Guidance on Environmental Flows - Integrating E-flow Science with Fluvial Geomorphology to Maintain Ecosystem Services

Guidance on Environmental Flows

Integrating E-flow Science with Fluvial Geomorphology to Maintain Ecosystem Services

2019 edition

WEATHER CLIMATE WATER

WORLD
METEOROLOGICAL
ORGANIZATION

WMO-No. 1235

2019 edition

WORLD
METEOROLOGICAL
ORGANIZATION

WMO-No. 1235

EDITORIAL NOTE

METEOTERM, the WMO terminology database, may be consulted at http://public.wmo.int/en/resources/meteoterm.

Readers who copy hyperlinks by selecting them in the text should be aware that additional spaces may appear immediately following http://, https://, ftp://, mailto:, and after slashes (/), dashes (-), periods (.) and unbroken sequences of characters (letters and numbers). These spaces should be removed from the pasted URL. The correct URL is displayed when hovering over the link or when clicking on the link and then copying it from the browser.

WMO-No. 1235

Chair, Publications Board
World Meteorological Organization (WMO)
7 bis, avenue de la Paix
P.O. Box 2300
CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 84 03
Fax: +41 (0) 22 730 81 17
Email: publications@wmo.int

ISBN 978-92-63-11235-4

PUBLICATION REVISION TRACK RECORD

Date	*Part/ chapter/ section*	*Purpose of amendment*	*Proposed by*	*Approved by*

CONTENTS

ACKNOWLEDGEMENTS

WMO would like to acknowledge the work of the lead author, Dr Martina Bussettini, from the Italian Istituto Superiore per la Protezione e la Ricerca Ambientale, and co-author, Dr Paolo Vezza, from the Politecnico di Torino, as well as an excellent team of reviewers, which included Dr Roger Moussa from the French Institut national de la recherche agronomique, and Mr Juan José Leitón Montero from the Costa Rican Instituto Costarricense de Electricidad.

The *Guidance on Environmental Flows* has been prepared under the auspices of the WMO Commission for Hydrology.

1. INTRODUCTION

1.1 Setting the scene

Fluvial systems provide a wide range of necessary services for human society to thrive on. These are the so-called ecosystem services: food, drinking water, natural flood mitigation, energy and so forth. Such services are linked to an appropriate level of functionality of fluvial processes, which can be accounted for in terms of ecological objectives.

These ecological objectives in watercourses can be reached only if appropriate flow and sediment regimes and related quality of channel morphology are guaranteed. The establishment and maintenance of such flow regimes, namely environmental flows (e-flows), is therefore an essential element in preserving riverine ecosystems and the services they provide, and should be included as a constraint in water resource assessment and in national legislative frameworks.

It is well established that e-flows refer to the typical seasonal and interannual variability of the natural flow regime, and not only to the minimum amount of water (low flows) to be maintained in a river. In addition to this pure hydrological assessment of natural flow variability, there is also the necessity to link e-flow definition to the related hydromorphological processes and local ecological objectives of a river.

This guidance therefore presents a methodology (based on knowledge and literature on river system processes) to consider hydrological and morphological aspects in defining e-flows for environmental river management.

The report has been produced within the context of an agreement between the WMO Commission for Hydrology and the Italian National Institute for Environmental Protection and Research (ISPRA), to cooperate in the implementation of activities related to managing river flows and maintaining services offered to human society and ecosystems. The research can be contextualized inside the implementation of the WMO Hydrology and Water Resources programme.

1.2 Existing e-flow concepts and terminology

In the common view of river science, a specific flow regime in a river, capable of sustaining a complex set of aquatic habitats and ecosystem processes, is referred to as an "e-flow".

However, the term "e-flow" has other names or variants worldwide because river environmental management brings together scientists from different disciplines. For instance, instream flow needs, ecological reserve, ecological demand of water, environmental water allocation (or requirement), compensation flow or minimum flow are terms used across different regions of the world. Furthermore, the e-flow concept has evolved over time, and its meaning has been shifting from the traditional view of minimum water amounts to a more comprehensive and holistic understanding of a river system and its dynamics.

The term "environmental flows" was originally referred to in the Brisbane Declaration (2007), endorsed at the 10th International River Symposium (held in Brisbane, Australia, in 2007) by more than 750 delegates from 50 nations. In the declaration, "Environmental flows describes the quantity, quality and timing of water flows required to sustain freshwater ecosystems and the human livelihoods and well-being that depend on these ecosystems."

When used in a legal context, the concept can vary substantially and be used for binding obligations. As an example, in the implementation of European legislation on water protection, namely the European Union Water Framework Directive (WFD), the term in use is "ecological flows", meaning the hydrological regime that allows the achievement of the good ecological status of water bodies, which is the environmental objective of WFD.

As reported in previous e-flow guidance (Fisheries and Oceans Canada, 2013; European Commission, 2015), the e-flow concept should not be confused with similar terminologies such as “instream flow requirement” (Annear et al., 2004), which is mostly focused on flows within the main river channel (not really taking into account the riparian zone and flood-plains), or “minimum flow”, which merely limits the e-flow concept to the minimum amount of water to be respected during low-flow periods or dry seasons.

Referring to the terminology “ecological reserve”, “ecological demand of water” or “ecological flow” are consistent with the term “ecology” and the analysis of interactions between living organisms and the river system. However, a conceptual extension is needed here, as stakeholder requirements (for example, water allocation for different human activities) need to be included in e-flow assessment.

Therefore, in this guidance, the term “environmental flows” is selected because it provides the most inclusive definition considering the protection of natural ecosystems and human water needs.

However, it could be argued that the e-flow concept is based only on water flow requirements, not really including in the assessment how fluvial habitats are effectively shaped by the combined interaction of water, sediments, woody/organic material and riparian vegetation (Wohl et al., 2015). To broaden e-flow definition, this guidance is dedicated to presenting a new approach that considers river system dynamics when specifying e-flows, thereby expanding the environmental objectives and definitions to include geomorphological river changes.

In this Guidance, Chapter 2 describes trends of water demands for human activities. It underlines the sustainability of water withdrawals and the urgent need for a more comprehensive e-flow definition. Chapter 3 presents a review of existing approaches, along with available guidance and common practices for e-flow implementation at the global scale. Chapter 4 is dedicated to describing the proposed methodological framework, which integrates e-flow science with fluvial geomorphology. Chapter 5 presents a few case studies and applications of this framework. Chapter 6 concludes by providing a description of emerging approaches and potential for water resources management.

2. PRESSURES ON STREAMS AND E-FLOW RELEASES

2.1 Increasing water demand

The world’s population is expected to increase by 33% between 2011 and 2050, growing from 7 billion to 9.3 billion (United Nations Department of Economic and Social Affairs, 2015). Food demand is predicted to rise by 60% over the same period (Alexandratos and Bruinsma, 2012). Population dynamics and an ever-increasing global standard of living are driving production and consumption of goods and services to meet the escalating needs of a growing and richer population. Market demand for water-intensive products such as meat tends to increase with economic development, thus dramatically raising the water demand from agriculture. In addition, the growth in energy demand, which is also water intensive, is expected to surge (World Water Assessment Programme, 2016).

Water use (withdrawals and consumption) by different sectors is generally based on estimates, rather than measurements (World Water Assessment Programme, 2016). These estimates indicate that freshwater withdrawals increased globally by about 1% per year between 1987 and 2000 according to the Food and Agriculture Organization of the United Nations (FAO, 2015). Evidence suggests a slightly lower growth rate (0.6%) over the past 15 years. In much of the world’s most highly developed countries, freshwater withdrawals have now stabilized or slightly declined. This has been due, in part, to a combination of improved water-use efficiency and increased importation of water-intensive products, including food, from least developed countries (LDCs). It can therefore be deduced that the increase in water use is occurring mainly in those developing countries.

Agriculture accounts for about 70% of total freshwater withdrawals globally and for over 90% in most LDCs. Developed countries generally withdraw less for agriculture and more for

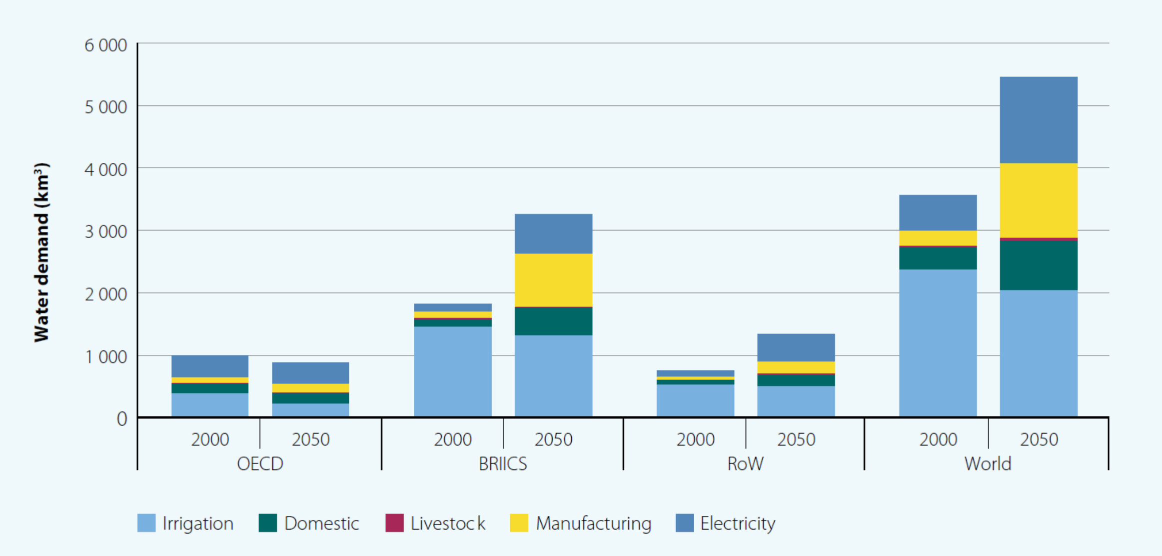


Figure 1. Global water demand (freshwater withdrawals): baseline scenario 2000 and 2050. Withdrawal is the total amount of water taken from a lake, river or aquifer for any purpose. The OECD baseline scenario is a business-as-usual scenario that assumes linear growth rates in water demand trends and the absence of new policies that would affect these growth trends (World Water Assessment Programme, 2016). BRIICS = Brazil, Russian Federation, India, Indonesia, China and South Africa; RoW = rest of the world. The figure measures the "blue water" demand only and does not consider rain-fed agriculture.

Source: OECD (2012)

energy production and large industry, which account for 15% and 5% of global withdrawals, respectively. Fulfilling the water-related needs of households (for drinking water, sanitation, hygiene, cleaning and so forth), institutions (for example, schools and hospitals) and most small- and medium-sized industries, municipal systems account for the remaining 10% of global freshwater withdrawals (World Water Assessment Programme, 2016).

Without improved efficiency measures, agricultural water consumption is expected to increase by about 20% globally above the 2012 level by 2050 (World Water Assessment Programme, 2016). Water demand for energy, and electricity generation in particular, will also grow significantly. Energy demand is expected to grow by more than one third in the period 2010–2035. According to these predictions, the Organisation for Economic Co-operation and Development (OECD) baseline scenario projected global water demand (in terms of freshwater withdrawal) to increase by some 55% due to growing demands from manufacturing (400%), thermal electricity generation (140%) and domestic use (130%) (OECD, 2012; Figure 1).

While OECD projects a global decrease in future water withdrawals for irrigation (Figure 1), FAO estimates a 5.5% increase in irrigation water withdrawals from 2008 to 2050 (Alexandratos and Bruinsma, 2012). This highlights the challenge of quantifying projected global water demand and associated water stresses. However, although OECD and FAO estimates are not necessarily contradictory, increasing irrigation efficiency may enable a larger proportion of water withdrawn to be consumed by crops in the field.

2.2 Hydropower development

Human population growth, economic development, climate change and the need to close the electricity access gap have stimulated the search for new sources of renewable energy. Therefore, major new initiatives in hydropower development are now under way. At least 3 700 major dams, each with a capacity of more than 1 MW, are either planned or under construction,

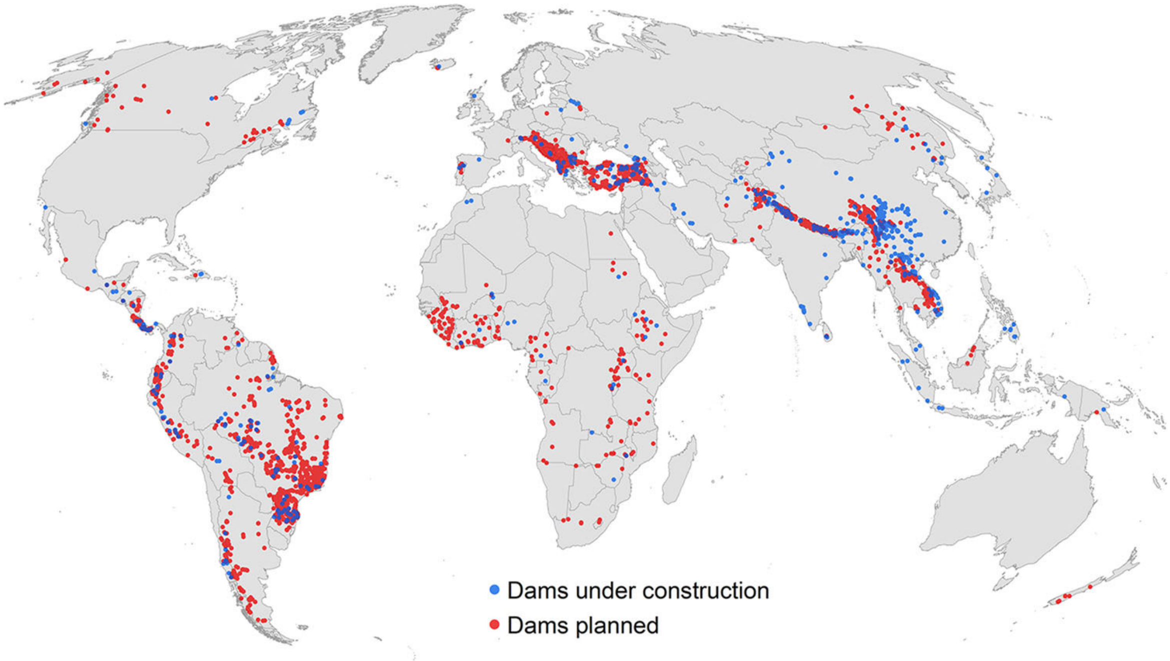


Figure 2. Global spatial distribution of future hydropower dams, either under construction (blue dots – 17%) or planned (red dots – 83%). The inventory was based on information derived from more than 350 scientific references, governmental and non-governmental sources, and from other public databases, reports and newspaper articles.

Source: Zarfl et al. (2015)

primarily in countries with emerging economies. These dams are predicted to increase the global hydroelectricity capacity by 73% above the 2014 level, to about 1 700 GW (Figure 2; Zarfl et al., 2015).

With regard to environmental impacts, Zarfl et al. (2015) estimated that this hydropower development will reduce the number of free-flowing large rivers by about 21% below the 2014 level. Moreover, the re-accelerating construction of hydropower dams will globally lead to the fragmentation of 25 of the 120 large river systems classified as free flowing (Nilsson et al., 2005), primarily in South America (Figure 2).

It is important to note that the compilation of Zarfl et al. (2015) provides a conservative estimate because it focuses on dams designed for hydropower production; dams designed primarily for water supply, flood prevention, navigation and recreation are excluded. The compilation also excludes very small hydropower dams (<1 MW) that are under construction or planned; their number is most likely very high but not documented comprehensively globally.

The International Commission on Large Dams (2011) estimated that only 22% of the world's technically feasible hydropower potential (15.6 million GWh per year) is exploited. Following a period of relative stagnation during the past 20 years, the boom in hydropower dam construction is unprecedented in scale and extent (Figure 3).

Despite the renewable nature of hydroelectricity, its technology also comes with severe social and ecological adverse effects (for example, relocation of people and transboundary conflicts, fragmentation of free-flowing rivers and habitat changes), thus further threatening freshwater ecosystems. There is an urgent need to evaluate and mitigate the social, economic and ecological ramifications of the strong increase in global dam construction.

