THEME: Environment (including climate change)
TOPIC: ENV.2011.2.1.2-1 Hydromorphology and ecological objectives of WFD
Collaborative project (large-scale integrating project)
Grant Agreement 282656
Duration: November 1, 2011 – October 31, 2015

REFORM

REstoring rivers FOR effective catchment Management

Deliverable D7.7 Policy Discussion Paper no. 3

Title Linking e-Flows to sediment dynamics

Author(s) Diego García de Jalón (UPM), Martina Bussettini (ISPRA), Massimo Rinaldi (UNIFI), Gordon Grant (USDA Forest Service, USA), Nikolai Friberg (NIVA), Paolo Vezza (UPV, Spain), Ian G. Cowx (UNIHULL) Fernando Magdaleno Màs (CEDEX) & Tom Buijse (Deltares).

Due date to deliverable: 31st October 2015
Actual submission date: 04 November 2015

Project funded by the European Commission within the 7th Framework Programme (2007 – 2013)

Dissemination Level

PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Front page: River Guadalquivir -Water flow carries sediments coming from hillslope erosion (photo by Diego García de Jálon, 2015).

This document is a policy discussion paper aimed at addressing possible alternative approaches for e-Flows assessment and identification within the context of best strategies for fluvial restoration. We emphasize dammed rivers in Mediterranean regions. The document is the outcome of the REFORM stakeholder workshop 'Linking eFlows to sediment dynamics', which took place in Rome on 9th – 10th September 2015.

It is the 3rd policy discussion paper prepared within the contect of the REFORM project. The two other policy discussion papers are:

1. Kampa, E., T. Buijse, W. Zeeman, M. Catalinas Pérez, S. Mariani [eds.] (2013) Discussion Paper, Stakeholder Workshop on River Restoration to Support Effective Catchment Management, Brussels, 26–27 February 2013. REFORM deliverable 7.7 Policy Discussion Paper no. 1
2. Hendriks, D.M.D, T. Okruszko, M. Acreman et al. (2015) Bringing groundwater to the surface; Groundwater-river interaction as driver for river ecology. REFORM deliverable 7.7 Policy Discussion Paper no. 1

Table of Contents

Executive Summary

Fluvial communities and their ecological integrity are the result of their evolutionary adaptation to river habitats. Flowing water is the main driver for development and maintenance of these habitats, which is why environmental flows (e-Flows) are needed where societal demands are depleting water resources.

Fluvial habitats are not only the result of water flow, however, but are shaped by the combined interaction of water, sediments woody/organic material, and riparian vegetation. Water abstraction, flow regulation by dams, gravel pits or siltation by fine sediments eroded from hillslopes are pressures that can disturb interactions among water, sediments, and other constituents that create the habitats needed by fluvial communities.

Present e-Flow design criteria are based only on water flow requirements. Here we argue that sediment dynamics need to be considered when specifying instream flows, thereby expanding the environmental objectives and definition of e-Flows to include sediments (extended e-Flows).

We recognize that currently used biological assessment systems and metrics are not sufficiently sensitive indicators of ecological status of water bodies impacted by sediment and flow management. To overcome current limitations of available metrics that use biological quality elements (BQEs) in assessing flow related impacts, we are proposing alternative assessment criteria that include hydromorphological (HYMO) aspects.

Our broadened definition of extended e-flows requires a broader set of protocols and tools derived from specific HYMO approaches (e.g. REFORM multiscale hymo framework).

To this aim, a framework for e-Flows assessment and identification of best strategies for fluvial restoration, including the context of rivers regulated by large dams, is presented.

Acknowledgements

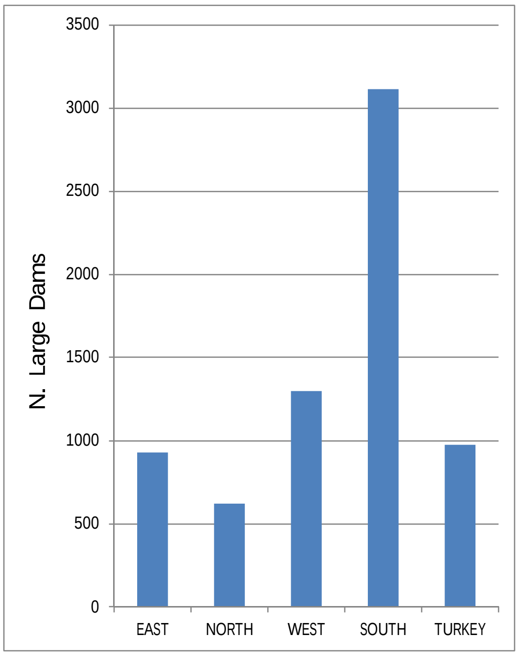
REFORM receives funding from the European Union’s Seventh Programme for research, technological development and demonstration under Grant Agreement No. 282656.

1 Introduction

We are living in the Anthropocene Era and we are becoming increasingly aware of the large body of evidence showing that human interactions with the hydrological cycle have serious consequences for rivers and ecosystems (Dynesius & Nilsson 1994; Vörösmarty et al. 2013). Gerten et al. (2013) pointed out the existence of a 'planetary boundary' for fresh water used by humans, and proposed ways forward to refine and reassess it. They suggested that a key element involves quantifying local water availabilities taking account of environmental flow requirements.

Human populations have water demands that are prioritized according to various needs: 1) vital water (drinking water, hygiene, sanitation), 2) social water (gardens, swimming pools) and especially 3) commercial water (required for hydropower, intensive agriculture, industrial processes, tourism infrastructure). In warmer climates all these demands are greater than in colder climates. Typically commercial water use represents more than 80% of all demand, which is often even greater than water availability.

Socio-economic drivers, such as agriculture, energy production and land development, and the pressures they create on water resources (e.g. through construction and operation of dams, irrigation systems) have important effects on hydromorphology and ecosystems. This is omnipresent across the whole of Europe, but particularly evident in Mediterranean rivers, due to their combination of a strong external water demand and hydromorphological characteristics related to low specific runoff. As temperature and rainfall are out of phase with each other in semi-arid climate regimes, i.e. higher summer temperatures and low river flows, and vice versa, Mediterranean rivers cannot naturally satisfy water demands. This situation has justified construction of a huge number of large reservoirs. According to the International Commission of Large Dams, the European member states with the largest number of reservoirs are: Spain (1082), Turkey (976), France (713), the UK (607) and Italy (542 [ICOLD, 2007]). Southern Mediterranean countries (excluding Turkey) are clearly the ones with the largest numbers of large dams, followed by Western countries and Eastern countries (including Russia & Ukraine) (Fig. 1).



