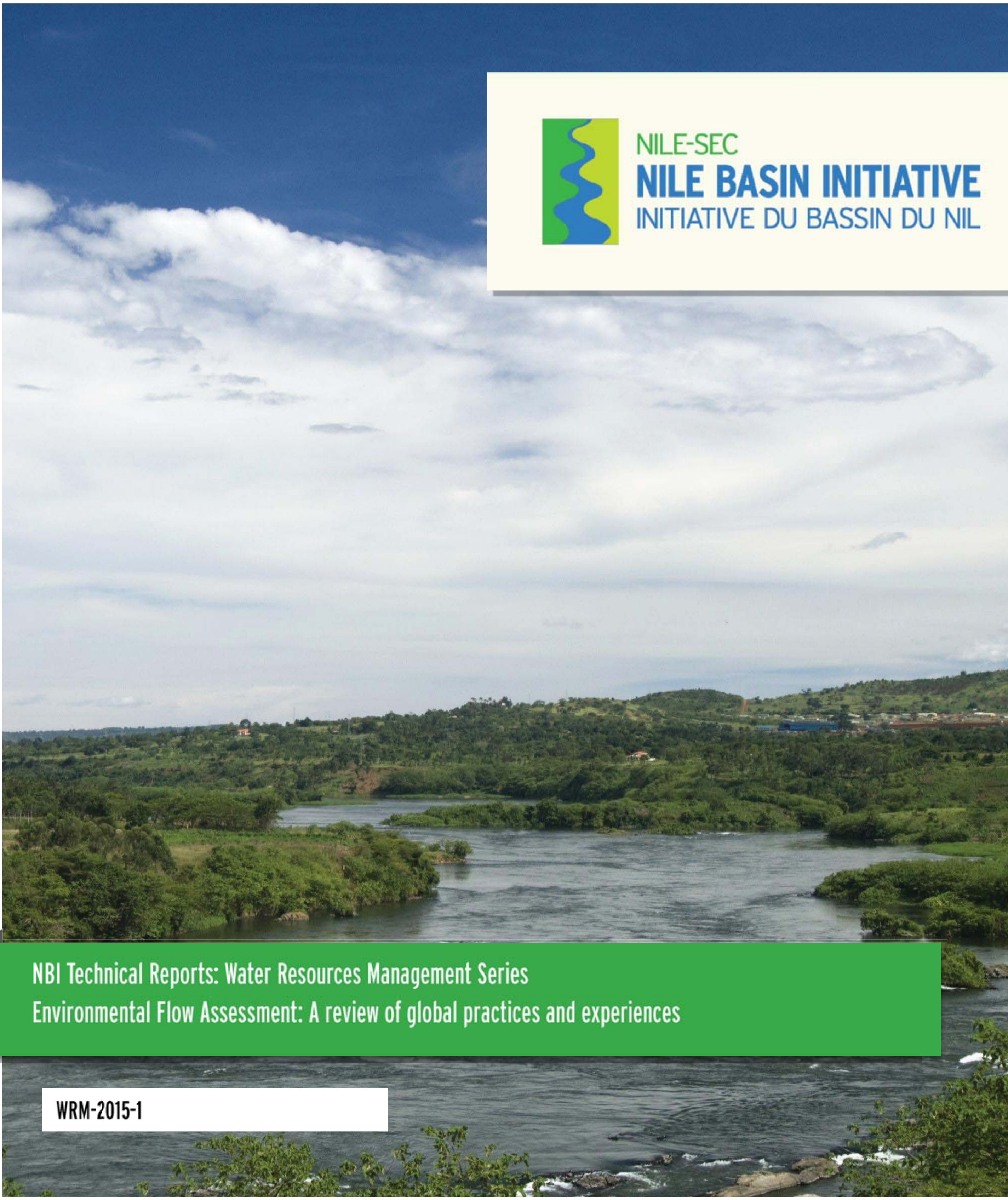

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NILE BASIN INITIATIVE
INITIATIVE DU BASSIN DU NIL

NBI Technical Reports: Water Resources Management Series
Environmental Flow Assessment: A review of global practices and experiences

WRM-2015-1

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

On behalf of:

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

of the Federal Republic of Germany

Document Sheet

This Technical Report series publishes results of work that has been commissioned by the member states through the three NBI Centers (Secretariat based in Entebbe- Uganda, the Eastern Nile Technical Regional Office based in Addis Ababa - Ethiopia and the Nile Equatorial Lakes Subsidiary Action Program Coordination Unit based in Kigali - Rwanda. The content there-in has been reviewed and validated by the Member States through the Technical Advisory Committee and/or regional expert working groups appointed by the respective Technical Advisory Committees.

The purpose of the technical report series is to support informed stakeholder dialogue and decision making in order to achieve sustainable socio-economic development through equitable utilization of, and benefit from, the shared Nile Basin water resources.

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Disclaimer

Contents

Abbreviations:

BBM	Building Block Methodology
DFA	Demonstration Flow Assessment
DRIFT	Downstream Response to Imposed Flow Transformations
DRM	Desktop Reserve Model
EF	environmental flows
EFA	environmental flows Assessment
EFM	environmental flow Method
EFR	environmental flow Requirement
ELOHA	Ecological Limits of Hydrologic Alteration
EPAM	Expert Panel Assessment Method
FLOWRESM	Flow Restoration Methodology
FSR	Flow Stressor Response
IBM	Individual-Based Model
IFIM	Instream Flow Incremental Methodology
IFR	Instream Flow Requirement
IHA	Indicators of Hydrologic Alteration
NBI	Nile Basin Initiative
NBSF	Nile Basin Sustainability Framework
PHABSIM	Physical Habitat Simulation Model
PROBFLO	New holistic EFA method (combination of probability and flow)
RVA	Range of Variability Approach
SPAM	Scientific Panel Assessment Method
SUMHA	Sustainable Management of Hydrological Alterations
WRM	Water Resources Management
WUA	Weighted Usable Area

1 Executive summary

Background

Nile Basin Initiative has initiated a process to develop a transboundary level guidance document on environmental flows, in an effort to establish general standards and norms for establishment of environmental flows in the Nile Basin. In this brief we present the outcomes of a review of available international environmental flow assessment literature of global practices/experiences, to provide a synthesis of current best scientific practice principles for environmental flow assessments (Background Document 1). In addition to this document aquatic ecosystems of the Nile Basin and their dependence on flow alterations (Background Document 2), and the management of environmental flows in the Nile River Basin (Background Document 3) will be evaluated.

Synthesis of global practices/experiences in establishing Environmental Flow Assessment (EFA) summary

The effect of environmental flow alterations to the wellbeing of surface aquatic ecosystems and the people who depend on these ecosystems is well known. Five key hydrological components of environmental flow alterations that are considered to be important to the socio-ecological benefactors of ecosystems and ecosystem service use include variability, magnitude, frequency, duration, timing and rate of change of flows. The science of environmental flows has developed rapidly over the past few decades, from being considered to be in its infancy phase in the 1990s to being well developed today with a range of dynamic tools and frameworks to direct environmental flow assessment on multiple spatial and temporal scales for multiple social and ecological endpoints. In addition, environmental flow management and related resource management issues rank highly on the international policy agendas of many developed and developing nations. Currently, numerous broad best practice environmental flow management principles have been established for application. These principles include guidance on stakeholders and their involvement in environmental flow management, preferable environmental flow methods and the limitations of the available methods. The principles also call for the application of regional scale appropriate holistic, adaptable, transparent environmental flow methods that consider multiple social and ecological endpoints and can be monitored, evaluated and updated by local technicians. Principles for environmental flow assessments also include the use of precautionary approaches and that environmental flow management should not be considered to be flawless but a continually developing science.

In the assessment we introduce and describe the four broad environmental flow assessment method categories and methods/tools with highlights, and case studies that consider combinations of these tools. The broad environmental flow assessment categories include: hydrological, hydraulic rating, habitat simulation (or rating), and holistic methodologies. These methods have various advantages and disadvantages and have been used to address a variety of environmental flow management related requirements internationally. The selection of an environmental flow assessment method should address the recommendations of the latest regional scale environmental flow management frameworks including the Ecological Limits of Hydrologic Alteration and Sustainable Management of Hydrological Alterations frameworks.

With the availability of current best scientific practice principles for environmental flow assessments and an abundance of environmental flow assessment methods, and associated case studies demonstrating the application of the tools and the advantages and disadvantages of the methods, the development of a framework for environmental flow assessments for the Nile Basin is achievable.

2 Study overview

The Nile Basin Initiative (NBI) recognises that the sustainable management of the shared Nile Basin water resources requires the establishment of relevant transboundary policy instruments (within the Nile Basin Sustainability Framework (NBSF)). The sustainable use of the socio-ecologically important water resources of the Nile Basin requires the coordinated management of the environmental flows on meaningful spatial scales. environmental flows (EF) describe the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (Brisbane Declaration, 2007). The NBI does not currently have any general standards and norms for establishment of environmental flows in the basin.

In an effort to establish general standards and norms for establishment of environmental flows in the Nile Basin, NBI has initiated a process to develop a transboundary level guidance document on environmental flows. The objective of the guidance document on environmental flows is to develop a structured and scientifically based NBI procedure for establishing environmental flow requirements for transboundary water resources planning purposes in the Nile Basin. This will be achieved through the implementation of a phased process during this project, namely; stocktaking and development of an appropriate Environmental Flow Assessment (EFA) procedure/s, piloting of the procedure and synthesis of the outcomes. The scope of work will include the following:

1. Stocktaking and procedure development
   a) Review and synthesize global practices/experiences in establishing EFs.
   b) Identify aquatic ecosystem types and the degradation threats to these ecosystems in the Nile Basin.
   c) Review Nile Basin practices/experiences on environmental flows.
   d) Present/discuss these findings with stakeholders in a regional review/validation workshop.
   e) Review recommended procedures for establishing environmental flow requirements for Nile Basin aquatic ecosystems.
2. Development of EFA procedures for the Nile Basin and presentation of developed methodology in workshop.
3. Pilot EFA procedures at different spatial scales at selected locations in the Nile Basin and reviewing pilot application of developed methodology in workshop.
4. Synthesise the outcomes of the assessment and provide recommendations for future management in the form of a guidance document on EFA in the context of the Nile Basin.

This brief describes the approach adopted and the findings of the 1a, a review and synthesis of global practices/experiences in establishing EFAs as a part of the stocktaking and procedure development phase of the study.

3 Environmental Flow Assessments in Water Resource Management (WRM)

The world has changed considerably in the past 100 years. Major changes include the increase in the world's population from just over 1 billion people in 1900s to over 8 billion people today. This has affected the way we use the resources of the world. In particular, the use of the world's freshwater resources has increased rapidly. By the year 2000 over half of the surface water resources on earth had been developed for use and by 2025 this is expected to increase to 70% (Postel et al., 1996; Postel, 1998; Tharme, 2003). In addition to the increasing demand for water resource use other impacts such as climate change are affecting the availability of resources and our ability to use and protect them (McCarthy et al. 2001, Malmqvist and Rundle 2002). If we do not manage our resources well, increasing pressure will continue to escalate the stress to water resources globally.

While water resource development for human use has affected the quality and volume of water available in our ecosystems, other impacts including the timing and duration of flows, habitat degradation and species invasions are also affecting ecosystem wellbeing (Dudgeon et al., 2006). All of these things are affecting the wellbeing and availability of water resources and the benefits, which people derive from these ecosystems (Vörösmarty et al., 2010; Isaak et al., 2012; Murray et al., 2012; Grafton et al., 2013; Dudgeon, 2014 for example) (Figure 1). While the effects of water quality alterations, habitat degradation, species invasion and over exploitation such as overfishing of water resources are well known (consider the reviews in Dudgeon et al., 2006; Dudgeon, 2014), the social and ecological consequences of flow alterations is something scientists and managers are only recently looking into.

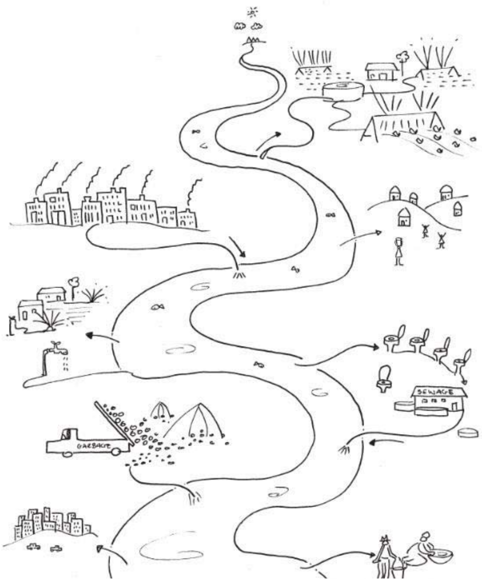


Figure 1: How people use water resources (from Palmer et al. 2002).

Suitable flows are an important component of the wellbeing of ecosystems (Figure 2). The impacts associated with flow alterations to surface water ecosystems are extensive and include the loss and fragmentation of biodiversity, habitat fragmentation, alterations to ecological processes and ecosystem service loss with associated social issues (Calow and Petts, 1992; Boon et al., 1992; 2000; Stanley and Warne, 1998; Postel et al., 1996; 1998; Richter et al., 1998; Snaddon et al., 1999; Pringle, 2000; WCD, 2000; Bergkamp et al., 2000; Bunn and Arthington, 2002; Postel and Richter, 2003; Tharme, 2003; Nilsson et al., 2005; Dudgeon et al., 2006; Poff et al., 2007 for example). Flows change considerably under natural or un-impacted conditions which influences the severity, type and effects of impacts (Vörösmarty et al., 2000; Nilsson et al., 2005; Dudgeon et al., 2006). Generally the global regions with highly variable flow regimes and their ecosystems are the most vulnerable to, and the most threatened by, flow modifications. Due to the scarcity of water and or the high variability of flows in these vulnerable areas, the people who use these ecosystem are in the greatest need for sustainable access to water resources (Dudgeon et al., 2006).

Dam development is a major driver of flow alterations globally where now as much as five times of the volume of all the world's rivers occur in dams, and some of the world's largest rivers stop flowing, or are likely to do so, as a result of dam related large-scale water abstraction/diversions (Nilsson & Berggren, 2000; Postel and Richter, 2003; Tharme, 2003). Sustaining freshwater flows and related resource management issues now rank high on the international policy agenda (Reitberger and McCartney, 2011).