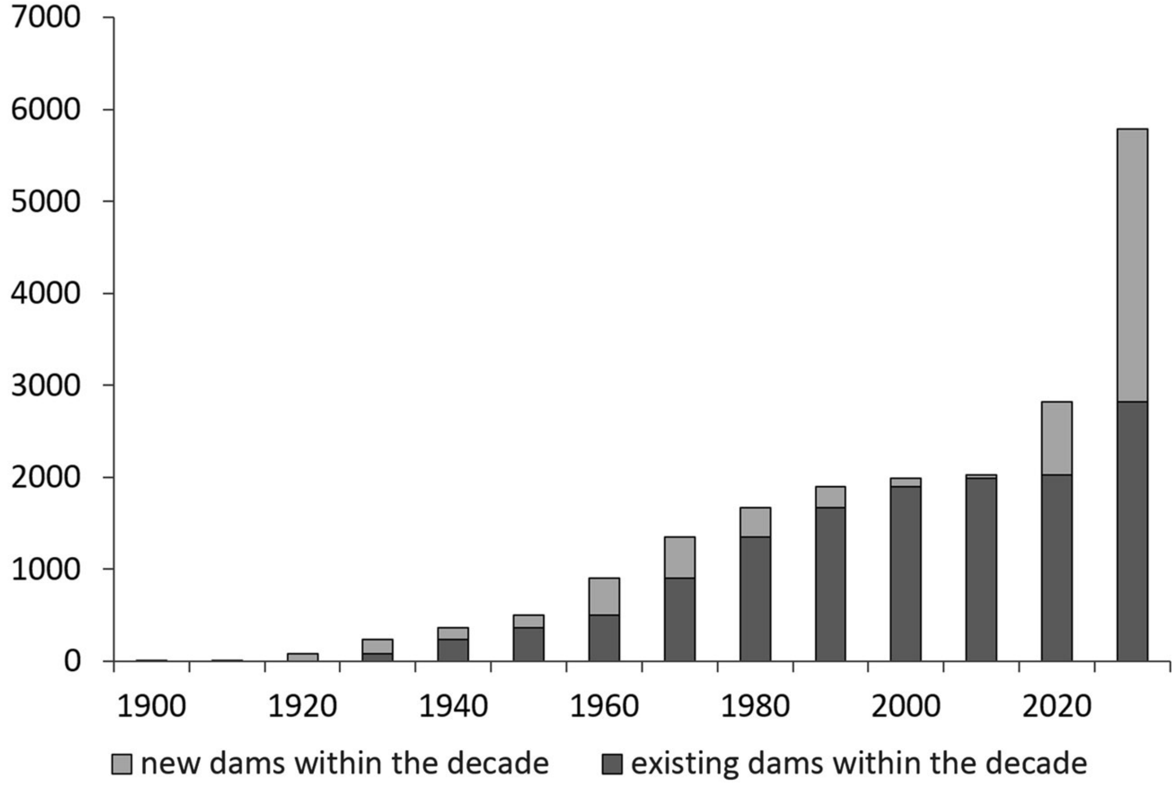


Figure 3. Existing number of hydropower dams (Lehner et al., 2011) and outlook for number of hydropower dams under construction or planned (Zarfl et al., 2015)

Source: Zarfl et al. (2015)

2.3 Ecosystem health, ecosystem services and e-flows

In the context of the predicted increase of water demand and hydropower development, e-flow assessment is essential to guarantee freshwater ecosystem services and continued access to water for people. It is therefore imperative that decision-makers assess the needs of water provisioning for the environment and take the actions required to preserve, sustainably manage and, where necessary, restore freshwater ecosystems based on available knowledge and datasets (World Water Assessment Programme, 2016).

Key decisions involve the allocation of sufficient amounts of water to ensure the sustainable functioning of human activities through e-flows (Brisbane Declaration, 2007). It is important to state that e-flows seek to maximize the socioeconomic opportunities provided by healthy and sustainable ecosystems and lower the risks associated with vulnerable water resources. Adequate management of ecosystem services also supports ecosystem resilience and the resilience of those who depend upon them to cope with stresses such as drought, extreme weather events and climate change.

A variety of approaches and tools are now available for e-flow assessment. Their implementation is included in integrated water resources management for the valuation of ecosystem services. The ecological, economic and sociocultural value of natural (and semi-natural) freshwater ecosystems refers to a variety of goods and services, including water purification, nutrient cycling, electricity production, fish provisioning, timber production, flood protection, biodiversity and wildlife habitat, erosion regulation, landscape aesthetic, opportunities for recreation and tourism, and cultural and historical symbols (Acuña et al., 2013).

There is therefore the need to assume that the quality, quantity, frequency, duration, timing and rate of change of river flow are essential for maintaining freshwater ecosystem functions, processes and services on which livelihoods and economic opportunities depend (Poff et al., 1997). Together with the flow regime, the sediment regime and river morphology are also important determinants that ensure the desired services of freshwater ecosystems (Wohl et al., 2015). Base flows mediated by riverbed geometry maintain a minimum habitat for aquatic species and soil moisture for riparian vegetation, while large floods recharge flood-plain aquifers, transport sediment, wood and organic material, and maintain habitat diversity. Therefore, it is crucial that in water resources management, a certain flow and sediment regime is accounted for in the maintenance of freshwater ecosystem functions and the services they provide to people.

On a global scale, there is significant momentum to incorporate e-flows into policymaking and river basin management plans. E-flows are already addressed in international agreements such as the United Nations Watercourses Convention, which entered into force in 2014 (Rieu-Clarke et al., 2012), regional frameworks such as the European WFD (European Commission, 2000, 2015) and national water policies such as the South African National Water Act (Forslund et al., 2009).

UN-Water proposed a global Sustainable Development Goal (SDG 6) for water, "Ensure access to water and sanitation for all", as fundamental to all other SDGs (which were adopted in 2015 and came into force on 1 January 2016). The proposed framework applies to all countries. Within the set of six SDG 6 supporting targets, target 6.4 ("By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity") and target 6.6 ("By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes") aim to promote decisions and actions that take into account human and environmental water requirements, as well as the need to increase the long-term viability of natural supply systems.

Achieving these targets will be determined by the indicators related to water stress, which are measured by the withdrawal to availability freshwater ratio and the change in the extent of water-related ecosystems over time. Success in this endeavour of achieving the targets will require actions covering the following three elements:

1. Bringing freshwater withdrawals into line with sustainably available water resources;

2. Restoring and maintaining ecosystems to provide water-related services;

3. Increasing water productivity for all uses.

Global water withdrawals continue to rise by about 10% every 10 years (Figure 1), but are expected to be much higher in developing regions. Complementary measures, such as e-flows, would be required to balance demands from different users, uses and services provided.

Maintaining a threshold level of e-flows will generate major social, economic and environmental returns (Rijsberman, 2004). For instance, watershed protection initiatives in the United States of America are estimated to have yielded US$ 7.5 to US$ 200, for every dollar invested, compared to conventional water treatment costs (Emerton and Bos, 2004). The use of improved water resources management and institutions, rather than traditional supply-side measures, can be effective and cost beneficial. For example, in Tamil Nadu, India, the creation of robust management institutions that would allow flexible allocation of water between uses could increase the state's production by 20% over 20 years, compared to reliance on fixed allocations (Grey and Sadoff, 2005).

3. REVIEW OF EXISTING APPROACHES AND GUIDANCE

E-flow assessment should determine the hydrological regime necessary for aquatic ecosystems to reach environmental goals. There has been a progressive evolution of methodologies for assessing the water needs of aquatic ecosystems since the 1970s (Acreman and Dunbar, 2004). First attempts focused on the definition of a "minimum flow" as a fixed percentage of average flows (Baxter, 1961; Tennant, 1976) or a low-flow duration statistic (for example, the 95th percentile flow, Q95). From 1980 to 1995, e-flow science was advanced, assimilated into practice and challenged. By the end of the 1990s, a general protocol was established for restoring regulated rivers (Stanford et al., 1996), and the natural flow paradigm (Poff et al., 1997) had become embedded in e-flow science (Petts, 2009). For instance, the association between the health of river ecosystems and flow variability was the centre of the United States Instream Flow Council Guidance (Annear et al., 2004), but even after 30 years, the philosophy of using simple operational rules fundamentally based upon minimum flows remains widespread (see the worldwide review provided in section 3.4 below).

Although the techniques for assessing e-flows can be categorized in a variety of ways, three basic ones are widely recognized: hydrological methods, hydraulic-habitat methods and holistic methodologies (King et al., 1999; Tharme, 2003; Acreman and Dunbar, 2004; Petts, 2009). These are described briefly below.

3.1 **Hydrological methods**

Hydrological methods are based on assessment of the natural flow regime as a key variable in the structure and functioning of aquatic ecosystems. The range and variation of flows over recent times have set a template for contemporary ecological processes, evolutionary adaptations and native biodiversity maintenance (Resh et al., 1988; Bunn and Arthington, 2002; Lytle and Poff, 2004; Doyle et al., 2005). The main assumption of this category is that e-flow recommendations designed from the natural flow regime will result in processes and conditions that will maintain native habitats and species. Depending on the desired level of environmental conservation, e-flow recommendations should reflect the natural flow regime.

There are numerous methodologies that rely primarily or solely on hydrological data for deriving e-flow recommendations (Tharme, 2003). The most comprehensive ones assume that the full range of natural variability in the hydrological regime is necessary to conserve aquatic ecosystems. The characterization of a natural range of variability, on the short-term features of the flow regime and also on the natural flow variability over longer periods (decades), aims at defining e-flows able to maintain a changing mosaic of habitat patches and ecological resilience to disturbance (Davies et al., 2014).

Supporting the need to sustain flows that mimic the natural climatically driven variability, hydrological methods may have the potential to move attention away from a single target community (for example, fish), possibly focusing on the ecological needs of the entire river corridor (Petts, 2009).

Hydrological-based methods are still the most widely used approaches internationally (Benetti et al., 2004; Rodríguez-Gallego et al., 2012; Speed et al., 2012; Linnansaari et al., 2013; European Commission, 2015), most probably because of local availability of streamflow time series (measured or simulated), low cost and ease of use of hydrological formulae, and limited needs of field visits and data collection.

However, the length of the hydrological dataset has had a great effect on the variability of hydrological e-flow estimates (Caissie et al., 2007). In general, appropriate validation of hydrological assessments in the target region must be carried out (Linnansaari et al., 2013). Kennard et al. (2010) suggested a record length of at least 15 years as appropriate for e-flow statistical integrity. Furthermore, other important issues related to hydrological e-flow estimation may refer to the problem of "naturalizing" the gauged flow records in catchments characterized by long-term human interference and the spatial distribution of gauging stations, which have to be located in low- and high-order streams.

Nevertheless, it is important to state that hydrological methods may lack ecological validity, not directly considering present and future river morphological conditions. High ecological uncertainty in the e-flow estimation can occur if flow–ecology relationships are not known for the type of river network under consideration. In particular, it is well known that e-flows play different roles in different fluvial morphological settings. Major infrastructures, such as large dams, can cause time-dependent morphological modification of the river channel. As river habitats are the result of a balance among interacting geomorphological forces (water, sediments and riparian vegetation), considering water flow only can be seen as a limited point of view to design ecologically effective e-flows.

3.2 Hydraulic-habitat methods

Hydraulic-habitat approaches assume that biological communities have evolved to exploit the full range of river habitats. The variability of flows determines when and for how long habitats are available to various species at different locations throughout the stream network (Petts, 2009).

With these methods, e-flow requirements are defined by assessing the hydromorphological conditions needed to meet specific habitat requirements for biota (Bovee et al., 1998; Merritt et al., 2010; Dunbar et al., 2012; Heggenes and Wollebæk, 2013). In particular, habitat features (such as water depth, flow velocity, substrate composition, channel geometry and cover availability) are used to predict species' distribution and abundance. Thus, the amount of habitat for biota is determined in relation to streamflow and channel morphological characteristics.

By the early 1990s, hydraulic-habitat approaches had expanded from the determination of purely hydraulic variables (Gippel and Stewardson, 1998) to a more complex representation of the river system (River Research and Applications, 2003). Specifically, many schemes addressed wider issues than hydraulic habitats of one or a few species, increasingly addressing the sustainability of communities and ecosystems within the whole river corridor (Merritt et al., 2010; Merenlender and Matella, 2013). They may have incorporated the access of aquatic biota to seasonal flood-plain and riparian habitats as well as the need for high flows for riparian species and floods to sustain the geomorphological dynamics of rivers (Grabowski and Gurnell, 2016).

To consider large temporal scales, habitat time series analysis (Milhous et al., 1990) plays an important role in e-flow definition (Parasiewicz et al., 2012*b*). It is useful to represent how habitat changes through time and to identify stress conditions created by persistent limitations in habitat availability. Habitat time series can be used to generate habitat duration curves and provide summary statistics on frequency and duration of habitat bottlenecks. These analyses could be developed to consider periods of habitat persistence related to key biological time windows (Parasiewicz et al., 2013).

Hydraulic simulation models can also be used to predict water depth and flow velocity in the river channel, as well as to evaluate the effects of flow regime changes on many aspects of the riverine environment, including riparian ecosystems (Merritt et al., 2010), river longitudinal connectivity and fish migration (Nel et al., 2011), sediment entrainment and deposition (for flushing flow and channel maintenance flow requirements; Robinson, 2012) and water quality (Davies et al., 2014).

Hydraulic-habitat methods are often considered more accurate than hydrological ones. However, these may require a considerable amount of fieldwork and expertise to collect the hydromorphological and biological data for model calibration. Even if the proposed methods remain focused on fixed-bed hydraulics, these models may have the ability to simulate changes in river flow and morphological conditions, enabling comparative analysis of different future management scenarios (Parasiewicz et al., 2012*b*).

3.3 Holistic methodologies

Holistic approaches are distinguished from single-purpose methods by the common feature that they aim to assess the e-flow requirements of the many interacting components of aquatic and riparian ecosystems (King et al., 2000; Arthington et al., 2006). The philosophy of these approaches is that all major abiotic and biotic components constitute the ecosystem to be managed, and that the full spectrum of flows, and their temporal and spatial variability, constitutes the environmental requirements. The flow components of a typical hydrograph are identified and described in terms of magnitude, duration, timing and frequency. The output is a description of a flow regime needed to achieve and maintain a specified river condition.

The holistic approaches generally consist of processes that allow river scientists from many disciplines to integrate data, model predictions and expert knowledge. Each specialist uses methods of their choice to develop an understanding of flow–ecosystem relationships, and then works with the other team members, within the overarching process of the holistic approach, to reach consensus on e-flows.

As an example, in the United Kingdom of Great Britain and Northern Ireland, an "expert panels" approach has been used to determine levels of "acceptable abstraction" in relation to the "ecological sensitivity" of river reaches (Acreman and Ferguson, 2010). In the United States, Poff et al. (2010) proposed a framework for assessing e-flow needs that combines a regional hydrological approach and ecological response relations. Stakeholders and decision-makers then explicitly evaluate acceptable risk as a balance among perceived value of the ecological goals, economic costs and scientific uncertainties.

In most of these methodologies, it is implicit that the attributes of the modified flow regime must lie within the range of values characterizing the historical hydrological pattern. This is based on the assumption that if a particular modified flow regime contains elements (for example, sequences of days of set discharge) that have never occurred in the historical record, then that modified flow regime is ecologically unacceptable.

The most commonly used holistic methodologies are the building block methodology (BBM; King et al., 2008) and the downstream response to imposed flow transformation (King et al., 2003). Arthington (1998) and Tharme (2003) provided thorough reviews of various holistic methodologies. In addition, the Ecological Limits of Hydrologic Alteration (ELOHA) framework has been developed to meet the needs of managing e-flows at regional, provincial or basin scales (Poff et al., 2010). ELOHA is a "top-down" method that defines environmental water requirements in terms of acceptable levels of change from the natural flow regime, involving the quantification of stress-response ecological relationships.

Depending on the depth of evaluation, data collection and extent of expert consultation, applications of the holistic framework can be time-consuming and expensive. Moreover, it is important to mention here that holistic methodologies still lack consideration of river morphological processes, as well as integration of e-flow assessment with sediment management and dynamics.

Meitzen et al. (2013) reviewed studies where field evidence indicated that geomorphology can have an impact on the effectiveness of e-flow strategies. They developed a question-based framework that facilitates geomorphology to be integrated into the practice, policy and implementation of e-flows.

3.4 E-flow estimation worldwide: commonly used methodologies and guidance

This section provides a general overview of the similarities and differences among approaches used in various regions of the world. The information provided could serve as a discussion, but it is not intended to review any potential e-flow methodological framework or to consider any aspect related to local legislation, or legal responsibilities for e-flow assessment. There is a wealth of literature about e-flow assessment methods, and the information collated here relies on that literature. The regions and countries mentioned below have been selected due to the high amount of reservoirs and regulated rivers in their territories [see Lehner et al. (2011) for details], which can be seen as hotspots for e-flow implementation. A region/country-based summary is reported in Table 1, which is supplemented by the detailed information given in the following paragraphs.

Table 1. Commonly used methods/methodologies for e-flow assessment in selected countries/regions

Country/ region	*Available guidance/ legislation*	*Most commonly applied methods/ methodologies*	*Notes*
Australia	Yes	Holistic	Monitoring and adaptive management based on holistic methodologies are commonly used
Canada	Yes	Hydrological/ holistic	An e-flow protocol is determined on a case-by-case basis, along with a public participation decision-making process
China	No	Hydrological	Most applied methods refer to minimum flow estimation
European Union	Yes	Hydrological/ hydraulic-habitat/ holistic	Hydrological approaches are the most commonly applied methods; not all Member States have national legislation on e-flows
India	No	Hydrological	Proposed recommendations for a longer-term e-flow research programme only are available
Japan	Yes	Holistic	Environmental minimum flow is assessed to maintain river functions, which meets maintenance flow for ecological processes and water uses by humans
Latin America	No	Hydrological	E-flow assessment is still referred to as a methodological proposition
New Zealand	Yes	Hydrological	Minimum flows based on proportions of the mean annual seven-day low flow (7 day MALF)
Russian Federation	Yes	Hydrological	Preliminary ecological thresholds are set using a hydrological flow index
South Africa	Yes	Holistic	The BBM framework can be resource intensive and time-consuming (1–2 years), but a simplified BBM can be applied in situations where considerable data on the river system already exist
Turkey	Yes	Hydrological	Some 10% of the annual average flow is determined as e-flows to be released from existing and new water abstractions
United Republic of Tanzania	Yes	Hydrological/ holistic	This country can be seen as a leading example for e-flow implementation in Central Africa
United States	Yes	Hydrological/ hydraulic-habitat/ holistic	Hydrological methods are largely applied; the ELOHA framework (Poff et al., 2010) has already been endorsed or applied in several states

3.4.1 *Australia*

All Australian jurisdictions have to provide e-flow assessments, which are strongly centred on holistic methodologies. Although different legislation has been implemented, monitoring and adaptive management based on holistic methodologies are used [see Arthington (1998) for a review of holistic methodologies commonly used in Australia].

