean Annual Flow in the rivers in Quebec (Caissie and El-Jabi 2003). The use of these indices for setting environmental flow standard has no scientific basis and the InStream Flow Council has opined that 7Q10 could even lead to severe degradation of fisheries (Annear et al. 2004).

Two other indices, Q95 and Q90 (daily flows exceeding 95% and 90% of the time respectively) have also been frequently used. Sometimes they are computed on a 10-daily or monthly time-step as well. In the UK, the Q95 has been proposed as a threshold at which abstraction is either not allowed or is restricted to a certain percentage depending on the season and river type. The U.K. Environment Agency (April 2013) has formulated an Environmental Flow Indicator (EFI) as a percentage deviation from the natural river flow for differing river 'types' and at different flows: low flows (Q95) and flows above Q95 by using a flow duration curve (UKTAG 2008). It depends also on the ecological sensitivity of the river to changes in flow.

Many studies have reported Q95 and Q90 values to be highly inadequate to meet environmental flow requirements and even the growth of some fish species (Caissie and El-Jabi 1995, Annear et al. 2004, Armstrong and Nislow 2012). Caissie et al. (2007) who compared several hydrological indices for their suitability in eastern Canada, found the 7Q10, 7Q2 and Q90 to be similar and concluded that they generate very low flow which "could have serious adverse biological effects on aquatic habitats".

Another method based on the FDC is the Q50 method, or median monthly flow method, which was developed by the New England U.S. Fish and Wildlife Service for catchments with good hydrological records (USFWS 1981). A modified Aquatic Base Flow (ABF) method was proposed for ungauged catchments by taking the median flow in August (month with lowest flow of the year). Further, in the state of Maine, a "Seasonal ABF" is followed by using the median flow for six 'seasons (Winter, Spring, Early summer, Summer, Fall and Early winter) recognised in a year. ABFs are the minimum level of flow after which no further abstraction of water is allowed.

Shifting FDC Technique

Recently, a variant of the FDC method has been proposed by Smakhtin and Anputhas (2006) for data-deficient situation such as those in India where practically all river discharge data are either classified or restricted for a variety of reasons, and ecological data on river biota are also very poor. The method relies on a reference FDC based on the monthly discharge time series of the unregulated river (observed or modeled) and calculates how much the flow can be modified for a specified desired condition of the river. The minimum requirement for desktop EFA application at any site in a river basin was suggested to be sufficiently long (at least 20 years) monthly flow time series reflecting, as much as possible, the pattern of natural flow variability (Smakhtin and Anputhas 2006). The FDCs are then represented by a table of flows corresponding to the 17 fixed percentage points: 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99 percent to cover the entire range of flows. The estimates of 'natural' MAR for smaller basins were obtained by means of hydrological regionalization.

The desired or negotiated condition of the river was referred to as the 'environmental management class' (EMC; Table 5) (sometimes known as "ecological management category" or "level of environmental protection" in other countries). Higher EMC requires more water with greater flow variability for ecosystem maintenance or conservation. Currently these

TABLE 5. Approximation of Environmental Management Classes (EMC) by total indicator scores (from Smakhtin and Anuputhas 2006)

Total indicator scores as a percentage of the maximum possible sum	EMC	Most likely ecological condition (adapted from DWAF 1999).	Management Perspective
91–100	A	Natural rivers with minor modification of in-stream and riparian habitat.	Protected rivers and basins. Reserves and national parks. No new water projects (dams, diversions, etc.) allowed.
75–90	B	Slightly modified and/or ecologically important rivers with largely intact biodiversity and habitats despite water resources development and/or basin modifications.	Water supply schemes or irrigation development present and/or allowed.
50–74	C	The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present.	Multiple disturbances associated with the need for socioeconomic development, e.g., dams, diversions, habitat modification and reduced water quality.
30–49	D	Large changes in natural habitat, biota and basic ecosystem functions have occurred. A clearly lower than expected species richness. Much lowered presence of intolerant species. Alien species prevail.	Significant and clearly visible disturbances associated with basin and water resources development, including dams, diversions, transfers, habitat modification and water quality degradation.
15–29	E	Habitat diversity and availability have declined. A strikingly lower than expected species richness. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem.	High human population density and extensive water resources exploitation. Generally, this status should not be acceptable as a management goal. Management interventions are necessary to restore flow pattern and to 'move' a river to a higher management category.
0–14	F	Modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitat and biota. In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible.	This status is assumed to be not acceptable from the management perspective. Management interventions are necessary to restore flow pattern, river habitats, etc. (if still possible/feasible)—to 'move' a river to a higher management category.

classes are purely conceptual and not based on any empirical relationship between flow and ecological conditions (Puckridge et al. 1998).

The rivers are placed into different EMCs, by expert judgment, using a scoring system. The rivers examined in India were placed in one of the six EMCs somewhat similar to those identified in South Africa (DWAF 1997). These were: the *unmodified and largely natural conditions* (rivers in classes A and B), *moderately modified (*class C rivers), *largely modified* (class D rivers), *seriously and critically modified* (classes E and F). The Environmental Water Requirement (EWR=EF) is then estimated for all or any of the EMCs and then the best one feasible under the given existing and future conditions is chosen. Alternately expert judgment and available ecological knowledge are used to place a river into the most achievable EMC.

The FDC for each EMC is determined by shifting the reference FDC to the left, along the probability axis gradually in steps (Figure 3). Thus, for a class A river the default environmental FDC is determined by shifting the reference FDC by one step, for class B by two steps and so on. A linear extrapolation is used to define the 'new low flows'. Shifting of the FDC to the left preserves the general pattern of flow variability, but with some loss of variability, and the total amount of E-Flow is reduced. The environmental FDC is then converted into a monthly flow time series by spatial interpolation procedure (Hughes and Smakhtin 1996).

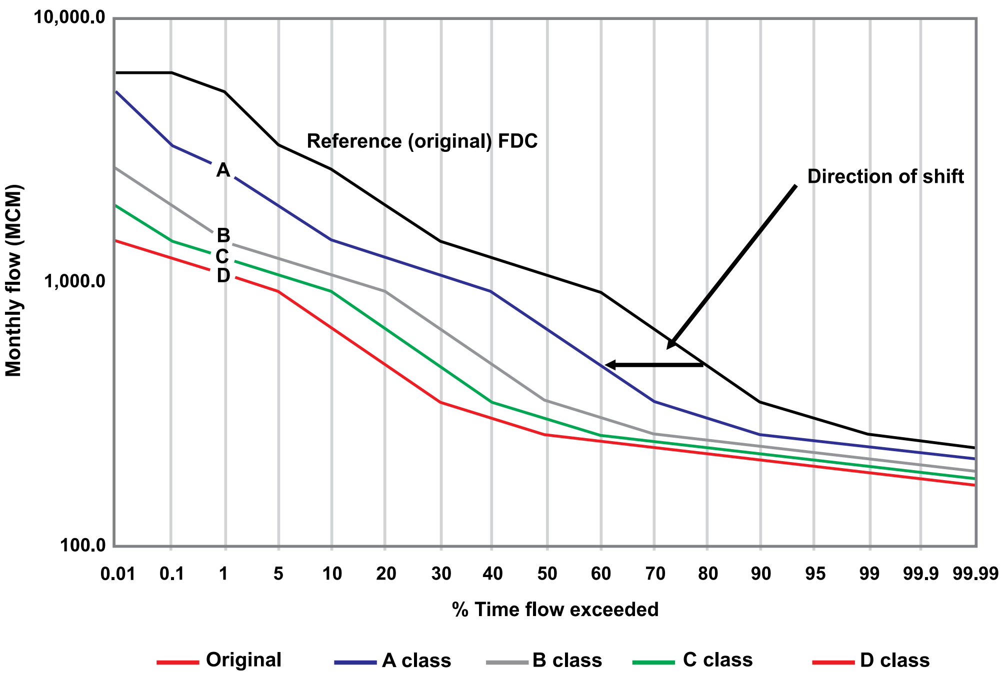

Figure 3. Estimation of environmental FDCs for different Environmental Management Classes by lateral shift (redrawn from Smakhtin and Anputhas 2006)

This method is somewhat similar to the Catchment Abstraction Management Strategy (CAMS) in the U.K. (Environment Agency 2001). Four elements namely, physical characteristics, fisheries, macrophytes and macro-invertebrates are considered for their sensitivity (scored on 1-5 scale) to reduction in flow. The scores are combined to categorize the river into one of the five environmental weighting Bands (most sensitive to least sensitive; mean score 5 to 1). Then a target *flow duration curve* (FDC), relative to the naturalized FDC, is defined, through expert judgement, that guides the setting of limits on abstraction.

Indicators of Hydrologic Alteration (IHA) and Range of Variability Approach

The foregoing account shows that various hydrological indices stress upon the amounts of flow with only little consideration of temporal variability (by season or months only) and are used to decide environmental flow requirements on the basis of assumed relationship between certain flow levels and a few fish species of interest. It was discussed in an earlier chapter that hydrological variability at any place has five main attributes: depth, duration, amplitude, frequency and timing which influence all kinds of organisms and these influences vary at different stages of their life cycle. In the case of flowing water systems, the velocity of flow, waves and turbulence are additional attributes which are related to depth and other hyadraulic characteristics of the stream. The five main attributes of intra-annual hydrological variability are graphically best represented by the hydrographs prepared for daily discharges through the year, though extreme events (high discharge) of a very short duration may affect the stream biota adversely. Hydrographs for many years are required to understand the interannual variability.

Richter et al. (1996) identified 32 ecologically-important hydrological parameters (later changed to 33) divided into five groups (magnitude, frequency, timing, duration, and rate of change) of the annual flow regime (Table 6). Human activities such as abstraction, reservoir storage, diversion or groundwater withdrawal alter some of these parameters and thereby affect the biological communities. Based on detailed statistical treatment of these parameters, Richter et al. (1996) developed an Index of Hydrological Alteration (IHA). The IHA simply compares hydrologic attributes of a site before and after a certain project activity, or two sites with different kinds or levels of impacts. It provides a statistical measure of change in the central tendency or degree of variation of an attribute of interest. The IHA variables can also be used for long-term trend analysis. The IHA itself is not an environmental flow method but has been incorporated into some recent holistic methods. The Nature Conservancy has developed a freely available software for computing the IHA from daily flow data (*http://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/IndicatorsofHydrologicAlteration/Pages/IHA-Software-Download.aspx*). This software also calculates an additional 34 parameters for five different types of Environmental Flow Components (EFCs), namely low flows, extreme low flows, high flow pulses, small floods, and large floods.