Apart from the North American and European industrialised democracies, South Africa and Australia have the most advanced methodological and legal environmental flow management procedures with several other African countries now introducing similar principles (Reitberger and McCartney, 2011). environmental flows (EF) concepts emerged with simplistic static approached that aimed to define either minimum or average flows to maintain the wellbeing of key ecological components or maintain instream habitat for example; but these were viewed as too simplistic to support complex flow-dependent ecosystem functions (Tharme, 2003, see box below). Today it is widely recognised that significant daily, flood-period, seasonal and inter-annual variations of long-term flow patterns are required to sustain ecosystem integrity (e.g. Poff et al., 1997; Mahoney and Rood, 1998; Bunn and Arthington, 2002). In addition, EFs must therefore vary in space and time to sustain the desired future ecosystem wellbeing, as agreed upon amongst stakeholders, together with the ecosystem services these ecosystems supply for human benefit (Pahl-Wostl et al., 2013). For successful implementation of EFs concepts participation of multiple stakeholders involved in water resource use and protection is required (sensu Pahl-Wostl et al., 2013).

ENVIRONMENTAL FLOWS ARE DEFINED AS THE 'QUANTITY, TIMING AND QUALITY OF WATER FLOWS REQUIRED TO SUSTAIN FRESHWATER AND ESTUARINE ECOSYSTEMS AND THE HUMAN LIVELIHOODS AND WELL-BEING THAT DEPEND ON THESE ECOSYSTEMS' (BRISBANE DECLARATION, 2007). IN ESSENCE ENVIRONMENTAL FLOWS INCLUDE THE AMOUNT OF WATER, AT DIFFERENT TIMES, IN A DESIRED QUALITY IN RIVERS, FLOODPLAINS, WETLANDS AND OR ESTUARIES TO MAINTAIN SUITABLY HEALTHY ECOSYSTEMS AND THE THINGS PEOPLE DERIVE FROM THEM FOR OUR WELLBEING.

ALTHOUGH WE'LL STICK WITH THE TERM "ENVIRONMENTAL FLOWS" SOME PEOPLE REFER TO INSTREAM FLOW REQUIREMENTS, ENVIRONMENTAL WATER REQUIREMENTS, AND ENVIRONMENTAL WATER ETC.

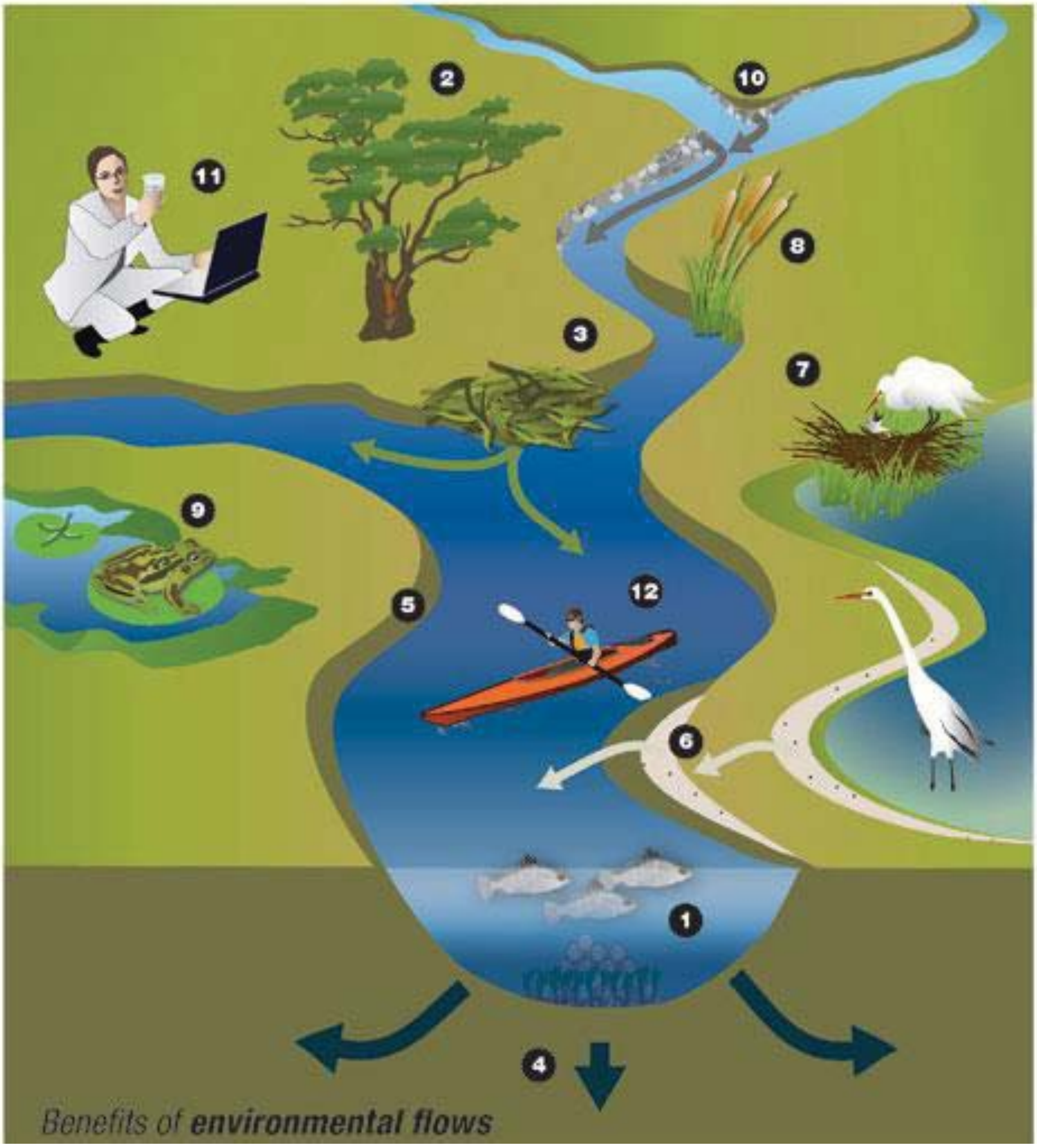


Figure 2: Maintaining suitable environmental flows results in; ecological cues for fish to breed (1), encourages plants to grow/flower/fruit and or seed (2), helps with our management of and cycling of organic material (3), helps us maintain other ecosystems such as ground water systems (4), stabilises river banks (5), assists with the removal of unwanted chemicals stored up in river banks etc. (6), provides habitats for animals (7), provides us with plants and other materials (8), maintains important ecosystem processes (9), including sediment movement (10), water quality maintenance (11) and opportunities for people to have fun (12). (Adapted from the Victorian Environmental Water Holder, 2013).

In this brief we aim to review available information from existing EF assessment literature to critically review and evaluate global practices/experiences to provide a synthesis of current best scientific practice. *Consider that in 1996, Castleberry et al. argued that no scientifically defensible method existed that could define the instream flows (or EFs) needed to protect aquatic ecosystems adequately. In 2011, Moyle et al. suggests that this is still the case! While many EF practitioners may disagree it is advisable to adopt the precautionary approach Moyle et al. (2011)*

advocate and consider available procedures and frameworks in an adaptive management context to ensure 'learning while doing'.

3.1 Establishment of environmental flow assessment methods

Only after the 1990's, the effects of altered flows in the environment began to be considered in a dedicated manner (Ward and Stanford, 1979; Ward, 1982; Petts, 1984; Lillehammer and Saltviet, 1984; Pahl-Wostl et al., 2013) (**Figure 3**). In a review of the development of EF assessment approaches in 2013, Poff and Matthews identified three discrete periods (or phases) of "EF research and management", development history. These periods were defined as:

- **Phase 1:** the emergence and synthesis period (pre mid 1990s),
- **Phase 2:** consolidation and expansion period (mid 1990s to 2007), and
- **Phase 3:** globalisation period (2007 to current; **Figure 3**).

Prior to the 1990s, scientists had only established a conceptual basis of natural and altered flow regimes, water resource use activities that alter the flow characteristics of water resources, and the impacts that these activities have on the ecosystem (Tharme, 2003; Poff and Matthews, 2013).

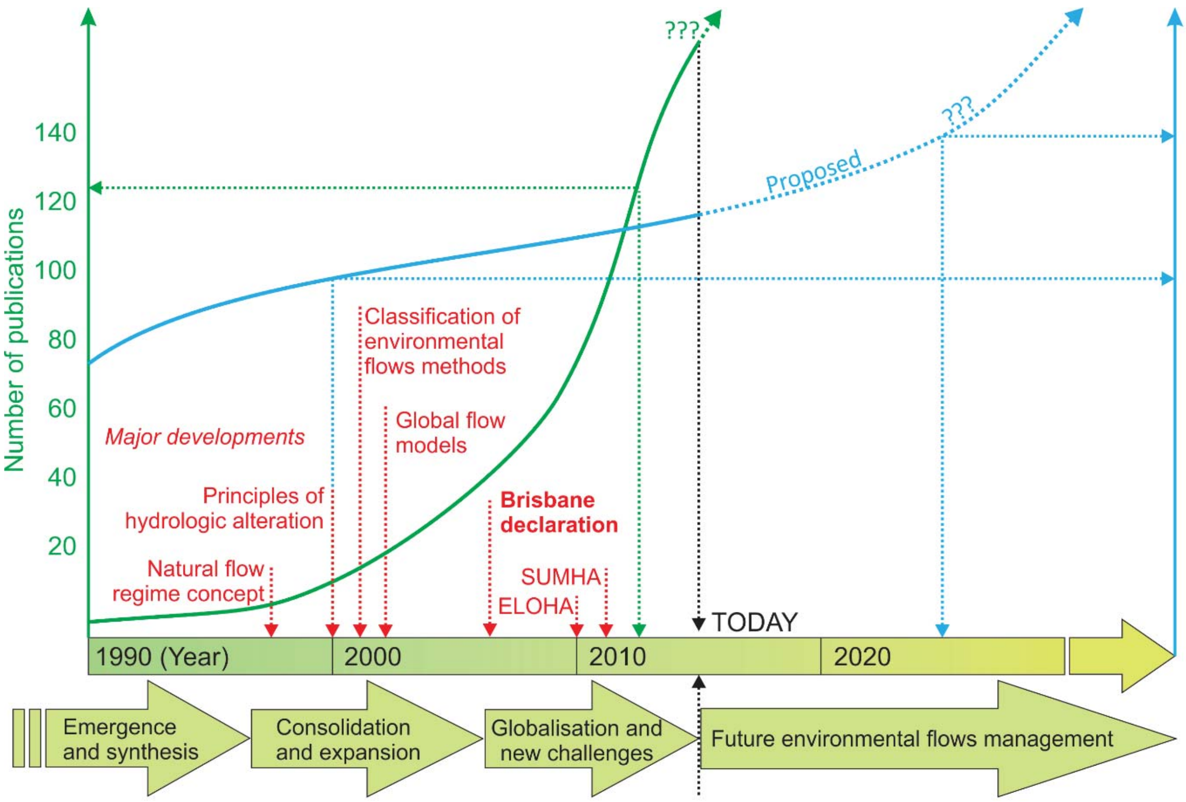
Phase 1:
During the emergence and synthesis period, the importance of why and how to manage EFs gained momentum (Calow and Petts, 1992; Boon et al., 1992; Richter et al., 1998; Postel, 1998; Snaddon et al, 1999; Poff and Matthews, 2013). In this period the concept of EFs emerged in an attempt to mitigate the undesirable flow related (hydrological) impacts of dams, water abstraction and water diversions in water resource management (Tharme, 2003; Poff and Matthews, 2013).

Phase 2:
During the consolidation and expansion phase, new up and coming 'dedicated EF practitioners', and scientists began to focus on how to manage rivers in an equitable, sustainable manner that achieves a suitable balance between water resource use and protection (cf. Poff and Matthews, 2013). Major developments of the consolidation and expansion period that have contributed to the modern principles of EF management include (cf. Poff and Matthews, 2013);

- the need to manage EFs in an equitable and sustainable way for water resource use and protection,
- recognition that while people are beneficiaries of sustainable flow management, the ecosystem should be considered either to be a legitimate 'user' or 'stakeholder' of EFs and not need to compete with other users for minimum flows but deserving ethical consideration for water on a par with human considerations as the 'reserve'(Naiman et al. 2002, Postel and Richter 2003),
- increased awareness and education around EF science (Postel and Richter, 2003), and buy-in of conservation, scientific and resource-use regulatory stakeholders to manage environmental flows sustainably,

- inclusion of EF (and other water resource use drivers of change) principles into holistic management frameworks such as Integrated Water Resources Management (Bernhardt et al., 2006),
- development of the concept of instream flow requirements and later environmental water requirements, and associated derivation tools,
- agreement on the broad socio-ecological effects of environmental flow alterations and exacerbating factors such as climate change,
- the establishment of policies and EF regulations for water resource developments,
- development of numerous environmental flow assessment tools and methods,
- recognition of the importance of managing EFs on multiple spatial scales with social and ecological considerations.

The consolidation and expansion period culminated with the 2007 Brisbane Declaration which established the modern definition of environmental flows as 'the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems'[1]. During this period EF considerations expanded to consider managing environmental flows on multiple spatial scales with social and ecological considerations and where necessary trade-offs. environmental flow principles and evaluation methods were also introduced to developing central and North African, South American and Asian nations during this period (Poff and Matthews, 2013).



ENVIRONMENTAL FLOW RESEARCH AND MANAGEMENT DEVELOPMENT PHASES

[1] http://www.watercentre.org/news/declaration

Figure 3: Schematic representation of the recent (from 1990) development in environmental flows research in relation to water resource development. Number of publications, environmental flow development phases and major recent developments included (adapted from Tharme, 2003 and Pahl-Wostl et al., 2013).

Phase 3:
During the final "globalisation and new challenges" phase which has brought us from the mid-2000s to present, we have experienced a continual increase in global awareness of environmental flow management and its importance (Poff and Matthews, 2013, **Figure 3**). With this, the need to consider EFs at regional and basin-wide spatial scales has emerged with a range of political, social and ecological challenges and validation issues. Although progress is being made to address these new challenges and new principles for, there is still much work to do. Some of these new challenges, recent developments and improvements to environmental flow evaluations and management principles include (cf. Poff and Matthews, 2013):

- environmental flow assessments must be evidence based and explicitly present the uncertainty associated with the assessment, (Lloyd et al., 2003; Poff, and Zimmerman, 2010; O'Brien and Wepener, 2012; Landis et al., 2013).
- Integrated environmental threats, such as climate change and human population growth with EF alterations should be considered (Nelson et al, 2009; Landis et al., 2013).
- environmental flow assessment tools that consider multiple stressors, that define the relationships between stressors and multiple social and ecological endpoints, that can evaluate the trade-offs between and socio-ecological endpoints are required (Vörösmarty et al., 2010; Arthington et al., 2006; O'Brien and Wepener, 2012; O'Brien et al., in preparation).
- Transparent, adaptable tools that can model future environmental flow alterations in the context of integrated environmental threats, such as climate change and human population growth need to be developed and implemented to assist in the management of future flows.