3.4.2 *Canada*

Where they exist, e-flow guidelines in Canada tend to be recommendations to the regulator and are not legally binding. In general, the protocol is determined on a case-by-case basis, and e-flow standards are typically developed in a public participation decision-making process. In many provinces, a two-tiered structure with two levels of assessment has been adopted, to differentiate between "no harmful alteration, disruption or destruction of fish habitat" cases ("no HADD", referred to as level 1) and "potential HADD" cases (referred to as level 2). For level 2, site-specific studies are to be carried out to determine specific e-flow rules (Linnansaari et al., 2013).

3.4.3 *China*

Many of the methods for assessing e-flows adopted in China have been simplistic, hydrology-based methods for minimum flow estimation (Wang et al., 2009; Yang et al., 2009). However, Speed et al. (2012) developed an alternative generic method for assessing e-flow needs in Chinese rivers. This assessment was based on holistic e-flow assessment methods used in countries such as Australia, South Africa and the United States.

3.4.4 *European Union*

The European WFD (European Commission, 2000) mandates the Member States of the European Union to achieve good ecological status in all water bodies. Although WFD does not directly mention e-flows, the European Commission provided a Common Implementation Strategy (CIS) guidance (European Commission, 2015). This recognized that water quality and quantity in rivers are intimately related within the concept of "good status", and, for the implementation of WFD, "ecological flows represent the amount of water required for the aquatic ecosystem to continue to thrive and provide the services we rely upon". This CIS guidance intended to support a shared understanding of ecological flows and ways to use them in the next cycle of river basin management plans at the European level. It does not offer a full protocol for the implementation of e-flows in all water bodies, but underlines that Member States are encouraged to make best use of the shared e-flow understanding in all steps of the WFD process. It is interesting to note the European guidance reviews approaches applied in Europe to assess e-flows. Not all Member States have national legislation specifically concerning e-flows. Hydrological approaches are the most widely used, whereas holistic approaches are rarely applied.

3.4.5 *India*

Smakhtin and Anputhas (2006) discussed the advantages and limitations of different e-flow assessment approaches and proposed recommendations for a longer-term e-flow research programme in India. Although, the study did not give prescriptions for e-flow estimation for the entire country, it can be seen as an important step towards the development of national e-flow tools and policies. In their report, continuous monthly time series were proposed as e-flow standards using a simple spatial interpolation procedure at a catchment scale, whereas the final e-flow demand was presented in two forms: as a flow duration curve and as a monthly flow time series. Despite the important presence of large reservoirs, it seems that limited efforts have been carried out to implement e-flows in Indian river systems (Anuran and Jha, 2014).

3.4.6 *Japan*

In Japan, environmental river management is split among the national (central) government, prefectural government and city/town government, which are separately responsible for e-flow design and implementation in different river types and classes. Based on the guidance of the Ministry of Land, Infrastructure and Transport River Bureau, Japan is using an holistic approach to define an environmental minimum flow (Ministry of Land, Infrastructure and Transport River Bureau, 2007) in which "the proper use of rivers, maintenance of water flows, and conservation of riverine ecosystems is needed to ensure a safe and secure living environment, sustainable development of society, efficient use of national land, and environmental conservation". Environmental minimum flow is assessed to maintain "normal" (healthy) functions of river flow, which meets (minimum) maintenance flow and water uses by humans. Specifically, minimum flow is defined as a flow needed for shipping, fisheries, tourism, water quality, prevention of saline water intrusion, occlusion of the river mouth, protection of river management system, and sustenance of groundwater, landscape, habitat for animals and plants that should be sustained considering comprehensive needs and interactions between rivers and humans.

3.4.7 *Latin America*

E-flow assessment and implementation in Latin American countries seem to be still referred to as methodological propositions (Rodríguez-Gallego et al., 2012). Methods for estimating e-flows vary across the continent, but the use of hydrological formulae is generally the preferred approach. Hydraulic-habitat methods and holistic methodologies are much less widely used. Most of the studies and guidance reported in Latin American literature are recent, carried out in the last 15 years (Benetti et al., 2004; Jiménez, 2005; Alonso-EguíaLis et al., 2007; Barrios et al., 2007; Díez-Hernández and Ruiz-Corbo, 2007). Colombia, Costa Rica and Mexico stand out as having implemented more sophisticated methodologies. Despite the many dams and reservoirs, in Brazil, simple hydrological assessment methods are still commonly used for minimum flow estimation (50% or 70% of 7Q10, 10% of Q90, 5–20% of Q90). In recent studies, this amount of water released from dams has been demonstrated insufficient to support aquatic species (Neves et al., 2012; de Souza Castro et al., 2015).

3.4.8 *New Zealand*

In New Zealand, a national guideline on e-flow has been established based on hydrological methods. It defines minimum flows and total allocation based on proportions of 7 day MALF depending on the size of the river. Small rivers are those with mean annual flow < 5 $m^3\ s^{-1}$ and minimum flow and total allocation are set at 90% and 30% of 7 day MALF, respectively. Large rivers are those with mean annual flow > 5 $m^3\ s^{-1}$, and minimum flow and total allocation are set at 80% and 50% of 7 day MALF, respectively. This approach has been criticized by Snelder et al. (2011), who underlined how minimum flow rules may have variable consequences for environmental protection and reliability of supply for abstractors.

3.4.9 *Russian Federation*

Methods to determine e-flows have been developed in the former Soviet Union since the 1970s. E-flows were mainly termed "sanitary flows" or "ecological flows" (the term "sanitary" was used as a close synonym of "environmental"). Detailed information on the e-flow methods developed in the former Soviet Union was presented by Imanov (2003). These methods were based on hydrological approaches, whereby a flow index, determined from the hydrological time series, was used for e-flow assessment. Ecological justification of e-flows has been limited, but has allowed preliminary ecological thresholds to be set in the absence of detailed ecohydrological studies and funds (Abbasov and Smakhtin, 2009).

3.4.10 *South Africa*

E-flows in South Africa are prescribed using holistic methodologies. BBM is commonly used to build one consensus-based flow regime that supposedly results in a predefined river condition based on best available scientific data. The approach assumes that the involved experts have a comprehensive knowledge of what constitutes a critical flow event within the river in question. While the application of a comprehensive BBM framework can be resource intensive and time-consuming (1–2 years; Tharme, 2003), a simplified BBM can be applied in situations where considerable data on the river system already exist.

3.4.11 ***Turkey***

Due to specific environmental laws in Turkey, 10% of the annual average flow is determined as e-flows to be released from existing and new water abstractions. According to field studies (Karakoyun et al., 2015), it was demonstrated that this amount of flow is insufficient, and current procedures seem to be inappropriate, without making necessary ecological assessments at local and catchment scale.

3.4.12 ***United Republic of Tanzania***

The Tanzanian National Water Policy of 2002 and other complementary reforms in the environmental sector include provisions for e-flow assessment. The Tanzanian legislation was strongly influenced by South African experience. Acreman et al. (2005) articulated a ten-step approach for establishing the laws, institutions, capacity, training and data centres needed to implement an e-flow programme in the United Republic of Tanzania and other developing countries. Dickens (2011) provided a critical analysis of e-flow assessment in the United Republic of Tanzania and Kenya, highlighting that the work that has been done has been creative and well considered. There is more to be done, but the United Republic of Tanzania can be seen as a leading example of how a country in Central Africa can tackle the issue of e-flows and how this integrates with effective resource management.

3.4.13 ***United States of America***

In the United States, there is no nationwide framework for establishing e-flows. In the different states of the country, there is guidance or local legislation that somehow limit flow alteration. Hydraulic-habitat methods have been the preferred approach in many states, and have been extensively used to determine e-flows in the last few decades (Tharme, 2003). Hydrological methods are applied in many states, in which hydrological formulae are defined after grouping rivers using their ecological or societal values. The ELOHA framework, which suggests river classification as a first step in e-flow assessment, has already been endorsed or applied in several states (see the case studies available at the ELOHA toolbox website [https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/ELOHA/Pages/ecological-limits-hydrolo.aspx]).

4. INTEGRATING E-FLOW SCENCE WITH FLUVIAL GEOMORPHOLOGY

E-flow science and related scientific literature consider natural flow regimes as essential to sustaining the health of riverine ecosystems. Nevertheless, streamflow is mediated by river morphology to support many fundamental ecological processes. Many scientists emphasize the need to broaden the e-flow regime concept, incorporating sediment transport and balance in the context of regulated river management. In an effort to frame a comprehensive methodology for e-flow assessment, this chapter discusses how recently developed tools from different scientific disciplines (hydrology, fluvial geomorphology and biology) can be integrated and used together to describe the physical template that depends on river ecological functions.

The presented methodology has five primary objectives. The first is to identify the appropriate scale of analysis. The integration of e-flow science with fluvial geomorphology is crucial to describe the multiple-scale characteristics of river systems and the related hydromorphological processes. Second, the physical habitat template must be described and used as a metric to quantify the impact of hydrological and morphological alterations. Third, the main sensitivities of biotic communities to hydromorphological alterations must be investigated, along with the definition of river ecological objectives. Fourth, there is a need to increase the awareness that sediment and morphological dynamics are vital components of river systems. Many aquatic and riparian organisms depend on the size distributions of bed materials and the availability of certain combinations of geomorphic units. Therefore, coupling e-flows and sediment dynamics will promote more holistic and effective river restoration and conservation measures. Lastly, the fifth objective is to provide an e-flow conceptual framework that is applicable to rivers across a wide geographic and geomorphic spectrum, by explicitly presenting a flexible and robust characterization of the multiple-scale morphological characteristics of river systems and quantitatively estimating the spatio-temporal variation of habitat availability for target biotic communities.

4.1 Definition of e-flows: procedural steps

The integrated approach presented here for e-flow definition is based on disciplines such as hydrology, fluvial geomorphology and ecology. The described methods and procedural steps have been conceived to be used in water resource management and can be applied to any typology of rivers, in large and heterogeneous regions.

In accordance with the objective of this guidance, the procedure for the definition of e-flows encompasses four main parts: (1) morphological characterization of the river system, (2) hydrological and sediment regime analysis, (3) ecological response to altered flow regime and selection of target communities, and (4) comparison and selection of possible flow release scenarios (Figure 4). The following sections describe each methodological step.

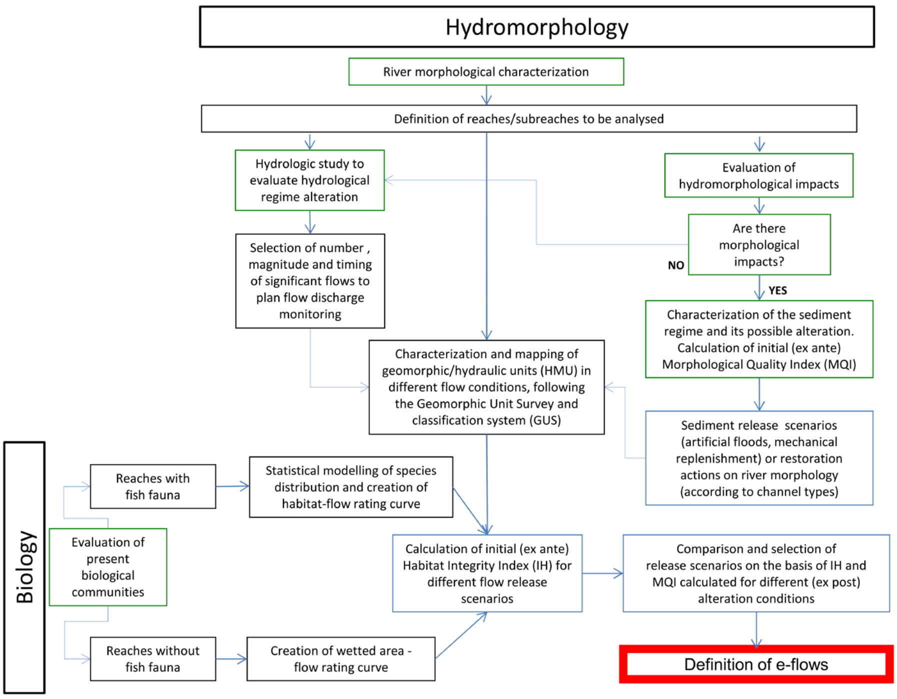


Figure 4. Flow chart reporting the main procedural steps for e-flow assessment. The methodological approach integrates recently developed tools from the disciplines of hydrology, fluvial geomorphology and biology. In particular, a new system for the survey and classification of river geomorphic units (Rinaldi et al., 2015*a*) is integrated by the application of mesoscale habitat simulation models that can predict habitat availability for biotic communities. The index of habitat integrity (IH) (Rinaldi et al., 2015*b*; Vassoney et al., 2019) and the morphological quality index (MQI; Rinaldi et al., 2013) are used to compare ex ante/ex post scenarios and select the most appropriate e-flow regime.

4.2 Morphological characterization of the river system

Stream morphological characterization is used to: (1) identify the homogeneous hydromorphological reaches (and the related geomorphic units) that are the survey features for successive evaluations, (2) evaluate the status of alteration of the river reach and (3) define the strategies for releasing e-flows.

Homogeneous hydromorphological reaches (same channel morphology and hydrological characteristics) have a homogeneous response in terms of hydromorphological processes. Therefore, e-flows should be defined considering this reach spatial scale. Within a selected homogeneous reach, geomorphic units represent the spatial resolution to evaluate and quantify the ecological benefits of e-flows. In natural streams, the geomorphic units (for example, pool, riffle or rapid; see Rinaldi et al., 2015*a*) have similar dimensions and extents as the so-called mesohabitat (Kemp et al., 1999; Parasiewicz, 2001; Petts, 2009; Parasiewicz et al., 2013; Vezza et al., 2014). For single-thread channels, they have a longitudinal dimension comparable to the channel width; in multichannel streams, such a dimension is comparable to the low-flow channel width (Rinaldi et al., 2015*b*).

The geomorphic unit (or mesohabitat) generally ranges between about 1 m and 100 m (Bain and Knight, 1996; Kemp et al., 1999; Hauer et al., 2011; Parasiewicz et al., 2013). Such a dimensional scale differs from the smaller spatial units (for example, fluvial elements), which correspond to the microhabitat scale (average dimension of 10 cm; Rinaldi et al., 2015*b*). The scale of the geomorphic unit or mesohabitat is taken as a reference scale in this methodology because it determines the occurrence and diversity of physical habitats sensu lato, that is, it is not related to the presence of some specific organism, species, population or individual (Kemp et al., 1999; Petts, 2009). It is also important to say that the geomorphic unit scale is strictly linked to the life cycle of several communities, such as the fish fauna (Gosselin et al., 2012; Wilkes et al., 2015). Therefore, this spatial scale is deemed representative to establish links between physical and biological elements.

The description of geomorphic units has to be carried out inside a subreach, a portion of a morphological reach, which is representative of the entire reach in terms of spatial distribution and relative proportions of typical geomorphic units (Rinaldi et al., 2016*b*; Belletti et al., 2017).

A morphological reach is defined according to a hierarchical segmentation procedure (Gurnell et al., 2016) that considers, for each spatial unit, the variation of some characteristic variables which are significant for such a spatial scale. It is classified on the basis of: (1) channel pattern and confinement conditions, (2) significant discontinuities of control variables (discharges or slope) and (3) sediment type in the channel. This hierarchical segmentation procedure is based on the state of the art of fluvial geomorphology and was developed within the REFORM (REstoring rivers FOR effective catchment Management) project, funded by the European Union 7th Framework Programme. The methodological framework presented in this guidance delineates regional landscapes into nested spatial units at catchment, landscape unit, segment, reach, geomorphic unit and finer scales.

The definition of channel morphology implies a general characterization of geomorphic units occurring in the reach (presence/absence of units characterizing a certain morphology) using the available information derived from aerial imagery, satellite imagery or field visits. Each channel typology exhibits a certain typical spectrum of geomorphic units, whose assemblage is the result of processes that determined the local morphology, according to the guiding variables and the boundary conditions that act at the upper spatial scales (Figure 5).

The selection of reach (or reaches) to be studied inside a hydrographic network depends on the objectives of the application, which can differ in nature (as an example, a derivation channel can affect the hydromorphological pattern of a single reach, of more reaches or of an entire physiographic unit). If a single channel reach is considered in the analysis, the representative reach, in terms of typical geomorphic units, will have a length ranging from 10 to 20 times the bankfull width, which includes at least some geomorphic units greater than 10. In a larger channel, particularly in braided rivers, such a representative length can be reduced to a minimum of twice the channel width. The maximum dimension of a subreach coincides with the reach itself.

Detailed information can be collected at the scale of geomorphic units according to the procedure described by Rinaldi et al. (2015*a*) and classified according to the geomorphic unit survey and classification (GUS) system (Belletti et al., 2017).