Olden and Poff (2003), in their analysis of large number of hydrological indices, have observed that only a subset of the IHAs should be used in any analysis. Black et al. (2005)

Table 6. Summary of Indicators of Hydrologic Alteration (IHA) variables and ecological influences (adapted from The Nature Conservancy 2009. Indicators of Hydrologic Alteration, Version 7.1 User's Manual, 76p. http://nature.ly/TNC-IHA)

IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
1. Magnitude of monthly water conditions	Mean or median value for each calendar month	• Habitat availability for aquatic organisms • Soil moisture availability for plants • Availability of water for terrestrial animals • Availability of food/cover for fur-bearing mammals • Reliability of water supplies for terrestrial animals • Access by predators to nesting sites • Influences water temperature, oxygen levels, photosynthesis in water column
2. Magnitude and duration of annual extreme water conditions	1-day, 3-day, 7-day, 30-day and 90-day mean annual minimum 1-day, 3-day, 7-day, 30-day and 90-day mean annual maximum Number of zero-flow days Base flow index: 7-day minimum flow/ mean flow for year	• Balance of competitive, ruderal, and stress- tolerant organisms • Creation of sites for plant colonization • Structuring of aquatic ecosystems by abiotic vs. biotic factors • Structuring of river channel morphology and physical habitat conditions • Soil moisture stress in plants • Dehydration in animals • Anaerobic stress in plants • Volume of nutrient exchanges between rivers and floodplains • Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments • Distribution of plant communities in lakes, ponds, floodplains • Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
3. Timing of annual extreme water conditions	Julian date of each annual 1-day maximum and each 1-day minimum	• Compatibility with life cycles of organisms • Predictability/avoidability of stress for organisms • Access to special habitats during reproduction or to avoid predation • Spawning cues for migratory fish • Evolution of life history strategies, behavioral mechanisms
4. Frequency and duration of high and low pulses	Number of low pulses within each water year Mean or median duration of low pulses (days) Number of high pulses within each water year Mean or median duration of high pulses (days)	• Frequency and magnitude of soil moisture stress for plants • Frequency and duration of anaerobic stress for plants • Availability of floodplain habitats for aquatic organisms • Nutrient and organic matter exchanges between river and floodplain • Soil mineral availability • Access for waterbirds to feeding, resting, reproduction sites • Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
5. Rate and frequency of water condition changes	Rise rates: Mean or median of all positive differences between consecutive daily values Fall rates: Mean or median of all negative differences between consecutive daily values Number of hydrologic reversals	• Drought stress on plants (falling levels) • Entrapment of organisms on islands, floodplains (rising levels) • Desiccation stress on low-mobility streamedge (varial zone) organisms

developed the Dundee Hydrological Regime Alteration Method (DHRAM) as a modification of the IFA to be compatible with the requirements of the EC Water Framework Directive. Gao et al. (2009) examined the application of DHRAM together with the new concept of seasonal Ecodeficit and Ecosurplus proposed by Vogel et al. (2007), and concluded that the three metrics provided a good representation of the degree of alteration of a stream flow time series and explained most of the variability associated with the ensemble of 32 IHA statistic. Recently the suitability of Ecodeficit and Ecosurplus was further tested and confirmed by Kannan and Jeong (2011).

Recognising that each of the IHA parameters will vary over the long term (say 20-30 years), the Range of Variability was introduced as an additional consideration to identify flow targets as ranges for each of the IHA parameters (Richter et al. 1997, 1998). Three levels of each IHA variable were delimited by percentile values (non-parametric approach) or 1-2 standard deviations from the mean (parametric approach). The Range of Variability analysis (also included with the IHA software) adds further statistical support to the IHA. But both IHA and RVA together do not recommend any environmental flow standard; they are useful tools to assess the changes to flow regimes. Ecological studies to correlate biological responses with hydrological alterations (as also the alterations in physical habitats) are needed for defining the environmental flows.

Sustainability Boundary Approach (SBA) and Presumptive Standards

Having set the range of variability in IHA parameters, Richter (2010) attempted to define extent to which the natural hydrograph can be allowed to change without impacting the ecosystem functions. This he called the Sustainability Boundary Approach (SBA). The flow is altered by a certain percentage of allowable augmentation or reduction of the flow. The allowable alteration, which can vary throughout the year, is determined by applying some environmental flow assessment methods and in consultation with the stakeholders. The sustainable boundary approach considers restricting hydrologic alterations to within a percentage-based range around natural or historic flow variability and maintaining the natural hydrograph with due consideration of both the low and high flows instead of recommending the environmental flow itself.

These boundaries were reflected in the "Ecological Limits of Hydrologic Alteration" framework (or method) published simultaneously by Poff et al. (2010). The implementation of ELOHA, discussed later in this chapter, is somewhat expensive and time consuming. Therefore, Richter et al. (2011) proposed, as an interim measure, another method called 'Presumptive Standard'. A review of several case studies indicated that 6 to 20% of normal to low flows can be allowed to deplete cumulatively but with occasional allowance for greater depletion in seasons or flow levels during which aquatic species are thought to be less sensitive. On the basis of these findings from the review, Richter et al. (2011) suggested that "a high level of ecological protection will be provided when daily flow alterations are no greater than 10%; a high level of protection means that the natural structure and function of the riverine ecosystem will be maintained with minimal changes". Greater alteration by up to 20% was expected to provide 'moderate level of protection' which means that "there may be measurable changes in structure and minimal changes in ecosystem functions. Alterations greater than 20% will likely result in moderate to major changes" (Figure 4).

It was recognised that these conservative and precautionary values of presumptive standard may be insufficient to fully protect ecological values in certain types of rivers, particularly smaller or intermittent ones and yet water managers may feel excessively constrained by having to operate within the limits of these boundaries (Richter et al. 2011).

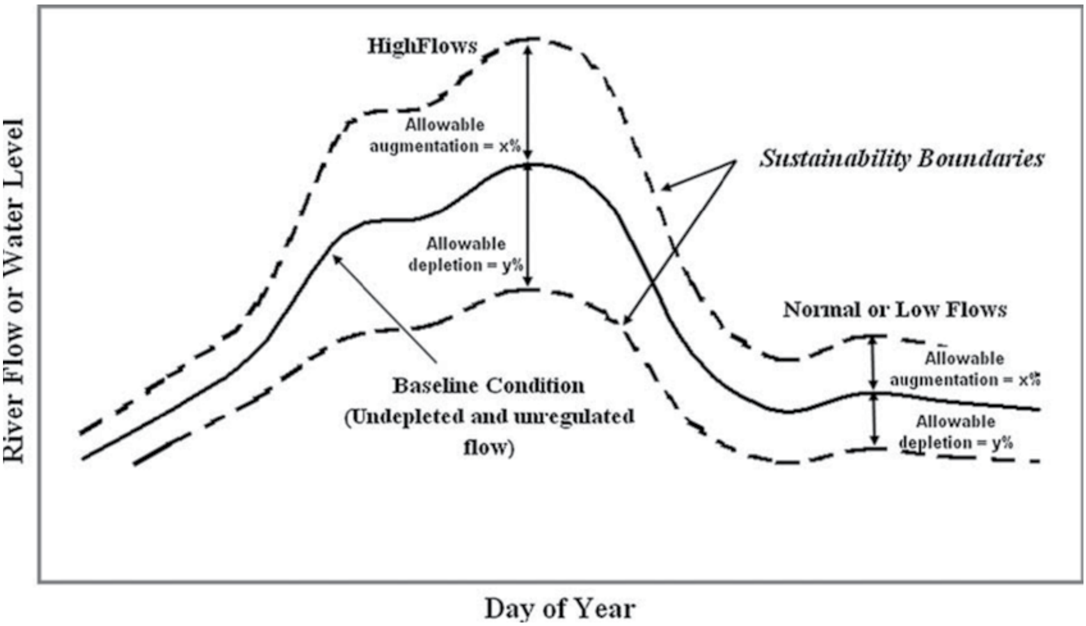

Figure 4. Illustration of the Sustainability Boundary Approach (SBA) to setting goals for sustainable water management (reproduced with permission, from Richter 2010)

HYDRAULIC RATING METHODS

Whereas the hydrological methods address the relationship between flow regime and the habitat suitability for stream biota only indirectly the hydraulic rating methods (a term coined by Loar et al. 1986) assume a relationship between discharge and some hydraulic measure of a stream across single river cross-section as surrogate for habitat factors (Jowett 1997, Tharme 2003). The influence of stream hydraulics on the distribution of benthic fauna along the river course had already been highlighted by several studies (Gore 1978, Statzner 1981, Statzner and Higler (1986). Hydraulic methods relate various parameters of stream geometry such as width, depth and wetted perimeter, based on surveyed cross-sections, to discharge rates (Jowett 1989). The relationship between flow and biological response are shown in Figure xx. Minimum or optimal flows, usually for fish spawning, or maximum production by benthic invertebrates, are generally identified from a discharge near the breakpoint of the wetted perimeter-discharge curve (Collings 1974, Prewitt and

Carlson 1979). For methods for instream habitat surveys, reference may be made to a recent publication by Jowett et al. (2008).

The commonly applied hydraulic rating methodologies and associated hydraulic simulation models used to derive environmental flow recommendations were reviewed by Tharme (1996). Hatfield et al. (2012) described only three methods in this category of which the Wetted Perimeter Method is reported to be the third most used methodology in North America (Reiser el al. 1989). Generally, however, hydraulic methods are not suitable for the assessment of seasonal flow requirements.

Wetted Perimeter Method

Wetted perimeter is the distance along the bottom and sides of a stream channel cross-section in contact with water. The wetted perimeter increases with the flow in a stream channel but the rate of increase declines after a certain level of flow depending upon the channel morphology (Figure 5).

The Wetted Perimeter method, developed in early 1970s by the Montana Department of Fish, Wildlife and Parks (for a detailed review see, Leathe and Nelson 1986), is a fixed flow hydraulic rating method based on this relationship between flow and wetted river perimeter at selected cross sections of the river stretch. The point of inflection (point of maximum curvature) where the change in wetted perimeter becomes small, is taken as the minimum flow requirement for the represented habitat.

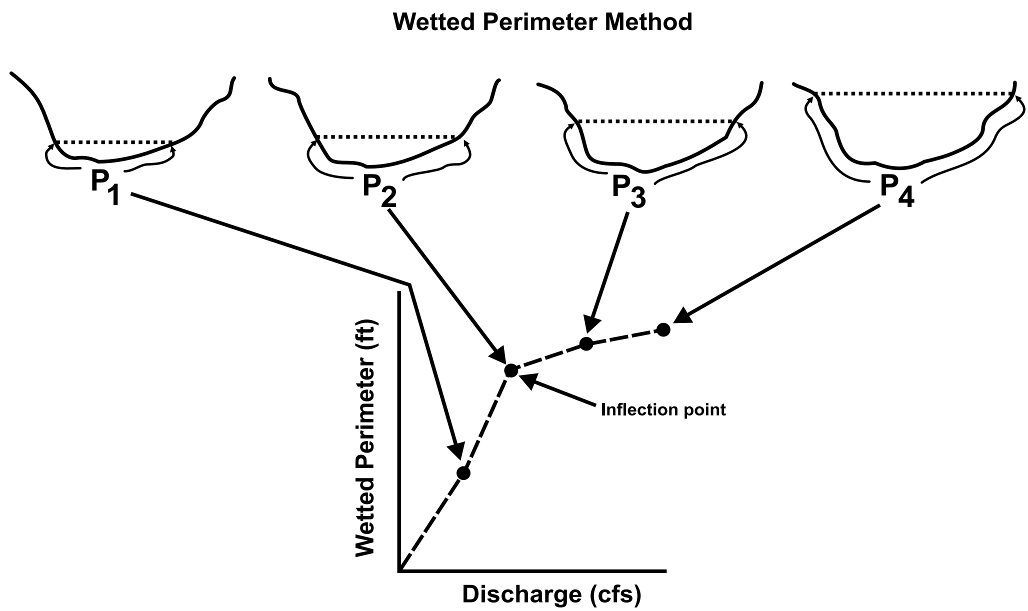

Figure 5. Relationships between flow and biological response for a hypothetical river, where biological response is expressed in terms of the measures such as the flow for historic flow methods, wetted perimeter for hydraulic methods and weighted usable area for habitat methods (redrawn from McCarthy 2003)

The method was developed on the assumption that “the food supply can be a major factor influencing a stream’s carrying capacity during the non-winter months. The principal food of many of the juvenile and adult game fish…is aquatic invertebrates, which are produced primarily in stream riffle areas” (Leathe and Nelson 1986). Riffles are typically selected because they exhibit sensitivity of width, depth, and velocity to changes in flow. They are usually the shallow habitats of the river. At a minimum flow estimated for a riffle, other habitat areas can be assumed to be well protected.