In an attempt to meet some of these EF principles established during the globalisation and new challenges phase of EF development, the Ecological Limits of Hydrologic Alteration (ELOHA) framework was established which called for the establishment of environmental flows for entire river networks, on meaningful spatial scales such as basin or multiple basin scales in multiple political and or legislative contexts (Poff et al., 2010; Poff and Matthews, 2013) (Figure 4). The approach incorporates the classification of river segments into ecologically relevant river types and the generation of testable hypotheses describing the ecological responses to flow alteration for the river types and the societal preferences for ecological conditions (Poff et al., 2010; Poff and Matthews, 2013).

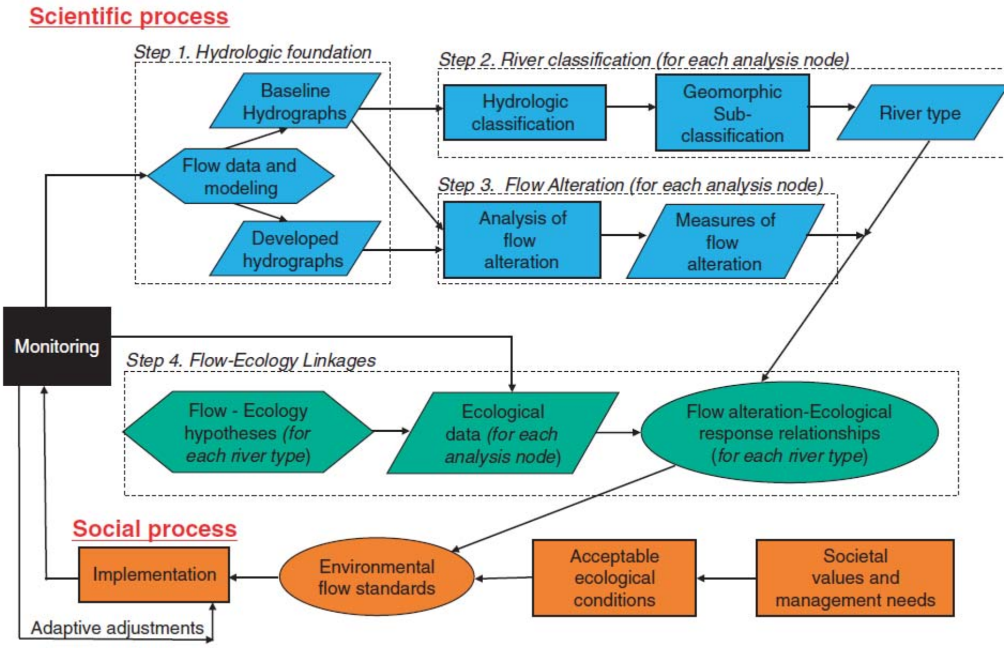


Figure 4: The Ecological Limits of Hydrologic Alteration (ELOHA) framework by Poff et al. (2010) with the five procedural phased highlighted in within the scientific and social processed of the framework.

Following after ELOHA, Pahl-Wostl et al. (2013) established the Sustainable Management of Hydrological Alterations (SUMHA) Framework that provides a systematic approach for the determination of environmental flow requirements (EFRs) on both the natural and social science fronts and, in particular, on the interaction between social/political and environmental systems (Figure 5). The SUMHA framework addresses environmental flows in the context of water governance where trade-offs between social and ecological objectives can be considered within an appropriate legislative framework. The SUMHA framework advocates transparency and adaptability and the use of transdisciplinary research closely linked to implementation initiatives.

Finally, O'Brien et al., (in preparation) has demonstrated the use of established regional scale ecological risk assessment procedures to evaluate the socio-ecological consequences of altered flows on multiple spatial scales using a new approach called 'PROBFLO'. The approach has been established to address recommendations from the ELOHA and SUMHA frameworks while being flexible enough to be applied on reach scale case studies where the uncertainty is reduced (Figure 6). PROBFLO allows for the application of the environmental flow assessments on multiple scales, to evaluate the socio-ecological consequences of altered flows within local, regional and international legislative and policy contexts. This transparent, adaptable, evidence based risk assessment approach allows for the consideration of trade-offs between a range of management options, evaluated as scenarios so that the socio-ecological consequences of altered decision making can be considered. The outcomes of the assessment, and many of the flow-ecology and flow-ecology-society relationships are related to testable hypotheses with associated uncertainties. These uncertainties can be reduced following testing which results in improvement of the outcomes.

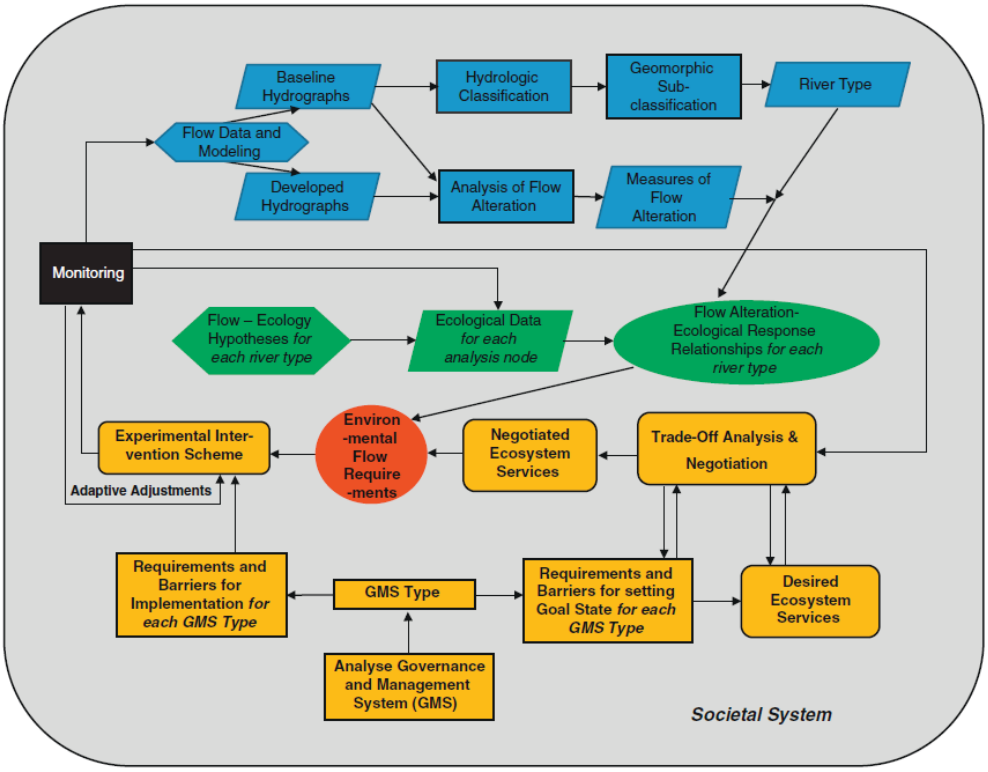


Figure 5: The Sustainable Management of Hydrological Alterations (SUMHA) Framework by Pahl-Wostl et al. (2013), which emphasises the interaction between social/political and environmental systems considered in Environmental Flow Assessments.

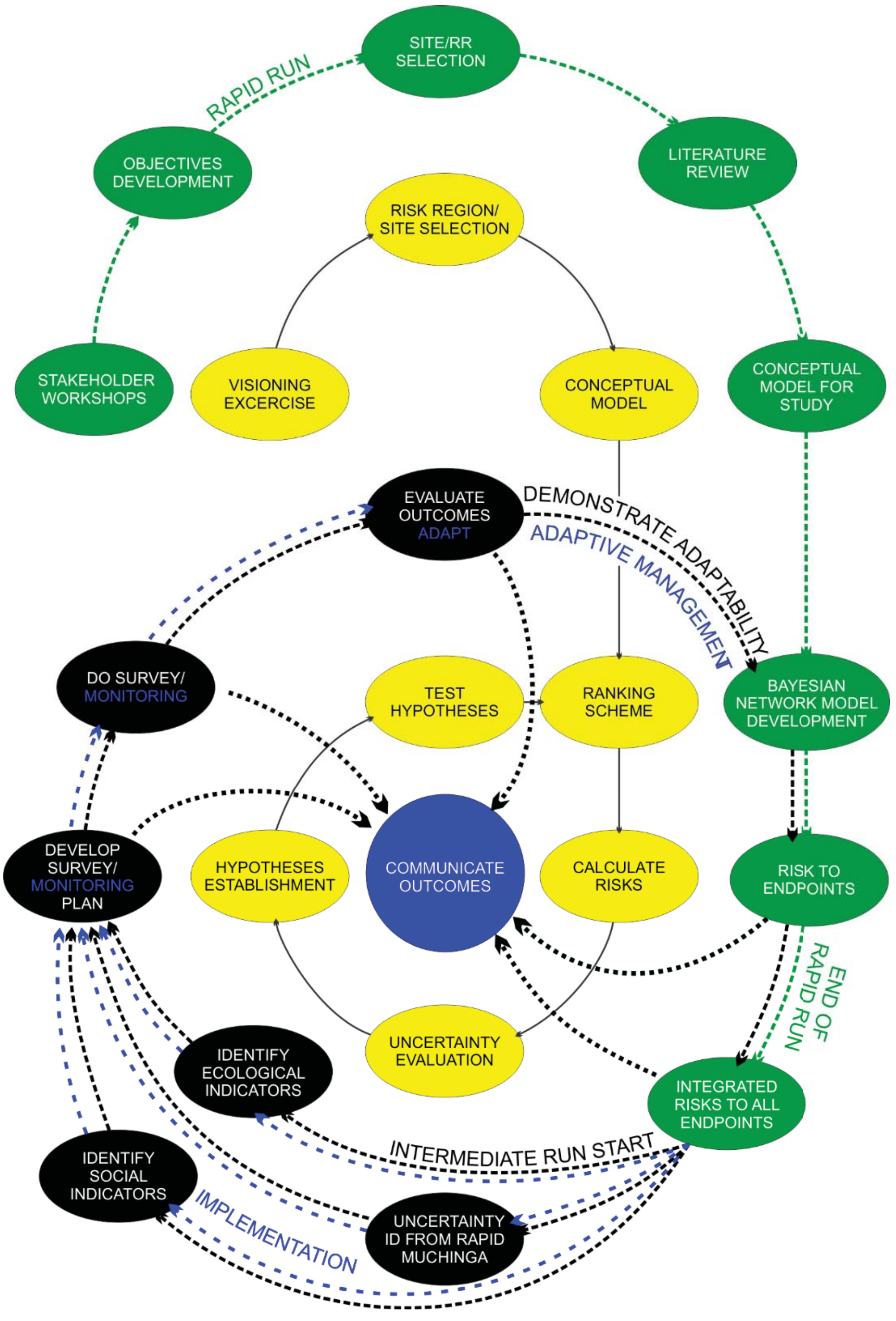


Figure 6: Schematic representation of the procedural steps of the PROBFLO framework (yellow and blue) with the adaptive management cycle emphasised. Tasks proposed to be considered for case study presented in the schematic to illustrate scoping “rapid runs” (green) and then the “intermediate” (black) portion of the application of the PROBFLO assessment with the adaptive management cycle demonstrated and finally the establishment of the a monitoring plan for the implementation of PROBFLO to allow the approach to be adapted in the future.

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3.2 Environmental flow policies, conventions and declarations

The following section will outline the development, obstacles to implementation as well as guidelines for addressing these obstacles of EF policies, conventions and declarations on a global scale. For a regional assessment of EF policies, conventions and declarations please refer to *Background Document 3 Management of environmental flows in the Nile River Basin: practices and experiences.*

With the rapid development of EF concepts and procedures from the 1990s, water resource managers have also established EF policies, conventions and declarations that now contribute to the use and protection of water resources across the globe (Le Quesne et. al. 2010) (Figure 7). Despite the considerable EF policies, conventions and declarations, in the majority of cases EF provisions remain at the policy development, debate and EF requirement phase rather than implementation. Although EF policy development is well established internationally, water flows and levels continue to be degraded on a wide scale. Unfortunately according to Le Quesne et. al. (2010) a defining characteristic of many EF legislations is the lack of progress in translating these policies and intentions into action. Implementation limitations have been attributed to the lack of political will and stakeholder support, insufficient resources and capacity and institutional barriers, amongst others (Poff and Mathews, 2013).

Figure 7: environmental flow declarations, conventions and policies are usually legalised (from Palmer et al. 2002).

<u>ENVIRONMENTAL FLOW POLICIES</u> INCORPORATE THE SYSTEMATIC RECOGNITION AND PROTECTION OF ENVIRONMENTAL FLOWS ACROSS DEFINED GOVERNED REGIONS, LED BY PUBLIC AUTHORITIES. THESE POLICIES ARE CONSIDERED TO BE SUCCESSFUL AFTER ACHIEVING IMPLEMENTATION. THE RANGE OF POLICIES BY WHICH WATER RESOURCES ARE GOVERNED AND REGULATED INCLUDES LEGISLATION, REGULATIONS AND ENFORCEMENT, NATIONAL STRATEGIES, ACCORDS AND TREATIES, OPERATIONAL PLANS, AS WELL AS CUSTOMARY APPROACHES (LE QUESNE ET. AL. 2010). ENVIRONMENTAL FLOW POLICY INCORPORATES MULTIPLE ASPECTS OF WATER MANAGEMENT REQUIRED TO SYSTEMATICALLY PROTECT ENVIRONMENTAL FLOWS, FROM HIGH-LEVEL RECOGNITION TO REGULATIONS, INSTITUTIONAL IMPLEMENTATION, AND ADAPTIVE MANAGEMENT.

3.2.1 Environmental flow policy development

Although the formal establishment of EF policies are considered to be a modern development, mankind have been negotiating water flow allocations from the onset of the development of water resources. From as early as the 1830s have stakeholders of water resources formally negotiated water flow allocations which have led to formal agreements we would consider to represent EF policies today (Le Quesne et. al. 2010). This being said, the "sophisticated and widespread" understanding of EFs as a public policy imperative remains a comparatively recent development (Poff and Mathews, 2013).

