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Nature and limitations of environmental flow methodologies and its global trends

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Abstract

Recent days there is a raising awareness in all over the world of the premier role of the flow regime as a key driver of the ecology of the rivers and associated flood plains. Since the 1970s, there has been a progressive evolution of methodologies for assessing the Environmental Flow Requirements (EFRs) of riverine ecosystems, from ad hoc, case-specific approaches through to well-described, formal methodologies with more broad scale application. Historically, and still today in many instances, the focus of environmental flow assessment was entirely on the maintenance of economically important freshwater fisheries. More recently, however, the field has expanded to include assessments of the flow needs for other biota, like riverine invertebrates and water-dependent birds, and for biotic assemblage diversity. Many assessments now also encompass aspects of ecosystem structure, such as channel form, riparian vegetation and floodplain wetlands, and to a lesser extent function. The latter includes ecosystem processes like nutrient cycling and primary production. This paper illustrates the data and expertise requirements for each category of methodologies as well their limitations and its global trends.

Keywords: Environmental flow, riverine ecosystem, environmental flow methodologies

1. Introduction

1.1 Types of environmental flow assessment methodology

Major works on instream flow were done in the USA and since 1960s and 1970s a sundry of methods has been developed predominantly by biologists and hydrologists. Some of these methods are generic in nature (i.e. can be applied to most of the rivers), not all of the methods may be applicable for all rivers. The methods differ in data requirements, for example some methods require only flow data, while other requires more data entailing hydraulic and biological information. These methods have now been applied over 25 countries, yet a little bit works have been done in the application of these methods to tropical rivers.

There is no single best way for environmental flow assessment. Each method, approach or framework will thus be suitable only for a set of particular circumstances. Criteria for selecting a specific method, approach or framework include the type of issue (i.e. abstraction, dam, and run-of river scheme), expertise, time and money available, as well as the legislative framework within which the flows must be set. During recent years, the distinction between methods, focusing on ecological requirements, and frameworks, focusing on environmental flows, has become diffuse. Many of these are now more and more holistic and use multi-stakeholder groups and multi-discipline expert teams to define the amount of water to leave in the river (Dyson et al. 2003).

Environmental flow assessment methods fall into two categories; prescriptive and interactive approaches (Table 1.1).

Table 1.1
Prescriptive and Interactive Approaches of Environmental Flow Method (EFM) (Davis and Hirji, 2003)

Prescriptive Approaches	Interactive Approaches
Often provide a single flow regime to maintain a single objective (river condition) Motivate for the inclusion of specific parts of the flow regime.	Provide a range of flow regimes, each linked to a different river condition. Explain the consequences of flow manipulations.
Suited for application where objectives are clear and the chance of conflict is small.	Suited for application where the eventual environmental flow is an outcome of negotiations with other users.
Are divided four broad categories like hydrological index method, hydraulic rating, expert panel, holistic approach	One is In stream Flow Incremental Methodology (IFIM) and another is Downstream Response to Impose Flow Transformation(DRIFT)

1.1.1 Prescriptive approaches

Hydrological index method determines a ‘minimum’ environmental discharge, which is vital to the ecological functioning of the river. The most commonly used methods in hydrological index method are the Tennant (or Montana) Method is a desk-top [1] approach that is relatively inexpensive, quick, and easy to apply. It was developed using calibration data from hundreds of rivers in the mid-Western states of the USA to specify minimum flows to protect a healthy river environment. The method is based on the premise that the flow of a stream is a composite manifestation of characteristics such as size of the drainage area, geomorphology, climate, vegetation and land use. Tennant notes that the studies conducted over a period of ten years using this method have shown that aquatic habitat conditions are similar on most streams carrying same portion of average flows. Eight classes of flow classifications were established by Tenant analyzing a series of field measurements and observation to correlate habitat quality with various percentages of Mean Annual Flow (MAF). The percentages of MAF for habitat quality

[1] Use existing data such as river flows from gauging stations and for fish data from regular survey. The advantage is that it directly addresses the two areas of concern (flow & ecology); and directly takes into account the nature of the river, yet it is difficult to derive biotic indices that are only sensitive to flow and not to other factors such as habitat structure and water quality.

range from < 10% (severe degradation) to 60-100% (optimum range) while the flushing flow requirement being 200% of MAF (Davis and Hirji, 2003).