The point of inflection is determined at various levels of flow (including extremely low and high flows) and several cross sections along the river course. The selection of cross-sections for assessment is quite important. They must represent habitats for the rest of the river or river reaches. Cross sections are selected in wider parts of the river keeping in view the requirements of the fish species. Recommended flows are averaged for wetted perimeters of several cross sections (typically 15; Stewardson and Howes 2002).

The Wetted Perimeter method is not a standard-setting method but can be adapted for the purpose by deciding the proportion of wetted width as the threshold at specific locations. The determination of the point of inflection has been a matter of some discussion in the literature for high subjectivity, and a few statistical methods have been suggested for it (Gippel and Stewardson 1998, Men et al. 2012). Using HEC-GeoRAS modelling of riffle wetted area, Reinfelds et al. (2004) showed that the magnitude of the discharge selected to represent 100% habitat availability is of crucial importance to the determination of point of inflection (breakpoint). Wetted perimeter breakpoint results are also influenced by the degree to which areas of non-riffle habitat are included in the analysis.

Toe-Width Method

A method very similar to the wetted perimeter method was developed at about the same time in Washington State (Swift 1976, 1979) by US federal and state agencies. Based on the measurement of water depths and velocities at 336 transects over known salmonid fish spawning areas, at 8 to 10 different flows in 28 streams, data were analysed for a relationship between fish habitat and stream flow. In view of a highly significant correlation of the flow (needed for spawning) with the toe-width (distance across the stream channel, from the toe of one stream bank to the other), the method is known as the Toe-Width method (also known as the Swift Method). The method has apparently not been tried outside Washington State.

Riffle Analysis

A modification of the wetted perimeter method is the riffle analysis method which pays special attention to riffles as passages for fish migration. In California, the method is used to identify minimum stream flow rates necessary for the passage of salmon and trout through critical riffles. Adequate water depths of sufficient width are required for the passage of adult and juvenile salmonids. Water depth is measured at multiple locations across a transect along the riffle’s shallowest course from bank to bank. Field data are compared to species-specific and life stage-specific water depth criteria meeting the percent total and percent contiguous proportion of the critical riffle width (CDFG 2012). Data for a wide range of discharge rates and percent of transect meeting the minimum depth criteria for the species are plotted to determine flow rates necessary for passable flows. Higher flow rate between the two criteria (percent total and the percent contiguous) that meet the minimum depth for the target species and life stage are used as the required minimum flow (CDFG 2012).

Similar to the wetted perimeter method, this method is also not a standard-setting method, is subjective and prone to errors (Gippel and Stewardson 1998) but may be useful in conjunction with other methods (Annear et al. 2002). The method however will have to be adapted to different stream types, based on gradient, channel width, or other factors.

In Colorado, flow requirements for habitat protection in riffles based on the criteria for three hydraulic parameters: mean depth, percent of bankfull wetted perimeter, and average water velocity (Espegren 1996, 1998). The data are analysed by a hydraulic model, R2Cross, and hence the method is known as R2Cross method. The method assumes that a discharge required to maintain habitat in the riffle is sufficient to maintain the same in nearby pools and runs for most life stages of fish and aquatic invertebrates.

Adapted Ecological Hydraulic Radius Approach (AEHRA)

A recently developed hydraulic method, Adapted Ecological Hydraulic Radius Approach, uses hydraulic radius as the surrogate for hydraulic habitat. The hydraulic radius is determined using the Manning flow resistance equation, surveyed or generalised cross sections and the largest 'minimum ecological velocity'. The minimum ecological velocity refers to the minimum velocity required to maintain the river course and the elementary functions of instream ecosystem components (Liu et al. 2011).

Flow Event Method

Stewardson and Gippel (2003) developed a new approach to characterise flow variations and its application in environmental flow planning using knowledge of the influence of flow events on biological and geomorphic processes. This method incorporates the available knowledge in the development of flow recommendations and accounts for the natural dynamism in flow-related ecosystem processes by using the natural flow regime as a template for the environmental flow regime. The method involves five steps: (1) Listing ecological factors of flow related importance in streams, such as drying and inundation, light attenuation, mixing and advection of dissolved gases and solutes, transport of inorganic sediments and organic matter, and drag and abrasion, (2) characterization of individual flow events and their distribution in time, and evaluation using hydraulic parameters (by methods similar to wetted perimeter method), (3) modeling of hydraulic relationships, using one-dimensional hydraulic model like HEC-RAS or other appropriate models, (4) evaluation of flow management scenarios, and (5) specifying environmental flow rules or targets. The method was applied to Snowy River in Australia to demonstrate it.

Lotic Invertebrate Index for Flow Evaluation (LIFE)

Another method that can be placed in the category of hydraulic rating methods, assesses the response of invertebrate biota at the level of species or families to flow velocity. The method, called the Lotic Invertebrate Index for Flow Evaluation was developed in the U.K. from the extensive database on flow preferences of the stream invertebrates (Extence et al. 1999). An index of perceived sensitivity to water velocity was developed by allocating all recorded taxa to one of six flow groups (Table 7). The method is not known to have been used in management as yet (but see Orwin and Glazaczow 2009).

Table 7. Macroinvertebrate Flow Groups (after Extence et al. 1999)

Taxa	Flow Group	Velocity Requirement
I	Rapid flows	> 100 cm/s
II	Moderate to fast flows	20-100 cm/s
III	Slow or sluggish flows	< 20 cm/s
IV	Flowing (usually slow) and standing waters	—
V	Standing waters	—
VI	Drying out or drought impacted sites	—

HABITAT SIMULATION METHODS

Habitat Simulation methods are also called as Habitat Modelling Methods, Habitat Rating Methods or Microhabitat Methods (Loar et al. 1986). These methods are an extension of the hydraulic methods (Jowett 1989) as they also use the hydraulic conditions, which meet specific habitat requirements for biota, to determine flow requirements (Bovee et al. 1998). Whereas some features of the physical habitat (depth and velocity) are directly related to flow, other features (e.g., substrate and cover) are indirectly related. These methods use a variety of models to establish relationship between flow regimes and the amount and quality of physical habitat for various species, as well as with other environmental aspects of interest such as sediment transport, water quality and fish passage. These methods differ from the hydraulic methods in the emphasis on quantification of physical habitat using field data from multiple cross-sections to define the hydraulic aspects of species microhabitats along a stream (Stalnaker 1979, Herricks and Braga 1987, Tharme 1996, Brown and King 1999).

So far about 60 different habitat modeling methods (or approaches) have been developed. Most of them originate from various States in the USA and have only occasionally been applied in other countries. However, some of them have contributed to the evolution of more complex modeling approaches such as the IFIM that are now widely used. Among the relatively simpler methods, two are described here briefly.

Habitat Quality Index

Binns and Eiserman (1979) developed a Habitat Quality Index (HQI) to predict trout standing crop in Wyoming streams. Data on a large number of variables were collected from 36 streams which differed in elevation (1,146 to 3,042 m), average late summer stream width (1.4 to 44 m), average daily flow (0.6 to 1.46 $m^3 s^{-1}$) and stream gradient (0.1% to 10%). Multiple regression analysis indicated that the trout standing crop was best correlated with Data on nine habitat attributes namely, late summer stream flows, annual stream flow variation, water velocity, trout cover, stream width, eroding stream banks, stream substrate, nitrate nitrogen concentration, and maximum summer stream temperature. Predictive models were developed of which the best HQI model explained 96% of the variation in trout standing crop. The HQI was however not found suitable for streams in Alberta (Courtney 1995).

The Unites States Fish and Wildlife Service (USFWS) developed a similar index, the Habitat Suitability Index (HSI) for brown trout (*Salmo trutta*) as a part of the Habitat Evaluation Procedure for evaluating alternative resource uses in environmental impact assessments (USFWS 1980, 1981). Wesche et al. (1987) tested the HSI on nine streams in southeastern Wyoming but did not find significant correlation with brown trout standing stock. Better results were obtained by replacing some of the habitat variables and fishing pressure was found to significantly influence brown trout standing stock.

In-Stream Flow Incremental Methodology (IFIM)

As already pointed out, earlier studies in the United States had focused on 'minimum' instream flow requirements for the salmonid fish alone. After the National Environmental Policy Act of 1970, multiple benefits of instream flows were highlighted and a need was felt to quantify the effect of incremental changes in stream flow to evaluate alternative development schemes. This resulted in efforts to develop the Instream Flow Incremental Methodology (IFIM) which had its beginning in the late 1970s by an interdisciplinary team led by the U.S. Fish and Wildlife Service after the establishment of the Cooperative Instream Flow Service Group (CIFSG) which brought together several state and federal agencies.

IFIM is a process and a decision-support system designed to help in the assessment of consequences of different water management alternatives that can affect riverine habitats. A major component of IFIM is a suite of computer models called the Physical HABitat SIMulation model (PHABSIM), which incorporates hydrology, stream morphology and microhabitat preferences to generate relationships between river flow and habitat availability (Bovee 1982). Habitat availability itself is measured by an index called the Weighted Useable Area (WUA) which is the wetted area of a stream weighted by its suitability for use by an organism.

The following account of IFIM is adapted from the two publications – a primer prepared by Stalnaker et al. (1995) and an updated detailed account by Bovee et al. (1998) and from USGS Fort Collins Science Center (www.fort.usgs.gov/products/software/ifim)

The Instream Flow Incremental Methodology requires many activities which can be undertaken in five stages involving the identification of the problem, planning of the studird for assessment, implementation, analysis of alternatives analysis, and the resolution of the problem. The sequence of activities for IFIM are shown graphically in Figure 6, and described below briefly.

The First Stage in following the IFIM assessment requires :

(i) a legal-institutional analysis which identifies various stakeholders, their concerns, information needs, and relative influence, as well as the decision process. It is expected to result in a better understanding of the project, its objectives and likely impacts.

(ii) a biophysical analysis of the project/study area in order to determine its location and the areal extent od the riverine ecosystem which is expected to be affected by physical and chemical changes, and the biological resources of greatest importance and concern.

The problem identification is facilitated by a scoping meeting of the concerned governmental agencies and stakeholders. Several alternatives are identified and considered in detail, along with the consequences of such alternative hydrological alterations. A baseline hydrologic time series is also mutually agreed upon at the meeting.