Having a hierarchical morphological characterization of the river system, from river segments to homogeneous hydromorphological reaches, allows extrapolation of the results up to the catchment scale or to a regional extent (for example, Parasiewicz, 2003; Vezza et al., 2012;

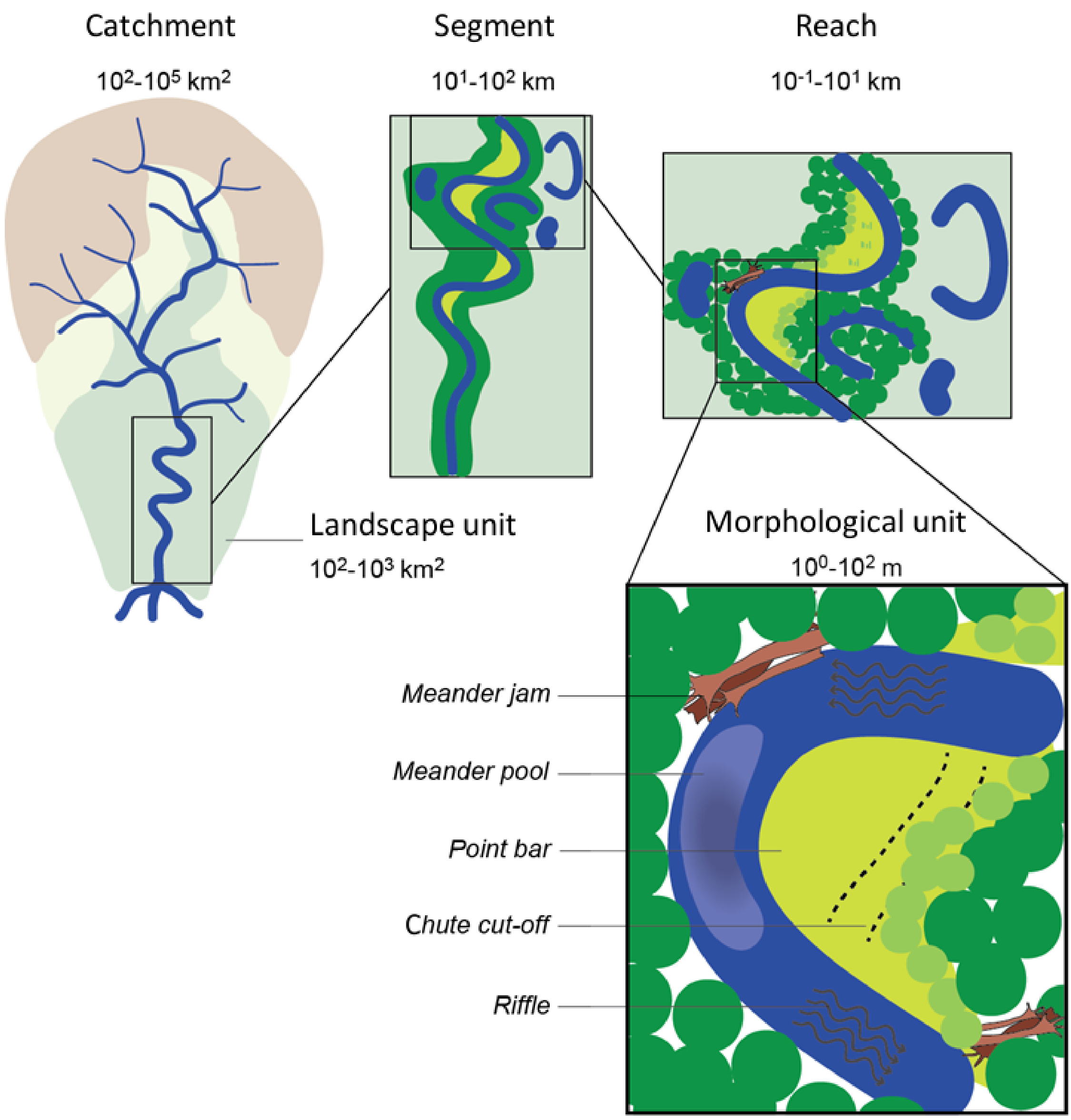


Figure 5. Example of a hierarchical approach from the catchment scale to the geomorphic units

Source: Rinaldi et al. (2016*a*)

Parasiewicz et al., 2013). Moreover, such a characterization offers the possibility to evaluate morphological modifications also in the long temporal scale, so that management decisions can be made in a provisional mode.

It is important to state that the techniques used for geomorphic unit description may vary according to the available ecohydrological knowledge. Local data availability, modelling capacity, experience and skills, and financial resources should play an important role in collecting the appropriate information needed for morphological characterization. When sparse data only are available, such as in developing countries, remote-sensing techniques may be seen as a low-cost, feasible solution for morphological river description.

4.3 Hydrological and sediment regime analysis

The distribution of physical habitat for a specific organism or community changes with the channel flow and river morphological template. Given a certain hydromorphological configuration, the aerial extent and the hydraulic characteristics of available wet channel units are different for different values of river discharge.

To describe the hydrological regime of a river and to carry out morphological characterization, a sufficiently long time series of flow data is needed. The minimum length to appropriately quantify the statistical uncertainty in the estimation of hydrological metrics is 15 years according to Kennard et al. (2010). In the methodology for defining e-flows presented herein, it may be possible to use a shorter time series, down to a minimum of 1–3 years.

Such a reduction in length is accounted for by compensating it with flexibility in water licensing, allowing changes in parameters in the abstraction licence until a time series of at least 15 years is available.

The average yearly hydrograph and the flow duration curve, with or without water derivation to be analysed, are generally used to select the most significant flow values to carry out the morphological description and characterize the physical habitat in the different bioperiods (for example, rearing and growth or spawning) of the aquatic biocoenosis. Three hydromorphological surveys carried out in different flow conditions (characteristic of low-flow and high-flow regimes) are considered as the minimum required number to detect the spatial and temporal variations of habitat (Vezza et al., 2014; Rinaldi et al., 2015*b*), but a larger number of measurements (four/five) is recommended in most cases.

Channel morphology can undergo several modifications in time following alterations that have an influence on the frequency of channel-forming discharge floods (approximately bankfull discharge with a return period of 2–5 years) or on the natural sediment regime. In such cases, the change can be assessed based on the longest temporal scales, and it is possible to evaluate the future hydrological and morphological conditions in provisional mode (Rinaldi et al., 2016*b*).

In particular, if the hydromorphological pressures on the reach impair the longitudinal continuity of sediment flow (for example, dams, weirs or deviation channels altering the channel-forming discharges) and the consequent hydromorphological modifications, it will be necessary to envisage scenarios of coupled releases of water and sediments aimed to preserve or enhance the hydromorphological status of the stream. To elaborate such scenarios, characterization of sediment regime and its alteration, in terms of sediment budget and sediment flow, is needed. Several approaches can be used to do this, and MQI is hereby used to quantify the impacts of hydromorphological alterations (Rinaldi et al., 2013). This is carried out through the combined evaluation of three main aspects: (1) the geomorphological functionality, that is, whether or not the processes and related forms responsible for the correct functioning of the river are prevented or altered by artificial elements or by channel adjustments; (2) the artificiality, that is, the presence and frequency of artificiality (artificial elements, pressures, interventions or management activities) independently of the effects of these artificial elements on channel forms and processes; and (3) the channel adjustments, that is, relatively recent morphological changes (over the last hundred years) that are indicative of a systematic instability related to human factors.

4.4 Ecological response to altered flow regime and selection of target communities

Ecological responses to hydrological and morphological (hydromorphological) alterations have been studied extensively. Poff and Zimmerman (2010) reported a systematic review of the last 40 years, where information was provided on the different sensitivities of biotic communities to the alteration of stream hydromorphological conditions through a quantitative analysis.

From the available information, it is possible to acknowledge that several metrics related to fish communities, such as individual abundance, species diversity and structure of the population respond in a consistent and negative way even to slight to moderate alterations of natural hydrological regime. This differs from other components of fluvial ecosystems (for example, macroinvertebrates), which have an ambivalent ecological response, resulting in positive or negative effects and depending on the morpho-climatic local context of the river. Such recent acknowledgements corroborate the conclusions of earlier publications (Poff, 1997; Bunn and Arthington, 2002), the systematic review carried out by Lloyd et al. (2003) and the work of Friberg et al. (2013). The latter highlighted how, at the European level, 69% of the analysed fish species showed significant response to hydromorphological pressures.

The reasons for the consistent ecological response of fish to hydromorphological alterations are multifold.

For completion of their life cycles, fish depend directly on the availability and diversity of fluvial habitat, as they are present in every type of aquatic environment (Moore and Gregory, 1988; Baras, 1997; Lamouroux et al., 1999; Ferreira et al., 2007). In freshwater, fish are the organisms that live the longest, and they occupy all levels of the trophic chain, even if they are more frequently at the upper end (Baras and Nindaba, 1999; Ovidio et al., 2002). Consequently, during their life, fish undergo and respond to single or cumulative effects of several events structuring the quality of their habitats (Baras and Lucas, 2001; Tuhtan et al., 2012; Wilkes et al., 2015).

Therefore, the fish community is proposed as a main target community for the definition of e-flows. Owing to its consistent ecological response, the composition and status of the fish community can be used to evaluate and ecologically validate specific e-flow releases. It is worth mentioning that some fish species (for example, salmonids) have an important economic value and attract public attention to policies related to the management of ecosystems (such as fisheries or tourism management) (Melstrom et al., 2015). A methodology to define e-flows, based on the status of local fish populations, can therefore be an efficient tool to determine the impact of hydromorphological alterations (future or present) and to inform stakeholders on the alteration of the environmental status of water bodies.

However, the fish community is not always present in watercourses. It is therefore possible to subdivide rivers according to the presence or absence of such a community.

In reaches where fish fauna is present, some local considerations have to be made to define the fish species to be analysed (for example, Vezza et al., 2014). Such considerations can depend on the ecological context and the public interest in protecting particular species. In general, the composition of natural fish communities varies within a hydrological region according to local morpho-climatic conditions (for example, location, altitude, average slope, morphology or thermal regime).

To determine the composition of the target fish community, it is necessary to list the available species based on the official and historical data available from the public administration or local environmental agencies (fish maps, catch data from anglers, environmental monitoring and so forth) and on the life-cycle and migration trajectories of involved populations. These lists can be subsequently integrated through direct fish sampling in the reaches where derivations are planned.

The Mesohabitat Simulation Model (MesoHABSIM, http://mesohabsim.org/), the SimStream software (running in the QGIS platform and downloadable from ftp://ftp.isprambiente.it/, username “ihuser” and password “SE38f45f”) and an IH index (Rinaldi et al., 2015*b*) are used to assess present and future impacts on the fish community. MesoHABSIM (Parasiewicz, 2007; Parasiewicz et al., 2013) refers to mesohabitats or geomorphic units (such as pools, riffles or rapids) and can be easily integrated with the hierarchical characterization of river systems (Gurnell et al., 2016) and the GUS system (Belletti et al., 2017). In addition, habitat time series analysis is used to predict the spatio-temporal habitat availability for the fish community. The SimStream software supports MesoHABSIM application and data management in a geographic information system (GIS) environment. The IH index, based on the MesoHABSIM approach, is designed to measure the amount of habitat loss due to water abstractions and the increase of continuous duration of limited amount of habitat. For the periods of limited amount of habitat, the statistical analysis of habitat time series is used to represent how habitat changes through time and to identify stress conditions created by persistent limitation in habitat availability (see Chapter 5, case study 1).

The use of MesoHABSIM for this purpose is not necessarily a precondition of this application. Any mesoscale habitat model [for example, those of Borsányi et al. (2003) or Hauer et al. (2009)] can be utilized for this purpose. However, MesoHABSIM is internationally recognized and is the most developed model to run analysis at the mesohabitat-scale resolution. Moreover, this model has already been integrated with hydromorphological assessment tools (Rinaldi et al., 2015*b*), performing analyses at reach and watershed scales.

For rivers in which the fish community is naturally absent (for example, mountainous watercourses or headwaters at elevations greater than 2 000 m above sea level, or streams with an intermittent flow regime), the methodology presented in Figure 4 can be applied using hydromorphological conditions as a primary ecological objectives. Specifically, in rivers without fish fauna, the application has the following rules:

– In reaches in which river morphological conditions are not affected by anthropogenic alterations, that is, all indicators A4–A9 of MQI (see definitions below) fall in classes A or B (see Rinaldi et al., 2013 for details on indicator classes), the relationship between wetted area and discharge is used as a proxy of habitat availability for IH index calculation.

– In reaches in which river morphological conditions are strongly altered (at least one of the indicators A4–A9 of MQI falls in class C), the IH calculation is not applied and river morphological assessment (based on MQI) should be carried out to predict possible river management alternatives.

Indicators A4–A9 of MQI are as follows:

A4: Alteration of sediment discharge in the reach

A5: Crossing structures (bridges, fords and culverts)

A6: Bank protections

A7: Artificial levees

A8: Artificial changes of river course

A9: Other bed stabilization structures (sills and ramps) and revetments

4.5 Comparison and selection of possible flow release scenarios

In water resources management, e-flow assessment, even if focused on a short river reach, needs to be placed within a watershed context for a better understanding of the hydromorphological processes characterizing the watercourse and of the human activities affecting its state. Furthermore, a proper watershed-scale assessment is needed to identify the reference hydrogeomorphology patterns together with the reference aquatic community structure.

Thus, such physical and biological elements must be assessed together with an integrated and comprehensive methodology that can predict the impact of future management scenarios (Rinaldi et al., 2015*b*).

The methodological approach proposed in this guidance attempts to overcome the limitation of current e-flow assessment, to incorporate fluvial geomorphology as a main component of aquatic habitat. Using the proposed approach, decision-makers can rely on a quantitative framework for evaluating alternative management scenarios and assessing e-flow ecological effectiveness.

The combination of two metrics presented here (MQI and IH index) takes into account the hydromorphological characteristics of a river to assess the habitat magnitude, its quality (structure) and the frequency and duration of habitat bottlenecks. These are all expected to have a direct influence on the condition of the fish community. Comparing different management scenarios using MQI and the IH index is a feasible solution for different river types and has been proven robust and universal (Parasiewicz et al., 2013; Rinaldi et al., 2015*b*).

This approach of comparison scenarios is flexible and effective for water resource management and planning. It is less costly than evaluation through biological direct observations, which can be strongly affected by variability and species mobility. Furthermore, e-flow effectiveness can be evaluated within shorter periods of time because there is no need to wait for the biological communities to adjust to the new circumstances. Biological monitoring over time can be used when communities are affected only by hydromorphological pressures for which e-flows were designed as a mitigation measure. In that case, the positive ecological response will corroborate once again the entire methodological framework.

4.6 Sequential procedural steps

As a summary of the procedure described in this chapter, the following ordered structure of 10 procedural steps should be used in common applications. The order in which steps are performed may change slightly depending on data availability and the amount of time and effort needed to perform each step:

Step 1. Classification of river segments affected by water abstraction in homogeneous hydromorphological reaches

Step 2. Acquisition or reconstruction of streamflow time series at a daily or hourly scale, in the presence and absence of water abstraction

Step 3. Qualitative evaluation of sediment regime alterations and estimation of future river morphological changes

Step 4. Evaluation and planning of possible future mitigation measures, if water abstraction generates changes in the river sediment regime

Step 5. Detailed description of morphological units in selected reaches (identified in step 1) for at least three or four different discharge conditions

Step 6. Evaluation of habitat availability and construction of a habitat flow rating curve

Step 7. Generation of possible water management scenarios and flow releases downstream of the abstraction

Step 8. Calculation and comparison of the IH index and MQI for each scenario

Step 9. Selection of the desired water management scenario that minimizes river habitat deterioration or excludes a decrease in terms of IH index and MQI quality classes

Step 10. Monitoring of e-flow releases and morphological changes of the river due to the selected water and sediment management scenario (step 8) by analysing the composition of morphological units over time and the related values of the IH index and MQI

5. METHODOLOGY APPLICATION AND CASE STUDIES

The definition of e-flows with the proposed methodology, encompassing hydromorphological characterization and hydrological regime description, can have different degrees of detail depending on the type of pressure (large or small dams), the pluviometric regime, the hydrological regime and the channel morphology (single channel, multiple channels or transitional). The following sections report a few specifications for applications.

5.1 Type of pressure

Dams creating a reservoir cause alteration to the hydrological and sediment regimes. Such alteration, with respect to former conditions, determines substantial modifications to fluvial habitat. For these cases, assessment of the impact on hydrology and sediment transport should be carried out.

Releasing e-flows should be conceived in relation to sediment dynamics and erosional and depositional phenomena that characterize a river. Therefore, pre- and post-impact assessments through mapping of geomorphic units need to be carried out to describe the initial conditions and the present ones.

When significant alteration of the hydrological regime occurs, field data monitoring related to the different flow conditions should be agreed with the stakeholders. In addition, where strictly necessary, release from abstractions should be envisaged. Impoundments may have less relevant impacts on sediment flow and on channel-forming floods. Depending on the local hydromorphological context and on the type of water abstraction, in some cases, consideration of sediment release may not be necessary (for example, for weirs in high-energy confined rivers).

5.2 Hydrological regime

Different regions in the world undergo different precipitation regimes. With reference to the entire hydrological cycle and to the transformation of rainfall in runoff, different river hydrological types can be identified. These can be reduced to two macrocategories: perennial and intermittent types. This is because channel flow is present all year long and the timing of low flows and floods (seasonality) depends on the precipitation regime.

The characterization and mapping of geomorphic units should be carried out when flow conditions are representative of the precipitation and hydrological regime, considering the local seasonal variability.

Using the presented methodological approach, three hydromorphological surveys and descriptions are considered the minimum number to build the habitat flow relationship and to calculate the IH index (Rinaldi et al., 2015*b*). As the range of variation between minima and maxima of the local hydrological regime increases, a greater number of hydromorphological descriptions (4–10) is recommended. In the case of an intermittent hydrological regime, a specific set of surveys has to be carried out in the absence of surface flow to quantify the remaining wetted areas inside the channel and the related availability of aquatic habitats over time.