- environmental flow policies are being established internationally and are summarised from Le Quesne et. al. (2010) below (Figure 8):
- In some of the world's most densely populated regions such as Asia, where water resource use sustainability challenges are perhaps greatest, many countries are starting to recognise the importance of environmental flows. For example in Japan in the 1997 revision of its 1896 River Law, fluvial environment conservation was introduced as a clear objective of river administration (Figure 8, #1). The recent reviews of China's river basin "Master Plans" have introduced environmental flows across the country and have in particular resulted in the restoration of flows to the Yellow River, the world's largest water re-allocation for environmental needs programme (Figure 8, #2). The 1991 Water Apportionment Accord of the Indus River System between the provinces in Pakistan recognised the need for a quantity of water to maintain the Indus delta's functioning (Figure 8, #3). The Mekong River Commission's transboundary plan to develop hydropower and reduce flood risk hinges squarely on the ability to maintain the river's unique flood regime and associated biodiversity, which includes the provision of food to 60 million of the world's poorest people (Figure 8, #4). Vietnam has initiated comprehensive national water policy reform that recognises the maintenance of healthy aquatic ecosystems (Figure 8, #5). In India, a rudimentary recognition of environmental needs is included in hydropower development policy, and the establishment of a new Ganga River Basin Authority in 2008 included as an objective for the maintenance of minimum ecological flows in the river Ganga (Figure 8, #6).
- In Australia's Murray-Darling Basin, EF policies have been debated and for many years and have resulted in a change in water resource use methods and a series of government initiatives for restoring over-allocated flows, which includes the allocation of many billion US$ worth of financial resources for the state purchase of water rights (Figure 8, #7). environmental flow policy development in Australia also resulted in the globally recognised Brisbane Declaration of 2007 which defined EFs as the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems. In 2008, the New Zealand government proposed a national standard establishing environmental flows and water levels to limit all resource consent decisions on applications to take, use, dam and divert water from rivers, lakes, wetlands and aquifers (Figure 8, #8).
- In Africa, the South African National Water Act of 1998 is widely recognised as one of the most ambitious international attempts to integrate environmental flows into the core of water policy reform. Building on South Africa's work, the 2005 Southern African Development Community Regional Water Policy, representing 200 million people and covering 9.3 million square kilometres, recommends that member states should allocate

sufficient water to maintain ecosystem integrity and biodiversity in their mechanisms for allocating water resources among many users (Figure 8, #9). This has resulted in:
  - efforts in Mozambique to undertake reform that prioritises environmental water allocation above economic water uses (Figure 8, #10),
  - discussions to address the restoration of environmental flow releases from dams across the Zambezi basin (Figure 8, #11),
  - the introduced water laws and policies in Kenya and Tanzania to recognise EF, and policy debates which are progressing in a number of other African states and basins (Figure 8, #12), and
  - numerous international river commissions, Orange-Senqu River Commission (ORASECOM), Limpopo Watercourse Commission (LIMCOM) and the Zambezi Watercourse Commission (ZAMCOM) which all consider the establishment of sound EF management principles in their mission statements or objectives.
- Progress toward the implementation of EF policies in Europe has been varied, the 2000 European Union Water Framework Directive designates restored hydrology as one of the key elements of good ecological status which is the aim of the directive (Figure 8, #13).
- In the USA multiple EF policies and laws have been introduced. Many USA states now recognise instream flows and seasonally varying flow standards that are linked to biological needs (Figure 8, #14). In Canada EF provisions that require consideration of environmental flows in water allocation and water management planning have been established (Figure 8, #15).
- The Mexican 1992 Water Act recognises EF needs now (Figure 8, #16), and there is active policy development on EF in many Latin American countries, such as Chile, Ecuador, Colombia, Costa Rica, and Puerto Rico (Figure 8, #17).
- The Brazilian water law recognises environmental water needs, and national policy discussions are currently underway to introduce EF regulations for hydropower development (Figure 8, #18).

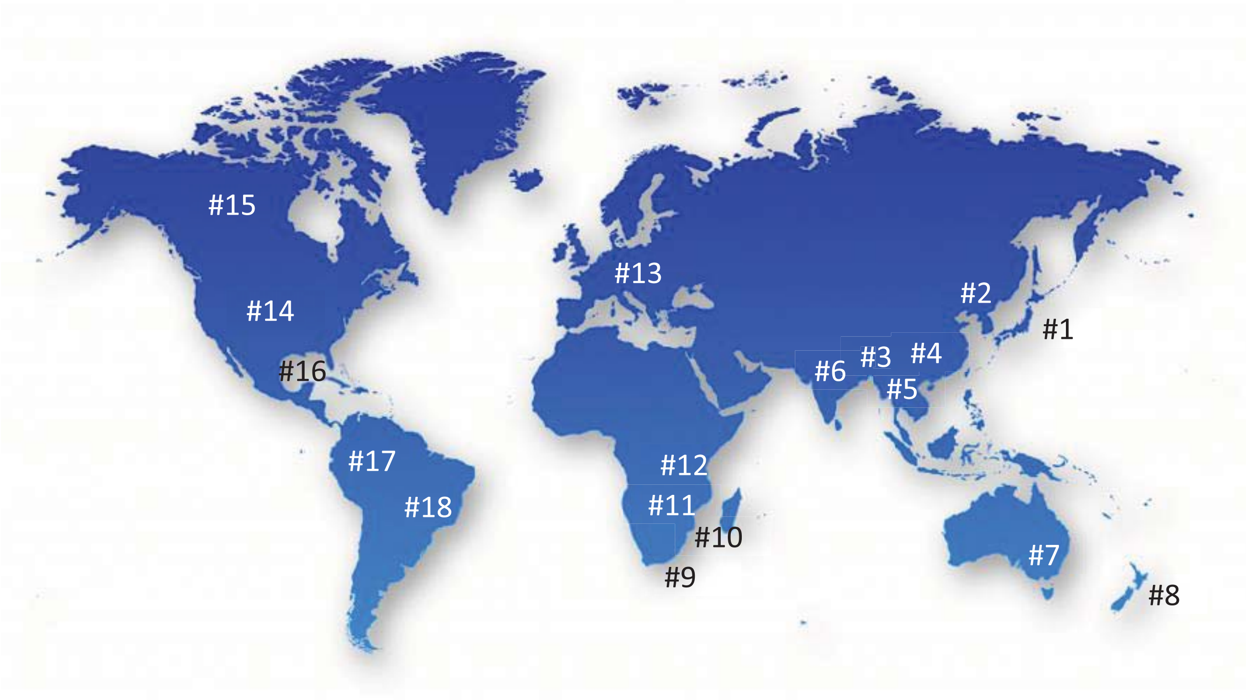


Figure 8: Global overview of the development of environmental flow policies from the Asian region (#1 - #6), Oceania (#7 - #8), sub-Saharan Africa (#9 - #12), Europe (#13), North America (#14 - #16) and South America (#17 and #18).

More specific information pertaining to the case studies highlighted here are available in Chapter 5 of, *The Implementation Challenge: Taking stock of government policies to protect and restore environmental flows* (Le Quesne et. al. 2010).

3.2.2 Environmental flow policy implementation obstacles

Many obstacles are considered by stakeholders to occur that affect EF policy aspiration resulting in actual implementation (Moore 2004; Le Quesne et. al. 2010). Many stakeholders consider EF policy implementation issues related to stakeholder support and political will (31%, Figure 9), with legal and institutional arrangements and stakeholder engagement limitations also ranking high (23%, Figure 9). Only 11% and 10% of the stakeholders considered financial and expertise limitations to be important, and finally public acceptance, scenario modelling capacity was only considered to be important by 7% of the stakeholders. Only 6% of the stakeholders considered the lack of hydrological data to be an obstacle in implementing EF policies and a final 4% of the stakeholders listed other issues that may affect EF policy implementation.

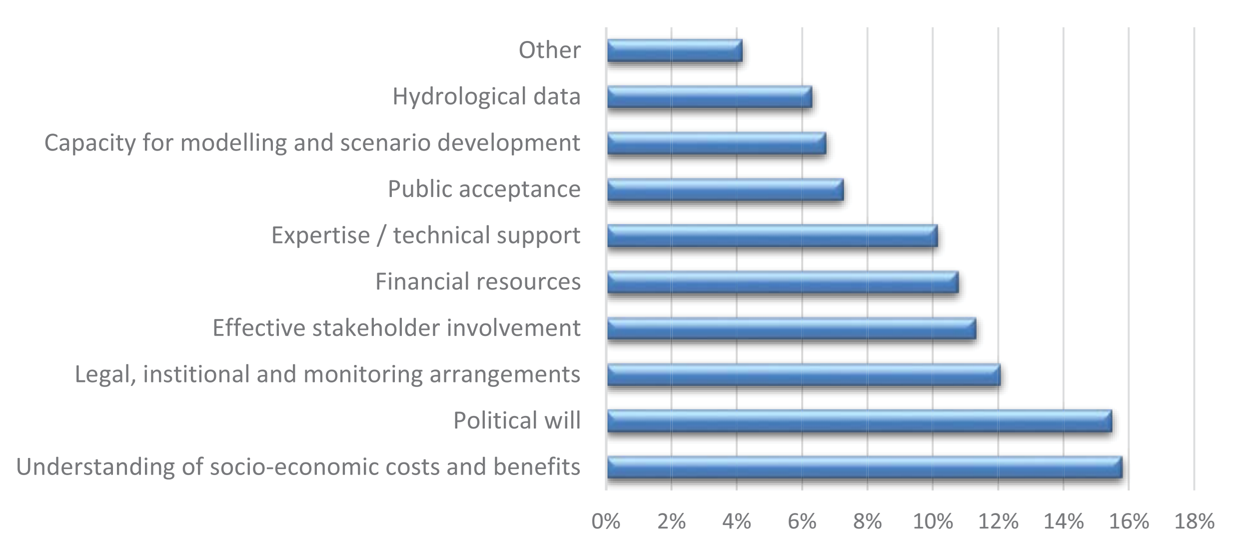


Figure 9: Stakeholder perceived difficulties and obstacles to understanding and implementing environmental flows represented as percentage (from Moore, 2004)

3.2.3 Guidelines for addressing environmental flow policy implementation obstacles

The guidelines proposed by Le Quesne et. al. (2010) to mitigate obstacles to EF implementation include:

- Undertake a phased approach to implementation.
- Be opportunistic.
- Don't exceed available capacity (human resource capacity)
- Limit allowable water abstraction and flow alteration as soon as possible.
- Develop a clear statement of objectives for environmental flows policy.
- Develop a clear institutional framework, including independent oversight.
- Create sustainable financing mechanisms, in particular financial resources where re-allocation of water is required.
- Conduct proof-of-concept pilot projects.
- Allow flexibility for implementation methods, while setting a clear deadline and goals for implementation.

4 Environmental Flow Assessment Methods

There are many environmental flow assessment methods (EFM), also referred to as environmental flow (EF) assessment procedures) which have been extensively reviewed (EPRI 2000, Tharme 2003, Hatfield et al. 2003, Annear et al. 2004; Petts, 2009; Moyle et al., 2011; Adams, 2014). Although EFMs are dominated by riverine ecosystem methods, they do extend to estuarine, wetlands, lakes and other ecosystems. By 2003, as many as 207 EFMs from 44 countries, within six world regions were established (Tharme, 2003). Since then many additional techniques have been established some of which are being implemented on a global scale (Moyle el al., 2011).

ENVIRONMENTAL FLOW ASSESSMENT METHODS (EFM) ARE BEEN DEFINED AS THE PROCEDURES THAT CHARACTERISE THE EXTENT OF THE ORIGINAL FLOW REGIME OF A RIVER THAT SHOULD CONTINUE TO FLOW DOWN THE RIVER AND ONTO ITS FLOODPLAINS (AND OTHER ASSOCIATED ECOSYSTEMS), TO MAINTAIN SPECIFIED AND VALUED FEATURES OF THE ECOSYSTEM.

environmental flow methodologies can be categorised into four main categories including:

- hydrological,
- hydraulic rating,
- habitat simulation (or rating), and
- holistic methods.

Further combinations of these four categories (Tharme, 2003) have evolved. Although some authors have proposed other categories, in this review we will demonstrate that these four categories are still applicable and can be used to categorise and discuss the majority of EFMs.
environmental flow assessment methods have historically been applied at two or more levels including; reconnaissance-level initiatives relying on hydrological modelling and low confidence probability modelling, and more comprehensive usually 'habitat scale' assessments, where flow-ecological and flow-ecological-social evaluations are considered with reference to the habitat from which socio-ecological values are derived (Figure 10).

The consequences of flow alterations can also be considered in terms of the flows 'removed' from ecosystems and their consequences (top-down approach) or the flows, usually minimum, 'required' to maintain an ecosystem in an appropriate state (bottom-up approach) (Moyle et al., 2011). While the top-down approach usually considers at least five attributes of the flow regime, including; magnitude, frequency, duration, timing, and rate of change of flows, the bottom-up approach defines what needs to remain in the river to meet selected socio-ecological management objectives (Moyle et al., 2011).

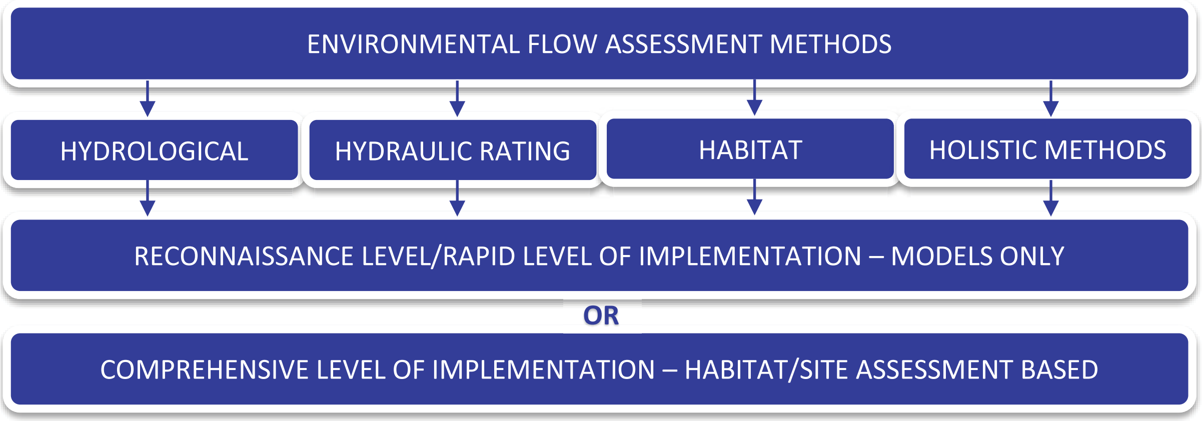


Figure 10: Categories of environmental flow Methods with different levels of application.

4.1 Types of environmental flow assessment methods

This section presents the EFMs according to the four EFM categories, and combinations of these categories proposed by Tharme (2003) including; hydrological, hydraulic rating, habitat simulation (or rating), and holistic methodologies.

4.1.1 Hydrological environmental flow Methods

Hydrological EFMs are primarily based on hydrological evaluation methods, hydrological data, and the consideration of a range of 'hydrological statistics' associated with naturalised, historical monthly or daily flow records, for making environmental flow recommendations (sensu Tharme, 2003) (Figure 11). The outcomes of these EFMs include fixed-percentage or look-up table components, where a set proportion of flow, often expressed as a percentage of the annual runoff of an ecosystem (for example), is provided. Occasionally, hydrology-based EFMs are dominated by hydrological modelling components and include some catchment variables that are incorporated into the models to take account of hydraulic, biological and/or geomorphological criteria, or incorporate various hydrological formulae or indices.