Second Stage is devoted to detailed planning of the study. It starts with the identification of the information needs to address the concerns of each stakeholder group, the information available and the gaps which require collection of new data/ information. The study plan is then discussed in all necessary details before preparing a

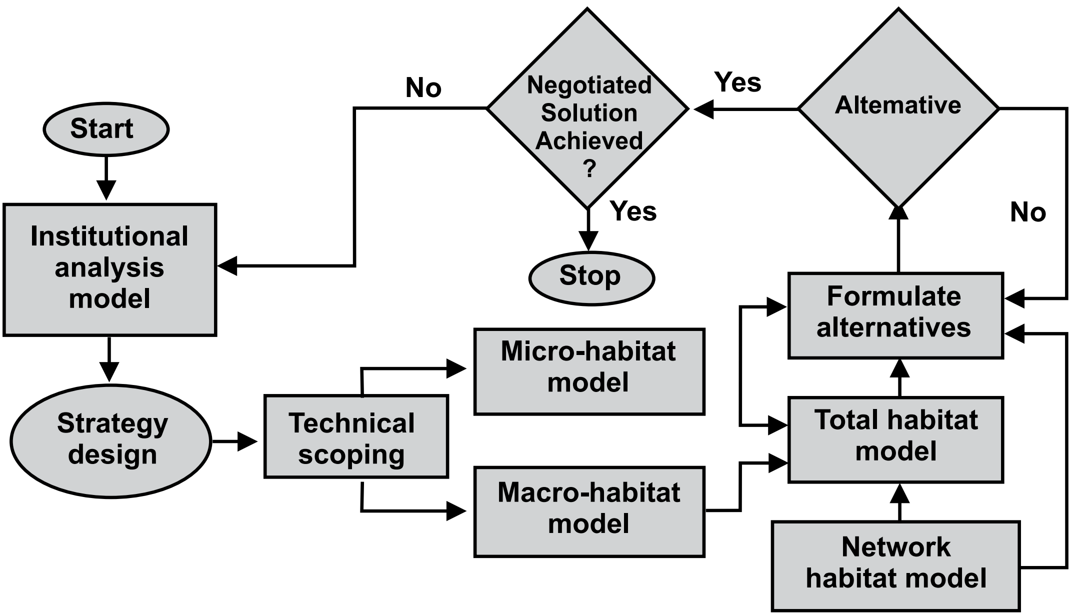

Figure 6. Flowchart for Instrem Flow Incremental Methodology (IFIM)

clear, concise document which should include the details of activities, people responsible, time schedule and budget. The objectives and information needs of each activity or part of activity are listed together with the methods for data collection.

Better planning helps identify the temporal and spatial scale of evaluation, (ii) specific data needs, methods for data gathering, and methods for quantifying the impacts of various alternatives.

Special attention is required for setting up the baseline hydrological time series, which may often be a synthetic time series representing present water uses, operational procedures, and wastewater discharges etc. As the method was initially developed with fisheries in view, fisheries managers were required to describe the biological reference conditions for different life history phases of fish populations. However, other biota can be incoporated into the study design.

The next stage is that of study implementation involving data collection, model calibration, predictive simulation, and synthesis of results. Time series data on various water quality and hydraulic parameters such as temperature, pH, dissolved oxygen, flow velocity, depth) are collected at several pre-identified sampling sites and the flow-habitat relationships are computed. IFIM relies heavily on models, and model calibration and quality assurance are keys to reliable estimates of the total habitat within the study area during simulation of the alternative flow regimes. Within IFIM, habitat analysis is performed at different scales: Macrohabitat (basin, networks, river segments), Mesohabitat (classes based on slope, channel shape, structure) and Microhabitat (depth, velocity, substrate, cover). Total habitat is synthesized by integrating large-scale macrohabitat variables with small-scale microhabitat variables (Figure 7). The habitat

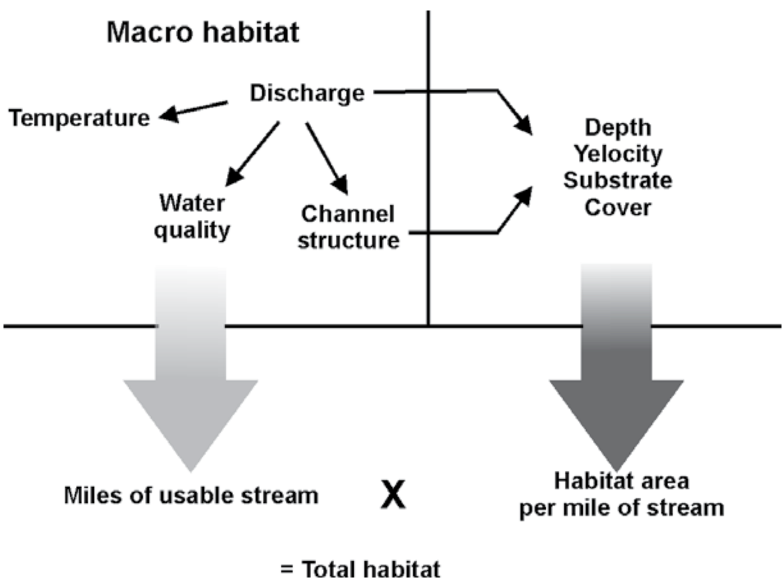

Figure 7. Total habitat combines elements of macrohabitat and microhabitat:

time series are developed for different life history stages provides for rational judgments about alternative schemes.

At the macrohabitat level, flow affects temperature, water quality and channel structure. At the microhabitat level, discharge and channel structure affect depth, velocity, and substrate characteristics. Total habitat is the obtained as the product of the micro- and macro-habitat estimates. IFIM depends upon the Physical Habitat Simulation (PHABSIM) methodology for the assessment of flow-habitat functional relationships at different scales. It is described later.

Phase three results in estimates of the relation between flow and total habitat, as well as measures of the amount of habitat available under chosen baseline conditions and various project alternatives.

The fourth stage of IFIM is devoted to a comparison and evaluation of several alternatives as identified earlier by the stakeholders. Potential impacts of each alternative are examined and new alternatives may be also considered. Simulation modeling is used for this task.

In the final stage, multidisciplinary teams of experts use their professional judgment about the biological resources and social needs to evaluate the flow requirements and help reach a negotiated settlement which usually requires a trade-off between conflicting interests. Post-project monitoring and evaluation are encouraged to allow for an adaptive management.

In recent years, IFIM has been supported with the development of several software packages for study objectives design, legal institutional analysis, habitat evaluation, habitat suitability index, alternative analysis, etc. (see http://www.fort.usgs.gov/).

PHABSIM

PHABSIM is a specific model designed to calculate an index to the amount of microhabitat available for different life stages at different flow levels. It considers habitat–flow relationships at different life stage of the species in view of the changing habitat requirement of the species during their life cycle. PHABSIM also indicates the changes in the area of hydraulic habitats with discharge fluctuations, therefore, provides a simple negotiation and management tool. It must be noted however that the IFIM and PHABSIM developed separately though parallel to each other. The history of development of PHABSIM is provided in the User Manual (Waddle 2012). PHABSIM has two major analytical components: stream hydraulics and life stage-specific habitat requirements (Figure 8)

The stream hydraulic component predicts depths and water velocities at specific locations on a cross section of a stream. Water depth, velocity, substrate material, and cover are measured at specific sampling points on several cross section at different flows. Hydraulic measurements, such as water surface elevations, are also noted and the data are used to calibrate the hydraulic models and then predict depths and velocities at flows different from those measured. The hydraulic models have two major steps. The first is to calculate the water surface elevation for a specified flow, thus predicting the depth. The second is to simulate the velocities across the cross section. Each of these two steps can use different modelling techniques depending upon the data availability.

The habitat component weights each stream cell using habitat suitability indices that assign a relative value between 0 and 1 for each habitat attribute indicating the suitability of that attribute for specific life stage of the organism. These indices are developed on the basis of direct observations in the field, expert opinion or a combination of both. Lastly, the hydraulic estimates of depth and velocity at different flow levels are combined with

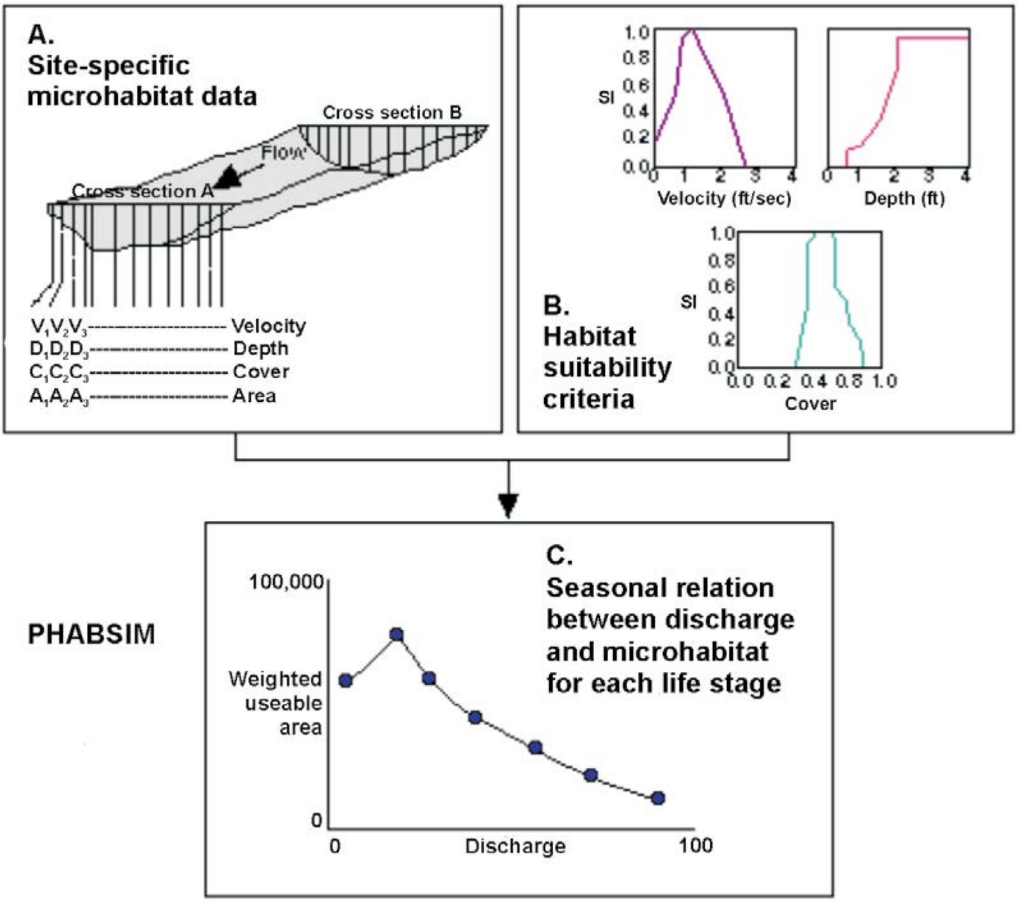

Figure 8. Conceptualization of how PHABSIM calculates habitat values as a function of discharge. (A) First, depth (**Di**), velocity (**Vi**), cover conditions (**Ci**), and area (**Ai**) are measured or simulated for a given discharge. (B) Suitability index (**SI**) criteria are used to weight the area of each cell for the discharge. The habitat values for all cells in the study reach are summed to obtain a single habitat value for the discharge. The procedure is repeated through a range of discharges to obtain the graph (C).

the suitability values for those attributes to weight the area of each cell at the simulated flows. The sum of weighted values for all cells is known as weighted usable area (WUA). It is expressed as:

WUA = [Σ Ai * Ci] Reach length (1,000 feet)

where: Ai = surface area of cell i; Ci = combined suitability of cell i (i.e., composite of depth, velocity and channel index individual suitabilities)

The combined suitability of the cell is derived from the component attributes of each cell which are evaluated against the species and life stage habitat suitability curve coordinates for each attribute to derive the component suitabilities. Individual component suitabilities can be aggregated in several different ways into a single composite cell suitability.

Many variations of this basic approach have been suggested in the literature. A time series analysis of WUA versus discharge function provides insight to the impacts of water availability at different times of the year at different life cycle stages. Major components of the methodology include:

- Study site and transect selection
- Transect weighting
- Field collection of hydraulic data
- Hydraulic simulation to determine the spatial distribution of combinations of depths and
- velocities with respect to substrate and cover under a variety of discharges
- Habitat simulation, using habitat suitability criteria, to generate an index of change in habitat relative to change in discharge

PHABSIM provides an index of the microhabitat availability if the species' preferences for depth, velocity, substrate material/cover, or other microhabitat attributes are known. It does not indicate the actual use of the habitat by the target organisms. PHABSIM does not predict also the effects of flow on channel change.