5.3 Fluvial morphology

The dimensions of geomorphic units vary according to the channel morphology of the hydromorphological reach, and range from about 1 m to 100 m. It is possible to identify one or more units inside a single transversal portion of the reach (for example, in braided channels). Such differences in scales and spatial distribution of geomorphic units require different efforts and resources for data collection in the field. High-resolution satellite imagery can be used in the proposed methodology together with the GIS applications developed for the MesoHABSIM methodology (Vezza et al., 2017), and can ease field data collection.

Hydraulic simulations (one or two dimensional) may be helpful for applications in non-wadable rivers to describe the flow pattern in each geomorphic unit and the frequency distribution of water depth and flow velocity (Parasiewicz et al., 2012*a*; Cheviron and Moussa, 2016). Moreover, periodic monitoring of geomorphic unit composition and the related available habitat for fish should be carried out. In particular, this should be done to evaluate the ecological effectiveness of morphological restoration measures or to assess the impact of new interventions (for example, morphological or sediment regime changes, construction of new water abstractions and morphological modifications due to major flood events).

5.4 Case studies

Tables 2, 4 and 5 present three case studies to illustrate the methodology. Case study 1 shows recent developments of tools that integrate hydraulic-habitat models with fluvial geomorphology, describing the calculation of the IH index. Case study 2 highlights the need for including river morphological modifications in e-flow assessment. Morphological modifications can be caused by the alteration of hydrological and sediment regimes and refer to changes in channel geometry and planforms over time. Case study 3 describes regional-scale monitoring programmes of hydroelectric dams in Italy that implement the proposed methodology for e-flow design and evaluation.

Table 2. Case study 1: recent developments of tools that integrate hydraulic-habitat models with fluvial geomorphology

<table>
<tr><th>Section</th><th>Content description</th></tr>
<tr><td>Continent</td><td>Europe</td></tr>
<tr><td>Country</td><td>Italy</td></tr>
<tr><td>Basin</td><td>Po River Basin</td></tr>
<tr><td>River</td><td>Taro River (Parma Province)</td></tr>
<tr><td>Objective</td><td>Quantify spatio-temporal alteration of habitat structure due to hydrological alteration. The local fish community is the ecological target for this analysis.</td></tr>
<tr><td>Spatial scale</td><td>River reach. GUS (ISPRA, 2016; Rinaldi et al., 2016a) provides basic information for the survey and characterization of mesohabitats that were used to: (1) apply habitat simulation models for river habitat evaluation and e-flow assessment (MesoHABSIM; Figure 6) and (2) calculate the spatio-temporal variation of habitats through calculation of the IH index in relation to the fish community. In particular, the integration of mesoscale habitat models and GUS can define a consistent modelling framework that allows data to be collected at different flow conditions and a more appropriate scale (which can be a reach, segment, landscape or catchment scale) for addressing environmental river management problems.

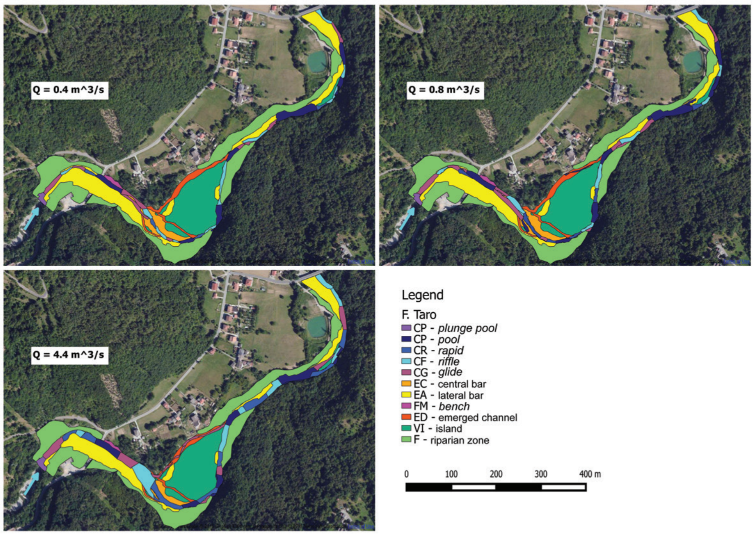


Figure 6. Spatial distribution of channel and flood-plain geomorphic units (bankfull channel and flood-plain units) for the Taro River (Parma, Italy) for three different flow conditions (0.4, 0.8 and 4.4 $m^3 s^{-1}$)
Source: Rinaldi et al. (2016a)</td></tr>
<tr><td>Frequency</td><td>Seasonal (based on the hydrograph).</td></tr>
<tr><td>Background</td><td>GUS can support understanding of the links among hydromorphological conditions, ecological conditions and biota, because geomorphic units represent physical habitats for the flora and fauna that inhabit rivers. However, investigation of geomorphic units alone at a given time cannot provide information about the conditions of physical habitats and thus the conditions for biota. Physical habitats in rivers show high turnover rates as well as high spatial heterogeneity in response to hydromorphological dynamics driven mainly by the hydrological regime. As a consequence, key properties of habitat conditions (for example, size, water depth, flow velocity, shear stress, substrate composition, temperature, and availability of cover and food) affecting habitat use by the river biota change over time. For these reasons, it is more appropriate to consider geomorphic units and physical habitats as dynamic instead of static features, to study them through time, and to study the biota synchronously (in space and time) to link the physical to the biological environments and their dynamics.</td></tr>
</table>

Approach/ method	GUS was used to integrate the MesoHABSIM model and to assess spatio-temporal alterations of habitat structure. In addition, two new habitat indices, based on GUS and MesoHABSIM, were applied to assess the habitat integrity for fish in different river environments. First, the index of spatial habitat availability (ISH) was used to describe the average amount of habitat loss due to a particular pressure. Second, the index of temporal habitat availability (ITH) was used to measure the increase of continuous duration of events when habitat bottlenecks created stress to the fauna. The two habitat indices, ISH and ITH, were calculated as follows: • Based on GUS, geomorphic units were delineated and classified at different flow conditions (Figure 6). Detailed hydromorphological surveys could be repeated from three to five times depending on the hydrological regime of the river and the objectives of the study. • Through the MesoHABSIM model, the habitat flow rating curve and the habitat time series were generated for each target species (and life stages) in the period of interest. Common applications refer to daily discharge series to generate habitat time series. • Using habitat time series, ISH was calculated for each fish species (and life stage) as the ratio between the average available area (expressed in m^2) in reference ($A_{Hd,r}$) and altered conditions (A_{Hd}). The ISH value for the entire fish community was then defined by the minimum value among all target species (and life stages) in the river section: $$\mathrm{ISH} = \min\left(\begin{cases} 1 - \dfrac{\lvert A_{Hd,r} - A_{Hd} \rvert}{A_{Hd,r}}, & \left\lvert \dfrac{\lvert A_{Hd,r} - A_{Hd} \rvert}{A_{Hd,r}} \right\rvert < 1 \\ 0, & \left\lvert \dfrac{\lvert A_{Hd,r} - A_{Hd} \rvert}{A_{Hd,r}} \right\rvert > 1 \end{cases}\right)_{\text{species}} \quad (1)$$ • To calculate ITH, habitat time series were statistically analysed using the uniform continuous underthreshold (UCUT) curves (Parasiewicz et al., 2013). Specifically, the ITH compared duration and frequency of underthreshold events in reference and altered conditions using Q97 (the flow value was exceeded 97% of the time) as the reference habitat threshold (AQ97; *sensu*, Parasiewicz et al., 2012*b*). An indicator of stress days alteration (SDA) reported the average distance between two UCUT curves representing cumulative duration of habitat underthreshold events in reference ($d_{c,r,AQ97}$) and altered ($d_{c,AQ97}$) conditions (Equation 2). ITH for each species (and life stage) was finally calculated using a negative exponential curve (Equation 3), and the ITH community value was given by the minimum value among all target species: $$\mathrm{SDA} = \frac{1}{d_{max,r}} \cdot \sum_{k=1}^{k=d_{max,r}} \left(\frac{\lvert d_{c,AQ97} - d_{c,r,AQ97} \rvert}{d_{c,r,AQ97}} \right) \quad (2)$$ and $$\mathrm{ITH} = \min\left(e^{-0.38\ \mathrm{SDA}}\right)_{\text{species}} \quad (3)$$ Depending on the study objectives, index calculation could be performed at intra-annual and interannual scales, and using daily and hourly discharge (for example, Figure 7). Hourly streamflow records were considered suitable for rivers affected by hydropeaking, due to the particular timescale of hydropower production and dam operations. Moreover, in areas where specific conservation objectives are required, index values could be calculated for single taxa, allowing restoration strategies to be focused on especially threatened species.

Scenarios

ISH and ITH (Figure 7) were used to quantify the impact of a particular water abstraction. The average amount of habitat loss and the increase of continuous duration of low habitat events were estimated for the local fish community (Table 3). When possible, adult and juvenile life stages were considered in the analysis.

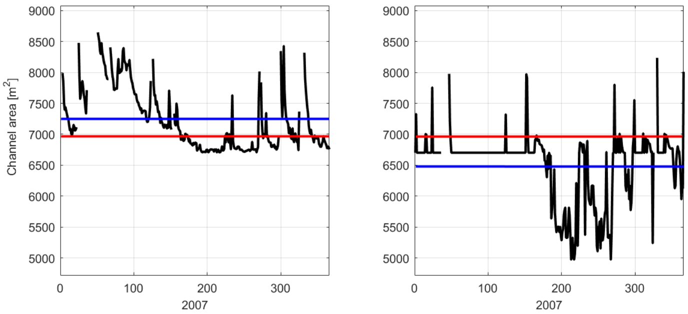


Figure 7. Habitat time series for: (left) reference and (right) altered conditions for barbel (*Barbus* sp.) in the Taro River (Parma, Italy) in 2007. Blue solid lines represent average values of habitat availability used to calculate ISH. Red solid lines refer to the minimum habitat threshold during low flows (AQ97) in reference conditions, which is used to generate UCUT curves and calculate the ITH value.

Source: Rinaldi et al. (2061*a*)

Table 3. ISH, SDA and ITH values for the local fish community in a selected reach of the Taro River (Parma, Italy), 2007

Species/life stage	*ISH*	*SDA*	*ITH*
Brown trout/adult	0.92	1.60	0.54
Brown trout/juvenile	0.97	0.86	0.72
Vairone/adult	0.95	0.13	0.95
Vairone/juvenile	0.99	0.93	0.70
Barbel/*Barbus* sp.	0.90	2.28	0.42
Chub/adult	0.97	0.83	0.72
Italian freshwater goby/adult	0.91	0.94	0.69

Source: Rinaldi et al. (2016*a*)

Key results

Results derived from habitat index applications showed the potential of linking GUS to habitat modelling and evaluation, to provide useful indicators that can be used for hydromorphological and ecological status assessment.

Key findings and learned lessons

According to previous research studies carried out in Italy, the geomorphic unit (mesohabitat) scale demonstrated its appropriateness to describe and evaluate the impact of water abstractions. The applied IH index can be considered as a flexible tool because it can capture spatial and temporal alteration of habitat structure. The integrated methodology applied in this case study can quantify the effect of hydrological and morphological alteration on the aquatic habitat, and the analysis can be carried out for different kinds of pressures. Future index applications and testing must be conducted for different hydropower facilities, hydropeaking and sediment flushing.

Sources: Parasiewicz et al. (2012*b*, 2013); Rinaldi et al. (2015*a*); ISPRA (2016)

Table 4. Case study 2: need for including river morphological modifications in e-flow assessment

<table>
<tr><th>Section</th><th>Content description</th></tr>
<tr><td>Continent</td><td>Europe</td></tr>
<tr><td>Country</td><td>Greece</td></tr>
<tr><td>Basin</td><td>Nestos River Basin</td></tr>
<tr><td>River</td><td>Nestos River</td></tr>
<tr><td>Objective</td><td>Water abstractions and hydroelectric dams cause hydrological and morphological alterations, which affect biotic communities. Morphological alterations refer to modification of sediment transport, channel geometry and planforms over time. Using the proposed multiscale hydromorphological framework for e-flow assessment, this case study evaluated how morphological river changes may affect habitat availability for fish in the near future.</td></tr>
<tr><td>Spatial scale</td><td>River segment located at the Nestos River estuary in northern Greece (Figure 8). The Nestos River catchment is a transboundary basin between Bulgaria and Greece. In the Hellenic territory, Nestos Basin occupies 2 843 km2 (52% of the total watershed area), traversing the Rhodope mountain range and flowing into the Mediterranean Sea near the island of Thasos. The flow regime in the Greek part of the river is regulated by two major hydropower dams (Thissavros and Platanovrisi) and a minor irrigation dam (Toxotes), with the latter located 30 km upstream of the mouth. In this case study, the analysed river segment is located downstream of the Toxotes Dam.

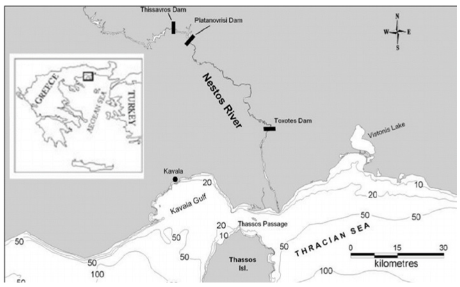


Figure 8. Location of the Nestos River estuary. The analysed river segment is located downstream of the Toxotes Dam.

The starting point in evaluating habitat for the fish community is determination of the hydrogeomorphic needs of all fish species present locally. These hydrogeomorphic conditions can be related to the flow regime and the local river morphology. Because the amount of water in rivers (flow) is a primary factor influencing habitat availability, this relation at the reach scale is captured with the help of habitat flow rating curves [Figure 9; see Koutrakis et al. (forthcoming) for details].

Changes in river morphology may indicate hydromorphological pressure effects. This case study simulated the environmental impact on the fish habitat over time, due to a lack of sediment at the Nestos River mouth after Thissavros and Platanovrisi Dam construction (Vezza et al., 2018). Future morphological changes (channel narrowing and down-cutting, and disconnection from secondary channels) were taken into account to estimate habitat availability for fish in 2030.

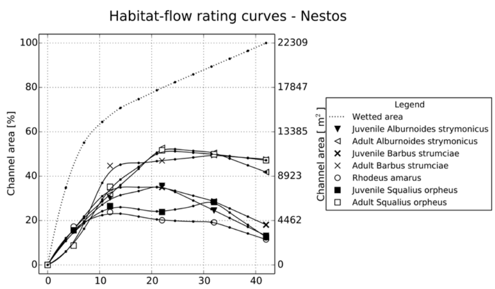


Figure 9. Habitat flow rating curve for case study 2, representing habitat conditions in the Nestos River below Toxotes Dam. Rating curves for the wetted area were obtained through field data collection and MesoHABSIM application.

Source: Koutrakis et al. (forthcoming)</td></tr>
</table>

Frequency	Annual (based on the hydrograph).
Background	The selected river section accumulates all pressures from the operation of all dams in the river and endures stresses from hydropower production and agricultural abstractions. As a starting point in evaluating habitat for the fish community, the river segment was divided into homogeneous hydromorphological reaches (same channel morphology and same hydrological characteristics). Two hydromorphological reaches, characterized by wandering and anabranching morphology, were identified for further analysis (Vezza et al., 2018).
Approach/ method	Habitat time series (Milhous et al., 1990) and UCUT curves were calculated to assess spatio-temporal habitat availability in past, present and future hydromorphological conditions. UCUT curves can be used to describe magnitude, frequency and duration of habitat events and were defined for a given period, in which the sum length of all underthreshold events of the same duration were plotted as a cumulative frequency. The UCUT analysis was based on the assumption that habitat is a limiting factor, and events occurring rarely in nature create stress to aquatic fauna and shape the community. For a specific habitat threshold (expressed in square metres or percentage of the channel area), the number of habitat stress days that occur under those desired conditions could be calculated and used as a benchmark for comparative analyses. The IH index was calculated based on the habitat time series and UCUT curves. This index measured the average amount of habitat loss due to Nestos River damming (through ISH), and estimated the increase of continuous duration of events when habitat bottlenecks create stress to the fauna (through ITH; see case study 1 for details). The IH index was calculated as the minimum value between ISH and ITH for past, present and future hydromorphological conditions.
Scenarios	River Nestos has narrowed and deepened in the last 15 years; less sediment available for downstream reaches has led to channel degradation. Riparian vegetation colonized secondary channels and encroachment occurred in both studied reaches and exacerbated the changes in morphological character. In 2003, both reaches were of moderate morphological quality (0.5 ≤ MQI <0.7) and likely to regain good functionality if efficient measures had been put in place. After 2003, following the operation of Thissavros and Platanovrisi Dams and related sediment trapping, incision and disruption of longitudinal, lateral and vertical connectivity, the values of MQI dropped down to a bad status (0.0 ≤ MQI <0.3). Yet, no measures to restore sediment supply downstream have been implemented.