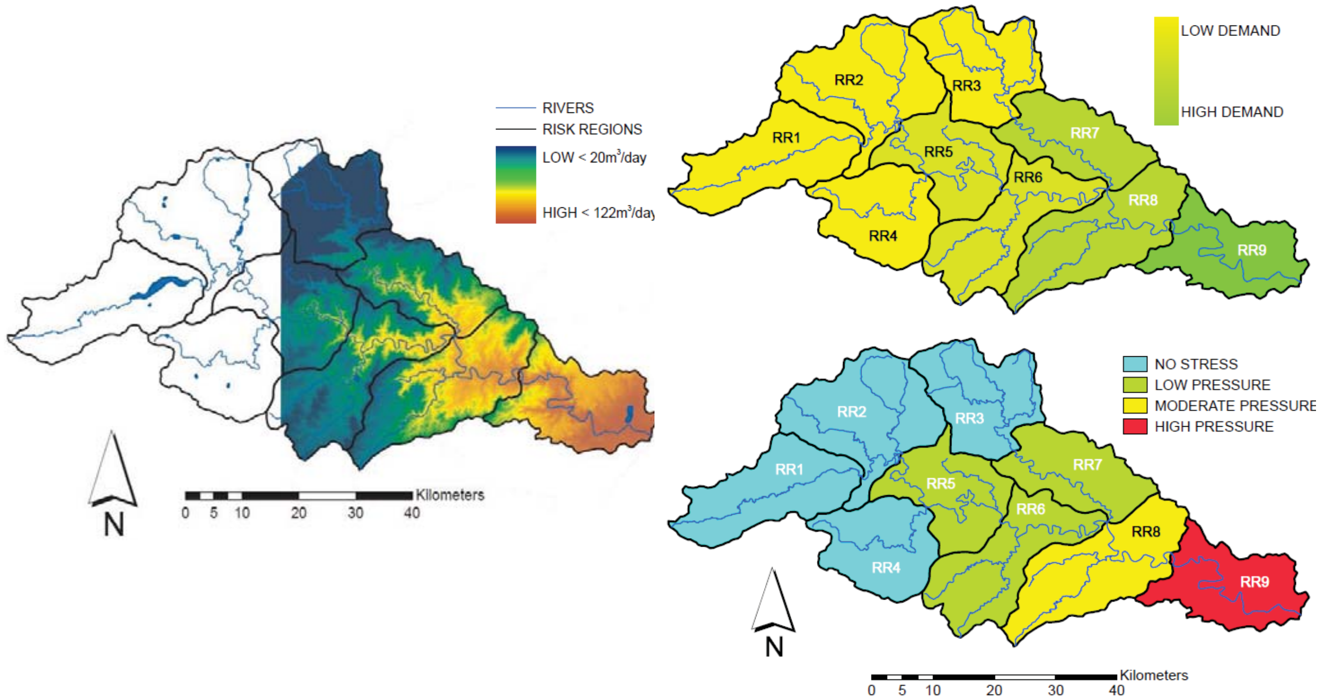


Figure 11: Example of a simple Hydrological environmental flow Method which involves the modelling of average available flows and relates flows to abstraction demand in a catchment and associated stress (from O'Brien 2011).

Reviews of established hydrological and regionalisation techniques used to derive the latter flow indices for gauged and ungauged catchments are available from Gordon et al. (1992), Stewardson and Gippel (1997) and Smakhtin (2001), Tharme (1997), Dunbar et al., (1998), Karimi et al. (2012), Kapangaziwiri et al. (2012) and Hughes et al., (2014).

Examples of Hydrology-based EFMs include the **Tennant (Montana) method** (Reiser et al., 1989), which until 2003 at least was one of the most commonly implemented hydrological EFMs worldwide (Tharme, 2003). This standard setting approach did make some assumptions about habitat, hydraulic and biological wellbeing in its development. It comprises a table linking different percentages of average or mean annual flow to different categories of river condition, on a seasonal basis, as the recommended minimum flows (Tharme, 2003). Several forms of the basic Tennant Hydrological Environmental Flow Assessment (EFA) method exist.

Texas method (Matthews and Bao, 1991),
Basic flow method (Palau and Alcazar, 1996),
Range of variability approach (RVA; Richter et al., 1996, 1997),
Flow translucency approach (Gippel, 2001)
Desktop-level environmental flow requirement (EFR) determination tool (Hughes and Hannart, 2003)
Desktop Reserve Model (DRM, Hughes and Münster 2000; Hughes and Hannart, 2003; Hughes et al., 2014)
SPATSIM (Hughes and Palmer, 2005)

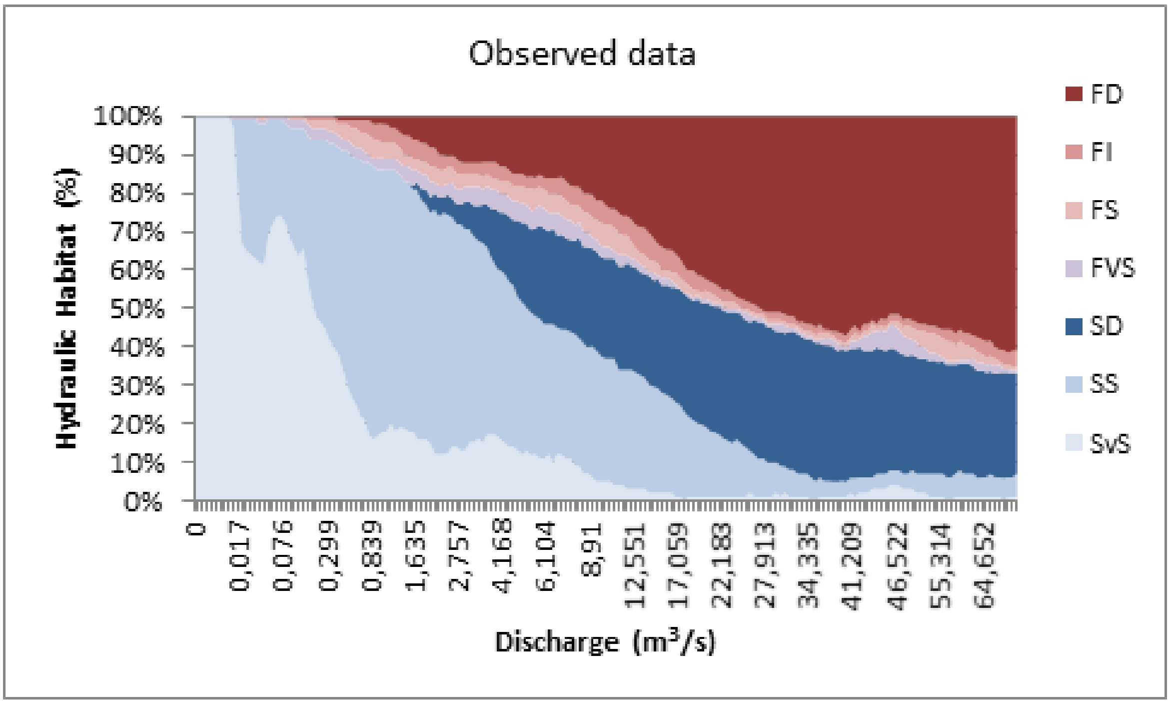


Figure 12: Example of the outcomes of the application of the Desktop Reserve Model which includes area curves of availability of fish flow classes for a river in South Africa using observed data. Where velocity depth classes refer to: FD – fast deep, FI – fast intermediate, FS – fast shallow, FVS – fast very shallow, SD – slow deep, SS – slow shallow, and SvS – slow very shallow.

HYDROLOGICAL ENVIRONMENTAL FLOW METHODS CAN BE IMPLEMENTED ON MULTIPLE SPATIAL SCALES (SITE TO BASIN SCALE) WITH AVAILABLE (MODELLED AND/OR OBSERVED) HYDROLOGICAL (PAST AND CURRENT) DATA. ALTERATIONS TO THE VOLUME, TIMING AND DURATION OF FLOWS IS RELATED TO FLOW-ECOLOGICAL INDICATORS (IN SOME CASES). THIS APPROACH DOES NOT ALLOW FOR THE EVALUATION OF THE RELATIONSHIPS BETWEEN FLOWS, HABITATS AND THE ECOLOGICAL COMPONENTS OF ECOSYSTEMS THAT DEPEND ON FLOWS/HABITATS.

4.1.2 Hydraulic rating environmental flow Methods

In an attempt to link habitat associated ecological components to hydrological flow alterations some ‘transect based’ EFA methodologies evolved and were term hydraulic rating (also known as habitat retention) EFA methodologies (Loar et al., 1986). These approaches use changes in simple hydraulic variables, such as wetted perimeter or maximum depth, usually measured across single, limiting river cross-sections (e.g. riffes), as a surrogate for habitat factors known or assumed to be limiting to target biota (Tharme, 2003). Within these approaches assumptions are made (or hypotheses established) to ensure that some threshold value of the selected hydraulic parameter at altered flows will maintain an ecological or social objective of an ecosystem in a desired state (Tharme, 2003). The most commonly hydraulic rating methodologies applied internationally include;

Generic wetted perimeter method (Reiser et al., 1989)
R-2 cross method (Tharme, 2003)

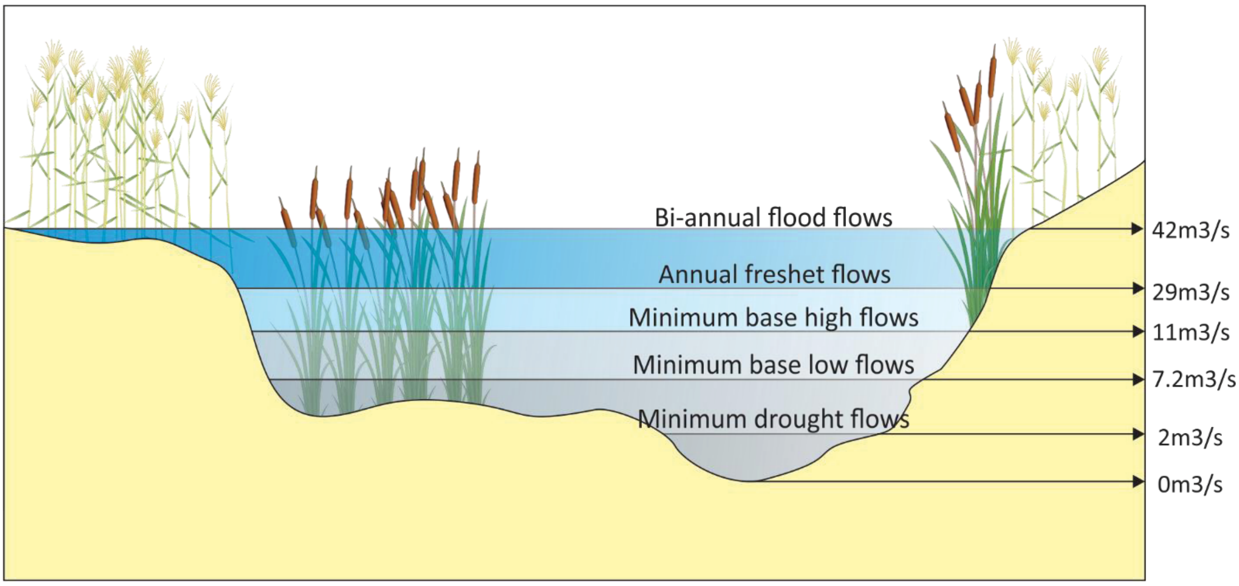


Figure 13: Example of a simple cross section of a river with different environmental flows overlaid onto the cross section.

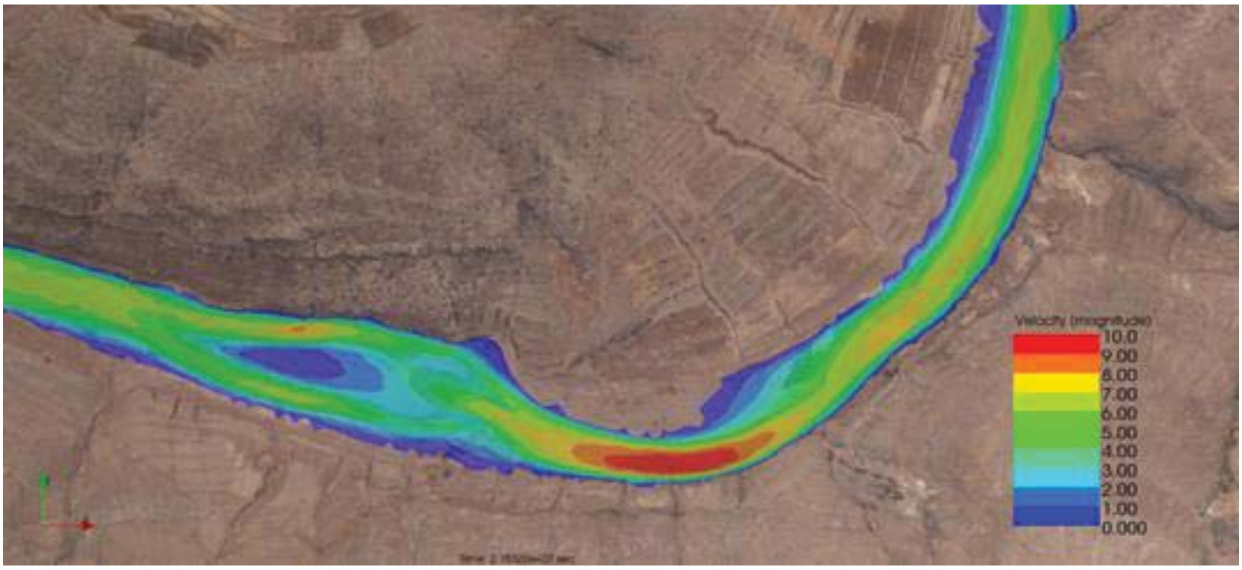


Figure 14: Example of a two dimensional hydraulic model of a section of a river at a specific discharge with different velocities overlaid onto the model.

HYDRAULIC RATING ENVIRONMENTAL FLOW METHODS CAN BE IMPLEMENTED ON MULTIPLE SCALES FROM SITE TO REACH SCALE WITH ACCURACY WITH AVAILABLE (MODELLED AND/OR OBSERVED) HYDROLOGICAL (PAST AND CURRENT) DATA OVERLAID ONTO THE MODELS TO PROVIDE A DIRECT RELATIONSHIP BETWEEN THE HYDROLOGY AND HYDRAULIC VARIABLES (VELOCITY/DEPTH ETC.). ALTERATIONS TO THE VOLUME, TIMING AND DURATION OF FLOWS IS RELATED TO FLOW-ECOLOGICAL INDICATORS (IN SOME CASES). THIS ALLOWS FOR THE EVALUATION OF THE RELATIONSHIPS BETWEEN FLOWS AND HABITATS AND INFERS THE RELATIONSHIPS WITH ECOLOGICAL COMPONENTS OF ECOSYSTEMS THAT DEPEND ON FLOWS/HABITATS.