MesoHABSIM

As PHABSIM methodology focused on microhabitats, several efforts were made to develop models on the scale of mesohabitats and macrohabitats. Parasiewicz (2001, 2007a,b) developed a mesohabitat scale (i.e., channel units, like run, riffle, pool, etc.) MesoHABSIM which integrated system-scale assessment of ecological integrity in streams with quantitative information on physical habitat distribution to simulate habitat changes at the watershed scale, from the perspective of river management. Similar meso-scale models were developed later by Harby et al. (2007) for river Rhone (France), Halleraker et al. (2007) in Norway and Paul and Locke (2009) in Canada.

RHYHABSIM

Jowett (1989) developed a River HYdraulic and HABitat SImulation Model (RHYHABSIM) "to provide hydrologists, engineers and resource managers with an integrated solution to some of the more common hydrometric and hydraulic computations in flow assessment, such as calculation of flow, stage/discharge rating curves, water surface profile analysis, incremental flow analysis (IFIM), including flushing flows, sediment deposition, and flow fluctuations and water temperature modelling". It considers a cross section of the river as the basic stream geometrical unit. A reach of river has a number of cross-sections and is usually a section of river with similar morphology (i.e., slope, geology, channel form, and flow). Braided or multi-channel sections of a river can also be modelled and reaches along a longer section of river can be combined. The model can predict water level, velocity and habitat suitability over a range of flows. Several new features such as fish passage and habitat selection have been added (see www.jowettconsulting.co.nz/home/rhyhabsim). The model has been tested in Denmark (Thorn and Conallin 2006).

Riverine HABitat SIMuation (RHABSIM)

It was developed as an extensive conversion of the PHABSIM system by the U. S. Fish and Wildlife Service in association with TR Payne (http://ecobas.org/www-server/rem/mdb/rhabsim.html). It is a fully integrated program for river hydraulics and aquatic habitat modeling using the Instream Flow Incremental Methodology (IFIM) (Payne 1994).

System for Environmental Flow Analysis (SEFA)

Recognising the need for improved approaches to riverine habitat modeling and more comprehensive environmental flow assessments, Jowett, Milhous and Payne came together to merge the PHABSIM, RHABSIM, and RHYHABSIM into a new software, System for Environmental Flow Analysis (SEFA) which emulates the modular decision-making approach of the Instream Flow Incremental Methodology. SEFA includes several hydraulic models and the capacity to import results of others, computation of hydrologic statistics, development of habitat suitability criteria, calculation of habitat indices, water temperature and dissolved oxygen modeling, sediment scour, transport, and deposition analysis, habitat time series, and several other features. Details can be seen at http://www.sefa.co.nz/

The IFIM evolved over the more than two decades as it has been continually elaborated and improved upon with the advancements in modeling tools and the availability of desktop computer programs (Bovee 1982, Stalnaker et al. 1995, Bovee et al. 1998). However, despite its wide use in the USA and many other countries, IFIM has been criticised all along its progressive development (Mathur et al. 1985, Scott and Shirvell 1987, Armour and Taylor 1991, King and Tharme 1994, Williams 1996). Its main component PHABSIM has also been extensively used, further developed and yet criticised for being expensive, time consuming and very technical (Armour and Taylor 1991). Annear and Conder (1983) found PHABSIM models to be biased relative to other instream flow methods namely, the Tennant method, wetted perimeter method and the habitat retention models. More recent comments on IFIM's weaknesses come from Hatfield et al. (2003) and Moyle et al. (2011). Hudson et al. (2003) highlighted the need for including factors such as temperature or water quality changes with changing flow regimes, river mouth openings, flushing flow requirements, maintenance of lateral and longitudinal stream processes and maintenance of river channel processes.

It is interesting to point out the contribution of the IFIM to the development of holistic methodologies. South Africa realised the need for methodologies to assess the water requirements of rivers only in 1987. When South Africa initiated a research program for the ‘establishment in South Africa of one or more scientifically acceptable methodologies for assessing the instream flow requirements in the country’s rivers’, IFIM was selected for testing and assessment of its applicability in the Olifants river (King and Tharme 1994). The methodology was found to be “an outstanding training tool in a range of topics” but confusing and incomplete, unable to “provide a recommendation for a comprehensive modified flow regime”. Simultaneous detailed statistical analysis of daily flow records for several rivers revealed that the several types of flow patterns occur within any one geographical area. In view of the difficulties encountered, South Africa started developing alternate methodologies for “situations where time, finances and relevant biological data are limited” (King and Tharme 1994). The IFIM was also tested in Australia at about the same time (Pusey and Arthington 1991).

CASiMiR
(Computer Assisted Simulation Model for Instream Flow Requirements)

Over the past few years, researchers at the University of Stuttgart have developed a suite of fuzzy logic based habitat simulation programmes for fish, benthos and vegetation (Jorde 1996, Schneider et al. 2010). These habitat simulation programmes provide a spatial distribution of habitat suitability for the given taxa based on survey data and hydraulic preference curves. Details can be found at http://www.share-alpinerivers.eu/tools-and-resources/our-softwares-1/casimir-softwares

HOLISTIC METHODOLOGIES

The term holistic refers to methodologies which consider the whole riverine ecosystem. Conceptually, this means that the environmental flow requirement is assessed for all abiotic and biotic components of the river ecosystem, including the associated wetlands, groundwater and estuaries, instead of focusing on a few physical features and a few organisms. Holistic approaches or methodologies are based also on the premise that the modified flow regimes which are similar to the historical flow regimes in their spatial and temporal variability, are required to sustain stream morphology, habitats, all kinds of organisms and their interactions and to ensure the stream’s ecological integrity (Arthington 1998, King et al. 2003). According to King et al. (2008), the basis of the Holistic Approach is the systematic construction of a modified flow regime, through a bottom-up or a top-down process. The bottom-up process, followed by most of the approaches, builds a modified flow regime from scratch on a month-by-month and element-by-element basis, where each element represents a well defined feature of the flow regime intended to achieve particular ecological, geomorphological, water quality, social or other objectives in the modified system (Tharme 2003). The top-down process defines environmental flows in terms of acceptable degrees of departure from the natural (or another reference state) flow regime and therefore, considers different scenarios.

The holistic approaches, both the bottom-up and the top-down, require inter-disciplinary teams of experts drawn from many disciplines of natural and social sciences and engineering and also involve participation of stakeholders. A process of interaction and consensus building allows integration of data and knowledge to achieve a mutually agreed upon description of a flow regime required to maintain a specified river condition. The history of development of holistic approaches (or methodologies) is described in Arthington (1998) and King et al. (2008).

Building Block Methodology (BBM)

The need for a holistic approach was felt first in the beginning of 1990s almost at the same time in South Africa and Australia. The approach was conceptualised during an International Seminar and Workshop on Water Allocation for the Environment (Brisbane, 1991) and described jointly by the scientists from the two countries (Arthington et al. 1992). However, the Building Block Methodology was developed in South Africa as an out come of discussions in several workshops organised during 1991-1996 for suggesting a rapid first estimate of the EFR for several rivers targeted for water-resource development. The BBM was first unveiled in 1994 (King and Tharme 1994) as an alternative to the IFIM as mentioned above. The methodology was described in detail with the background of its development, an outline of its underlying concepts and assumptions, methods and results of the field studies, and the position of the methodology in the South African Department of Water Affairs and Forestry (Tharme and King 1998). King and Louw (1998) provided a summary in another publication.

The key concept underlying the BBM is that the flow regime of a river can be segregated into components which can be described distinctly in terms of their timing, duration, frequency and magnitude. These components, called as 'Building Blocks' of flow usually fall into the following categories: dry-season base flows (low flows); wet-season base flows (low flows), wet-season floods, dry season freshes and dry-season subsurface flows. Each block of flow performs an important ecological or geomorphological function in the river ecosystem but some blocks of the total flow regime of any river are more important than others. The minimum volume of water required for each 'block' is described, and the modified flow regime is obtained by combining the building blocks in a manner that it mimics the virgin flow regime It is noteworthy that the natural flow regime paradigm (Poff et al. 1997) was published only in December 1997.

The basic approach of BBM is to examine the hydrograph as a whole, and through available data and expert judgements determine an overall flow regime that will maintain the riverine ecosystem in some pre-determined desired state. This desired state is determined in terms of Ecological Management Classes (see Table 8). The process involves the participation of stakeholders in a workshop, besides the field studies by experts. Following account of the activities required for using BBM are summarised from the Manual (King et al. 2008) that is freely available on the knowledge hub of the South African Water Research Commission (http://www.wrc.org.za/Pages/KnowledgeHub.aspx). The methodology involves following steps (Table 9):

Table 8. Ecological Management Classes according to DWAF (1997) used in BBM (from Brown et al. 2008).
TWQR - Target Water Quality Range; SASS - South African Scoring System; CEV - Chronic Effects Value; AEV - Acute Effects Value.

Class	Flow Regime: Quantity and Variability	Water Quality	Instream Habitat	Riparian	Biota
A	Negligible modification from natural.	Negligible modification from natural. Negligible risk to sensitive species. Within Aquatic Ecosystems TWQR for all constituents.	Negligible modification from natural conditions. Depends on the instream flow and quality objectives which are set.	Negligible modification from natural conditions. There is control of land uses in the riparian zone that ensures negligible modification of vegetation within set distance from banks.	Negligible modification from Reference Conditions, based on the use of a score or index such as SASS.
B	Slight risk to especially intolerant biota.	Slight risk to intolerant biota (use Aquatic Ecosystems TWQR and CEV to set objectives).	Slight modification from natural conditions. Depends on the instream flow and quality objectives which are set.	Slight modification from natural conditions.	Slightly modified from Reference Conditions. Especially intolerant biota may be reduced in numbers or in extent of distribution.
C	Moderate risk to intolerant biota.	Moderate risk to intolerant biota (use Aquatic Ecosystems TWQR and CEV to set objectives).	Moderate modification from natural conditions. Depends on the instream flow and quality objectives which are set.	Moderate modification from natural conditions.	Moderately modified from Reference Conditions. Especially intolerant biota may be absent from some locations.
D	High risk of loss of intolerant biota.	High risk to intolerant biota (use Aquatic Ecosystems TWQR, CEV and AEV to set objectives).	High degree of modification from natural conditions. Depends on the instream flow and quality objectives which are set.	High degree of modification from natural conditions.	Highly modified from Reference Conditions. Intolerant biota unlikely to be present.

Table 9. Ten steps required to define an environmental flow release regime using the BBM

1	Define a natural flow regime for the water body in terms of daily discharge time series for a representative 10-year period
2	Analyse the flow regime in terms of the magnitude, frequency and duration of high, medium and low flows
3	Assemble biological survey data or use models for the water body to determine the expected biological communities and life stages for the river in reference condition
4	Determine flow regime requirements for each species/community and life stage using published literature
5	Verify the requirements by identifying elements of the flow regime in the historical record
6	Check that flow release elements will deliver other important variables such as water quality, including temperature and sediment load
7	Define the building blocks
8	Record results in an environmental flow release regime table
9	Add up individual flow needs to assess overall implications for water resources
10	Repeat the analysis for each water body ensuring that environmental flow upstream are sufficient to meet needs downstream

The environmental flow assessment using the BBM comprises of three phases: preparation for a Workshop, the Workshop and the follow-up. Each phase is described below.