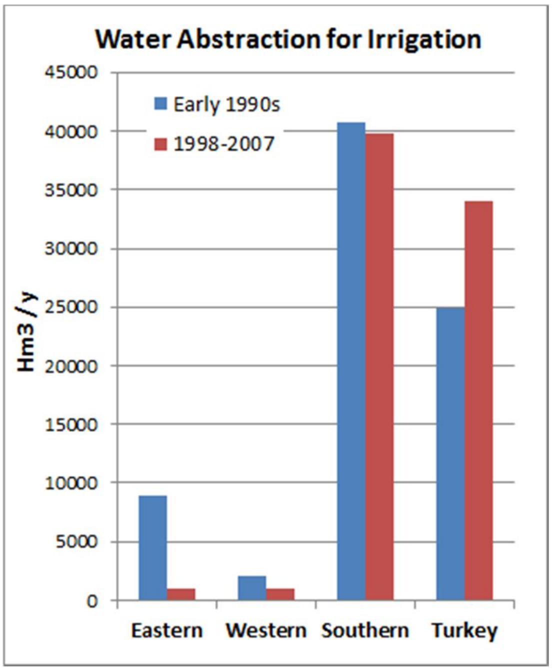


Figure 1.a) Number of large dams per European countries (data from ICOLD). b) Water abstraction used for irrigation by European countries (European Env. Agency, 2010)

Of all European regions, Mediterranean countries also use the most water stored in reservoirs for irrigation. In addition, historical land overexploitation and today´s intensive agriculture on slopes cause high catchment erosion, sediment yield, and transport. This latter problem is widespread and shared by continental lowland basins too.

Dams and other pressures, such as weirs and water abstraction, have important effects on the hydromorphology and ecosystems. The environmental effects of dams and the reservoirs they impound vary greatly with their regional or environmental setting, which controls the natural flow regime, and their size (morphometry and capacity) and purpose, which affect dam outlet and reservoir characteristics and operational procedures of the dam and its reservoir. The impacts of large dams have a global dimension and there are many comprehensive reviews of the effects and ecological impacts downstream of dams (e.g. Ward and Stanford, 1979; Petts, 1984; Williams and Wolman, 1984; Ligon et al. 1995; Grant et al, 2003, and Grant, 2012; Vörösmarty et al., 1997) estimated that the maximum water storage behind 746 of the world's largest dams was equivalent to 20% of global mean annual runoff and the median water residence time behind those impoundments was 0.40 years. However, dams do not only regulate water flow. More recently, Vörösmarty (2003) estimated that more than 50% of the basin-scale sediment flux in regulated basins is trapped in artificial impoundments; based on discharge-weighting large reservoirs trap 30% and small reservoirs an additional 23%.

Figure 2.- a) Reservoirs are sediment traps. Barasona Reservoir in R. Esera (Ebro Basin). Over 80 % of reservoir capacity has been lost. b) Armouring river bed (R. Pas). Incision caused by smaller substrate size selective erosion. c) Lateral bank erosion in meander. R. Gallego. d) Sediment deposits in lateral banks. R. Guadalete (photo by D.G.De Jalon, 2015)

1.1 WFD and e-Flows

This paper draws on the CIS Guidance Document 'Ecological flows in the implementation of the Water Framework Directive' (2015) as a starting point. Our main objective is to emphasize the importance of hydromorphology, especially for rivers that are heavily regulated by large dams. Thus, we adopt the perspective of the Guidance Document that e-Flows are more than just minimum flows, and have to include all the components of hydrological regime.

E-Flows play different roles in different fluvial settings. Ideally we can view e-Flows as restoration measures since their aim is to support the achievement of good ecological status in rivers subject to hydrological pressures. When these pressures are exerted by major infrastructures such as large dams, however, the changes caused in the river ecosystem can be so profound that e-Flows can only be considered as mitigation measures. In addition, River Basin Management Plans (RBMPs) often consider e-Flows as preventive measures for many river sections that are not regulated or affected by water abstraction. Furthermore, for fluvial segments under some form of protection, e-Flows represent conservation measures. With such different objectives of e-Flows, the question arises: should all types of e-Flows be quantified in a single manner?

In the context of WFD, ecological flows are defined as a *flow regime consistent with the achievement of the environmental objectives of a water body* (i.e. good ecological status – [GES] - for natural water bodies; good ecological potential – [GEP] -for heavily modified - HMWB - and artificial water bodies; good quantitative and chemical status for groundwater bodies). Ecological flows represent therefore a "potential" measure to reach the objectives, as the real measure will derive from the evaluation of all the physical, legal, socio-economic constraints related to the water body.

As a potential measure, ecological flows come into play when the results of WFD Art.5 risk analysis on a catchment show that some water bodies are at risk of failing their objectives due to an inadequate (in terms of magnitude and timing) flow regime (e.g. a reach downstream of a reservoir). Whether it is possible to manage such a regime to make it consistent with the environmental objectives set requires determining the current natural or anthropic constraints on the catchment (hydromorphological economic, social, etc.) through analysis of scenarios. Such scenarios need to evaluate remedial measures not only in terms of their impacts on the status of WBs, but also on the uses of water in the actual system. This is crucial when addressing HMWB, as they are designated on the basis of their legitimate use.

2 Problem description

The CIS ‘Guidance Document ‘Ecological flows in the implementation of the Water Framework Directive’ (2015) presents an overview of methodologies for e-Flows implementation. However, it does not address in depth certain crucial aspects, among which is the definition of a hydromorphological regime consistent with a desired ecological state and relevant scales to be used in the assessment.

2.1 The e-Flows concept: only water?

River and their ecosystems reflect hierarchies of control. We can consider rivers as complex organisms, whose functioning needs both water flowing and its particular metabolites (sediments, woody debris, organic, dissolved solids and gases. However, a large dam on a river disturbs not only the natural water flow regime, but often to a greater extent, the natural fluxes of these metabolites. Therefore, when we use environmental flows as an instrument to improve the ecological status of water bodies, we should also consider the fluxes of all 'metabolites' that allow the existence of biological communities. Such holistic methodologies considering the many interacting components of aquatic systems, including sediments, are increasingly recommended although in many cases assessment of e-Flows is mainly based on hydrological and hydraulic assessment (Anderson K. et al, 2006; Meitzen et al. 2013).

In the context of the WFD, e-Flows represent a possible measure to reach the objectives of good ecological status or potential. There still is too little experience in the implementation of e-Flows based measures: a review of the hydrological measures applied at the EU level, based on the information deriving from the River Basin Management Plans showed that they have been established according to the “minimum flow” concept (Sanchez-Navarro & Schmidt, 2012). As such, no consideration has been given to the morphological evolution of the affected reaches or channels, which could have caused a consistent channel conveyance change. Beyond the flow regime, sediment transport plays a fundamental role in determining and maintaining channel morphology and related habitats.

A river habitat is the result of a balance between interacting geomorphological forces: water, sediments and riparian vegetation in a spatial template (fluvial reach). Water flow has the hydraulic energy able to erode, transport ant deposit sediments and riparian vegetation growth is able to consolidate deposited sediments, but old vegetation stands may reduce water erosion capacity. Thus, habitat morphology depends also on the structure and composition of the riparian stand and on its present interaction with the hydro-geomorphic pattern of the river.

The importance of sediment transport and related geomorphic processes as key components to evaluate has only recently begun to be acknowledged. Meitzen et al. (2013) emphasized how fluvial geomorphology and riverine ecology represents an ideal confluence to examine the contribution of the geomorphic field tradition to environmental flows. They developed a question-based framework that will facilitate holistic and interdisciplinary environmental flow assessments.

2.2 Definition of environmental objectives and monitoring the efficiency of measures

According to the WFD, the environmental objective of a river water body coincides with its ecological status, mainly given by the combination of the status of the relevant biological quality elements, each assessed through indicators. However, the majority of these commonly used indicators do not respond, with a necessary degree of sensitivity, to hydrological and morphological pressures or to multi-stressors systems, as acknowledged by the scientific community (Friberg et al, 2011, 2013; Friberg 2014). Therefore, objectives can hardly be defined and/or measured in terms of current biological indicators. Among biological quality elements, fish is the most reactive one to HYMO pressures, but no efficient/official method to assess their status is currently available for use in Mediterranean countries like Spain or Italy.