4.1.3 Habitat-based environmental flow methods

Habitat based EFMs are based on detailed analyses of the quantity and suitability of instream physical habitat for the arrangement of target species or assemblages under different discharges (or flow regimes) (Tharme, 2003; Moyle et al., 2011) (Figure 15). These EFMs integrate hydrological, hydraulic and biological response data. Typically, the flow-related changes in physical microhabitat are modelled in various hydraulic programs, using data on one or more hydraulic variables, most commonly depth, velocity, substratum composition, cover and, more recently, complex hydraulic indices (e.g. benthic shear stress), collected at multiple cross-sections within a representative reach of the study area (Tharme, 2003). The simulated available habitat conditions are linked with information on the range of preferred to unsuitable microhabitat conditions for target species, life-history stages, assemblages and/or activities, often depicted using seasonally defined habitat suitability index curves. The resultant outputs, usually in the form of habitat-discharge curves for the biota, or extended as habitat time and exceedance series, are used to predict optimum flows as EFRs. Habitat simulation methodologies include the **instream flow incremental methodology** (IFIM, including its foundation models, the **physical habitat simulation model** (PHABSIM) *also considered in the holistic methods section*), and more recently established suites of habitat simulation models of similar character and data requirements (Bovee 1982, Bovee et al. 1998, Payne and Associates, 2000).

- **PHABSIM** (Souchon et al. 2008)
- **InSTREAM** (Moyle et al., 2011)
- **MesoHABSIM** (Parasiewicz 2001, 2007)
- **Demonstration Flow Assessment** (Railsback and Kadvany, 2008)

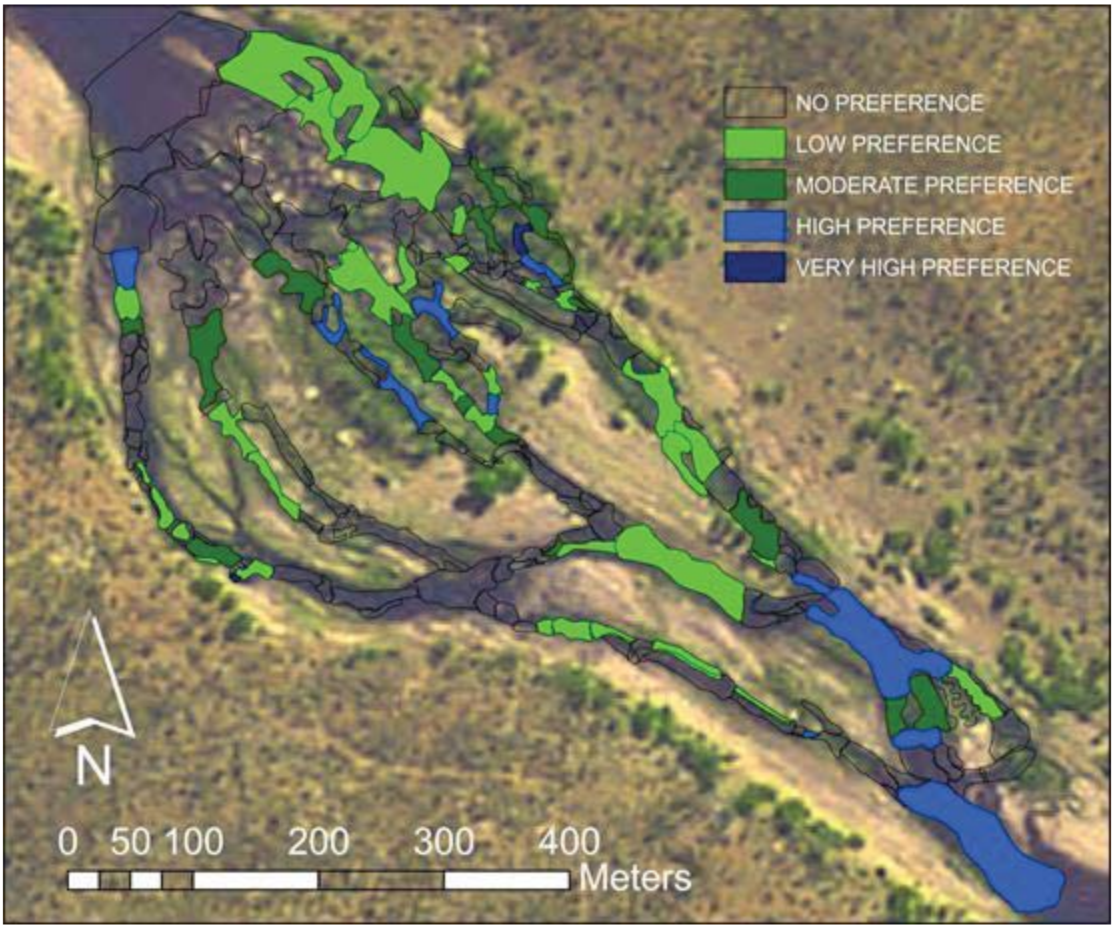


Figure 15: Example of the outcomes of a habitat-based environmental flow method which describes the habitat preferences for a species of fish in a study area for a specific discharge.

HABITAT-BASED ENVIRONMENTAL FLOW METHODS CAN BE IMPLEMENTED ON MULTIPLE SCALES FROM SITE TO REACH SCALE WITH ACCURACY AND INCLUDE AVAILABLE (MODELLED AND/OR OBSERVED) HYDROLOGICAL (PAST AND CURRENT) DATA OVERLAID ONTO THE MODELS TO PROVIDE A DIRECT RELATIONSHIP BETWEEN THE HYDROLOGY, HYDRAULIC (VELOCITY/DEPTH ETC.) AND ECOLOGICAL VARIABLES. ALTERATIONS TO THE VOLUME, TIMING AND DURATION OF FLOWS ARE RELATED TO FLOW-ECOLOGICAL INDICATORS (IN SOME CASES). THIS ALLOWS FOR THE EVALUATION OF THE RELATIONSHIPS BETWEEN FLOWS-HABITATS AND ECOLOGICAL COMPONENTS OF ECOSYSTEMS THAT DEPEND ON FLOWS/HABITATS.

4.1.4 Holistic Environmental Flow Assessment methodologies

Holistic EFAs have been developed to facilitate the establishment of the balance between the use and protection of water resources on a holistic scale rather than meet the protection or use requirements of a few target ecosystem components (Arthington et al., 2004). The approach confirms to the precautionary principle by simulating the “natural flows paradigm”, including the volume, timing and duration of flows as far as possible to meet known social and ecological endpoints (Arthington *et al*. 1992; King and Tharme 1994; Poff *et al.* 1997; Arthington et al., 2004). Holistic EFAs are generally based on the use and protection requirements of multiple stakeholders, who together establish a vision for the wellbeing of the ecosystem being analysed in the EFA (Arthington et al., 2004).

Holistic EFMs which were interestingly developed primarily in South Africa, Australia and the United Kingdom (Tharme, 2003), have contributed greatly to the field of environmental flow assessments. The **building block methodology** (BBM) was established in South Africa (King and O'Keeffe, 1989) and progressed further through collaboration with Australian researchers (Arthington et al., 1998). In 2003 the BBM was the most frequently applied holistic EFM in the world and the precursor to:

- the bottom-up **Flow Stressor Response** (FSR) method (O' Keeffe et al., 2001),
- and the top-down holistic methodology comprising of four modules (biophysical, social, scenario development and economic), termed the **downstream response to imposed flow transformations** (DRIFT) process (King et al., 2003).

The DRIFT approach offered innovative advances in EFAs that focused on the identification of the consequences of reducing river discharges from natural, through a series of flow bands associated with particular sets of biophysical functions, and of specific hydrological and hydraulic character. This is established in terms of the deterioration in system condition through the evaluations of multi-disciplinary specialists. As the methodology is scenario-based, there is considerable scope for the comparative evaluation of the consequences of a number of recommended flow regimes. Additionally, links between social consequences for subsistence users, are evaluated alongside ecological and geomorphological ones, and economic implications in terms of mitigation and compensation. Combinations of the scenario-based BBM and DRIFT approach have also been established and referred to as the adapted BBM-DRIFT. For more information on DRIFT consider King and Brown (2006), and Arthington et al. (2007).

O’Brien et al., (in preparation) has recently demonstrated the use of established regional scale ecological risk assessment procedures to evaluate the socio-ecological consequences of altered flows on multiple spatial scales using a new approach called ‘PROBFLO’. As described, the approach has been established to address recommendations from the Ecological Limits of Hydrologic Alteration (ELOHA) and Sustainable Management of Hydrologic Alteration (SUMHA) frameworks while being flexible enough to be applied in reach scale case studies where the uncertainty is reduced. PROBFLO allows for the application of the environmental flow assessment on multiple scales, to evaluate the socio-ecological consequences of altered flows within local, regional and international legislative and policy contexts (Figure 16). This transparent, adaptable, evidence based risk assessment approach allows for the consideration of trade-offs between a range of management options, evaluated as scenarios so that the socio-ecological consequences of altered decision making can be considered. The outcomes of the assessment, and many of the flow-ecology and flow-ecology-social relationships in an assessment are related to testable hypotheses with associated uncertainties that can be reduced if tested. This results in improvements of the outcomes. The approach has been established to direct managers towards current best scientific practice and decision making. These include decisions that;

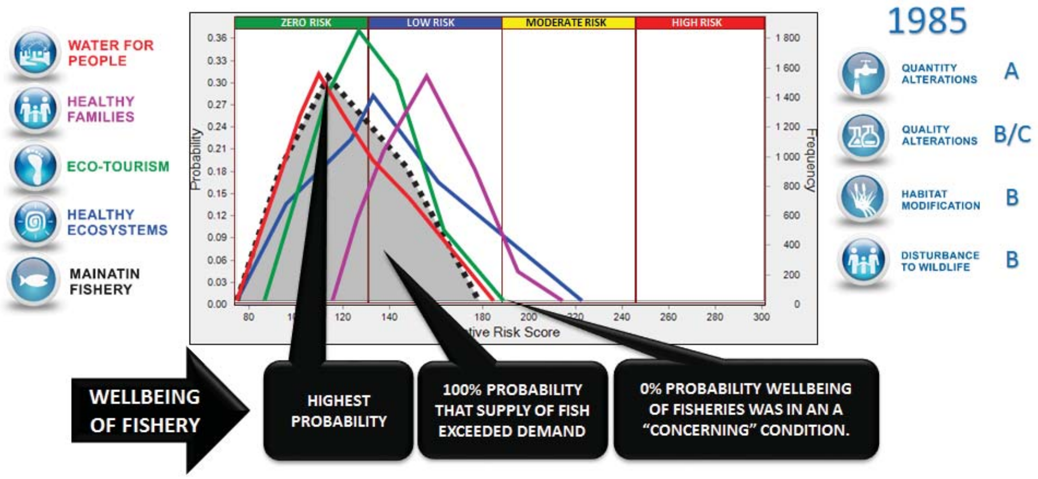
1. consider both social and ecological requirements for ecosystem services,
2. minimise socio-ecological impacts of new flow alteration developments,
3. direct water development to least-sensitive water bodies, and
4. prioritise flow restoration efforts on a regional environmental flow management scale.

Professional opinion always plays a role in EFA, in selecting the methods to be used and the methods by which results are analysed, and it can also be used for actually prescribing flow regimes. Some expert opinion based holistic methods have also been established such as the **expert panel assessment method** (EPAM; Swales et al., 1994; Swales and Harris, 1995) and the **scientific panel assessment method** (SPAM; Thoms et al., 1996; Tharme, 2003). Other increasingly comprehensive, diverse methodologies have emerged including the **flow restoration methodology** (FLOWRESM; Arthington, 1998), developed during an EFA for the Brisbane River in Australia (Tharme, 2003).

HOLISTIC ENVIRONMENTAL FLOW ASSESSMENT METHODOLOGIES CAN BE IMPLEMENTED ON MULTIPLE SCALES FROM SITE TO BASIN SCALE WITH HIGH ACCURACY AND INCLUDE AVAILABLE (MODELLED AND/OR OBSERVED) HYDROLOGICAL (PAST, CURRENT AND FUTURE) DATA AND PROVIDE A DIRECT RELATIONSHIP OF THE SOCIAL AND ECOLOGICAL CONSEQUENCES OF ALTERATIONS TO THE VOLUME, TIMING AND DURATION OF FLOWS. THESE PROBABILITY MODELLING PROCEDURES CAN BE ADAPTABLE AND IMPROVED WITH MONITORING DATA AFTER IMPLEMENTATION. THESE APPROACHES ARE EXPERT AND DATA INTENSIVE BUT PROVIDE RELIABLE OUTCOMES WITH ASSOCIATED MINIMAL UNCERTAINTY.

More examples of the application of and outcomes of the holistic EFMs include the application of the Downstream Response to Imposed Flow Transformation (DRIFT) framework for the Okavango River system (southern Africa) where a transboundary diagnostic analysis (TDA) was completed in 2010 by the three governments who share the system (King et. al. 2014) (Figure 17). The outcomes included scenarios for analyses of increasing water resource use that spelled out the costs and benefits in terms of the health of the river ecosystem, associated social structures and local and national economies (Figure 18 and Figure 19). The results were used to help create a transboundary strategic action programme, which the Member States are now beginning to act on.

A.