The first phase is devoted to a structured set of activities which prepare the background document for the workshop (in the second phase). It requires:

- collection of all available information on the concerned river, its current state and likely impacts and other issues related to the proposed project activity;
- a planning meeting of specialists including a hydrologist; hydraulic modeller; fluvial geomorphologist; aquatic chemist; animal ecologists (specialising in studies of fish, aquatic invertebrates, other major fauna in the river), plant ecologists (instream and riparian vegetation) and a sociologist;
- identification of representative reaches and sites within the study area;
- a social survey of the study area to record the dependence of local communities on the riverine ecosystem for various resources and river-dependent livelihoods;
- determination of the economic, social and ecological importance of the study area;
- determination of the Ecological Management Class for the river in the study area;
- description of the virgin and present daily flow regime (with identification

of various flow components (blocks) along with their characteristics and importance for different river functions);

- survey and hydraulic analysis of channel cross-sections at each of the identified sites;
- assessment of the geomorphological characteristics of the study area;
- assessment of the past, present and required future water chemistry (quality), keeping in view the Ecological Management Class of the river;
- biological surveys at selected sites in the study area (complementing the literature surveys); and
- analysis of groundwater hydrology at each site, in case of floodplain reaches.

The second phase (the Workshop) starts after the background document is examined by all the specialists and other participants (water managers, engineers and river scientists). It comprises of a visit to each site by the full team, exchange of information through short presentations at the workshop, identification and description of the flow requirement for each site, by small groups, month by month, starting with the low flows, compilation of these flows into an EFR by consensus. The Workshop participants identify also the low flow and high flow components (to be expressed as percentages of the mean and median annual runoff) and flows in drought years. Finally, the workshop examines the recommended flow regimes for all the EFR sites, and identified the short-, medium- and long-term needs for further studies which may help refine the recommended flows.

The third phase of the methodology is devoted to the development of scenarios by the BBM team of possible consequences for the functioning of the river of flows that do not meet the EFR.

The Building Block Methodology was the first development in the direction of holistic methodologies and followed a bottom-up approach. It has been improved upon, modified and widely used in many countries. The scientists associated with its development started preparing a manual for is use from the very beginning and a full-fledged manual was published in 2000 (King et al. 2000). Whereas earlier methods had recognised some 'blocks' of the flow regime such as flows for river morphology, passage and spawning of fish, etc. BBM attached overriding importance to all parts of the flow regime by making it the focus of the study. BBM has been appreciated for its comprehensive view of ecosystem and the flow regime components, suitability for both regulated and unregulated rivers, potential for application to other aquatic ecosystems, and consideration of ecological management classes (Tharme 2003). The strengths and limitations of the BBM (as developed until 1998) were discussed in detail by Arthington (1998) based on its implementation in case of Logan river in Australia (Arthington and Lloyd 1998). The BBM was recently applied in India for the assessment of environmental flows in the upper reaches of river Ganga (O'Keefe et al. 2012; Kaushal and Babu 2013), However, it may be stressed that BBM is a prescriptive approach and specifies flow regime for a single desired (pre-determined) river condition (King and Brown 2006). It can be subjective depending upon the specialists' understanding of the flow-ecology relationships and smaller flow events which may be of ecological significance, may get ignored.

Desktop Reserve Model (DRM)

Several related developments have occurred in South Africa to improve upon hydrological modeling and integrate the models on a larger spatial and temporal scale. Researchers at the University of Rhodes developed at about the same time, and following similar approach, another model to provide "a method for generating low confidence, initial instream flow requirement estimates" for rivers in South Africa. This was named as the *Desktop Reserve Model* (DRM) (Hughes and Munster 2000, Hughes and Hannart 2003). The DRM utilises monthly flow data and separates the total flow into high flows and low flows during "normal years" (maintenance flows) and "drought years" (*drought flow).* Within the model two measures of hydrological variability are used: the Hydrological Index (CVB) representing climatic variability, and the Base Flow Index (BFI; proportion of base flow to the total flow). The total environmental flow is presented as a fixed monthly percentage of the MAR. The method has been described in some detail also by Smakhtin et al. (2006) along with its application in Nepal. The model has been also tried in Swaziland, Zimbabwe, Mozambique (Lagerblad 2011) and Tanzania (Kashaigili et al. 2007).

Another hydrological model developed to provide operating rules for reservoir releases (Hughes et al. 1997) has been modified into a Daily IFR Model to define a time series of instream flow requirements for a river based on a time series of reference flows. It is essentially the daily time step equivalent of the Desktop Reserve model.

Considering the greater importance of low flows, a ***Flow-Stressor Response model*** has been developed (O'Keefe et al. 2002). It starts with defining relationships between low flows and stress. The highest level of stress is assumed in habitat conditions under which the specific component of the biota is unlikely to survive. Required flow levels are estimated from the critical stress levels obtained through a modeling exercise and consultations between an ecologist and a hydrologist.

Recently, the Desktop Reserve model, Flow-Stressor Response model, Reserve Management model, Agrohydrological model and several other water related models have been integrated into a SPATSIM-HDSF framework to facilitate Environmental Water Reserve management in South Africa (Clark et al. 2012).

Downstream Response to Imposed Flow Transformation (DRIFT)

The central rationale of DRIFT is that different components of the flow regime of a river elicit different responses from the riverine ecosystem, and therefore, modification of a particular component of the flow regime will affect the riverine ecosystem differently than will the modification of the other component. DRIFT was developed in actual water-resource development projects, on the Palmiet River and Breede River in South Africa, and in the Lesotho Highlands Water Project in Lesotho (see Brown et al. 2008). DRIFT allows an exploration of multiple scenarios, and considers socioeconomic effects as well as environmental effects.

The initial development of DRIFT identified its several attributes besides its compliance with the requirements of the South African Department of Water Affairs and Forestry for use in the management of aquatic ecosystems (King et al. 2004). DRIFT follows a holistic approach inasmuch as it addresses all parts of the intra-annual and inter-annual flow regime, and all living and non-living parts of the river ecosystem from source to sea. It is a scenario-based approach, combining data, experts' experience and local knowledge of the concerned river to provide predictions of changes in the river with flow manipulations. It also predicts the social and economic impacts of these river changes. All the data and knowledge used in compilation of the scenarios are stored in a database for creating further scenarios and for future use. Further, its application could be automated because of its grounding in a range of custom-built software.

Whereas BBM relied on the natural (historical) flow data for a site as the reference, DRIFT is based on the present-day hydrology, and uses the natural flow regime for comparative purposes to assess the nature of past changes. As opposed to the bottom-up approach of the BBM, DRIFT uses a top-down approach. It takes the current flow regime as a starting point, and describes the consequences for all aspects of the river, of altering the volume of water in the river in different ways. It is designed to describe biophysical and socio-economic consequences of the changing river condition at different levels of modification of the current flow regime. Thus, it is designed specifically for use in negotiations over water resources (Brown et al. 2005). Its application requires two other exercises to be conducted in parallel with it: a macro-economic assessment of the wider implications of each scenario, and a Public Participation Process whereby people other than subsistence users can indicate the level of acceptability of each scenario.

DRIFT consists of four modules (Figure 9). The Biophysical Module describes the river ecosystem and develops the capacity for changes in the ecosystem with flow changes. The Socio-Economic Module describes the links between riparian people who are subsistence users of river resources, the resources they use, and their health. Here also the capacity is developed to predict impacts on people's lives with the changes in the river. Another module builds scenarios (Scenario Creation Module) of potential future flows and the impacts of these on the river and the riparian people. The fourth module is an Economic Module which examines the economic costs associated with flow changes in terms of compensation and mitigation costs.

The steps required for its implementation are described below. It makes use of one hydrological software programme, DRIFT-HYDRO, and a series of interlinked MS Excel spreadsheets, the DRIFT Database. The activities concerning the river-related biophysical components require specialists in the fields of hydrology, hydraulics and fluvial habitat, water quality, geomorphology/sedimentology, macrophytes, algae, fisheries, ecology of macroinvertebrates, aquatic parasites, aquatic and semi-aquatic mammals, water birds, zooplankton and herpetofauna. The socio-economic team is project specific, and may include specialists in sociology, anthropology, public health, animal heath, water supply, resource economics, scheme economics and public participation.

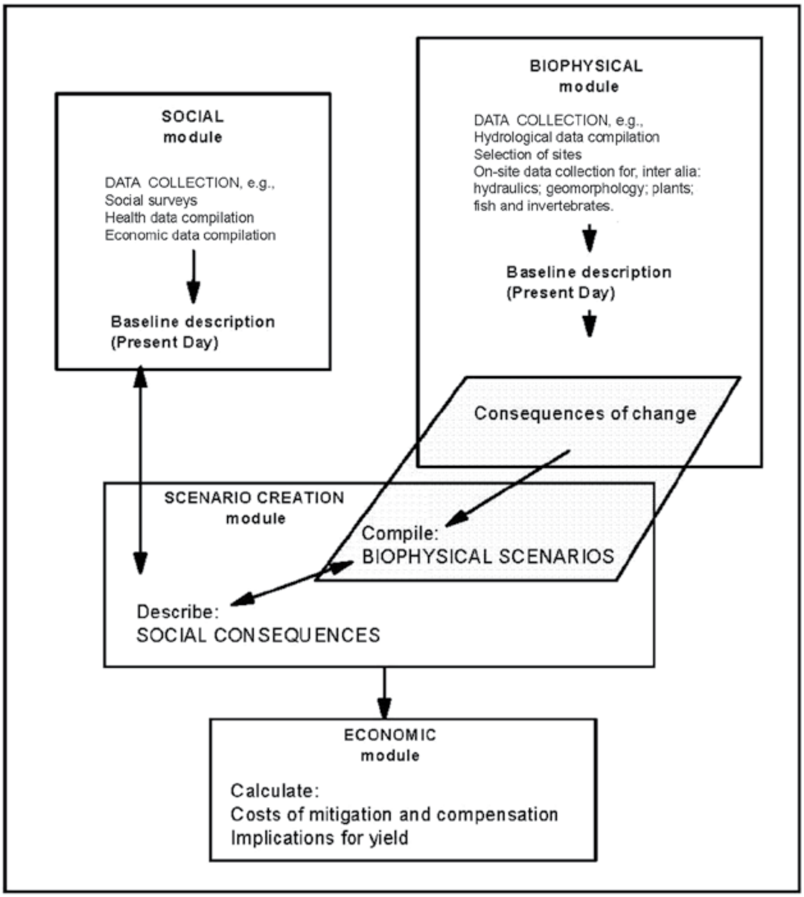

Figure 9. DRIFT modules (adapted from Brown & Joubert 2003)

Step 1: Hydrological data are prepared with the help of DRIFT-HYDRO for use by the biophysical specialists;

Step 2: Hydrological statistics is linked to cross-sectional river features at a number of representative river sites, and used by specialists to produce predictions of the biophysical consequences of flow change;

Step 3: The DRIFT Database is populated with the flow-ecosystem relationship predictions;

Step 4: DRIFT Database is used to develop scenarios of flow change linked to ecosystem change;

Step 5: DRIFT-HYDRO is used to generate modified flow regimes linked to each of the scenarios developed;

Step 6: The social impacts of each scenario are identified;

Step 7: The economic cost of compensation and mitigation is calculated for each scenario, and

Step 8: The impact on system yield for each scenario is estimated.

DRIFT-HYDRO enables the user to prepare the hydrological data, including separation of flow categories; generate the required summary statistics; manipulate the flow categories according to required levels of change; generate flow scenarios as well as output tables and graphs. The DRIFT Database stores the matrix of flow-response couplets, predicted by the specialists, for a range of possible flow changes; uses this matrix to compute the ecological consequences of different volumes and distributions of water being made available for river maintenance (flow scenarios); summarises the ecological consequences of flow scenarios relative to the present ecological state of the river; and allows predictions to be updated when new information becomes available.