Table 1.2
Description of Prescriptive Approaches (Davis and Hirji, 2003)

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

Other examples of hydrological index methods include the Flow Duration curve analysis. Flow Duration Curve (FDC) method utilizes historical flow records to construct flow duration curves for each month to provide cumulative probabilities of exceedance for various flows. Based on at least 20 years of daily flow records, a flow recommendation is made for each month. This method includes the provision to eliminate anomaly events, after which the recommended flow for instream protection is set at the 90th percentile (flow equaled or exceeded 90% of the time) for normal months and the 50th percentile during high flow months.

The hydraulic rating methods use changes in hydraulic variables, such as those in the 'wetted perimeter', the area of riverbed submerged, to define environmental flows. These provide simple indices of available habitat in a river at a given discharge. The method is based on the assumption that fish rearing is related to food production, which is turn is related to how much of the river bed is wet. It uses relationships between wetted perimeter and discharge, depth and velocity to set minimum discharge for fish food production and rearing (including spawning). The relationships are constructed from measuring the length of the wetted perimeter at different discharges in the river of interest. The resulting recommend discharges are based on the inflection points on the wetted perimeter/discharge curve, which are assumed to represent the maximum habitat for minimum flow before the next inflection point (Figure 1.1).

Expert panel method has the common feature that they use a team of experts to make judgments on the flow needs of different aquatic biota. The composition of the panel will depend on the specific environmental and social features of the river in question, but typically includes a hydrologist, geo morphologist, aquatic botanist, and fish biologist (Davis and Hirji, 2003).

Holistic approaches include those that build an understanding of the functional links between all aspects of the hydrology and ecology of the river system. Perhaps the best known is the Building Block Methodology (BBM), developed in South Africa. The basic premise of the BBM is that riverine species are reliant on basic elements (building blocks) of the flow regime, including low flows and floods that maintain the sediment dynamics and geomorphologic structure of the river. An acceptable flow regime for ecosystem maintenance can thus be constructed by combining these building blocks. An environmental flow regime is then constructed on a month-by-month basis, through separate consideration of different components of the flow regime (Figure 1.2) to achieve and maintain this condition.

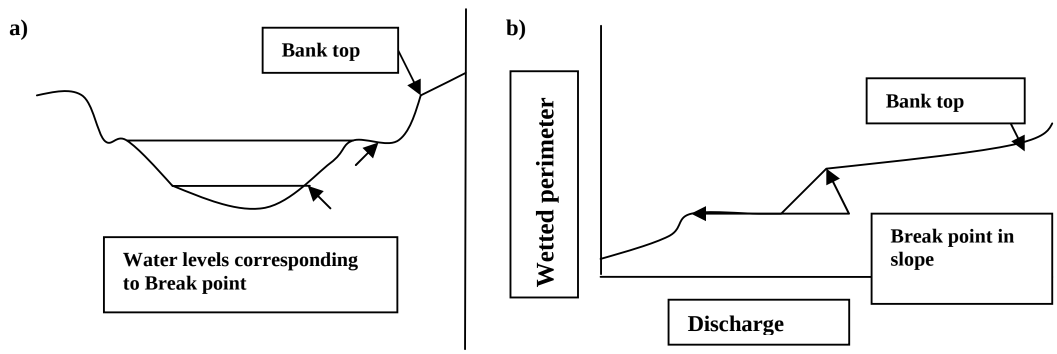

Figure 1.1. Wetted-perimeter method: (a) hypothetical channel cross-section and (b) graph of wetted perimeter versus discharge. Breakpoints in slope indicate the maximum available fish habitat for the least amount of water, until the next breakpoint (Davis and Hirji, 2003).