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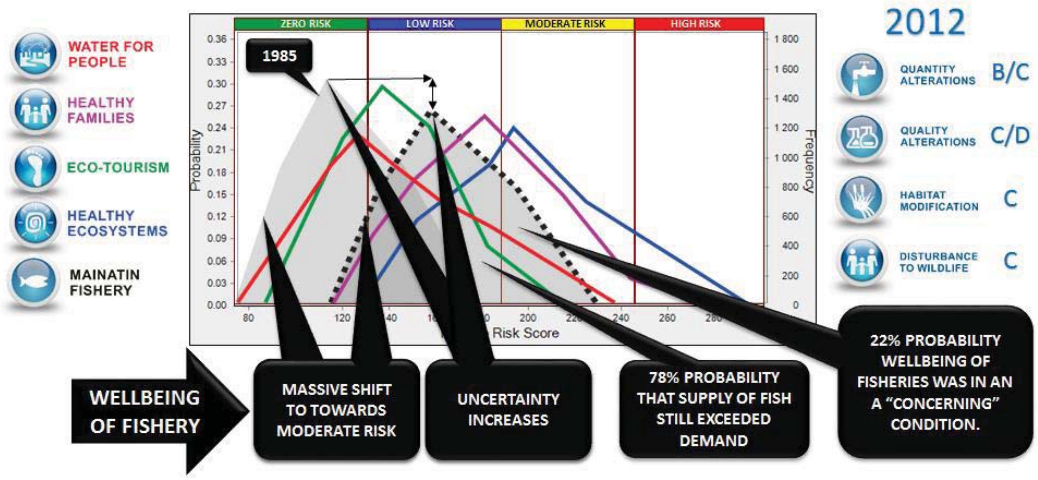

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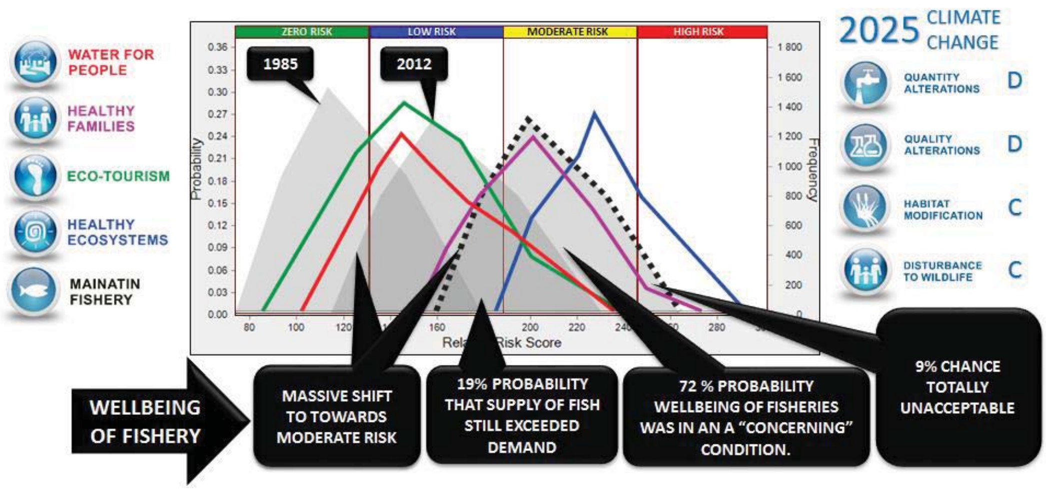

Figure 16: Example of the outcomes of a holistic environmental flow assessment (PROBFLO) which considered the relative risk of multiple endpoints (risk to fisheries wellbeing highlighted) and associated conditions of selected driver variables for a reach of a river in southern Africa during the high flow period in 1985 (A), 2012 (B) and modelled for 2025 (C) with climate change impacts.

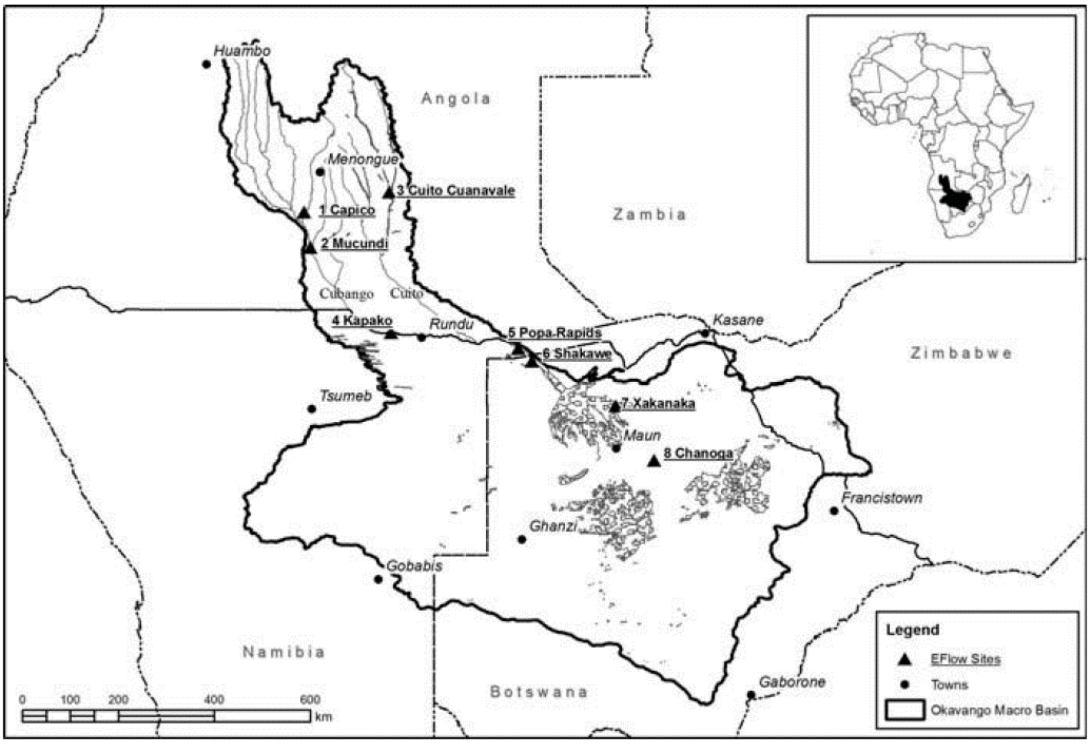

Figure 17: Study area of the application of the DRIFT environmental flow assessment for the Okavango to produce the transboundary diagnostic analysis for the system (King et. al. 2014).

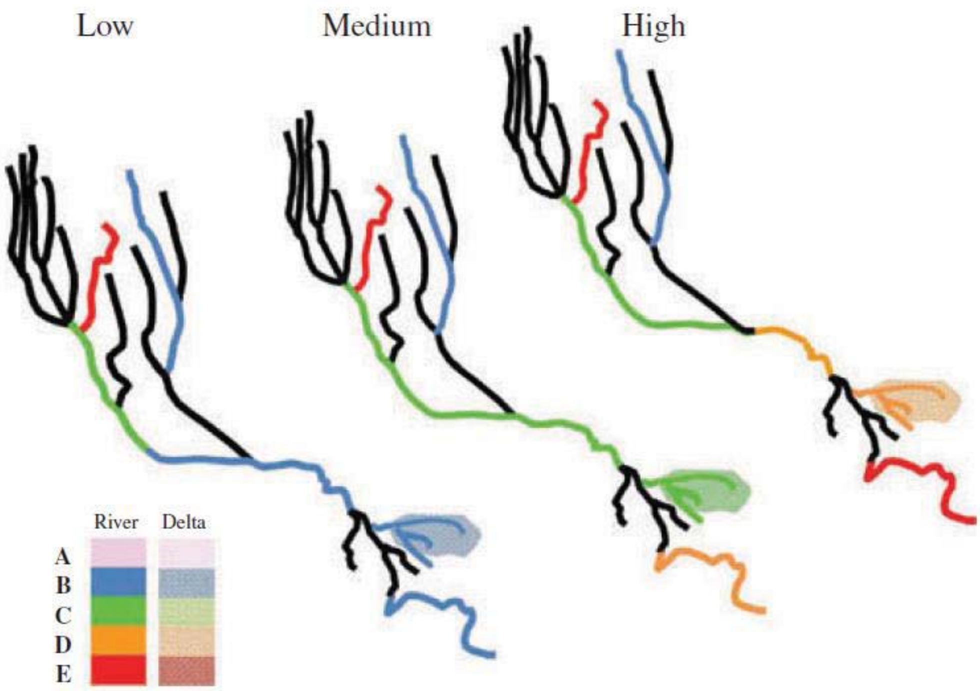

Figure 18: Results of the application of the DRIFT environmental flow assessment for the Okavango to produce the transboundary diagnostic analysis for the system (King et. al. 2014). Colours represent the relative wellbeing of the indicators considered in the study in different parts of the system for the low, medium and high water-use scenarios. A: Natural ecosystem; B: Largely natural; C: Moderately modified; D: Largely modified; E: Critically modified.

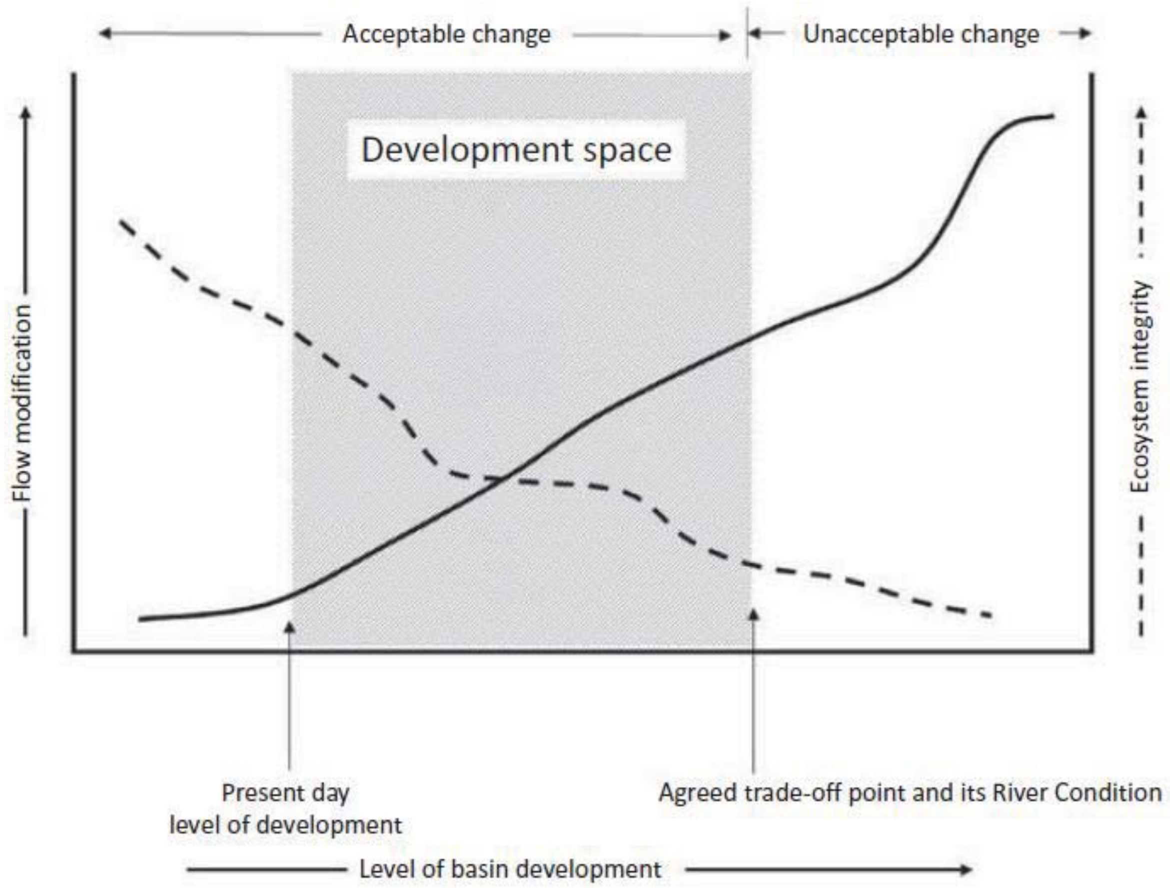

Figure 19: The concept of Development Space, which is defined by present-day conditions and the negotiated limit of ecosystem degradation as basin development proceeds from King et. al. (2014).

4.2 Overview of environmental flow assessment management frameworks

Current best practice EFAs on a basin scale includes the selection of, and implementation of a suitable EFA framework. This allows for the holistic assessment of EFAs on suitable spatial scales where ecological and if necessary social consequences can be considered in a structured manner. These EFA frameworks have been developed to allow for a phased approach for EFAs within large basins where multiple EFA case studies can be undertaken at different levels of confidence which all contribute to the greater management of flows on a basin scale. In this section two EFA frameworks, the Ecological Limits of Hydrologic Alteration and the Sustainable Management of Hydrologic Alteration, are reviewed.

Ecological Limits of Hydrologic Alteration (ELOHA)

In an attempt to address impaired riverine ecosystems caused by hydrologic alteration on large spatial scales (≥ basin scale), where the pace of impairment exceeds the ability of scientists to assess the effects of hydrologic alteration on a river-by-river basis, the ELOHA framework has been established (Poff et al., 2010). The approach combines a number of existing hydrologic techniques and EFMs that are currently being used to various degrees and that can support comprehensive regional flow management. The flexible approach allows stakeholders to analyse and synthesise available scientific information into ecologically based and socially acceptable goals and standards for management of environmental flows. The ELOHA framework includes the synthesis of existing hydrologic and ecological databases from many rivers within a user-defined region to develop scientifically defensible and empirically testable relationships between flow alteration and ecological responses (Poff et al., 2010). These relationships serve as the basis for the societally driven process of developing regional flow standards. This is to be achieved by first using hydrologic modelling to build a 'hydrologic foundation' of baseline and current hydrographs for stream and river segments throughout the region. Second, using a set of ecologically relevant flow variables, river segments within the region are classified into a few distinctive flow regime types that are expected to have different ecological characteristics. These river types can be further sub-classified according to important geomorphic features that define hydraulic habitat features. Third, the deviation of current-condition flows from baseline-condition flow is determined. Fourth, flow alteration–ecological response relationships are developed for each river type, based on a combination of existing hydro-ecological literature, expert knowledge and field studies across gradients of hydrologic alteration. Scientific uncertainty will exist in the flow alteration–ecological response relationships, in part because of the confounding of hydrologic alteration with other important environmental determinants of river ecosystem condition (e.g. temperature). Application of the ELOHA framework should therefore occur in a consensus context where stakeholders and decision-makers explicitly evaluate acceptable risk as a balance between the perceived value of the ecological goals, the economic costs involved and the scientific uncertainties in functional relationships between ecological responses and flow alteration (Poff et al., 2010). The ELOHA framework also should proceed in an adaptive management context, where collection of monitoring data or targeted field sampling data allows for testing of the proposed flow alteration–ecological response relationships. This empirical validation process allows for a fine-tuning of environmental flow management targets. The ELOHA framework can be used both to guide basic research in hydro-ecology and to further implementation of more comprehensive environmental flow management of freshwater sustainability on a global scale. (Poff et al., 2010).