The Biophysical specialists' team prepares a list of ecosystem components which will respond to a change in river flow through a change in their abundance, concentration and extent (area). This is entered as a DRIFT Generic List and comprises of:

Level 1: Ecosystem Components, e.g., geomorphology, water quality, vegetation, fish.

Level 2: Sub-components: Major divisions within the Components, such as groups of chemical components (e.g., nutrients), animal communities (e.g., feeding guilds) or plant communities (e.g., vegetation zones).

Level 3: Elements. Individual species or chemical compounds that occur in specific Sub-components.

The actual Sub-components and Elements within each Component are decided by the specialist responsible for that Component. The total number of entries allowed in each is, however, limited by database design. The lists should not include processes.The specialists first provide a conceptual model (that can be refined later) for each Generic List item, and then quantitative models are developed for the relationship between each Generic List item and flow characteristic. Within DRIFT, component-specific methods are used by each specialist to derive the links between river flow and river condition (biophysical), or between changing river condition and social and economic impact (socio-economic).

DRIFT database is described in detail by Brown and Joubert (2003). The database includes two modules, DRIFTSOLVER and DRIFT CATEGORY. DRIFTSOLVER contains an integer linear programming MCA method, which generates optimally distributed flow scenarios for different total annual volumes of water that are combined with the outputs of the Biophysical Module to develop scenarios of biophysical consequences. DRIFT CATEGORY facilitates their evaluation in terms of river condition.

Recently, the DRIFT has been developed fully into a Decision Support System (DSS) by adding the use of indicators dependent on other indicators and a time-series approach. The DSS has the capability to produce appropriate numerical and graphical summary outputs. The DSS is now available as software together with a user manual (Figure 10; Brown et al. 2013).

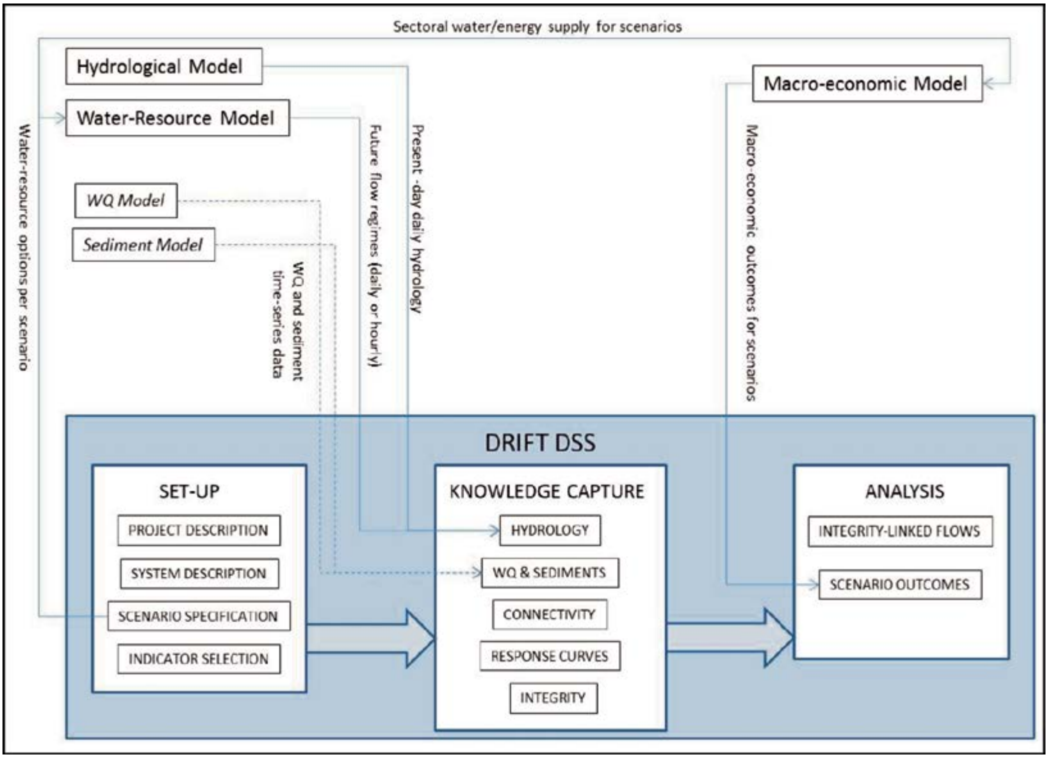

Figure 10. Arrangement of modules in the DRIFT-DSS and inputs required from external models (from Brown et al. 2013).

Benchmarking Method

While the South African researchers were developing the BBM using the bottom-up approach, a top-down approach was used to develop the Benchmarking Methodology in Queensland (Australia) for use in basin-wide water resource planning and management, and specifically, to provide a framework for defining environmental water 'requirements' and 'provisions' (Brizga et al. 2002). The main steps of the methodology are shown in Figure 11. The methodology addresses the question – how much can a river's flow regime be altered before the aquatic ecosystem becomes affected or seriously degraded? Benchmarking is preferred for assessing the risk of environmental impacts due to water resource development at a whole-of-catchment scale in Queensland.

The Benchmarking Methodology evaluates the geomorphological and ecological condition of many sites subjected to various degrees of flow regime change. The flow regime of the river system is described by a set of geomorphologically and/or ecologically relevant flow statistics using daily time step hydrological data for each site. Near-natural reference reaches and a set of benchmark reaches subject to varying levels of impact resulting from existing water resource development are compared for the purpose. The benchmark reaches are selected to cover a range of levels of change in flow regime. Ecological impacts in each of the benchmark reaches are assessed.

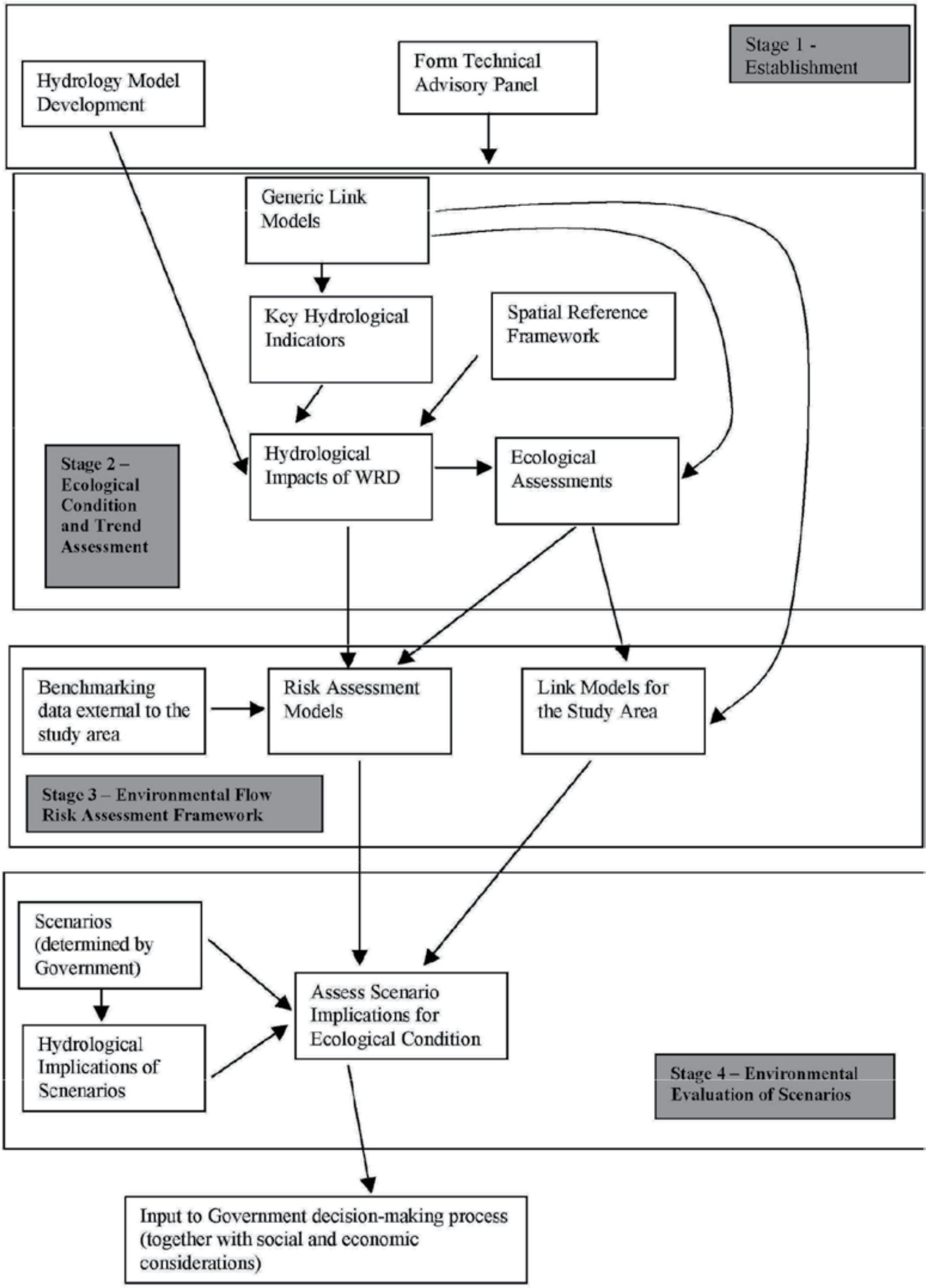

Figure 11. Main steps in the Benchmarking methodology (from Brigza et at. 2002)

The ecological implications of different levels of departure from the natural value are determined for each indicator which are subsequently used to develop benchmarking models linking flow regime change with geomorphological and ecological responses. These models are then used to develop a risk assessment framework for the evaluation of the potential environmental impacts of future scenarios of water resource management.

Multidisciplinary teams of scientists with expertise in relevant fields help in describing the current ecological condition and trend assessment with future developments as also the effects of other human activities besides the changes in flow. Identification of the hydrological impacts of water resource development is necessary to separating out the ecological effects of flow changes from the impacts of other human activities. Generic models which define the linkages between various components of flow regimes and ecological processes help in this separation by selecting relevant flow indicators, and assessing the hydrological impacts based on analysis of modelled hydrological information. Risk assessment models which show the levels of risk of geomorphological and/or ecological impacts at different degrees of change in specific flow indicators, form the basis for setting targets for the achievement of environmental flows in the study area.

Specialists' Team-Based Methods

Arthington (1998) described several other holistic methodologies which utilise the judgement of multidisciplinary teams of specialists. The first among these was the ***Expert Panel Assessment Method*** (Swales and Harris 1995) proposed by New South Wales Fisheries as a suitable planning technique for initial assessment of proposed developments. It was tested also in the Murray Darling basin.

One of its derivative was the *Scientific Panel Assessment Method* which used "key ecosystem/ hydrology features and (surmised) interactions as a basis for assessment" (Thoms et al. 1996) after visual inspection of many sites along the whole reach of the Barwon-Darling River. Visual observations were integrated with the collection and interpretation of field data and background information gathered from prior empirical studies and the theoretical literature.

Walter et al. (1994) describe the *Habitat Analysis Method* which was developed by the former Queensland Department of Primary Industries, Water Resources, to determine environmental flow requirements as part of the Water Allocation and Management Planning (WAMP) initiative (Burgess and Vanderbyl 1996). The method employs a Technical Advisory Panel with disciplinary and/or local knowledge of each catchment to determine the flows required to sustain the 'riverine system'.