The notions of 'ecological status' and 'ecological potential' are highly dependent upon generally negotiated choices of metrics and thresholds, the definitions of which are constrained by the limits of assessment methods, their interpretability and ability to accurately assign a given system to a particular class (Friberg et al. 2011). Therefore, there is a need to develop HYMO pressures -specific indicators based on HYMO responsive biological elements, including alternative sampling strategies. Moreover, because of the strong nexus between hydromorphology and biology, where hydrology is the main pressure affecting the status of water bodies, it is suggested to define objectives also in the context of a hydromorphological restoration action and measure it through hydrological and morphological parameters.

2.3 The e-Flows in Mediterranean streams: The Bonsai river syndrome

Mediterranean and semi-arid countries are heavily affected by large dams and thus the implementation of adequate e-Flows is strongly needed. We have seen that dam impacts have wider ecosystem effects, and to design e-Flows we need to determine the drivers of flow and sediment changes below dams. A framework summarizing the effects of large dams on fluvial processes and hydromorphological variables is shown in Figure 3 (Garcia de Jalon et al. 2013). Besides the changes on instream flows, we find other significant fluvial processes altered by dams, like sediment fluxes, bank stabilization, substrate armouring, riparian vegetation encroachment, and even water physico-chemical degradation. These processes are responsible for changing habitats that often are unable to maintain reference communities and often causing a decline in biodiversity and an invasion of exotic species.

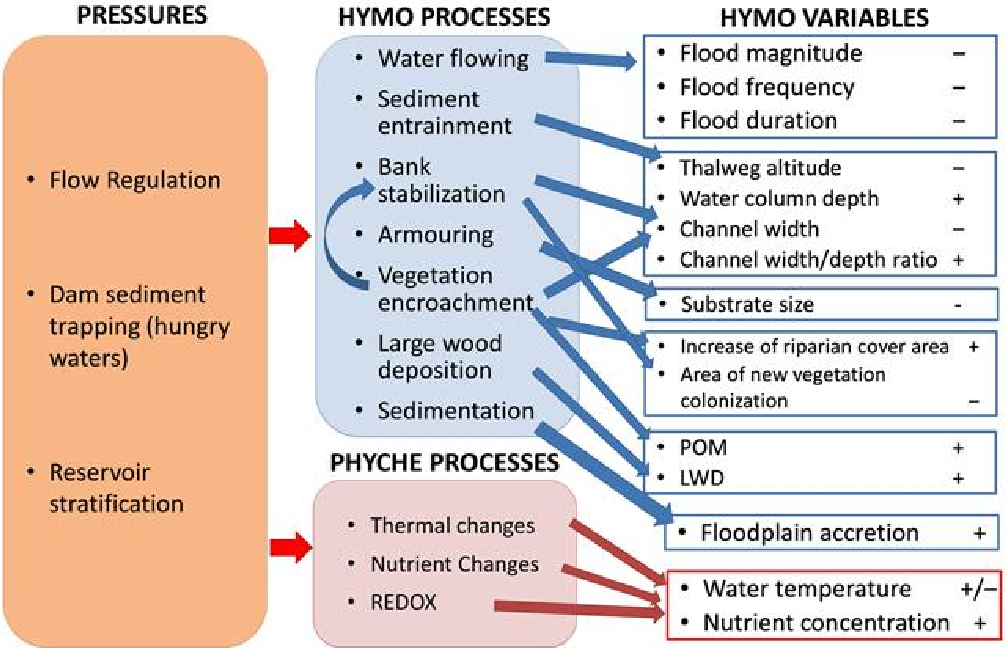


Figure 3.- Conceptual frame work of large dams and reservoirs effects on Hydromorphological (HYMO) and Physic-Chemical (PHYCHE) processes and variables (POM=Particulate Organic Matter; LWD=Large Woody Debris).

Water releases downstream of a dam entrain sediments through a size selective process that causes river substrate evolution with different stages (Collier et al. 2000):

- Over many years there is a 'wave' of sediment deficit that moves downstream along the river, changing its substrate traits: sediment calibre increases, as does armouring
- Later, substrate comes to equilibrium between the regulated flow regime and sediment input by tributaries.
- The effects on the biota vary in space and time according to these stages of substrate change

Therefore, setting e-Flows (including water & sediments) must take into account this substrate evolution for each reach of the river.

E-Flows are assessed by a variety of methods and approaches, but are rarely applied in Mediterranean countries. Most of the e-Flows proposed in the RBMPs represent a very low percentage of the mean annual flows (Figure 4). Those particular e-Flows regimes may be supported by modelling but empirical data proving their positive effect on downstream waterbody status enhancement is still missing (European Commission, 2015).

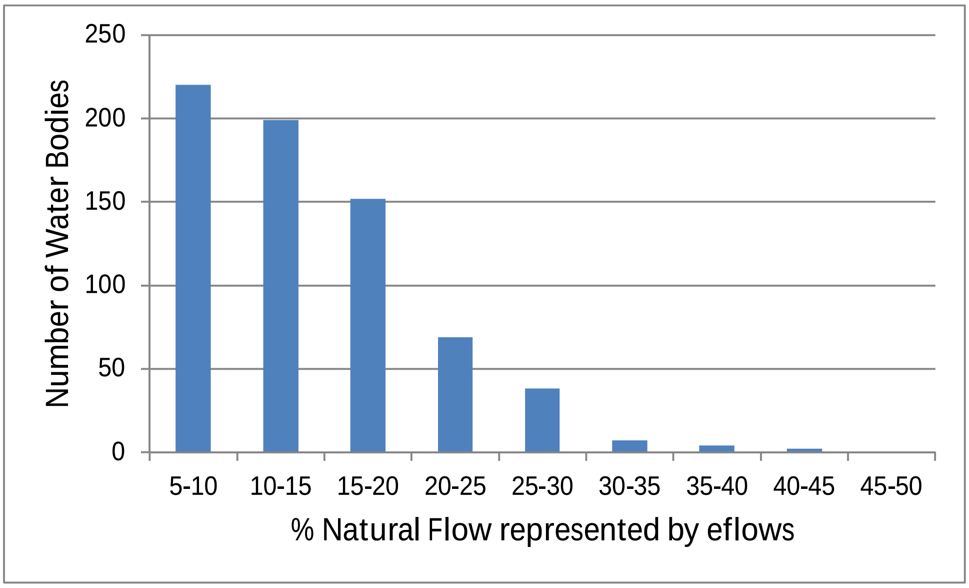


Figure 4.- Percentage of Natural flow represented by designated eFlows for the river water bodies in the Spanish Duero Basin District from its RBMP (D. Garcia de Jalon, 2014).

We should remark on the great influence of riparian vegetation dynamics (Hupp, 1999; Gurnell, Corenblit et al. 2007, Corenblit & Steiger 2009) that must be considered in specifying e-Flows below large dams, especially in warm climates that promote intensive growth and recruitment. This vegetation encroachment stabilizes the new channel, even within extraordinary floods.