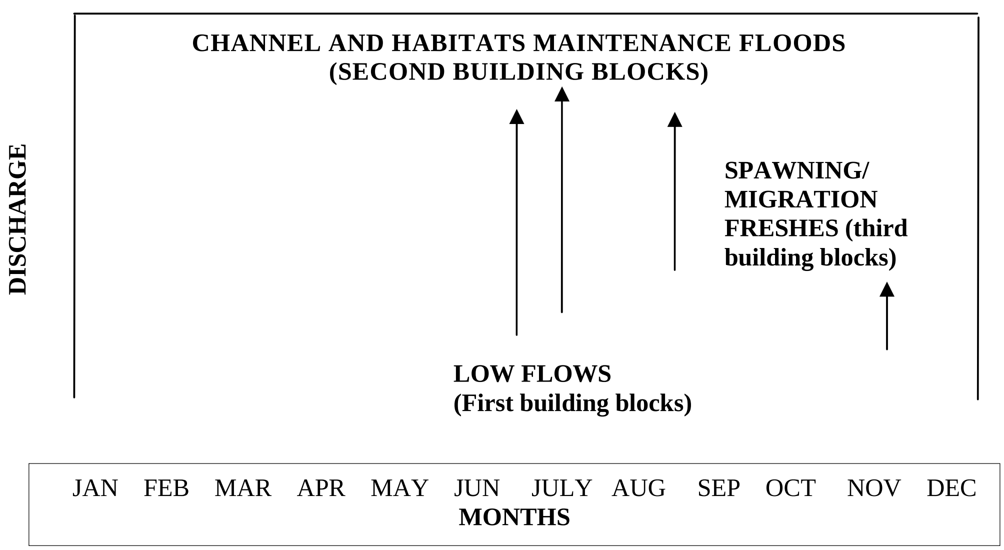

Figure 1.2. The "Building Blocks" of the modified flow regime created using the BBM. (Davis and Hirji, 2003)

1.1.2 Interactive approaches

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

Physical Habitat simulation System (PHABSIM) is a major component of IFIM. PHABSIM uses the hydraulic simulation models to predict depth and velocity at unmeasured flows using basic physical and engineering principals that were standard practice in the late 1970's by U.S. Geological survey. The resulting software suite multiplied surface area for a section of stream by the univariate suitability curve values for depth, velocity, and channel condition to arrive at a habitat index called weighted usable area. PHABSIM predicts physical microhabitat changes associated with flow such as reduction of stream flow (Dyson et al., 2003).

The Downstream Response to Imposed Flow Transformation (DRIFT) framework was developed in South Africa, with its first major application being in Lesotho. Similar to the Building Block Methodology it forms a more holistic way of working as it addresses all aspects of the river ecosystem. It is a scenario-based framework, providing decision-makers with a number of options of future flow regimes for a river of concern, together with the consequences for the condition of the river (Dyson et al., 2003).

Table 1.3
Other existing methodologies (Marchand, M., 2003)

Method/origin	Type	Description
7Q10	Hydrological	Low flow that is expected to occur for 7 consecutive days only once in 10 years. It is used to set standards for dilution of wastewater: Dilution at this flow would still maintain quality standard. However, considered completely appropriate for instraem flow protection as it would grossly underestimate minimum ecological flows.
10%MAF	Hydrological	A simple low flow index, hydrological type calculated as 10% of the Mean Annual Flow (MAF) of the study river (Gordon et al., 1992).It is widely used in New Zealand, Spain, and Chile. It takes low time, cost and data requirements, and limited specialist expertise is required.
30%MMF	Hydrological	The hydrological index represents 30% of the mean monthly discharge for the study river, and is calculated on a month-by-month basis (Gordon et al., 1992).It is widely used in New Zealand. It takes low time, cost and data requirements, and limited specialist expertise is required.
Wetted Perimeter method	Hydraulic rating	It is based on the hydraulic relationship between flow (i.e. discharge) and wetted river perimeter at a selected transect(s) (Stalnaker *et al*. 1994). Using the relationship, the flow corresponding to the wetted perimeter (wetted width of the stream transect), which is needed to minimally protect all habitats, can be estimated.