Sustainable Management of Hydrologic Alteration (SUMHA)

In EFAs very little consideration of the trade-offs between human and environmental water needs is provided (Pahl-Wostl et al., 2014). Building on recent advances in environmental flow science, water governance and management Pahl-Wostl et al. (2014) identify a clear need for a more systematic approach to the determination of EFRs that address socio-ecological endpoints in particular and have proposed the SUMHA approach. The framework supports scientific analysis and practical implementation of EFRs involving systematic compilation, sharing and evaluation of experiences from different riverine ecosystems and governance systems around the globe. The concept of ecosystem services is introduced into the framework to raise awareness for the importance of ecosystem functions for the resilience of social-ecological systems, to support negotiation of trade-offs and development of strategies for adaptive implementation (Pahl-Wostl et al., 2014). Experience in implementation of environmental flow policies reveals the need for an engaged, transdisciplinary research approach where research is closely linked to implementation initiatives on the ground. We advocate that this is more effective at building the foundations for sustainable water management (Pahl-Wostl et al., 2014).

4.3 Advantages and disadvantages of environmental flow assessment procedures

Many EFMs have been established and used extensively around the world. In many cases these EFAs have been designed to meet the information requirements of local flow management questions and are not necessarily suitable for application in a regional scale context outside of the region where they have been developed. The advantages and disadvantages of the EFAs are generally comparable within each EFA group. Below a comparison of the resource requirements, specialist requirements, adaptability and transparency, considerations of flow-ecology-social consideration, validity of outcomes and then uncertainty evaluation of EFM considered is provided in Table 1.

The financial cost of the different EFMs considered in the study and summarised in Table 1, has been based on limited available published data and from EFA project managers from South Africa, Europe and the United States of America. This low confidence overview depends largely on number of sites, regional specialist service costs, availability of data and complexity/detail of assessment (Figure 20).

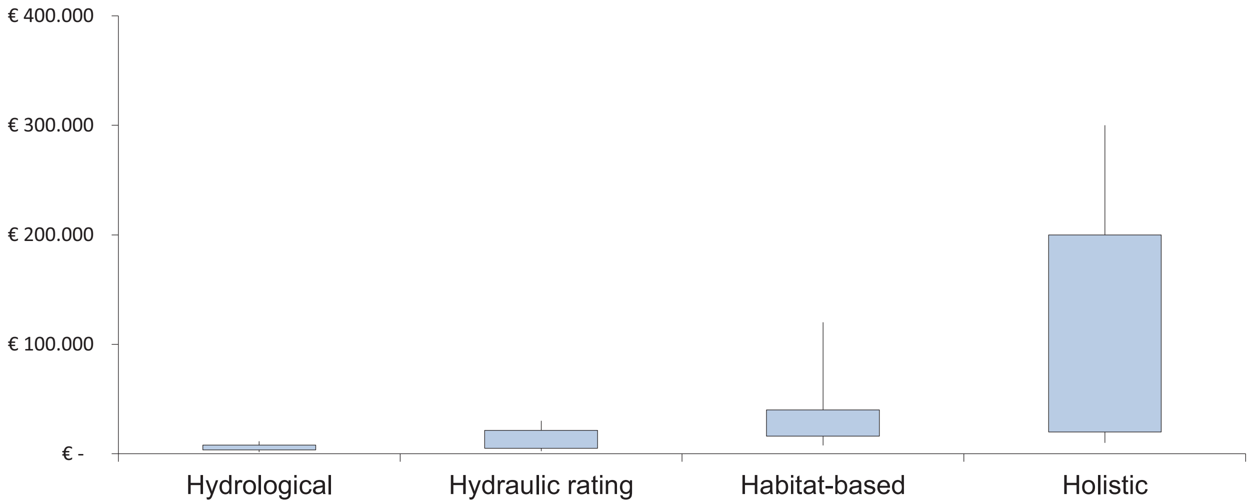

Figure 20: Graphical representation of the cost (in Euros) to undertake the different environmental flow assessments, per site according to available data and EFA project managers. Box lines represent min and max and box range represents 25%tile and 75%tile.

Table 1: Advantages and disadvantages of the environmental flow assessment categories (adapted from Reitberger and McCartney, 2011).

	Hydrological Environmental Flow Methods	**Hydraulic rating Environmental Flow Methods**	**Habitat-based Environmental Flow Methods**	**Holistic Environmental Flow Methods (combines components of other EFAs)**
TIME REQUIREMENTS & LEVEL OF DETAIL FOR ASSESSMENTS:	0 → 3 MONTHS	0 → 6 MONTHS	6 → 12 MONTHS	12 → 36 MONTHS
1. Desktop	✓ Modelled data.	✓ Unusual – modelled.	✓ Limited data used.	✓ Limited data used.
2. Intermediate (usually with 1 site visit)	✓ Modelled/real data.	✓ Limited real data.	✓ Real data for few components only.	✓ Real data for few components only.
3. Comprehensive (usually with 2 site visit)	✓ Real long term data.	✓ Real data.	✓ Data for all Components.	✓ Data for all Components.
DATA REQUIREMENTS:				
1. Hydrological data	✓ Required	✓ Required	✓ Required	✓ Required
2. Hydraulic data	✗ NA	✓ Required	✓ Required	✓ Required
3. Habitat data	✗ NA	✗ NA	✓ Required	✓ Required
4. Water quality	✗ NA	✗ NA	? Useful	✓ Required
5. Water resource use scenarios	✗ NA	✗ NA	✗ NA	✓ Required
6. Ecological requirements	✗ NA	✗ NA	? Partial	✓ Required
Fish			✓ Common	✓ Common
Invertebrate			✓ Common	✓ Common
Riparian Vegetation			? Uncommon	✓ Common
Other			? Unusual	? Unusual
7. Social data	? Unusual	? Unusual	? Unusual	✓ Common
8. Economic data	? Unusual	? Unusual	? Unusual	? Useful

HUMAN RESOURCES (SPECIALIST) REQUIREMENTS: 1. Environmental flow specialist 2. Hydrologist 3. Hydraulic engineer 4. Ecologists 5. Sociologists 6. Economists	Required Required NA NA Useful Useful	Required Required Required NA Useful Useful	Required Required Required Required Useful Useful	Required Required Required Required Required Useful
FINANCIAL REQUIREMENTS (COSTS): *Depends largely on number of sites, regional specialist service costs, availability of data and complexity/detail of assessment. Cost guidance range provided in Euros (€) per site according to available data and EFA project managers (refer to* Figure 20*).*	 Proposed range: Minimum: 1,500 € Average: 6,500 € Maximum: 11,500 €	 Proposed range: Minimum: 2,500 € Average: 8,500 € Maximum: 32,000 €	 Proposed range: Minimum: 7,500 € Average: 20,000 € Maximum: 120,000 €	 Proposed range: Minimum: 10,000 € Average: 45,000 € Maximum: 300,000 €
TRANSPARENCY AND ADAPTABILITY: Depends on the confidence of the assessment, the data used and ability to replicate the assessment.	Approach based on real transparent data. Modelling techniques generally transparent.	Approach based on real transparent data. Modelling techniques generally transparent.	Use of complex tools affects transparency & high dependence on solicitations also affects transparency.	Use of complex tools affects transparency & high dependence on solicitations also affects transparency.
FLEXIBILITY: Relates to the ability of the EFA type to address management requirements, adapt to case studies, environment and use scenarios.	Approach is found-ational to all other EFA methods & is not suitable to address socio-ecological issues.	Approach also found-ational to other EFA methods but does not address socio-ecological issues.	Approach links hydrology to habitat limited links to socio-ecological endpoints.	Flexible approach designed to link hydrology to socio-ecological endpoints.

UNCERTAINTY PRESENTED: Some of the EFA approaches incorporate modelling tools and or solicitations that affect the uncertainty of the assessment. In some occasions these uncertainties are not presented.	✓ Established EFA approach requiring validation, sensitivity analyses and uncertainty presentations.	✓ Established EFA approach requiring validation, sensitivity analyses and uncertainty presentations.	? Wide range of modelling tools and use of solicitations affects uncertainty which is not always presented.	✓ Wide range of modelling tools and use of solicitations affects uncertainty. This is not always presented but best scientific practice requires detailed uncertainty evaluations which is available.
CONFIDENCE: In the context of EFA outcomes contributing to the establishment of a sustainable balance between the use and protection of water resources.	✗ This EFA type on its own provides managers with an understanding of the hydrological dynamics of ecosystems but should not be used in isolation to establish Environmental Water Requirements to address the use and protection of water resources.	✗ Similarly, this type of EFA approach allows managers to relate hydrological dynamics to the physical hydraulics for flow/habitat management. But should not be used to establish Environmental Water Requirements to address the use and protection of water resources.	? This type of EFA approach can be used to establish protection requirements but is usually provided out of context of the need to balance use and protection of water resources.	✓✓✓ Holistic EFAs have been designed to establish Environmental Water Requirements to specifically address the use and protection of water resources. These tools also usually allow for trade-offs between flow related use and protection requirements to be evaluated.

5 Challenges to environmental flow assessments in developing countries and enforcement

Many developing countries do not have resource protection measures and Integrated Water Resource Management Plans for example. In these countries in particular, limited consideration of environmental flows within water resource management policies exists. In addition, although many local and regional stakeholders of these regions require suitable environmental flow management strategies; lack of political will, availability of technical skills, financial resources and data availability affect the development of EF policies. Additional factors including limited knowledge of complex social and ecological systems and global threats such as climate change also affect the establishment of EF policies and the implementation of EFAs.

In some developing regions of the world where environmental flow alterations associated with water resources developments are closely linked to economic development, environmental flow assessments and the associated flow management is widely considered to be "restrictive" and to hamper economic development. This view is however limited, and needs to be addressed by promoting environmental flow awareness and stakeholder engagement activities that include training activities and the considerations of lessons learnt from developed nations.

In addition, the inappropriate use of low confidence EFA outcomes for flow management, and the inappropriate application of EFMs has resulted in incorrect management actions which have had negative socio-ecological consequences that have on occasion resulted in conflicts. *It is important the EFAs and the EFMs used to manage altered flows in the environmental are used appropriately.*

Although many EFAs have been undertaken in developing nations many nations have not adequately implemented the outcomes. Factors considered to be affecting the implementation and enforcement of EFAs include:

- Enforcement can only be supported through policy development and legislation development. Without sound EF legislation there is no accountability for affecting the wellbeing of water resources.
- Human and financial resource limitations affects implementation and enforcement.
- The focus of many nations is to develop their resources, this is often accomplished at the cost of the environmental wellbeing which includes implementation of suitable environmental flow management plans.
- Limited buy-in from stakeholders who instead of contributing to implementation challenge the outcomes of the assessments.
- The frequency of civil unrest and conflict is relatively greater in developing nations compared to developed countries. In regions affected by unrest EF implementation and or enforcing is limited.

6 Conclusions and recommendations

The effect of environmental flow alterations to the wellbeing of surface aquatic ecosystems and the people who depend on these ecosystems is well known in the developed world. Five key hydrological components of environmental flow alterations that are considered to be important to the socio-ecological benefactors of ecosystems and ecosystem service use include:

- variability of flows,
- magnitude,
- frequency,
- duration,
- timing and
- rate of change of flows.

The science of environmental flows has developed rapidly over the past few decades, from being considered to be in its infancy phase in the 1990s to being well developed today with a range of dynamic tools and frameworks to direct environmental flow assessment on multiple spatial and temporal scales for multiple social and ecological endpoints. In addition, environmental flow management and related resource management issues rank highly on the international policy agendas of many developed and developing nations. Currently, numerous broad **best practice environmental flow management principles** have been established for application in developed and developing regions of the globe. These include:

Best practice environmental flow management principles

- Environmental flow management should be incorporated into IWRM that advocates balance between the protection and use of water resources, in an equitable manner (on a regional scale), with the consideration of environmental flows in the context of other synergistic anthropogenic (such as water quality) and other drivers of change such as climate change.
- The participation of stakeholders to establish a vision for EFAs that consider all of the needs of local and regional interested and affected parties is important to be a foundational component of EFAs.
- Environmental flow management should include society in decision making process, promote broad scale buy-in and participation in water resource management on regional scales.
- Environmental flow management should encourage awareness and education and transfer skills and or capacity development/transfers, especially for developing regions.
- Environmental flow management approached must be evidence based and present the uncertainty associated with the assessment explicitly.
- The approached should consider climate change and human population growth.
- The methods should consider the multiple stressors, define the relationships between stressors and multiple social and ecological endpoints, and evaluate the trade-offs between and socio-ecological endpoints are preferential.
- They should develop transparent, adaptable outcomes-based (implementable) results which can be monitored and tested by local expertise are preferable.

- Case studies should be subjected to the scientific peer review process to promote objectivity and continue to develop best scientific practices.
- Approached should adopt the precautionary approach in an adaptive management context.
- Mitigation measures should be incorporated to avoid or reduce the likelihood of negative impacts.
- Environmental flow management should not be considered to be flawless but a continually developing science.

The four broad environmental flow assessment method categories, and combinations of these categories include:

- hydrological,
- hydraulic rating,
- habitat simulation (or rating), and
- holistic methodologies.

These methods have various advantages and disadvantages and have been used to address a variety of environmental flow management related requirements internationally. The selection of an environmental flow assessment method should address the recommendations of the latest regional scale environmental flow management frameworks including the Ecological Limits of Hydrologic Alteration (ELOHA) and Sustainable Management of Hydrological Alterations (SUMHA) frameworks.

The findings of this assessment demonstrate that best current environmental flow assessments include:

- holistic assessments that consider ecological and social consequences of altered flows,
- establishment of environmental flows (EF) frameworks that allow different application of environmental flow Methods (EFM) in a structures manner that can later be used to manage flows on a basin scale (please refer to chapter 4.2).
- use of robust, tested methods that are adaptable and transparent and applicable on multiple spatial scales that allow for the evaluation of multiple management scenarios and offer structured assessments of the trade-offs between social and ecological objectives.

These principals should be considered in the development of EF studies in the Nile Basin.

7 Way forward

The scope of this brief has been to review the global practices and experiences of Environmental Flow Assessments (EFA). This included the establishment of current global best practice principals for environmental flow assessments which should be considered for the environmental flows (EF) applications in the Nile Basin. For this to be achieved a Nile Basin specific EF framework which takes these best practice principals into consideration should be established.

Following on the completion of this brief, the ecosystems within the Nile Basin that should be considered for flow management will be reviewed and presented in Background Document 2. Furthermore the policies and formal guidelines for local states in the Nile Basin will be evaluated and presented in Background Document 3. This information will allow stakeholders of the Nile Basin Initiative (NBI) to evaluate best flow management principles, in the context of the ecosystems in the Nile basin and their wellbeing and the local legislative context of the study area so that a suitable framework for environmental flow assessments in the Nile Basin can be developed.

This study will proceed to the regional stakeholder review/validation workshop. At this workshop recommended procedures for establishing environmental flow requirements for Nile Basin aquatic ecosystems will be discussed and reported on to propose a best practice environmental flow framework for the Nile Basin. The framework and selected environmental flow assessment methods will then be tested on different spatial scales in the Nile Basin and the outcomes of the assessment will be synthesised to provide recommendations for future management.

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ENTRO

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