Prevention of vegetation encroachment could be a basic objective of effective e-Flows, particularly in Mediterranean streams, where common irrigation reservoirs release high summer flows, thus supporting maximum plant growth potential as the normal summer drought is eliminated (Lobera et al. 2014, Gonzalez del Tanago et al. 2015a and 2015b; Stella et al. 2013, Magdaleno F. et al. 2011). Ultimately, river dimensions are so reduced that they develop into small remnant: a 'Bonsai river'.

3 Policy options

Water and sediment transport in rivers are intrinsically linked and actions on one component will interact with the other. Therefore, managing environmental flows without considering sediment dynamics will not yield the desired positive effects. By contrast, the combined management of the two components may have more cost-benefit impacts, from reduced water releases to temperature mitigation or pollutant abatement.

We propose a policy where water and sediments are considered together when dealing with the impacts of reduced flows and the use of e-Flows as a possible mitigation action, expanding the present definition of e-Flows and coupling flows with sediment dynamics. Benefits from this policy proposal come from both the ecological perspective as well as from reservoir management as sediments cause problems through siltation of reservoirs and loss of their functionality and ability to regulate, and by silting up river beds.

With this objective, we define a HYMO framework to assess the status and impacts of sediment and flow management and an e-Flows toolbox adapted to couple flows to sediment.

3.1 Hydromorphological framework for eFlows

Although the importance of sediment and geomorphological processes has been acknowledged in the CIS Guidance Document 'Ecological flows in the implementation of the Water Framework Directive' (2015), the links between hydrology and channel morphology are still only marginally considered in the evaluation of e-Flows.

Within the context of REFORM, a multi-scale, spatial-temporal geomorphological framework has been developed. This framework can be used to assess hydromorphological conditions and to identify suitable restoration measures. In this section, we will set e-Flows within the context of the broader REFORM hydromorphological assessment framework. The aim of this section is to provide a 'road map' on possible future developments with wider inclusion of geomorphological processes. The basic hypothesis (paradigm) is that enhancing morphological conditions will promote a positive ecological response.

Figure 5 illustrates three different groups of possible actions (hydrological regime, sediment and woody debris transport, together with direct morphological enhancement) producing morphological change (enhancement) and ecological response. Because hysteresis affects HYMO and ecological processes, complementary actions may be needed to speed up the habitat recovery processes. Measures like direct morphological reconstruction, removing mature riparian forests, eliminating or reducing transversal and longitudinal barriers, are examples of these complementary measures. In fact, it is now widely recognized that the geomorphological dynamics of a river and the functioning of natural physical processes are essential to create and maintain habitats and ensure ecosystem integrity (e.g. Kondolf et al. 2003; Wohl et al. 2005; Florsheim et al. 2008; Fryirs et al. 2008; Habersack and Piégay 2008).

The current approach to setting eFlows is to focus on the hydrological regime in anticipation of promoting some ecological response. However, two other types of actions are also possible: focusing on the sediment transport regime (e.g. releasing sediments downstream of dams or other obstructions) or directly manipulating channel morphology. Any of these actions may induce morphological channel changes, therefore promoting habitat recovery and diversity. The choice of the best option to be considered in combination with changes in the hydrological regime (i.e. sediment transport versus morphological enhancement) depends on the specific context, for example the reach sensitivity and morphological potential (see below). Therefore, selecting the appropriate measures requires setting the river reach within a wider spatial-temporal framework.

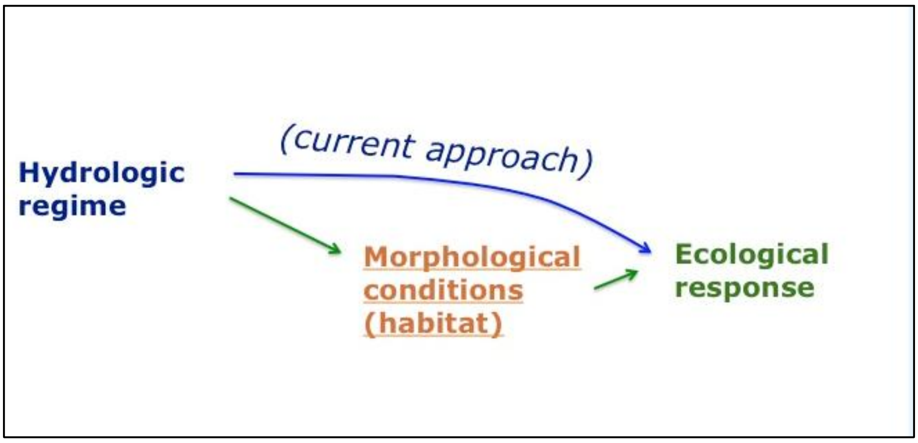


Figure 5 - Potential e-Flows actions involving possible modifications of the hydrological regime, sediment transport, or morphological reconstruction (Rinaldi, 2015). Note that the current e-Flows approach linking flows directly to ecological response ignores such complex interactions.

We make use of a hydromorphological assessment framework developed in REFORM to provide a stronger foundation for determining e-Flows. The spatial and temporal contexts are based on the multiscale, process-based, hierarchical framework developed in REFORM Deliverable 2.1 (Gurnell et al. 2014). The framework is structured into a sequence of procedural stages and steps to assess river conditions and to support the selection of appropriate management actions (REFORM Deliverable 6.2: Rinaldi et al. 2015).

The overall framework incorporates four stages (Figure 6):

I. delineation and characterization of the river system;
II. assessment of past temporal changes and current river conditions;
III. assessment of future trends; and
IV. identification of management actions.

Stage I

It aims to provide a catchment-wide delineation, characterization and analysis of the river system. This is fundamental to properly set the existing hydromorphological pressures (dams, weirs, water abstraction, etc.) within a catchment-wide context, and to better understand the factors controlling channel morphology and processes in the current condition.

Relevant aspects for e-Flows include: identification of main sediment sources, delivery processes, and sediment transport along the river network to set the existing alteration (e.g. dam) in the catchment context; evaluation of effective discharge and of the specific flow needed to initiate sediment transport; and evaluation of impacts of existing alterations on sediment budget.