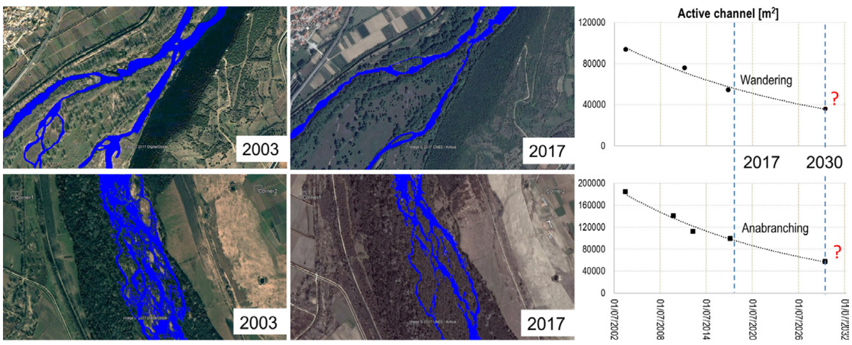
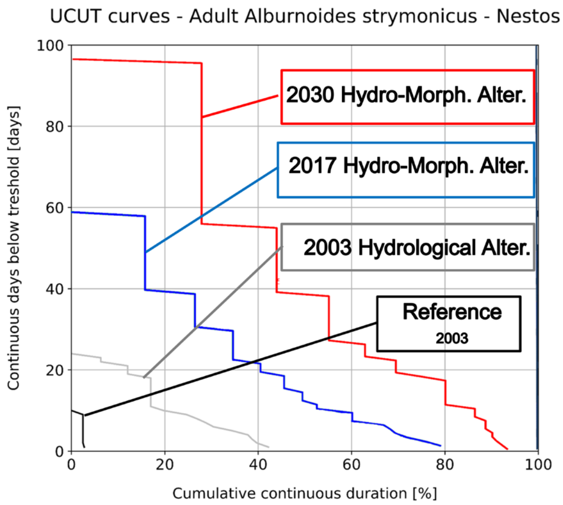


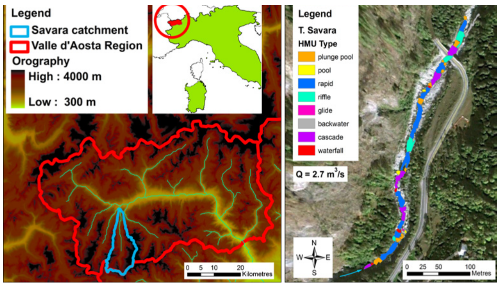
Figure 10. (Left) Satellite images showing active channel degradation (blue areas) between 2003 and 2017 in a portion of the two selected river reaches, characterized by wandering and anabranching morphology. (Right) Using the past evolution trend in terms of active channel area, a possible prediction for the year 2030 was carried out. As flow and sediment regime alteration was kept constant for the next years (conservative condition), red question marks are reported for future morphological scenarios.

Using the active channel trends in the past, it was possible to estimate a possible future morphological scenario (Figure 10). If the sediment supply does not increase at the mouth of the Nestos River, in a few years, it is likely that the main channel will be completely disconnected from all secondary ones, and residual bank-attached and central bars will probably disappear. This will have a negative effect on fish habitat availability, by reducing habitat quality and quantity, which are needed to maintain local fish populations.

Scenarios (*Cont'd*)	As an example, UCUT curves for past, present and future hydromorphological scenarios are reported in Figure 11. The example shows UCUT curves for a target local species, *Alburnoides strymonicus* – adult life stage. The increase in frequency of habitat events below threshold is reported as the average distance between two UCUT curves, for example, between reference condition (2003) and hydrologically or hydromorphologically altered conditions (2003, 2017 and 2030). This average distance was calculated for each target species (and life stage) over the entire range of durations below threshold, and the minimum value of the IH index among all species was used to compare hydromorphological conditions. The IH index was estimated as 0.41 (moderate habitat quality) when only alteration of hydrological regime occurred for the reference 2003 condition, whereas the index decreased to 0.20 (poor habitat quality) in 2017 when considering present hydromorphological alteration and to 0.02 (bad habitat quality) for the 2030 future hydromorphological scenario. In the River Nestos management context, downstream releases of sediment stored in reservoirs should be planned. However, releasing sediments from dams approximating natural sediment fluxes may be problematic (Kondolf et al., 2014). Alternative ways have to be considered to increase sediment supply in the downstream reaches of the river and to decrease the rate of morphological change.  **Figure 11. UCUT curves representing the alteration of habitat for a target species (adult *Alburnoides strymonicus*) for hydrological alteration only (reported as 2003 hydrological alteration) and hydromorphological alteration (2017 and 2030 hydromorphological alterations). The average distance between curves represents the average increase of habitat stress days and thus allows comparative analysis between reference (black line) and altered (grey, blue and red lines) conditions.**
Key results	The presented approach for e-flow design and evaluation captured the cumulative effect of hydrological and morphological alterations on the fish habitat for past, present and future hydromorphological conditions.
Key findings and learned lessons	Linking a hierarchical hydromorphological framework to a mesohabitat simulation model allowed an appropriate description of how physical habitat changed through space and time, and identified stress conditions created by persistent limitation in habitat availability. For dams creating a reservoir, e-flow design should be carried out by taking into account possible morphological changes due to the lack of sediments to implement more comprehensive habitat conservation or restoration measures.

Sources: Milhous et al. (1990); Kondolf et al. (2014); Koutrakis et al. (forthcoming)

Table 5. Case study 3: regional-scale monitoring programmes of hydroelectric dams: e-flow design and evaluation

Section	*Content description*
Continent	Europe
Country	Italy
Basin	Po River Basin
River	Savara River (Aosta Province)
Objective	Design e-flows and ensure release downstream of water diversions with hydropower purposes.
Spatial scale	Subcatchment. Between 2008 and 2013, possible variations of a wide range of hydrological/hydraulic and ecological characteristics were recorded in Valle d'Aosta region. The procedure included the survey of geomorphic units (mesohabitats) below 32 water abstractions. This monitoring programme was based on the methodology proposed in this guidance, and allowed streams to be surveyed for long stretches (from hundreds of metres to kilometres) to better observe habitat dynamics with flow in the complex morphology of Alpine high-gradient streams (Figure 12 reports an example for the Savara Stream, Valle d'Aosta, Italy).  **Figure 12. (Left) Location of the Savara catchment within the Valle d'Aosta region (north-western Italy). (Right) Hydromorphological unit (HMU) distribution in the selected river reach.**
Frequency	Seasonal (based on the hydrograph).
Background	Mountainous streams in the Alps are increasingly being exploited by water diversions for hydropower production. In the Valle d'Aosta region, the resulting alteration of flow regimes is causing an environmental impact on freshwater. Awareness of this issue has recently been raised by the Regional Water Management Agency. The Regional Water Protection Plan (Regione Autonoma Valle d'Aosta, 2006) aimed at ensuring the right balance between satisfying water needs for human activities and protecting or restoring the ecological status of water bodies, with required minimum e-flows to be released from existing and new water abstractions. Moreover, in 2008, an experimental programme was approved to assess minimum e-flows to be released from 28 water diversions owned by the main regional hydropower company. As part of this programme, the Savara Stream is used here as an example of assessment to support appropriate e-flow definition in Alpine watercourses. Specifically, the Savara Stream is altered by a water abstraction without storage capacity. Incremental e-flow releases were implemented between 2008 and 2013, and annual e-flow schemes were compared to assess resulting ecological improvements. A pool of indices was applied at an annual scale, monitoring physico-chemical, biological and hydromorphological quality elements, as well as the IH index presented in this guidance (Vezza et al., 2015).
Approach/ method	The e-flow evaluation was led using the MesoHABSIM approach, which modelled and simulated the spatio-temporal distribution of river physical habitat in a given stretch dependent on flow discharge. The procedure consisted of three key steps: (1) description of fluvial habitat in terms of a pool of parameters (for example, water depth, velocity, type of geomorphic units, substrate composition and cover distribution); (2) application of biological model of habitat suitability (for given species or communities) to obtain maps of suitable habitat that occur when certain values of discharge, variable in time, are ensured; and (3) analysis of spatio-temporal variations of fluvial habitat to translate the available suitable habitat distribution in the e-flow regime.

<table>
<tr>
<td>Scenarios</td>
<td>
Different scenarios of e-flow releases were compared as possible mitigation actions and their impact on the aquatic community evaluated using existing monitoring data, hydromorphological and biological indicators and by means of habitat hydraulic modelling through the MesoHABSIM approach. Specifically, the IH index (ISPRA, 2016), based on the MesoHABSIM approach, was used to evaluate the ecological effectiveness of e-flow releases on an annual scale (Figure 13). By transforming daily streamflow time series into habitat time series, the IH index is calculated as the minimum value of ISH and ITH (see also case study 1 in Table 2 for details):

$$IH = \min(ISH, ITH). \quad (4)$$

The IH score ranges between 0 and 1, where 0 represents a very high degree of alteration of the watercourse habitat quality, while 1 corresponds to a condition with no hydromorphological alterations, that is, where the habitat quality is equivalent to the reference condition. Between 2008 and 2013, the minimum and maximum values of the IH index were 0.06 in 2008 and 0.35 in 2012, showing that the released e-flows still have to be changed to enhance habitat condition for the fauna. To ensure good habitat quality throughout the year, it is proposed to generate hydropower only if the natural inflow is higher than 1.2 $m^3 s^{-1}$.

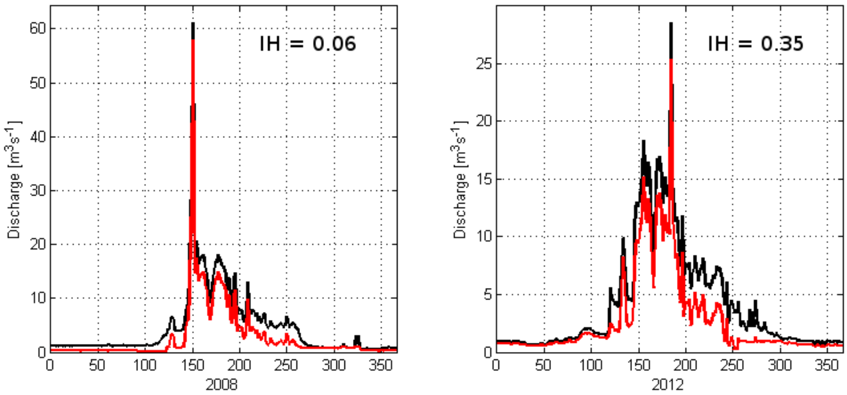


Figure 13. Natural (solid black line) and altered (solid red line) hydrograph in the Savara Stream for 2008 and 2012. Minimum and maximum values of the
</td>
</tr>
<tr>
<td>Key results</td>
<td>Through the mesoscale habitat modelling and the IH index, it is possible to evaluate the spatial and temporal distribution of habitat, in terms of morphological features and hydraulic parameters, as a function of discharge and to specify e-flows with neglectable uncertainty (Parasiewicz et al., 2012b).</td>
</tr>
<tr>
<td>Key findings and learned lessons</td>
<td>The results suggested, coherently with previous experiences, that in Alpine contexts, present physico-chemical water quality and biological indices, for the classification of the ecological status of water bodies, are not appropriate to reflect the effects of hydrological alteration, and thus to develop suitable mitigation measures. However, approaches based on the analysis of hydromorphological alteration and of habitat availability appear more suitable to compare the effects of different e-flow releases (European Commission, 2015).</td>
</tr>
</table>

Sources: Parasiewicz et al. (2012*b*); Vezza et al. (2014, 2015); European Commission (2015); ISPRA (2016)

6. EMERGING APPROACHES FOR WATER RESOURCES MANAGEMENT

Although water flow is important to provide aquatic and riparian habitats in rivers, other factors such as sediments, woody/organic material, and riparian vegetation may be of greater importance in shaping species biomass and abundance. A large dam on a river disturbs the natural water flow regime, and also, from a wider point of view, all downstream fluxes that allow the existence of biological communities.

Holistic methodologies considering the many interacting components of aquatic systems, including sediments, are increasingly recommended in e-flow assessment (Meitzen et al., 2013). However, in many cases globally, the amount of water to be released is assessed mainly using hydrological formulae (see Chapter 3). In particular, e-flow implementation should take into account the morphological evolution of regulated reaches or channels, which could have caused a consistent channel conveyance change.

Chapter 4 proposed a possible methodology to include sediment transport and related geomorphic processes as key components when specifying e-flows, thereby expanding traditional environmental objectives and e-flow definitions. Possible technical solutions and emerging approaches that have been globally implemented to re-establish water and sediment availability and transport have been presented by Kondolf et al. (2014). Specifically, they summarized proven techniques to pass sediment through or around reservoirs to preserve reservoir capacity and to minimize downstream impacts. This collective experience was reported using case studies from five continents, but more implementation is needed to mitigate downstream sediment starvation.

Unfortunately, many dams are planned and built without any consideration of sedimentation, or at best, the reservoir is designed to store anticipated sediment loads for 50–100 years before its functions are impaired. Managing sediment release in several existing reservoirs may require retrofitting dams with sediment passage facilities. However, providing sediment discharge gates or sediment bypass tunnels is expensive and sometimes impossible.

6.1 Routing sediments through or around reservoirs

Reservoir sedimentation affects most reservoirs globally. This leads to a decisive decrease of the active reservoir volume and therefore to loss of energy production and water available for water supply and irrigation. Based on broad experience, routing sediments through or around the reservoirs is an effective solution to re-establish sediment yield at a catchment scale. Sediment sluicing and flushing, sediment by-passing and off-channel reservoir storage techniques have demonstrated their effectiveness in countering reservoir sedimentation, reducing riverbed erosion downstream and increasing river morphological variability (Figure 14). Moreover, sediment release can be managed together with flow release to meet geoecological objectives for dynamic riverscapes.

Unfortunately, many dams are planned and built without any consideration of sedimentation, or at best, the reservoir is designed to store anticipated sediment loads for 50–100 years before its functions are impaired. Managing sediment release in several existing reservoirs may require retrofitting dams with sediment passage facilities. However, providing sediment discharge gates or sediment bypass tunnels is expensive and sometimes impossible.

The most important recommendation reported by Kondolf et al. (2014) refers to managing sediment through reservoirs from the beginning of reservoir design. This principle implies that existing plans for dams not yet built should be urgently and fundamentally revisited to consider a full range of sediment passage options. Even for existing dams, an assessment of options to improve sediment management is desirable and recommended.

6.2 E-flows and sediment release

Below dams, fluvial systems need water and sediments for recovering their natural forms and functioning. In addition, water managers need to recover reservoir storage capacity lost to sedimentation. Thus, a win–win option requires recovering connectivity of sediment flow, from the reservoir basin to the river downstream of the dam (García de Jalón et al., 2015).

It is important to state that e-flows and sediment releases should be coupled in a comprehensive reservoir management plan. De-coupling water and sediment may lead to ecological issues in downstream reaches. Wohl et al. (2015) reported that high-flow releases below dams into sediment-starved reaches lacking sediment inputs can cause channel down-cutting, bank erosion, disconnection from the flood-plain and riparian habitats. Conversely, low flows below dams combined with abundant sediment supply (for example, that provided by sporadic sediment flushing) can cause massive sediment deposition, siltation of the streambed, loss of aquatic habitats, and alteration of hyporheic exchange, water chemistry and thermal regime.

E-flows including sediments should be established at a catchment scale, through characterization and analysis of the river system and the existing hydromorphological pressures (dams, weirs or water abstraction). This understanding of the factors controlling channel morphology and processes in present conditions is crucial, as is identification of main sediment sources, delivery processes and transport along the river network.

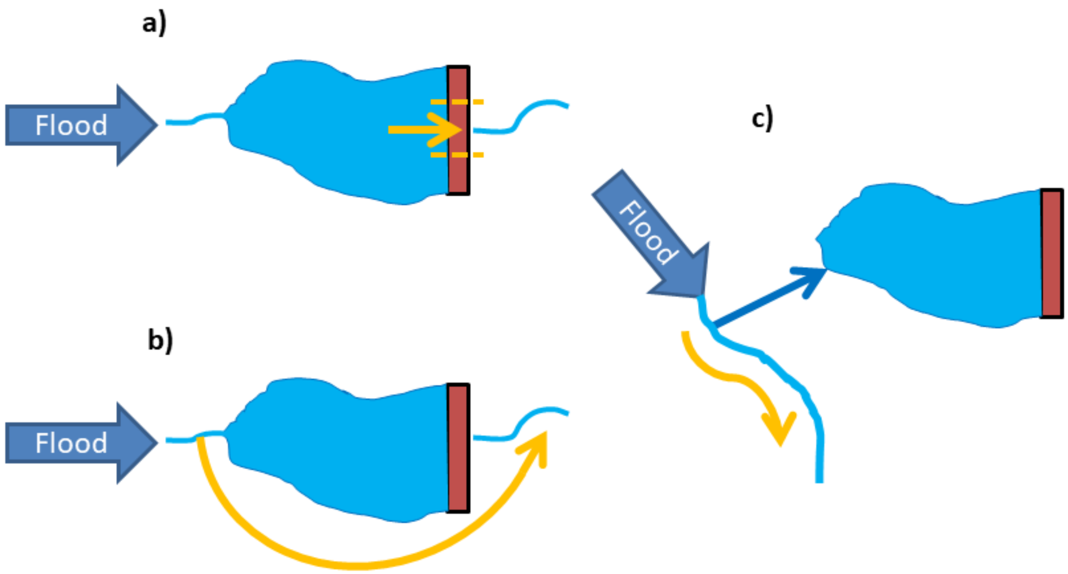


Figure 14. Reservoirs provided by different sediment routing solutions. The direction of sediment-laden waters is represented by yellow arrows. (a) Conventional reservoir, in which sediment is sluiced through the dam during periods of high inflows, with the objective of permitting sediment to be transported through the reservoir as rapidly as possible while minimizing sedimentation. Sediment flushing can be represented by a similar scheme, but, in contrast to sluicing, it focuses on scouring and re-suspending deposited sediment, which can happen independently to the sediment inflow into the reservoir. (b) Sediment by-passing diverting sediment-laden waters upstream of the reservoir into a high-capacity channel (or tunnel) and conveying the sediment-laden waters downstream of the dam, where they rejoin the river. (c) Off-channel reservoir storage, wherein a dam or a weir diverts water to an off-channel reservoir during times of clear flow, but does not divert when suspended sediment concentrations are high.