Method/origin	Type	Description
Q347= 95 percentile (various, particularly in UK)	Hydrological	Used in England and Wales as a low flow index. Annual statistics not generally considered suitable for setting flow objectives, seasonal considerations and durations are important.
Aquatic base Flow ABF (US)	Hydrological	August median flow or lowest median monthly flow during spawning months.
NGPRP (US)	Hydrological	Group years into dry, normal and wet. Take 90 percentile flows from normal group. Of interest as it attempts to account for climatic conditions and acceptable frequencies.
Hoppe (US)	Hydrological	Daily flow values for various trout life stage functions. Based on flow duration curve.
Texas (US)	Hydrological	Variable percentages of the monthly median flow. Scope for further investigation on a river ecotype basis.
Basic Flow (Spain)	Hydrological	Characteristic basic flow for a river type. Not thought worthy of further investigation.
Range of hydrological variability (US)	Hydrological	Indices of hydrological changes. Considerable potential for use in characterizing hydrological variation.
Singh (US)	Hydraulic	Estimates of hydraulic parameters at catchments scale. Of some interest, of considerable interest if easy to use and evidence for validation.
R2 cross (USA)	Hydraulic rating	Simulation of depth and water level over a shallow riffle using field data. For England and Wales, a simplified PHABSIM study would give same results. As above, may be useful if spawning habitat critically limiting.
BASQUE (Spain)	Hydraulic	Uses hydraulic for low land reaches and data on invertebrate flow relationships in uplands. A relatively coherent system for a relatively narrow range of river ecotypes. Potential for further investigation if a method of this type is required.
Statistical Hydraulics (France)	Hydraulic	Uses statistical model to predict frequency distributions of physical habitat. Not yet tested with biotic data, but considerable potential in the longer term.
Biotopes/functional habitat (UK/South Africa)	Hydraulic	Moves away to species to a habitat based approach. Invalidated, needs more development. Would gain from field comparison with other models.
HABIOSIM (Canada)	IFIM	Canadian microhabitat model
CASIMIR (Germany)	IFIM	Reach based shear stress simulation model developed for hydropower impact assessment. Worth investigating these techniques at the research level for use in England and Wales.
RCHARC(US)	IFIM	Riverine community Habitat Assessment and Restoration Concept. Used to compare habitat hydraulics of a reference situation with alternative scenarios.
AGAIRE (FRANCE)	IFIM	GIS system developed by EDF. Combines spatial and temporal data on a range of the themes in a manner of WIS (Water Information System). Including a, model of fish breeding habitat quality for brown trout.

Table1.4: Comparison of four main types of environmental flow methodologies presently used worldwide (King et al., 1999)

Methodology Type	Riverine ecosystem components addressed	Data needs	Assessments	Appropriate level of application
Hydrological Index	Whole ecosystem-non specific	• Virgin/naturalized historical flow records • Some use historical ecological data	• Hydrological • Some ecological expertise	Reconnaissance level of water resource developments, or as tool within other methodology
Hydraulic rating	Instream habitat for target biota	• Historical flow records • Discharge hydraulic variables, typically from single river cross-section • Hydraulic variable(s) as surrogate for	• Hydrological • Some hydraulic modeling • Some ecological expertise	Water-resource developments where no or Limited negotiation is involved
Habitat Simulation	• Primarily instream habitat for target biota • Some consider: channel form, sediment transport, water quality, riparian vegetation, wildlife	• Historical flow records • Many hydraulic variables –multiple cross-sections • Physical habitat suitability data for target species	• Hydrological • Advanced computer-based hydraulic and Habitat modeling • Specialist ecological expertise on physical habitat-flow needs of target species	Water-resource developments, often large-scale, involving rivers of high conservation and/or strategic importance, and/or with complex, negotiated offstream/instream tradeoffs; primarily developed countries
Holistic	Whole ecosystem – all/most individual components • Some consider: groundwater, wetlands, estuary, floodplain, social dependence on ecosystem, as well as instream and riparian components	• Historical flow records • Many hydraulic variables – multiple cross-sections • Biological data on flow- and habitat-related requirements of all biota and Ecological components	• Hydrological • Advanced computer based hydraulic modeling • Habitat modeling in some cases • Specialist expertise on all Ecosystem components • Some require social and Economic expertise	Water-resource developments, often large-scale, involving rivers of high conservation and/or strategic importance, and/or with complex offstream/instream tradeoffs; developing and developed countries

2. Global trends in the application and advancement of environmental flow methodologies and their limitations

Albeit by no means comprehensive, Table 1.3 and Table 2.2 indicates the environmental flow methodologies that are being applied around the world in both developed and developing countries. The most commonly used or preferred methodologies are noted where such information is available; it is noteworthy that many methodologies are poorly documented in the mainstream scientific literature. Intensive research into environmental flows is underway in North America, South Africa and Australia, while the field of flow assessments is expanding in Europe and parts of Asia particularly.

However, vast areas of South and Central America, Asia and Africa do not appear to have begun any significant research or application in this field. Certainly, literature pertaining to environmental flows is markedly less available for these regions.