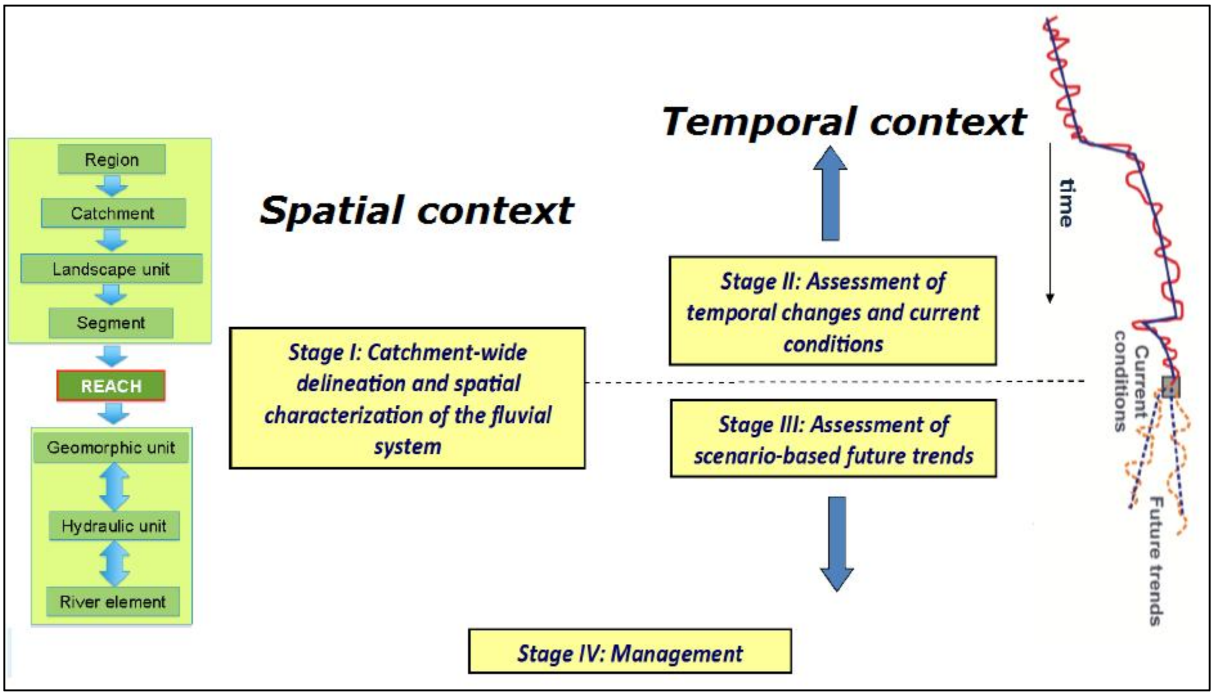


Figure 6 - Structure of the overall REFORM hydromorphological framework (Rinaldi et al. 2015). On the right side, the graph emphasises that the present state of the river system represents a spot within a long trajectory of evolution that needs to be known to understand current conditions and possible future trends. On the left side, the multi-scale hierarchical framework used for delineation and characterization of the fluvial system is presented (Gurnell et al. 2014).

Stage II

After setting the stream and causes of alteration in an appropriate spatial context, it is fundamental to investigate past conditions and factors influencing changes. A first step is to identify the major changes in controlling variables (e.g. factors influencing flow and sediment transport) that may have determined changes in the channel and river corridor conditions over the last centuries. These steps aim to reconstruct trajectories of morphological changes of the potentially impacted reaches. Relevant aspects for e-Flows include understanding how hydromorphological alterations (e.g. dams, weirs, water abstraction.) have impacted channel morphology, and the spatial and temporal extent of any alteration.

Stage III

Stage III applies methods and procedures to assess river conditions and its degree of hydromorphological alteration related to existing pressures. This type of assessment requires knowledge of past and current conditions. Three types of assessment are carried out.

1) Hydrological assessment: pre-impact and post-impact periods are analysed and the deviation of the hydrological regime from unaltered conditions quantified.
2) Sediment budget assessment: pre-impact and post-impact periods are analysed and the deviation of the hydrological regime from unaltered conditions quantified.
3) Morphological assessment: it consists of a geomorphological evaluation of river conditions including assessment of channel forms and processes, geomorphological adjustments, and human alterations.

The assessments enable classification of the state (e.g. good, poor) of each investigated river reach to identify portions of the river system that potentially require different types of management actions (e.g. preservation or enhancement). Relevant aspects for e-

Flows include: hydro peaking, modification of effective discharge, impacts on sediment budgets downstream of barriers to sediment transport.

Stage IV

Stage IV includes an assessment of potential morphological changes, identification of potential restoration measures, and evaluation of their impacts on future morphological trends. The first step diagnoses the condition and sensitivity of specific reaches to changes in hydrological and sediment conditions that can be associated to e-Flows. Adoption of some restoration action 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. This assessment is based on the knowledge gained during the previous stages, i.e. on current conditions and past changes. Based on the assessment of sensitivity and of morphological potential, target reaches and possible morphological conditions that can be achieved are identified.

The next steps are aimed at identifying possible restoration actions, and assessing scenario-based possible future trends related to selected actions. Relevant aspects for e-Flows include: 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.

3.2 Sediment Flow Management: the particular case of sediment replenishment

Managing hydrological and sediment regimes together to meet geo-ecological objectives in dynamic riverscapes deals with measures such as: a) to modify flow regime; b) to modify sediment transport regime; c) to modify sediment supply; d) to engineer channels and habitat. Any decision making on the measure(s) to be used (single or a combination of them) needs to diagnose the state of the channel and to predict its response to such measures. These diagnoses and predictions are based on the comparative assessment of upstream sediment supply to channel transport capacity. Suitable and detailed methods for this assessment are shown in Grant et al (2003) and Schmidt and Wilcox (2008).

Too much sediment in the channel must be managed primarily by reducing their production at source or intercepting it before reaching the channel. The lack of sediment in a river reach is a lot more common problem than excess sediment. The reintroduction of sediments in a reach with sediment deficit can be done by means of upstream dam removal, or by mitigating dam’s trapping effects, or by adding sediments directly to the river.

Below dams, fluvial systems need 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. To address these two issues, the accumulated sediments must be relocated below the dam either through flushing from the reservoir (White 2001) or by replenishment below the tail water (Figure 7). This latter process has been implemented in Japan, USA and Switzerland (Cajot et al. 2012).

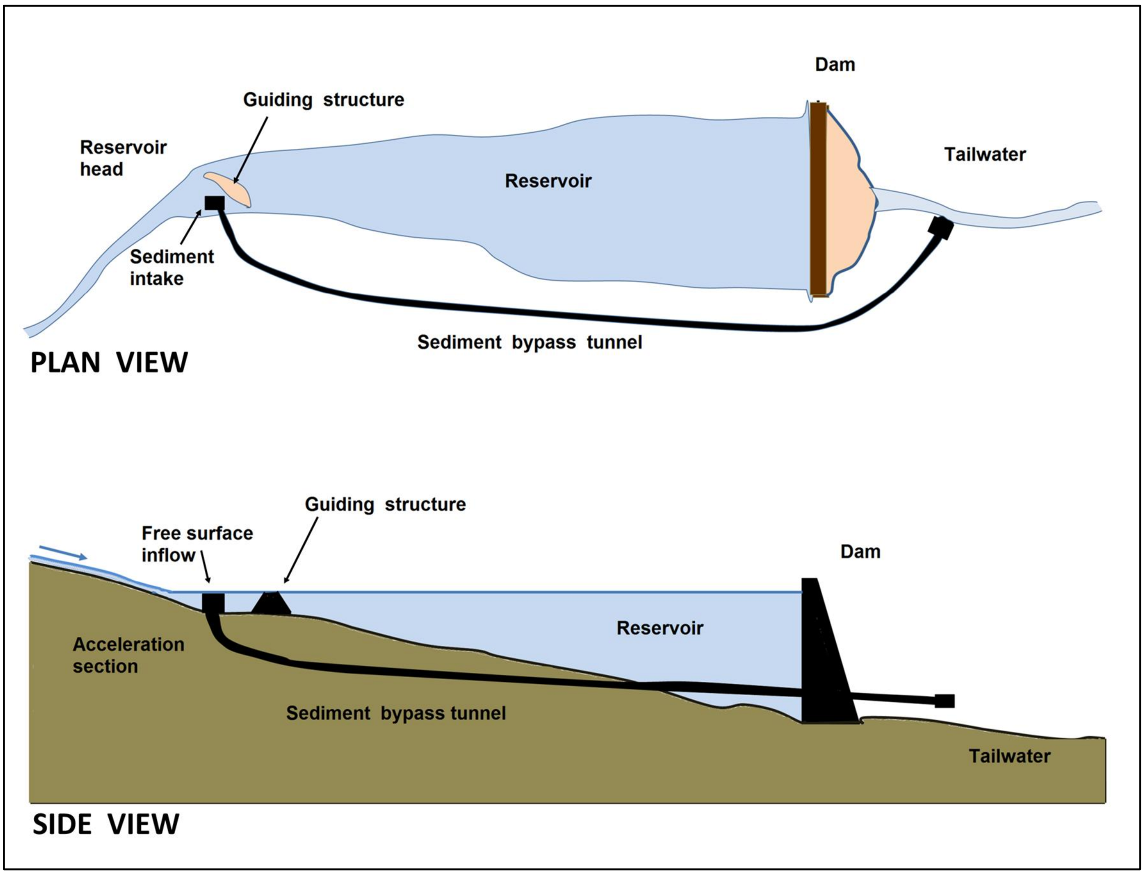


Figure 7.- Scheme of a sediment bypass tunnel system associated with a reservoir designed with the sediment intake located at the reservoir head under free surface conditions (based on Auel & Boess, 2012).