Source: Modified from Kondolf et al. (2014)

To characterize the main factors affecting channel morphology, the spatial and temporal contexts of a river can be based on a multiscale, process-based, hierarchical framework. Within the European REFORM project, Rinaldi et al.(2015*b*) proposed a sequence of procedural stages and steps to assess river conditions and to support the selection of appropriate management. This procedure incorporates: (1) delineation and characterization of the river system; (2) assessment of past temporal changes and present river conditions; (3) assessment of future trends; and (4) identification of management actions (Figure 15).

A catchment-wide delineation and spatial characterization of the fluvial system is needed to delineate, characterize and analyse the catchment and river system in their present conditions. Assessment of temporal changes and present conditions involves reconstructing the history and evolutionary trajectories of morphological changes that have resulted in the present river conditions. Assessment of scenario-based future trends identifies possible future scenarios of hydromorphological modification, whereas the final phase identifies possible hydromorphological restoration or management actions.

Establishing e-flows and sediment release from reservoirs therefore requires an evaluation of the likelihood that river change will take place, and of the morphological potential that could be achieved in response to a given modification of flows and sediment regime. This guidance proposes a methodology that identifies possible actions through assessing scenario-based possible future trends related to the selected actions. Relevant aspects to link e-flows to sediment regime may include, for example, identification of flows needed to initiate transport, coupling peak flows with sediment availability, determining and maintaining channel morphology and related habitats, quantification of sediment deficit or surplus, release of sediments downstream of barriers, removal of barriers and evaluation of effectiveness of different measures.

The basic hypothesis (paradigm) of coupling e-flows and sediment release is that enhancing morphological dynamics and conditions will promote a positive ecological response. Any actions considering e-flows and morphological channel changes will somehow promote habitat recovery and diversity.

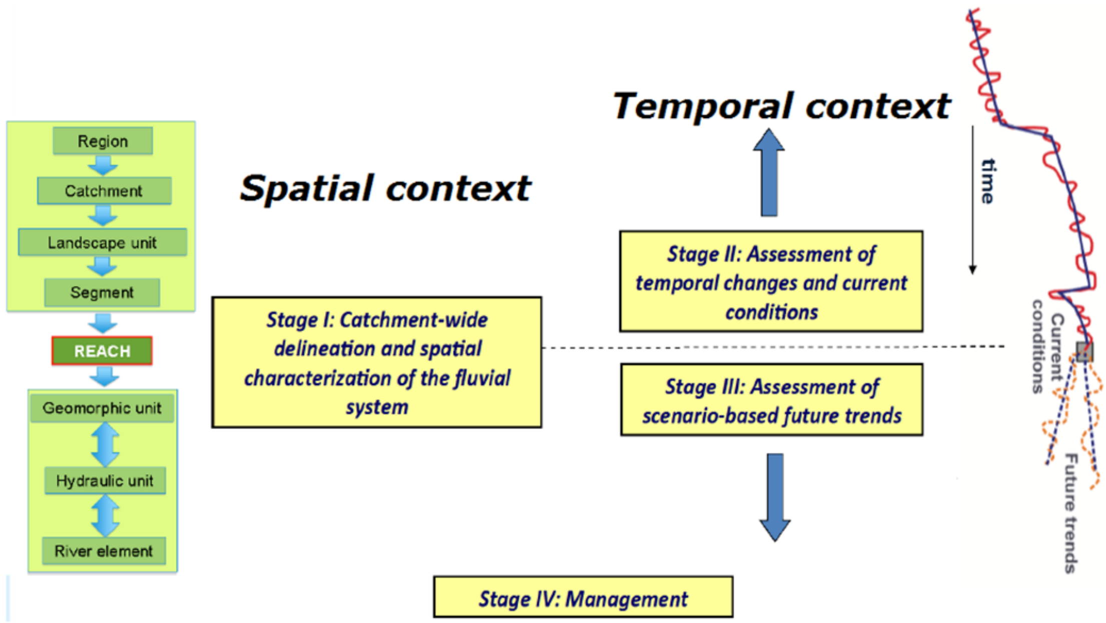


Figure 15. Structure of the overall hydromorphological framework (Rinaldi et al., 2015*b*). On the right-hand side, the graph emphasizes that the present state of the river system represents a spot within a long trajectory of evolution that needs to be known to understand present conditions and possible future trends. The left-hand side and middle of the figure show the multiscale hierarchical framework used for delineation and characterization of the fluvial system (Gurnell et al., 2016).

Figure 16. Graphical representation of the current e-flow approach and the conceptual idea of recognizing that the geomorphological processes of a river are essential to create and maintain habitats and ensure positive ecological response. Linking flows directly to ecological response may ignore the importance of geomorphological processes (García de Jalón et al., 2015)

Because hysteresis affects river hydromorphological and ecological processes, complementary actions to water and sediment releases may be needed to speed up the habitat recovery processes. Measures such as direct morphological enhancement or removal of encroached riparian vegetation are examples of these complementary measures. The choice of the best option to be considered in combination with changes in the hydrological regime (that is, sediment transport versus morphological enhancement) depends on the specific context, for example, the reach sensitivity and morphological potential. Therefore, selecting the appropriate measures requires setting the river reach within a wider spatial-temporal framework.

Figure 16 illustrates the approach in establishing e-flow release from reservoirs. The aim of this guidance is to provide a possible methodology for future e-flow implementation with wider inclusion of geomorphological processes.

Actions directed to link e-flows to sediment dynamics recognize that the geomorphological processes of a river are essential to create and maintain habitats and ensure ecosystem integrity. Long-term experiments are therefore needed to implement and validate the proposed approaches. Experimental use of reservoirs for research could provide empirical data that link e-flows with river morphological characteristics and biological communities. These experiments could also provide valuable data on how coupling flow and sediments create adequate habitats to be colonized by aquatic biota.

7. GLOSSARY

Bankfull channel	Water channel network, bars and islands. The limits coincide with banks, but are often difficult to identify, as the transition between the bankfull channel and the flood-plain is vague. The bankfull limits are thus identified with the bankfull stage (or level) (see the definition below).
Bankfull discharge	Discharge or river flow that fills the river channel up to the bankfull level. The frequency of bankfull discharge is usually 1–3 years. For rivers in dynamic equilibrium, the bankfull discharge corresponds to the formative or dominant discharge, that is, when changes in channel forms and dimensions occur.
Bankfull stage (or level)	Determines the limit of the bankfull channel, and corresponds to the flow stage at which water starts to spill out of the channel (on one or both banks) onto the surrounding flood-plain. It corresponds to the bankfull discharge (see above). Field identification of the bankfull level can be difficult (for example, in case of incised rivers).
Bioperiod	Period of time representing months or times of the year associated with distinct behaviour of species or life stages (for example, rearing, growth, migration and spawning).
Flow pattern	Above-water spatial unit formed by the interaction between local hydraulic and sediment conditions that produces a series of distinct flow patterns at the flow surface. Different flow types are distinguished: free fall, chute, broken standing waves, unbroken standing waves, rippled, upwelling, smooth and no perceptible flow.
Fluvial or river corridor	Near-natural area of land including the fluvial geomorphic units that are directly (or more frequently) affected by fluvial processes. Usually delimited by near-natural vegetation (that is, including the bankfull channel and flood-plain units). In some cases, it corresponds to the entire flood-plain.
Geomorphic unit	Area containing a landform (for example, bar, riffle or flood-plain) created by erosion and/or deposition inside (bankfull channel geomorphic unit) or outside (flood-plain geomorphic unit) the river channel. Some geomorphic features are formed in association with living and dead (for example, large wood) vegetation (also named biogeomorphic units).
Geographic information system (GIS)	Computerized informatic system (software) that allows the collection, entry, analysis, visualization and return of information from georeferenced geographic data.
Large river	River whose width is significantly greater than the bed sediment size and that is completely laterally unconstrained. In general, a lowland unconfined river, larger than 30 m in width and with a bankfull discharge of 20–50 $m^3 s^{-1}$.
Mesohabitat	Eco-hydraulic characteristics at the reach scale in terms of habitat types, about 1–10 m in size.
Microhabitat	Small area within a mesohabitat, about 10 cm in size.

8. REFERENCES

Abbasov, R.K. and V.U. Smakhtin, 2009: Introducing environmental thresholds into water withdrawal management of mountain streams in the Kura River basin, Azerbaijan. *Hydrological Sciences Journal*, 54:1068–1078.

Acreman, M.C. and M.J. Dunbar, 2004: Defining environmental flow requirements: a review. *Hydrology and Earth System Sciences*, 8:861–876.

Acreman, M.C. and A.J.D. Ferguson, 2010: Environmental flows and the European Water Framework Directive. *Freshwater Biology*, 55:32–48.

Acreman, M.C., J. King, R. Hirji, W. Sarunday and W. Mutayoba, 2005: *Capacity Building to Undertake Environmental Flow Assessments in Tanzania*. Proceedings of the International Conference on River Basin Management, Morogorro, United Republic of Tanzania, March 2005.

Acuña, V., J.R. Díez, L. Flores, M. Meleason and A. Elosegi, 2013: Does it make economic sense to restore rivers for their ecosystem services? *Journal of Applied Ecology*, 50:988–997.

Alexandratos, N. and J. Bruinsma, 2012: *World Agriculture Towards 2030/2050: The 2012 Revision*. ESA Working Paper No. 12-03. Rome, Food and Agriculture Organization of the United Nations.

Alonso-Eguía Lis, P.E., A. Gomez-Balandra and P.E. Saldaña-Fabela, 2007: *Requerimientos para implementar caudal ambiental en México*. Jiutepec, Mexico, Instituto Mexicano de Tecnología del Agua-Alianza/World Wildlife Fund/Fundación Gonzalo Río Arronte – Programa Hidrológico Internacional/United Nations Educational, Scientific and Cultural Organization/Secretaría de Medio Ambiente y Recursos Naturales – Gobierno de Mexico.

Annear, T., I. Chisholm, H. Beecher, A. Locke, P. Aarrestad, C. Coomer, C. Estes, J. Hunt, R. Jacobson, G. Jöbsis, J. Kauffman, J. Marshall, K. Mayes, G. Smith, R. Wentworth and C. Stalnaker, 2004: *Instream Flows for Riverine Resource Stewardship*. Revised edition. Cheyenne, Instream Flow Council.

Anuran, B. and R. Jha, 2014: *Environmental Flows State-of-the-art with Details Assessment of a Typical River Basin of India*. International Conference on Innovative Technologies and Management for Water Security, Chennai, India, 12–14 February 2014.

Arthington, A.H. and J.M. Zalucki (eds.), 1998: *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Holistic Methodologies*. Land and Water Resources Research and Development Corporation Occasional Paper 27/98. Canberra.

Arthington, A.H., S.E. Bunn, N.L. Poff and R.J. Naiman, 2006: The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications*, 16(4):1311–1318.

Bain, M.B. and J.G. Knight, 1996: *Classifying Stream Habitat Using Fish Community Analysis*. Ecohydraulics 2000, 2nd International Symposium on Habitat Hydraulics (M. Leclerc, H. Capra, S. Valentin, A. Boudreau and Y. Côté, eds.). Quebec City, Institut national de la recherche scientifique – Eau.

Baras, E., 1997: Environment determinants of residence area selection by *Barbus* in the River Outhe. *Aquatic Living Resources*, 10:195–206.

Baras, E. and M.C. Lucas, 2001: Impacts of man's modifications of river hydrology on the migration of freshwater fishes: a mechanistic perspective. *Ecohydrology and Hydrobiology*, 1:291–304.

Baras, E. and J. Nindaba, 1999: Diel dynamics of habitat use by riverine young-of-the-year *Barbus barbus* and *Chondrostoma nasus* (Cyprinidae). *Archiv für Hydrobiologie*, 146:431–448.

Barrios, E., N. Barajas, A. Rodríguez and I. González, 2007: *Three Models for Implementation of Environmental Flows in Mexico*. Proceedings of 10th International River Symposium and Environmental Flows Conference, Brisbane, Australia.

Baxter, G., 1961: River utilization and the preservation of migratory fish life. *Proceedings of the Institution of Civil Engineers*, 18(3):225–244.

Belletti, B., M. Rinaldi, M. Bussettini, F. Comiti, A.M. Gurnell, L. Mao, L. Nardi and P. Vezza, 2017: Characterising physical habitats and fluvial hydromorphology: a new system for the survey and classification of river geomorphic units. *Geomorphology*, 283:143–157.

Benetti, A.D., A.E. Lanna and M.S. Cobalchini, 2004: Current practices for establishing environmental flows in Brazil. *River Research and Applications*, 20:427–444.

Borsányi, P., K. Alfredsen, A. Harby, O. Ugedal and C.K.L. Borsányi, 2003: A meso-scale habitat classification method for production modelling of Atlantic salmon in Norway. *Hydroécologie Appliquée*, 14(1):119–138.

Bovee, K.D., B.L. Lamb, J.M. Bartholow, C.B. Stalnaker, J. Taylor and J. Henriksen, 1998: *Stream Habitat Analysis Using the Instream Flow Incremental Methodology*. Fort Collins, United States Geological Survey.

Brisbane Declaration, 2007: *Summary Findings and a Global Action Agenda*. 10th International River Symposium and International Environmental Flows Conference, 3–6 September 2007, Brisbane, Australia, https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/ELOHA/Documents/Brisbane-Declaration-English.pdf.

Bunn, S.E. and A.H. Arthington, 2002: Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, 30(4):492–507.

Caissie, D., N. El-Jabi and C. Hébert, 2007: Comparison of hydrologically based instream flow methods using a resampling technique. *Canadian Journal of Civil Engineering*, 34:66–74.

Cheviron, B. and R. Moussa, 2016: Determinants of modelling choices for 1-D free-surface flow and morphodynamics in hydrology and hydraulics: a review. *Hydrology and Earth System Sciences*, 20:3799–3830.

Davies, P.M., R.J. Naiman, D.M. Warfe, N.E. Pettit, A.H. Arthington and S.E. Bunn, 2014: Flow–ecology relationships: closing the loop on effective environmental flows. *Marine and Freshwater Research*, 65:133–141.

de Souza Castro, E.R.R., M.C. Moreira and D.D. da Silva, 2015: Environmental flow in the River Ondas basin in Bahia, Brazilian Cerrado. *Environmental Monitoring and Assessment*, 188:1–10.

Dickens, C., 2011: *Critical Analysis of Environmental Flow Assessments of Selected Rivers in Tanzania and Kenya*. Gland, International Union for Conservation of Nature; Scottsville, Institute of Natural Resources.

Díez-Hernández, J.M. and D.H. Ruiz-Corbo, 2007: Determinación de caudales ambientales confiables en Colombia: el ejemplo del río Placé (Cauca). *Gestión y Ambiente*, 10:153–166.

Doyle, M.W., E.H. Stanley, D.L. Strayer, R.B. Jacobson and J.C. Schmidt, 2005: Effective discharge analysis of ecological processes in streams. *Water Resources Research*, 41:1–16.

Dunbar, M.J., K. Alfredsen and A. Harby, 2012: Hydraulic-habitat modelling for setting environmental river flow needs for salmonids. *Fisheries Management and Ecology*, 19:500–517.

Emerton, L. and E. Bos, 2004: *Value: Counting Ecosystems as Water Infrastructure*. Gland, International Union for Conservation of Nature.

European Commission, 2000: Directive 2000/60/EC of the European Parliament and of the Council, 23 October 2000, establishing a framework for community action in the field of water policy. *Official Journal of the European Community*, L327:1–72.

———, 2015: *Ecological Flows in the Implementation of the Water Framework Directive*. Common Implementation Strategy Guidance Document No. 31. Luxembourg.

Ferreira, M.T., L. Sousa, J.M. Santos, L. Reino, J. Oliveira, P.R. Almeida and R.V. Cortes, 2007: Regional and local environmental correlates of native Iberian fish fauna. *Ecology of Freshwater Fish*, 16:504–514.

Fisheries and Oceans Canada, 2013: *Framework for Assessing the Ecological Flow Requirements to Support Fisheries in Canada*. Advisory Report 2013/017. Ottawa, Canadian Science Advisory Secretariat.

Food and Agriculture Organization of the United Nations (FAO), 2015: AQUASTAT, http://www.fao.org/aquastat/en.

Forslund, A., B.M. Renöfält, K. Maijer, K. Krchnak, K. Cross, M. Smith, M. McClain, S. Davidson, S. Barchiesi and T. Farrell, 2009: *Securing Water for Ecosystems and Human Well-being: The Importance of Environmental Flows*. Stockholm, Swedish Water House.

Friberg, N., M. O'Hare and A.M. Poulsen, 2013: *Impacts of Hydromorphological Degradation and Disturbed Sediment Dynamics on Ecological Status*. Deliverable 3.1 of the REFORM project (REstoring rivers FOR effective catchment Management); collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.

García de Jalón, D., M. Bussettini, M. Rinaldi, G. Grant, N. Friberg, P. Vezza, I.G. Cowx, F. Magdaleno-Màs and T. Buijse, 2015: *Linking E-flows to Sediment Dynamics*. Deliverable 7.7 of the REFORM project (REstoring rivers FOR effective catchment Management); collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.

Gippel, C.J. and M.J. Stewardson, 1998: Use of wetted perimeter in defining minimum environmental flows. Regulated Rivers: *Research and Management*, 14(1), 53–67.

Gosselin, M.P., I. Maddock and G. Petts, 2012: Mesohabitat use by brown trout (Salmo trutta) in a small groundwater-dominated stream. *River Research and Applications*, 28:390–401.