Table 2.1
Advantage and disadvantage of different environmental flow methodologies (King et al., 1999)

Type	Advantage	Disadvantage
Hydrological index methodologies	Inexpensive, rapid, require only historical flow records Highly appropriate at the reconnaissance level of water resources development	This methodology is specially limited from ecological perspective It does not adequately address the dynamic nature and variable nature of the hydrological regime
Hydraulic rating methodologies	Incorporate ecological based information on the instream Flexible to apply for many aquatic species and activities	It is applicable only instream flow Rely on simplistic assumption
Expert panel method	Team of experts to make judgments on the flow needs of different aquatic biota Integrate the knowledge of different experts	The results are specific and non-reproducible
Holistic approaches methodology	Build functional links all aspects of hydrology and ecology Covers many aspects of the river ecosystem	It is expensive and time consuming
Instream Flow Incremental Methodology	Considering both policies and technological issues Its implicit quantitative nature integrating micro and macro-habitat Examine a variety of alternative environmental flow scenarios for several species	It is comprehensive, but data intensive Selection of appropriate target species is very difficult It takes time
Downstream Response to Impose Flow Transformation	It addresses all aspects of the river ecosystem	It is not possible to specify all the data requirements and type of expertise

Table 2.2
Environmental Flow Methodologies Use in Various Countries (Tahrme et al., 1999)

Country	Environmental Flow Methodologies in use	Most widely used or preferred methodologies	Comments
Alaska	• IFIM; Tennant Method, including modifications thereof on the basis of professional judgment and fish data;	• Tennant Method • IFIM is used for special cases	• Holistic methodologies do not appear to have been applied • Estes (1996) provides further information
Australia	• State-dependent wide array of methodologies, including Tennant Method; FDCA and various other hydrological indices; Holistic Approach; BBM	• RHYHABSIM, IFIM, and various holistic methodologies	• Northern Territory and Australian Capital Territory do not appear to have employed any methodologies
Austria	• Habitat modeling; other methods unspecified	• Unspecified	• A future aim is to combine IFIM with elements of holistic methodologies
Britain and Wales	• Various methodologies: IFIM; hydrological tools (e.g. Micro LOW FLOWS); hydrological indices (e.g. Q95); Environmentally Prescribed Flow Method; holistic methodologies	• Unspecified	• A future aim is to combine IFIM/PHABSIM II analyses for target species with holistic elements • Holistic methodologies, specifically the
Canada	• Various methodologies: IFIM, including Biologically Significant Periods/Fish Rule Curve Approach; Tennant Method, including set percentages of Average Annual Flow (e.g. 25% MAF Method); Wetted Perimeter Method; correlation of fish year class to spawning flow; WSP model; water quality models; 7Q10 Method; Median Monthly Flow Method; FDCA	• IFIM used in all of the 7 provinces that apply instream flow methodologies, and Tennant Method or a modification thereof often routinely applied	• Northwest Territories does not employ any methodologies • Holistic methodologies do not appear to have been applied
Czech Republic	• IFIM	• IFIM	• IFIM-based procedures are under development
Denmark	• Hydrological methods	• Median Minimum Method	• It is recognized that other low flow
Finland	• EVHA (habitat simulation) and detailed approaches based on physical habitat for	• Unspecified	• There are no standard methods
France	• Habitat simulation methodologies, such as EVHA	• EVHA: applied in about 70 cases	• Ongoing research is taking place into continuous fish population modeling within an IFIM framework
Germany	• Hydrological indices, case-specific expert opinion, and a habitat simulation methodology, CASIMIR	• Mean of minimum daily flows for each year,	• CASIMIR has been applied for benthic invertebrates