Sediment replenishment basically consists of dredging or excavating the accumulation of sediments in a dam's reservoir and transporting them to the reach just below the dam, where natural or artificial floods will distribute them along the riverbed. In order to improve downstream ecological status we must select optimal sediments for replenishment, as coarser substrates are more beneficial for benthic communities than silt, which may impact interstitial habitats by clogging bed sediments, and causing high turbidity (Ock et al. 2013). The construction of check-dams, located upstream of reservoirs, where coarse particles settle, may trap larger sediments before they enter the functional reservoir and facilitate their removal by land-based excavation, and do not require any water level modification in the larger reservoir (Okano, 2004).

In order to relocate sediments in the riverbed efficiently, we need to know on the effects of grain size, the amount of sediments replenished, the frequency of operations and when the sediment should be deposited (Cajot et al. 2012).

Other effective measure to limit sediment trapping by reservoirs and to decrease the reservoir sedimentation involves constructing sediment bypass tunnels. These tunnels route sediments (both bed load and suspended load) around the reservoir into the tail water during flood events, thereby reducing sediment accumulation. Nevertheless the number of actual sediment bypass tunnels globally is limited (six in Switzerland and five in Japan) due to high capital and maintenance costs. The design of a bypass tunnel consists of a guiding structure in the reservoir, an intake structure with a gate, a short and steep acceleration section, a long and smooth bypass tunnel section, and an outlet structure (Auel & Boes 2011; Figure 6). Fukuda et al. (2012) demonstrated the recovery of riffles and pools and the grain size distribution in the downstream reaches below Asahi Dam reservoir, after the construction of a sediment flushing tunnel.

Other methods to eliminate the sediments accumulation in the reservoirs are based on a floating platform with hydraulic equipment that dredges the compacted sediment and pumps it through a piping system to be released it near the bottom outlet of the dam, where it can be eroded and passed through the outlet (Figure 8). This hydraulic system can be set to move sediment to the dam downstream section at a rate similar to the sediment yield reaching the reservoir, in order to maintain its storage capacity (Bartelt et al. 2012). It should be noted that in gravel bed rivers, this method has a major drawback, as is only able to remove fine sediments, whose release in the downstream reaches can degrade benthic communities.

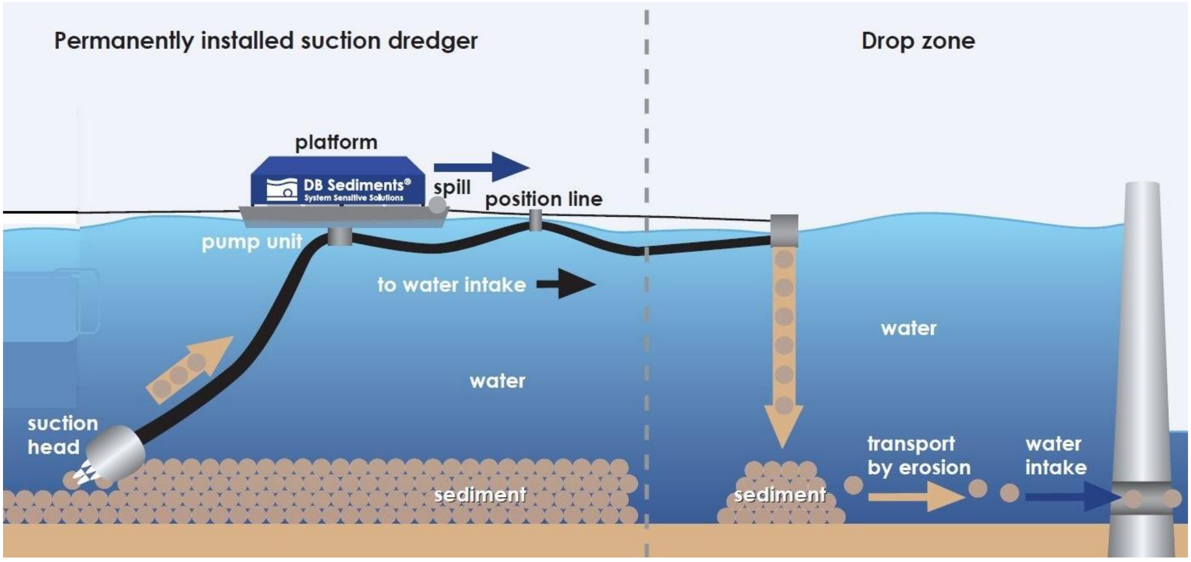


Figure 8.- Hydraulic pumping system to remove accumulated sediments from reservoir tails into the bottom outlet of the dam, in order to be flushed downstream the dam (Bartelt et al. 2012).

4 Conclusions and Recommendations

Estimation of e-Flows that are necessary to maintain the desired river ecological state is not straightforward, as the quantitative links between hydromorphology and biology are not yet well known, due to the insufficient number of consistent data and to the weak response of current biological metrics to hydromorphological pressures.

Geomorphic dynamics of a river and the functioning of natural physical processes are essential to create and maintain habitats and ensure ecosystem integrity and the links between hydrology and geomorphology are generally well known. Therefore, one approach to estimating e-Flows is to identify those flows required to maintain certain geomorphic processes and forms that directly contribute to aquatic habitat and ecosystem functioning. Such an approach would broaden the current strategy for setting e-Flows, which is to focus on the hydrologic regime in anticipation of promoting some ecological response.

Elements of this broadened approach include other types of actions beyond specifying flows alone, such as focusing on the sediment transport regime (e.g. releasing sediments downstream of dams or other obstructions), or directly manipulating channel morphology (i.e. morphological reconstruction). Any of these actions (hymo-based measures) may induce morphological channel changes, therefore promoting habitat recovery and diversity.

The choice of the best option to be considered in combination with changes in the hydrologic regime (i.e. sediment transport vs. morphological reconstruction) 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.

Within the context of the project FP7 REFORM, such a multiscale framework has been developed and can be used as a strong methodological foundation for determining e-Flows, dealing with hydrological, morphological and ecological processes in concert.

4.1 Constraints on flow and sediment management

The implementation of e-Flows is constrained by our understanding of the ecological processes, of the services they provide, and by the socio-economical requirements on water resources.