Grabowski, R.C. and A.M. Gurnell, 2016: Hydrogeomorphology–ecology interactions in river systems. *River Research and Applications*, 32:139–141.

Grey, D. and C. Sadoff, 2005: *Water Resources, Growth and Development: A Working Paper for Discussion*. Prepared for the Panel of Finance Ministers. Water Resources Sector Strategy, The World Bank, Washington, DC.

Gurnell, A.M., M. Rinaldi, B. Belletti, S. Bizzi, B. Blamauer, G. Braca, A.D. Buijse, M. Bussettini, B. Camenen, F. Comiti, L. Demarchi, D. García de Jalón, M. González del Tánago, R.C. Grabowski, I.D.M. Gunn, H. Habersack, D. Hendriks, A.J. Henshaw, M. Klösch, B. Lastoria, A. Latapie, P. Marcinkowski, V. Martínez-Fernández, E. Mosselman, J.O. Mountford, L. Nardi, T. Okruszko, M.T. O'Hare, M. Palma, C. Percopo, N. Surian, W. van de Bund, C. Weissteiner and L. Ziliani, 2016: A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. *Aquatic Sciences*, 78:1–16.

Hauer, C., G. Mandlburger and H. Habersack, 2009: Hydraulically related hydro-morphological units: description based on a new conceptual mesohabitat evaluation model (MEM) using LiDAR data as geometric input. *River Research and Applications*, 25:29–47.

Hauer, C., G. Unfer, M. Tritthart, E. Formann and H. Habersack, 2011: Variability of mesohabitat characteristics in riffle-pool reaches: testing an integrative evaluation concept (FGC) for MEM-application. *River Research and Applications*, 27:403–430.

Heggenes, J. and J. Wollebæk, 2013: Habitat use and selection by brown trout in streams. In: *Ecohydraulics: An Integrated Approach* (I. Maddock, A. Harby, P. Kemp and P. Wood, eds.), 157–176. John Wiley & Sons, Ltd.

Imanov, F.A., 2003: *Minimum Water Flow of Caucasus Rivers*. Baku, Nafta Press [in Russian].

International Commission on Large Dams, 2011: World Register of Dams, https://www.icold-cigb.org/.

Italian National Institute for Environmental Protection and Research (ISPRA), 2016: *Sviluppo di un sistema di rilevamento e classificazione delle Unità Morfologiche dei corsi d'acqua (SUM)*. Publication No. 122/2015, Appendix No. 4. Rome.

Jiménez, J., 2005: *Propuesta de Caudales Ambientales para el Río Tempisque-Costa Rica: Resumen de Aspectos Biológicos e Hidrológicos*. San Jose, Organization for Tropical Studies [in Spanish].

Karakoyun, Y., Z. Yumurtaci and A.H. Dönmez, 2015: Environmental flow assessment for energy generation sustainability employing different hydraulic evaluation methods: Çambaşi hydropower plant case study in Turkey. *Clean Technologies and Environmental Policy*, 18:583–591.

Kemp, J.L., D.M. Harper and G.A. Crosa, 1999: Use of 'functional habitats' to link ecology with morphology and hydrology in river rehabilitation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 9:159–178.

Kennard, M.J., S.J. Mackay, B.J. Pusey, J.D. Olden and N. Marsh, 2010: Quantifying uncertainty in estimation of hydrologic metrics for ecohydrological studies. *River Research and Applications*, 26:137–156.

King, J., C. Brown and H. Sabet, 2003: A scenario-based holistic approach to environmental flow assessments for rivers. *River Research and Applications*, 19:619–639.

King, J., R. Tharme and C. Brown, 1999: Definition and implementation of instream flows. In: *Dams, Ecosystem Functions and Environmental Restoration*. Sterling, Virginia, World Commission on Dams.

King, J.M., R.E. Tharme and M.S. de Villiers, 2000: *Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology*. Pretoria, Water Research Commission.

———, 2008: *Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology* (updated edition). Gezina, Water Research Commission.

Kondolf, G.M., Y. Gao, G.W. Annandale, G.L. Morris, E. Jiang, J. Zhang, Y. Cao, P. Carling, K. Fu, Q. Guo, R. Hotchkiss, C. Peteuil, T. Sumi, H.-W. Wang, Z. Wang, Z. Wei, B. Wu, C. Wu and C.T. Yang, 2014: Sustainable sediment management in reservoirs and regulated rivers: experiences from five continents. *Earth's Future*, 2:256–280.

Koutrakis, E.T., S. Triantafillidis, A.S. Sapounidis, P. Vezza, N. Kamidis, G. Sylaios and C. Comoglio. Evaluation of ecological flows in highly regulated rivers using the mesohabitat approach: a case study on the Nestos River, N. Greece. *Ecohydrology & Hydrobiology* (forthcoming).

Lamouroux, N., H. Capra, M. Pouilly and Y. Souchon, 1999: Fish habitat preferences in large streams of southern France. *Freshwater Biology*, 42:673–687.

Lehner, B., C.R. Liermann, C. Revenga, C. Vörösmarty, B. Fekete, P. Crouzet, P. Döll, M. Endejan, K. Frenken, J. Magome, C. Nilsson, J.C. Robertson, R. Rödel, N. Sindorf and D. Wisser, 2011: High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, 9:494–502.

Linnansaari, T., W.A. Monk, D.J. Baird and R.A. Curry, 2013: *Review of Approaches and Methods to Assess Environmental Flows across Canada and Internationally*. Research Document 2012/039. Ottawa, Canadian Science Advisory Secretariat.

Lloyd, N., G. Quinn, M. Thoms, A. Arthington, B. Gawne, P. Humphries and K. Walker, 2003: Does Flow Modification Cause Geomorphological and Ecological Response in Rivers? *A Literature Review from an Australian Perspective*. Canberra, Cooperative Research Centre for Freshwater Ecology.

Lytle, D.A. and N.L. Poff, 2004: Adaptation to natural flow regimes. *Trends in Ecology and Evolution*, 19(2):94–100.

Meitzen, K.M., M.W. Doyle, M.C. Thoms and C.E. Burns, 2013: Geomorphology within the interdisciplinary science of environmental flows. *Geomorphology*, 200:143–154.

Melstrom, R.T., F. Luni, P.C. Esselman and R.J. Stevenson, 2015: Valuing recreational fishing quality at rivers and streams. *Water Resources Research*, 51(1):140–150.

Merenlender, A.M. and M.K. Matella, 2013: Maintaining and restoring hydrologic habitat connectivity in Mediterranean streams: an integrated modeling framework. *Hydrobiologia*, 719:509–525.

Merritt, D.M., M.L. Scott, N. LeRoy Poff, G.T. Auble and D.A. Lytle, 2010: Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds. *Freshwater Biology*, 55:206–225.

Milhous, R., J. Bartholow, M. Updike and A. Moos, 1990: *Reference Manual for Generation and Analysis of Habitat Time Series*. United States Fish and Wildlife Services.

Ministry of Land, Infrastructure and Transport River Bureau, 2007: *Guidance for Standard River Flow Design*.

Moore, K.M.S. and S.V. Gregory, 1988: Response of young-of-the-year cutthroat trout to manipulations of habitat structure in a small stream. *Transactions of the American Fisheries Society*, 117:12–170.

Nel, J.L., E. Turak, S. Linke and C. Brown, 2011: Integration of environmental flow assessment and freshwater conservation planning: a new era in catchment management. *Marine and Freshwater Research*, 62:290–299.

Neves, B.V.B., C.B. Martinez, H.A. Santos and E.M.F. Viana, 2012: Considerações sobre a manutenção das vazões ecológicas nos rios. *Hidro & Hydro*, 14:26–31.

Nilsson, C., C.A. Reidy, M. Dynesius and C. Revenga, 2005: Fragmentation and flow regulation of the world's large river systems. *Science*, 308:405–408.

Organisation for Economic Co-operation and Development, 2012: *OECD Environmental Outlook to 2050: The Consequences of Inaction*. Paris.

Ovidio, M., E. Baras, D. Goffaux, F. Giroux and J.C. Philippart, 2002: Seasonal variations of activity pattern of brown trout (*Salmo trutta*) in a small stream, as determined by radio-telemetry. *Hydrobiologia*, 470:195–202.

Parasiewicz, P., 2001: MesoHABSIM: a concept for application of instream flow models in river restoration planning. *Fisheries*, 26:6–13.

———, 2003: Upscaling: integrating habitat model into river management. *Canadian Water Resources Journal*, 28:283–299.

———, 2007: The MesoHABSIM model revisited. *River Research and Applications*, 23:893–903.

Parasiewicz, P., E. Castelli, J.N. Rogers and E. Plunkett, 2012*a*: Multiplex modeling of physical habitat for endangered freshwater mussels. *Ecological Modelling*, 228:66–75.

Parasiewicz, P., K. Ryan, P. Vezza, C. Comoglio, T. Ballestero and J.N. Rogers, 2012*b*: Use of quantitative habitat models for establishing performance metrics in river restoration planning. *Ecohydrology*, 6:668–678.

Parasiewicz, P., J.N. Rogers, P. Vezza, J. Gortázar, T. Seager, M. Pegg, W. Wiśniewolski and C. Comoglio, 2013: Applications of the MesoHABSIM simulation model. In: *Ecohydraulics: An Integrated Approach* (I. Maddock, A. Harby, P. Kemp and P. Wood, eds.), 109–124. John Wiley & Sons, Ltd.

Petts, G.E., 2009: Instream flow science for sustainable river management. *JAWRA Journal of the American Water Resources Association*, 45:1071–1086.

Poff, N.L., 1997: Landscape filters and species traits: towards mechanistic understanding and prediction in stream ecology. *Journal of the North American Benthological Society*, 16:391–409

Poff, N.L. and J.K.H. Zimmerman, 2010: Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, 55:194–205.

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

Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M.C. Freeman, J. Henriksen, R.B. Jacobson, J.G. Kennen, D.M. Merritt, J.H.O. Keeffe, J.D. Olden, K. Rogers, R.E. Tharme and A. Warner, 2010: The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology*, 55:147–170.

Regione Autonoma Valle d'Aosta, 2006: *Piano di Tutela delle Acque (PTA) della Regione Autonoma Valle d'Aosta (RAVA), Allegato* G. Brussels, European Union.

Resh, V.H., A.V. Brown, A.P. Covich, M.E. Gurtz, H.W. Li, G.W. Minshall, S.R. Reice, A.L. Sheldon, J.B. Wallace and R.C. Wissmar, 1988: The role of disturbance in stream ecology. *Journal of the North American Benthological Society*, 7:433–455.

Rieu-Clarke, A., R. Moynihan and B.-O. Magsig, 2012: *UN Watercourses Convention: User's Guide*. Dundee, Centre for Water Law, Policy and Science.

Rijsberman, F., 2004: *The Water Challenge*. Paper prepared as one of 10 challenge papers for the Copenhagen Consensus project of the Environmental Assessment Institute, Copenhagen, Denmark.

Rinaldi, M., N. Surian, F. Comiti and M. Bussettini, 2013: A method for the assessment and analysis of the hydromorphological condition of Italian streams: the morphological quality index (MQI). *Geomorphology*, 180–181:96–108.

Rinaldi, M., B. Belletti, F. Comiti, L. Nardi, M. Bussettini, L. Mao and A.M. Gurnell, 2015*a*: *Geomorphic Units Survey and Classification System (GUS)*. Deliverable 6.2, Part 4 of the REFORM project (REstoring rivers FOR effective catchment Management); collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.

Rinaldi, M., A.M. Gurnell, B. Belletti, M.I. Berga Cano, S. Bizzi, M. Bussettini, M. González del Tánago, R. Grabowski, H. Habersack, M. Klösch, F. Magdaleno Mas, E. Mosselman, M. Toro Velasco and P. Vezza, 2015*b*: *Final Report on Methods, Models, Tools to Assess the Hydromorphology of Rivers*. Deliverable 6.2, Part 1 of the REFORM project (REstoring rivers FOR effective catchment Management); collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.

Rinaldi, M., B. Belletti, F. Comiti, L. Nardi, L. Mao and M. Bussettini, 2016*a*: *Sistema di rilevamento e classificazione delle Unità Morfologiche dei corsi d'acqua (SUM)*. Italian Institute for Environmental Protection and Research Manuals and Guidelines 132/2016. Rome.

Rinaldi, M., N. Surian, F. Comiti and M. Bussettini, 2016*b*: *IDRAIM – Sistema di Valutazione Idromorfologica, Analisi e Monitoraggio dei Corsi d'acqua – Versione Aggiornata 2016*. Rome, Italian National Institute for Environmental Protection and Research.

Robinson, C.T., 2012: Long-term changes in community assembly, resistance, and resilience following experimental floods. *Ecological Applications*, 22:1949–1961.

Rodríguez-Gallego, L., C. Chreties, M. Crisci, M. Fernández, N. Colombo, B. Lanzilotta, M. Saravia, C. Neme, S. Sabaj and D. Conde, 2012: *Fortalecimiento del concepto de Caudales Ambientales como Herramienta para la Gestión Integrada de los Recursos Hídricos*. Montevideo, PNUMA y Vida Silvestre Uruguay.

River Research and Applications, 2003: Environmental flows for river systems. *River Research and Applications*, Special Issue, 19:375–681.

Smakhtin, V. and M. Anputhas, 2006: *An Assessment of Environmental Flow Requirements of Indian River Basins*. Research Report 107. Colombo, International Water Management Institute.

Snelder, T., D. Booker and N. Lamouroux, 2011: A method to assess and define environmental flow rules for large jurisdictional regions. *Journal of the American Water Resources Association*, 47:828–840.

Speed, R., C. Gippel, N. Bond, S. Bunn, X. Qu, Y. Zhang, W. Liu and X. Jiang, 2012: *Assessing River Health and Environmental Flow Requirements in Chinese Rivers*. Brisbane, International Water Centre.

Stanford, J.A., J.V. Ward, W.J. Liss, C.A. Frissell, R.N. Williams, J.A. Lichatowich and C.C. Coutant, 1996: A general protocol for restoration of regulated rivers. Regulated Rivers: *Research & Management*, 12(4–5):391–413.

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

Tharme, R.E., 2003: A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications*, 19:397–441.

Tuhtan, J., M. Noac and S. Wieprecht, 2012: Estimating stranding risk due to hydropeaking for juvenile European grayling considering river morphology. *KSCE Journal of Civil Engineering*, 16:197–206.

United Nations Department of Economic and Social Affairs, 2015: *World Population Prospects: Key Findings & Advanced Tables, 2015 Revision*. New York.

Vassoney, E., A. Mammoliti Mochet, R. Rocco, R. Maddalena, P. Vezza and C. Comoglio, 2019: Integrating meso-scale habitat modelling in the multicriteria analysis (MCA) process for the assessment of hydropower sustainability. *Water*, 11(4):640.

Vezza, P., P. Parasiewicz, M. Rosso and C. Comoglio, 2012: Defining minimum environmental flows at regional scale: application of mesoscale habitat models and catchments classification. *River Research and Applications*, 28:675–792.

Vezza, P., P. Parasiewicz, M. Spairani and C. Comoglio, 2014: Habitat modelling in high gradient streams: the meso-scale approach and application. *Ecological Applications*, 24:844–861.

Vezza, P., A. Goltara, M. Spairani, G. Zolezzi, A. Siviglia, M. Carolli, M.C. Bruno, B. Boz, D. Stellin, C. Comoglio and P. Parasiewicz, 2015: Habitat indices for river: quantifying the impact of hydro-morphological alterations on the fish community. In: *Engineering Geology for Society and Territory*, Volume 3. Springer International Publishing.

Vezza, P., A. Zanin and P. Parasiewicz, 2017: *Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale*. Rome, Italian National Institute for Environmental Protection and Research.

Vezza, P., M. Bussettini, I. Garzia, E.T. Koutrakis, S. Triantafillidis and A.S. Sapounidis, 2018: *Considering River Morphological Changes in Environmental Flows Assessment*. Proceedings of 12th International Symposium on Ecohydraulics, Tokyo, Japan.

Wang, X., Y. Zhang and C. James, 2009: Approaches to providing and managing environmental flows in China. *International Journal of Water Resources Development*, 25:283–300.

Wilkes, M.A., I. Maddock, O. Link and E. Habit, 2015: A community-level, mesoscale analysis of fish assemblage structure in shoreline habitats of a large river using multivariate regression trees. *River Research and Applications*, 32(4):652–665.

Wohl, E., B.P. Bledsoe, R.B. Jacobson, N.L. Poff, S.L. Rathburn, D.M. Walters and A.C. Wilcox, 2015: The natural sediment regime in rivers: broadening the foundation for ecosystem management. *Bioscience*, 65(4):358–371.

World Water Assessment Programme, 2016: *The United Nations World Water Development Report 2016. Water and Jobs*. Paris, United Nations Educational, Scientific and Cultural Organization.

Yang, Z.F., T. Sun, B.S. Cui, B. Chen and G.Q. Chen, 2009: Environmental flow requirements for integrated water resources allocation in the Yellow River Basin, China. *Communications in Nonlinear Science and Numerical Simulation*, 14:2469–2481.

Zarfl, C., A.E. Lumsdon, J. Berlekamp, L. Tydecks and K. Tockner, 2015: A global boom in hydropower dam construction. *Aquatic Sciences*, 77:161–170.

For more information, please contact:

World Meteorological Organization

7 bis, avenue de la Paix – P.O. Box 2300 – CH 1211 Geneva 2 – Switzerland

Communication and Public Affairs Office

Tel.: +41 (0) 22 730 83 14/15 – Fax: +41 (0) 22 730 80 27

Email: cpa@wmo.int

public.wmo.int

JN 19553