Flow Restoration Methodology

The Flow Restoration Methodology was developed for restoring the River Brisbane (Australia) downstream of the Wivenhoe dam (Arthington 1998a). It is a hybrid methodology drawing upon the theoretical concepts embodied in the Holistic Approach and the Building Block Methodology and has the advantages of both of them. It differs from expert panel methods in requiring a more rigorous scientific approach involving original field or desktop research before alternative flow scenarios are developed and modelled, and practical constraints can be addressed (Brizga 1998b, 1998c). The details of this and related studies are discussed by Arthington (2012) in some detail.

ELOHA (Ecological Limits of Hydrologic Alteration)

Arthington et al. (2006) presented arguments and the scientific basis for a new top-down approach for broadly assessing environmental flow needs of a region such as the entire river basin or sub-basin when the environmental flow requirements of each river reach or river in region cannot be assessed in detail for any reason. It was developed by a multi-institutional, multinational team of river scientists into the Environmental Limits of Hydrological Alteration (ELOHA) framework with practical guidelines for its application (Poff et al. 2010; published online 2009).

ELOHA synthesizes existing hydrological and ecological data from many rivers within a region to generate flow alteration-ecological response relationships for rivers with different types of hydrological regimes. These relationships correlate measures of ecological condition, which can be difficult to manage directly, to stream flow conditions, which can be managed through wateruse strategies and policies.

The framework (or methodology) comprises of two parts: a scientific process which develops the Flow AlterationEcological Response Relationships, and a social process which uses these relationships for Environmental Flow Management. The flowchart of activities included in the two processes is shown in Figure 12 and the steps involved are summarised below from Poff et al. (2010) and Kendy et al. (2012; see The Nature Conservancy. http://nature.ly/ELOHA).

ELOHA comprises of two components: the Scientific Process and the Social Process. The Scientific Process deals with the hydrological and ecological aspects to develop relationships between the alteration of flow regime and ecological responses. The Process begins with the analysis of daily (or monthly) stream flow data for both pre- and post-development conditions with the help of hydrological models such as the Hydroecological Integrity Assessment Process (HIP) software (www.fort.usgs.gov/Resources/research_briefs/HIP.asp). It is necessary to get the data for a large number of river segments within a region and for a time period of 30 years or more so that the long term climate variabilityis duly represented. The data also needs to be analysed for the sites to be affected by the proposed water resource development project as well as those for which good biological data are availble. Data for ungauged sites may be constructed by hydrological modeling techniques which can also help simulate data for longer periods.

The next step in the Scientific Process is to categorise different reaches of the rivers on the basis of their flow regimes. Ecologically relevant flow statistics is used to distinguish between different reaches and those with similar flow regimes are then subdivided according to their geomorphic characteristics.

This is followed by computation of the degree of hydrological alteration (i.e., percent deviation of post-development flows from pre-development flows) by using a few ecologically relevant and most significant flow statistics that can also be used to set water management targets. The final step in this process is to develop relationships between any change in

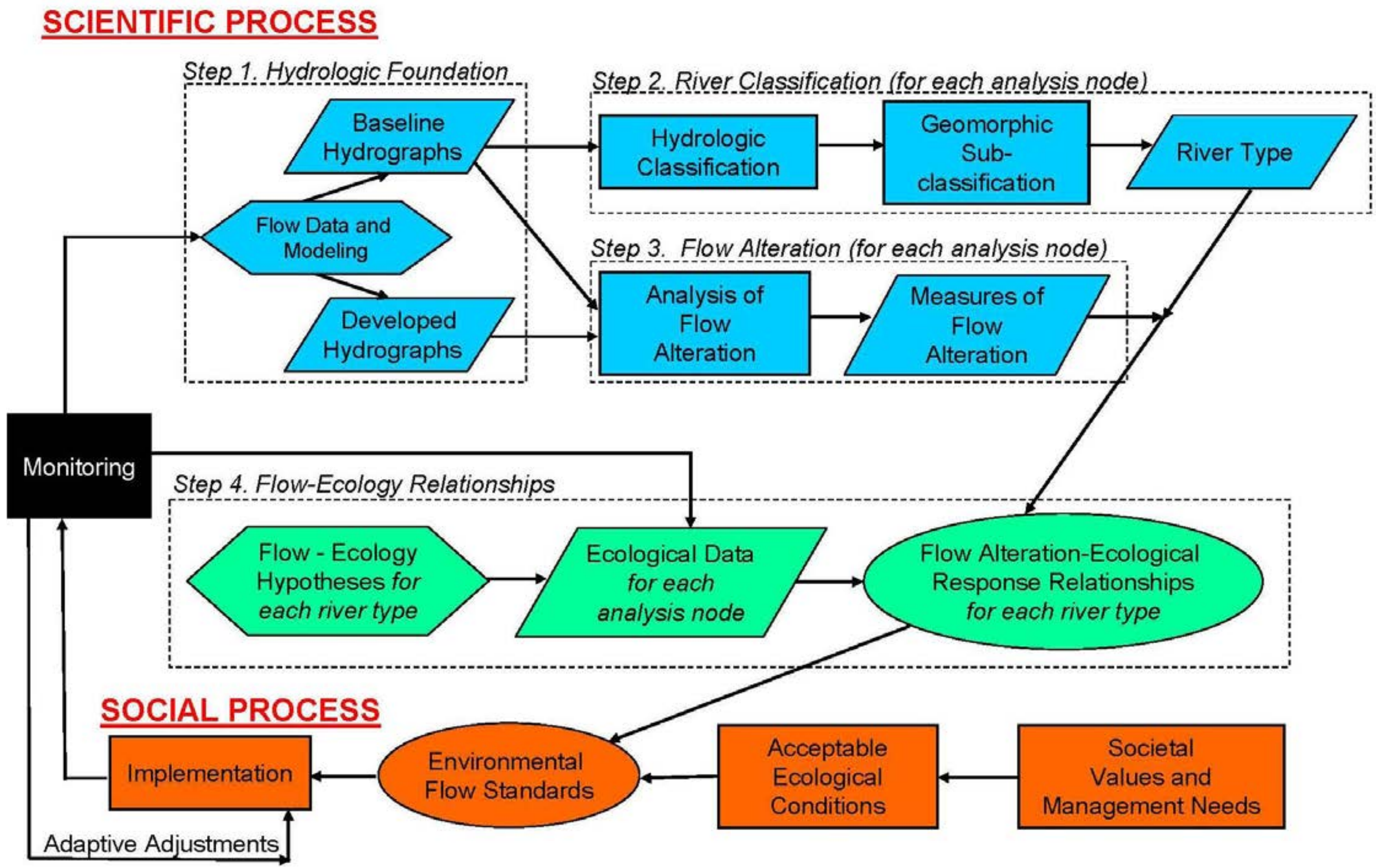

Figure 12. The scientific process in ELOHA methodology (reproduced with permission, from Poff et al. 2010)

ecological condition (several ecological variables can be considered) and the flow alteration. The relationships should be strong enough for validation with monitoring data, and readily comprehensible to the stakeholders.

The Social Process is primarily concerned with a dialogue with a wide range of stakeholders, especially those who will be affected by the altered flow regimes – either ipstream or downstream. The objective of the process is to "consider tradeoffs between human uses of water and ecological degradation based on the collective, scientifically informed-decision of the stakeholders about the desired ecological condition of the river". Several stakeholder meeting need to be organised for the consultation process during which ecological, social and cultural values of different each river segment or reaches are identified for protection (or restoration).

The next step requires linking the identified ecological conditions for their values with the corresponding degree of flow alteration for each river type by using flow alteration–ecological response relationships. The degree of flow alteration that will ensure the desired ecological condition is designated as the environmental flow 'target'. The targets set the task for implementing the Environmental Flowsby incorporating them into the planning for the development project.

The hydrologic model developed in the Scientific Process can be used to assess the practical limitations to, and opportunities for, implementing environmental flow targets at a site within the project area. The hydrologic model can also help identify and prioritize flow restoration options such as dam reoperation, and integrated management of ground water and surface water.

The ELOHA framework has been widely used and tested during the past few years throughout the United States and also in a few other countries. Latest updates on these trials and studies can be found on http://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/Pages/environmental-flows.aspx.

In Australia, the Tropical Rivers and Coastal Knowledge (TRaCK) research program has adopted ELOHA to integrate its existing environmental flows related studies such as the continental-scale eco-hydrological classification of hydrologic regimes for Australia (Pusey et al. 2009, Kennard et al. 2010), classification of river types and flow-ecology relationships (see www.track.org.au). Recently, the Australia scientists, jointly with Chinese researchers have developed a flow regime classification to lay the foundation for developing flow-ecological relationships and environmental flow assessments in China (Zhang et al. 2012; published online 2011).

While ELOHA is quite flexible and can be used in practically all situations irrespective of the stage of water resource development and the cause of flow alteration, and can possibly be adapted to a range of available data and scientific capacity, it must be noted that that it does not replace riverspecific approaches which require detailed analysis and may be required in some regions. ELOHA offers the potential to greatly accelerate the broadscale, comprehensive management of river flows to support sustainable goods and services, biodiversity, and human wellbeing.

Savannah Process

The Nature Conservancy considers ELOHA as a Level 1 approach within the hierarchical framework of EFA methodologies. Accordingly, it developed a Level 2 approach, referred to as the “Savannah Process” because it was first implemented on the Savannah River. This process involves facilitated expert workshops to produce a set of initial recommendations for experimental flow releases. Monitoring of such flows provide a learning opportunity to improve understanding of river processes and for adaptive management. The Savannah Process has been applied to the Patuca River in Honduras, besides in many rivers in the United States.

ELOHA has been elevated to Level 2 by the scientists and water managers in the Susquehanna (USA), Magdalena (Colombia) and Potomac (USA) river basins by using expert panels to assess flow needs for river types, rather than for individual rivers. Further, a Flow Regime Prescription Tool had been developed by the Hydraulic Engineering Center (HEC) of the U.S. Army Corps of Engineers and The Nature Conservancy to help expert panels make environmental flow prescriptions in a collaborative workshop setting.

CONCLUDING OBSERVATIONS

Over the past few decades considerable effort has gone into understanding the issues related to the rivers, their flow-ecology relationships, human impacts on their ecosystem services and above all the question, ‘how much water does a river need?’ Over the years the human perception of the rivers has changed. Hundreds of studies in different situations on different rivers have attempted to answer the same question although some studies were too simplistic and other have become too complex. Many of these studies are called as ‘methods’ even though the researcher has suggested only a minor change in an existing study as in case of the numerous hydrological indices. Many of the earlier methods have lost their value with advancements in our knowledge and objectives, but these are still being promoted for use in developing countries. The field of environmental flows assessment has witnessed a very rapid evolution during the past decade or so. It is a formidable task for developing countries such as those of South Asia to catch up with these developments and invest in research and capacity building to meet the challenge of rapidly degrading river ecosystems under the growing pressures of population increase and economic development. The assessment of Environmental Flows requires expertise in a large number of disciplines which include aquatic biology and ecology, fisheries (freshwater, brackish water and coastal), all groups of aquatic invertebrates (including zooplankton), amphibians and reptiles, birds. Mammals, benthic and planktonic algae, macrophytes, aquatic microorganisms, riparian vegetation and fauna, floodplain ecology, wetland ecology (including deltas and coastal lagoons and backwaters), estuarine ecology, agriculture, fluvial geomorphology, surface hydrology and hydraulics, groundwater hydrology, hydrological and hydrodynamic modeling, sociology, economics and data management. Of greater importance is the ability of the experts in each of these areas to interact with all other disciplines.

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