Whilst the latter issue is clearly recognized, ecosystem services related to natural processes and to e-Flows releases are yet not sufficiently acknowledged by managers and stakeholders. Therefore, ecological benefits that can be achieved by e-Flows, and in particular the added value of considering sediment related e-Flows should be clearly justified, both from an ecological perspective (maintenance and development of habitats) and from an economic one (e.g. less water discharge if combined with sediment delivering strategy, mitigate incision problems, etc.).

4.2 Precepts re policy

Water and sediments are intrinsically interconnected in natural river system. Fluvial communities have evolved to be adapted to this interaction, and thus many of their habitat requirements depend on HYMO dynamics. Setting e-Flows (including water & sediments) must take into account past morphological evolution and trajectories as well as the current status of the river system, and the water and sediment fluxes in the network, to inform the possible scenarios, prior to implementation of measures in each targeted reach of the river. Sediment management therefore needs to be built into the analytical and decision-making framework.

Environmental flows including sediments should be implemented and monitored within an adaptive management framework. Monitoring the outcomes of e-Flows is needed because our understanding of water and sediment requirements by key aquatic biota and ecosystem functions is not precise and often-critical decisions are made with relatively weak ecological evidence to support them. E-Flow monitoring programmes should have a practical approach to ensure that e-Flow implementation achieves its objectives and, in any case, identifies gaps and provides recommendations for relevant improvements.

4.3 Recommendations for future actions

There is a need for long-term research (that should incorporate existent experiences, including the outcomes from the REFORM project), based on the following specific critical points.

- Ecological benefits of e-Flows, although acknowledged, are not well supported by quantitative evidence and too few well-documented cases exist.
- As the majority of current biological methods do not detect the impact of hydromorphological pressures or the effects of hymo-based measures, including e-Flows, with a necessary degree of precision, revision of such methods should be promoted.
- Alternative biological methods should be developed, accounting for functionality measurement, riparian zones and stressor–specific deviation estimation.
- Riparian vegetation should be considered as a quality element per se as well as hymo.
- Long-term experiments are needed to implement and validate the revised/new approaches. In the meantime, as process-based hymo assessment methods can easily and directly assess hydromorphological alteration, they should be used along the whole gradient to support ecological assessment. Moreover, assessment of spatio-temporal alteration of local hydromorphology (physical habitat) could be used as a proxy for ecological status.
- Experimental use of reservoirs for research could provide empirical data that link instream flows with biological elements and their ecological status. Also, these experiments could provide valuable data of how coupling flow and sediments create adequate habitats to be colonized by aquatic biota.

The research agenda should include, as priority, all the necessary steps to develop new alternative, multi-scale approaches to ecological monitoring and assessment, so that WFD can be better implemented and possible enhancement proposed for its coherent implementation in time for the next revision of the RBMPs and of the Directive.

5 References

Anderson K. E. et al. (2006) Instream flow needs in streams and rivers: the importance of understanding ecological dynamics. In: *Frontiers in Ecology and the Environment* 4: 309–318.

Auel, C. & R.M. Boes. (2011) Sediment bypass tunnel design—review and outlook. In: Schleiss & Boes (Eds). *Dams and Reservoirs under Changing Challenges.*Taylor & Francis Group, London, 403 pp.

Bartelt, D. R. Bundesmann & I. Sevis (2012) Continuous Sediment Transfer (ConSed-Method). A way to reduce the risk of sedimentation and siltation, flooding, soil and coast erosion, and siltation of groundwater. ACWUA's 5th Best Practices Conference on Water Resources Management in the Arab Region. Muscat.

Cajot, S.; A. Schleiss, T. Sumi & S. Kantoush (2012) Reservoir Sediment Management Using Replenishment: A Numerical Study Of Nunome Dam. Procs. Int. Symp. On Dams for Chamging World. Kyoto.

Collier, M. Webb, R.H. & Schmidt, J.C. (2000) Dams and rivers: a primer on the downstream effects of dams (Vol. 1126). DIANE Publishing.

Corenblit D, Tabacchi E, Steiger J, Gurnell AM. (2007) Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. Earth Science Reviews 84: 56–86.

Corenblit, D. and J. Steiger (2009) Vegetation as a major conductor of geomorphic changes on the Earth surface: toward evolutionary geomorphology: Vegetation as a major conductor of geomorphic changes on the Earth surface. Earth Surf. Process. Landforms 34, 891–896

Dynesius M. & Nilsson C. (1994) Fragmentation and flow regulation of river systems in the northern third of the world. Science, 266, 753–762.

Florsheim, J.L. Mount, J.F. Chin, A. (2008) Bank erosion as a desirable attribute of rivers. Bioscience 58(6), 519-529.

Friberg N. Bonada N. Bradley D. C. Dunbar M. J. Edwards F. K. Grey J. Hayes R. B. Hildrew A. G. Lamouroux N. Trimmer M. Woodward G. (2011) Biomonitoring of human impacts in freshwater ecosystems: the good, the bad and the ugly. Advances in Ecological Research 44, 1– 68.

Friberg, N, O'Hare, M. and Poulsen A.M. (Eds) - (2013). Impacts of hydromorphological degradation and disturbed sediment dynamics on ecological status. D3.1 Impacts of HyMo degradation on ecology, EU FP7 project (Restoring rivers for effective catchment Management). Grant Agreement 282656FP7 REFORM.

Friberg N. (2014) Impacts and indicators of change in lotic ecosystem. Wires Water 2014. doi: 10.1002/wat2.1040.

Fryirs, K.A. Arthington, A. Grove, J. (2008) Principles of river condition assessment. In: Brierley, G. Fryirs, K.A. (Eds.), River Futures: An Integrative Scientific Approach to River Repair. Society for Ecological Restoration International, Island Press, Washington, DC, USA, pp. 100-124.

Fukuda, T. Yamashita, K. Osada, K. Fukuoka, S. (2012) Study on Flushing Mechanism of Dam Reservoir Sedimentation and Recovery of Riffle-Pool in Downstream Reach by a Flushing Bypass Tunnel, in: International Symposium on DAMS FOR A CHANGING WORLD-Need for Knowledge Transfer across the Generations & the World, Kyoto, Japan.

García de Jalón, D, C. Alonso, M. González del Tango, V. Martinez, A. Gurnell, S. Lorenz, C. Wolter, M. Rinaldi, B. Belletti, E. Mosselman, D. Hendrik and, G. Geerling (2013) Review on pressure effects on hydromorphological variables and ecologically relevant processes. REFORM Deliverable (D 1.2). http://www.reformrivers.eu/

Gerten, D. Hoff, H. Rockström, J. Jägermeyr, J. Kummu, M. Pastor, A.V. (2013) Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. Current Opinion in Environmental Sustainability 5, 551–558.

González del Tánago, M. Bejarano, M.D. García de Jalón, D. Schmidt, J.C. (2015ª) Biogeomorphic responses to flow regulation and fine sediment supply in Mediterranean streams (the Guadalete River, southern Spain). Journal of Hydrology 528, 751–762. doi:10.1016/j.jhydrol.2015.06.065

Gonzalez del Tánago, M. Martínez-Fernández, V. García de Jalón, D.G. (2015b) Diagnosing problems produced by flow regulation and other disturbances in Southern European rivers: the Porma and Curueño rivers (Duero Basin, NW Spain). Aquatic Sciences 1–13.

Grant, G.E. (2012) The Geomorphic Response of Gravel-bed Rivers to Dams: Perspectives and Prospects, in: Gravel-bed Rivers: Processes, Tools, Environments. John Wiley & Sons, Ltd. pp. 165–179.