Country	Environmental Flow Methodologies in use	Most widely used or preferred methodologies	Comments
Indonesia	• IFIM	• First studies in progress	• None
Italy	• Hydrological indices, including FDCA, daily and annual mean flows; IFIM; Tennant Method; Wetted Perimeter Method;	• Hydrological indices • IFIM in resource-intensive applications	• Relationships between fisheries standing crop and environmental variables are under development
Japan	• IFIM, including multidimensional hydraulic modeling	• Unspecified	• Re-evaluation using various methods
Netherlands	• Hydrological model, alternative approaches, including HEP, a general habitat suitability scoring model, an ecotope classification (ECLAS), a physical habitat model (MORRES), a habitat suitability model (EKOS),	• Unspecified	• None
New Zealand	• Various hydrological, hydraulic and habitat simulation methodologies (unspecified); IFIM; RHYHABSIM;	• RHYHABSIM: used on 25 rivers; IFIM	• None
Norway	• Hybrid approaches based on habitat modeling,	• Microhabitat modeling	• None
South Africa	• Various hydrological indices, including; IFIM; BBM; DRIFT; some alternative approaches, e.g. River Conservation Status Model; geomorphological change-flow, Biotopes Approach; hierarchical suite of methodologies for the determination of the Ecological Reserve: Planning Estimate and extended version; Preliminary Reserve Methodology; Comprehensive Reserve Methodology	• BBM, DRIFT; and range of methodologies for Reserve determination	• The Biotopes Approach is recommended for further investigation, • Habitat and water quality modeling techniques are recommended for incorporation into the BBM,
USA	• State-dependent, extremely wide array of methodologies covering hydrology-based, hydraulic rating, habitat simulation, and various hybrid or alternative approaches; 7 commonly used methodologies: IFIM; Tennant Method, Wetted Perimeter Method; 7Q10 Method; Professional judgment; R-2 Cross Method; hydrological methods based on flow records/FDCA; Water Quality methods; USGS Toe- Width Method; Arkansas Method; AVDEPTH program; HEC-2 program; HQI; Oregon	• IFIM, Tennant method • Wetted Perimeter; ABF; 7Q10 are other 3 methodologies frequently applied	• Holistic methodologies have not been formally applied • Habitat modeling techniques, especially using PHABSIM II, are under continual development

Realistically, the selection of an appropriate environmental flow methodology or methodologies for application in any individual country is likely to be case-specific and primarily limited by the availability of data on the river system of concern, and existing local constraints in terms of time, finances, expertise and logistical support.

Typically, in Northern Hemisphere developed countries, in such high profile cases, habitat simulation methodologies like IFIM, are currently most often used at this level of resolution (Tables 2.2). However, such approaches are often less appropriate than holistic methodologies from the perspective of Southern Hemisphere and developing countries, because of the latter's focus on whole ecosystem and on social dependence on the ecosystem (Tables 2.2).

Globally, in future, the inherent capacity of holistic methodologies to absorb advanced features, like hydraulic and habitat modelling tools, as these become available, as well as their consideration of all major ecosystem components, is liable to render them increasingly suitable compared with habitat simulation approaches. At this level of application, in all instances, technical capacity will need to be developed, and users will require up-to date formal training and ongoing guidance for the successful application of either advanced holistic or habitat simulation methodologies. However, holistic methodologies, such as the Building Block Methodology were specifically designed for situations where data, time and finances are scarce. The BBM can produce answers on EFRs in a few weeks or months. However, inevitably, the confidence in its outputs increases with investment in time and specialist inputs (King et al., 1999).

3. Conclusions and Recommendations

There are many different types of EFR methodologies, which range from very simple and expensive to very complex and expensive. Generally, the results obtained from an Environmental Flow Assessment (EFA) are considered more valuable when more effort is spent and more knowledge of the system is available. However, assessing a river system strongly influences the choice of a certain method. The above-mentioned literature on different methodologies and Table 1.3, Table 1.4, Table 2.1 give an overview of different EFA methods. Some 25 countries in all parts of the developed world implement EFAs. In addition, a few developing countries (Table 2.2) have begun implementation of EFAs or are assessing available techniques. Methodologies for assessing EFRs have been developing since the 1950s in the developed countries, yet many developing countries except South Africa have started to address environmental flows in the 1990s. Most of the methods involve different degrees of data and time requirements, as well as the reliability of the results and the level of experience required to apply the method. After analyzing critically, it can be portraying that a holistic ecosystems approach for assessing EFR, in which flows are recommended for all components or attributes of the riverine ecosystems, exhibits several advantages over other types of environmental flow methodology. The assessments in these methods are however, based on expert judgment, that is why they are also referred to as discussion-based methods. Moreover, people in rural communities, particularly in Asia, depend on the river ecosystem for their livelihood. Environmental Flow Assessment methods offer an opportunity to protect the interest of theses people.

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