Grant GE, Schmidt JC, Lewis SL (2003) A geological framework for interpreting downstream effects of dams on rivers. in 'A Unique River' Water Science and Application 7, American Geophysical Union, Washington, DC. pp. 209–225

Gurnell, A. M. and K. J. Gregory (1995) Interactions between semi-natural vegetation and hydrogeomorphic processes. Geomorphology 13:49–69.

Gurnell, A.M. Belletti, B. Bizzi, S. Blamauer, B. Braca, G. Buijse, A.D. Bussettini, M. Camenen, B. Comiti, F. Demarchi, L. García De Jalón, D. González Del Tánago, M. Grabowski, R.C. Gunn, I.D.M. Habersack, H. Hendriks, D. Henshaw, A. Klösch, M. Lastoria, B. Latapie, A. Marcinkowski, P. Martínez-Fernández, V. Mosselman, E . Mountford, J.O. Nardi, L. Okruszko, T. O'Hare, M.T. Palma, M. Percopo, C. Rinaldi, M. Surian, N. Weissteiner, C. Ziliani, L. (2014) A hierarchical multi- scale framework and indicators of hydromorphological processes and forms. Deliverable 2.1, Part 1, of REFORM (REstoring rivers FOR effective catchment Management), a Collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.

Habersack, H. Piégay, H. (2008) River restoration in the Alps and their surroundings: past experience and future challenges. In: Habersack, H. Piégay, H. Rinaldi, M. (Eds.), Gravel-bed Rivers VI - From Process Understanding to River Restoration. Developments in Earth Surface Processes, Elsevier, Amsterdam, The Netherlands, pp. 703-738.

Hupp, C.R. (1999) Relations among riparian vegetation, channel incision processes and forms, and large woody debris. In: Incised river channels, ed. S. E. Darby and A. Simon, 219–45. London: Wiley.

International Commission on Large Dams (2007) - World Register of Dams. Paris. (www.icold-cigb.net)

Ligon FK, Dietrich WE, Trust WJ. (1995) Downstream ecological effects of dams: a geomorphic perspective. BioScience 45: 183–192

Lobera, G. Besné, P. Vericat, D. López-Tarazón, J.A. Tena, A. Aristi, I. Díez, J.R. Ibisate, A. Larrañaga, A. Elosegi, A. Batalla, R.J. (2015) Geomorphic status of regulated rivers in the Iberian Peninsula. Science of The Total Environment 508, 101–114. doi:10.1016/j.scitotenv.2014.10.058

Magdaleno, F. & Fernández, J. A. (2011) Hydromorphological alteration of a large Mediterranean river: relative role of high and low flows on the evolution of riparian forests and channel morphology. River Research and Applications 27(3), 374-387.

Meitzen, K.M., Doyle, M.W., Thoms, M.C., and C.E. Burns (2013) Geomorphology in the Interdisciplinary Context of Environmental Flows. Geomorphology. 200: 143-154. http://dx.doi.org/10.1016/

Ock, G. Sumi, T. Takemon, Y. (2013) Sediment replenishment to downstream reaches below dams: implementation perspectives. Hydrological Research Letters 7, 54–59. doi:10.3178/hrl.7.54

Okano, M. Kikui, M. Ishida, H. Sumi, T. (2004): Reservoir sedimentation management by coarse sediment replenishment below dams. Proceedings of the ninth international symposium on river sedimentation, Yichang China.

Petts, G.E. (1984) Impounded Rivers. Chichester, John Wiley & Sons, Ltd.

Rinaldi, M. Belletti, B. Bizzi, S. Blamauer, B. Brabec, K. Braca, G. Bussettini, M. Comiti, F. Demarchi, L. García de Jalón, D. Giełczewski, M. Golfieri, B. González del Tánago, M. Grabowski, R. Gurnell, A.M. Habersack, H. Hellsten, S. Kaufman, S. Klösch, M. Lastoria, B. Mao, L. Marchese, E. Marcinkowski, P. Martínez-Fernández, V. Mosselman, E. Muhar, S. Nardi, L. Okruszko, T. Paillex, A. Percopo, C. Poppe, M. Rääpysjärvi, J. Schirmer, M. Stelmaszczyk, M. Surian, N. Van de Bund, W. Vezza, P. Weissteiner, C. (2015) Final report on methods, models, tools to assess the hydromorphology of rivers. Deliverable 6.2, a report in five parts of REFORM (REstoring rivers FOR effective catchment Management), a Collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.

Stella, J. C. Rodríguez-González, P. M. Dufour, S. & Bendix, J. (2013) Riparian vegetation research in Mediterranean-climate regions: common patterns, ecological processes, and considerations for management. Hydrobiologia 719(1), 291-315.

Vörösmarty, CJ; Fekete, B. Sharma, K. (1997) The potential impact of neo-Castorization on sediment transport by the global network of rivers. Procs. Human impact on erosion and sedimentation 261.

Vörösmarty, C.J. Meybeck, M. Fekete, B. Sharma, K. Green, P. Syvitski, J.P. (2003) Anthropogenic sediment retention: major global impact from registered river impoundments. Global and Planetary Change 39: 169–190.

Ward J.V. & Stanford J.A, (1979) The ecology of regulated streams. New York: Plenum Press.

White, R. (2001) Evacuation of sediments from reservoirs. Thomas Telford Publishing.

Williams, G.P. and Wolman, M.G. (1984) Downstream Effects of Dams on Alluvial Rivers. United States Geological Survey, Professional Paper 1286.

Wohl, E. Angermeier, P.L. Bledsoe, B. Kondolf, G.M. McDonnell, L. Merritt, D.M. Palmer, M.A. Poff, L. Tarboton, T. (2005) River Restoration, Water Resources Research 41, W10301, doi: 10.1029/2005WR003985.

Appendix 1

Programme and participants of the REFORM workshop 'Linking EFlows to sediment dynamics (Rome, 9 – 10 September 2015)

Programme

Title	Presenter(s)
Welcome & introduction to REFORM	Tom Buijse (Deltares, NL)
Setting the scene: the EU CIS Guidance on e-flows	Martina Bussettini (ISPRA, IT)
Session I: The contribution of geomorphic processes to E-flows	
When enough is too little	Nikolai Friberg (NIVA, NO)
Dams, geomorphic processes and water resources management	Gordon Grant (USDA Corvallis, USA)
A hydromorphological framework for e-flows	Massimo Rinaldi (UniFi, IT)
Using local hydro-morphology and habitat indices to evaluate e- flows	Paolo Vezza (PoliTo, IT)
Session II: E-flows in the Mediterranean contexts	
Including resilience, river fragmentation and regulation costs in the design of e-flows	Diego Garcia de Jalòn (UPM, ES)
E-flows implementation in Spain: recent experiences	Fernando Magdaleno Màs (CEDEX, ES)

Participants	Country
Ana Bernejo Albiñana	Spain
Helena Maria Alves	Portugal
Martina Bussettini	Italy
Tom Buijse	Netherlands
Ian G Cowx	UK
Nikolai Friberg	Norway
Diego García de Jálon	Spain
Gordon Grant	USA
Stephane Grivel	France
Jo Halvard Halleraker	Norway
Seppo Hellsten	Finland
Fernando Magdaleno Mas	Spain
Stefano Mariani	Italy
Massimo Rinaldi	Italy
Paolo Vezza	Italy