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## Environmental flows and water governance: managing sustainable water uses

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Human water security is often achieved with little consideration of environmental consequences and, even when these are acknowledged, the trade-offs between human and environmental water needs are increasing in frequency and amplitude on the increase. The environmental flows concept has continued to evolve in response to these challenges. However, the field is characterized by a limited transferability of insights, due to the prevalence of specific case-study analyses and a lack of research on the governance of environmental flows. Building on recent advances in environmental flow science, water governance and management, we identify a clear need for a more systematic approach to the determination of environmental flow requirements (EFRs) on both the natural and social science fronts and, in particular, on the interaction between social/political and environmental systems. We suggest a framework that details as to how these advances and interactions can be achieved. The framework supports scientific analysis and practical implementation of EFRs involving systematic compilation, sharing and evaluation of experiences from different riverine ecosystems and governance systems around the globe. The concept of ecosystem services is introduced into the framework to raise awareness for the importance of ecosystem functions for the resilience of social-ecological systems, to support negotiation of trade-offs and development of strategies for adaptive implementation. Experience in implementation of environmental flow policies reveals the need for an engaged, transdisciplinary research approach where research is closely linked to implementation initiatives on the ground. We advocate that this is more effective at building the foundations for sustainable water management.

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### Introduction

The past two decades have witnessed increasing global concern about the need for sustainable water and land management in an era of rapid change, and persistent water and food insecurity. Human population increase, economic development, climate change and other drivers alter water resource availability and use, resulting in increased risks of extreme low and high flows, drastically altered flow regimes, threats to water quality and water demands surpassing renewable supply. Human water security, when narrowly framed [1<sup>\*</sup>], is often achieved at the expense of the environment under such constraints [2,3,4<sup>\*\*</sup>], with harmful implications in the long run for social-ecological systems in their entirety as a whole. There is strong evidence that flow alteration leads to

ecological change in rivers around the world, from observational [5,6] and modelling [7] studies.

The concept of 'environmental flows' continues to evolve in response to these challenges, emphasizing aquatic and riparian ecosystems as legitimate water users within an Integrated Water Resources Management (IWRM) context (e.g. [8]). Environmental flows are defined as the '*quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems*' [9]. How much water to (re-)allocate to environmental flows and how to balance this with other water demands may be controversial issues.

Implementing the environmental flows concept requires dialogue amongst scientists, policy-makers, water managers and users, and local populations, about sustainable water usage that balances priorities amongst competing demands. Early static approaches aimed to define either minimum or average flows to support key fish species or maintain instream habitat ('sometimes revealingly termed 'compensation flows'); but these are now viewed as too simplistic to support complex flow-dependent ecosystem functions [10,11]. By contrast, it is now widely recognized that significant daily, flood-period, seasonal and inter-annual variations of long-term flow patterns are required to sustain ecosystem integrity (e.g. [12–15]). Environmental flow requirements (EFRs) thus must vary in space and time to sustain the desired future ecosystem state, as agreed upon amongst stakeholders, together with the bundles of services these ecosystems supply for human benefit. Rules are needed to determine EFRs, which in their turn are coordinated with other types of basin-wide water and land uses and management practices. More comprehensive, interdisciplinary methodologies have therefore been developed and applied to establish environmental flow needs in individual river basins around the world.

The diversity of approaches to set EFRs in various drainage basins has undoubtedly fostered innovation as well as a rapid evolution of methods appropriately tailored to local contexts [10]. In part, this diversity reflects the variable possibilities in different locations. In some, EFRs can be allocated upfront to sustain both aquatic and riparian ecosystems; alternatively, appropriate EFRs can be provided by technical intervention such as revision of reservoir operating rules [16]; in others, neither is possible. Experience with implementing EFRs in different eco-hydrological, socio-economic and governance contexts has shown that the main impediments to successful implementation is related to social factors rather than lack of knowledge about ecological processes. This includes limited involvement or support of stakeholders, of appropriate governance structures and of political will, the presence of conflicts of interest, and insufficient

resources and capacity in water management and allocation institutions [17–20]. Defining the desirable environmental state of water bodies in the context of all other benefits and services derived from the available water resources is a societal decision. Hence, development and implementation of EFRs should, from the outset, include the perceptions of a wide range of stakeholders on possible trade-offs and synergies [20], which must be informed by the best available scientific knowledge. Given the complexity and relative uncertainty inherent in the relations amongst water demands, land uses, hydrological variability, biodiversity and aquatic ecosystem services, the governance systems that manage environmental flows must be adaptive, flexible and capable of learning from experience and responding to unexpected developments.

We provide here an overview of the state of the art in EFR assessment, implementation and governance, and identify the principal knowledge gaps. The review concludes with a strong argument for the need to develop a widely applicable, integrative, conceptual and analytical framework, and an associated classification system for EFRs, based on eco-hydrological, as well as socio-economic, governance and management characteristics.

## Hydro-ecological assessment of environmental flow requirements (EFRs)

### How to determine EFRs at (sub) basin scale

Tharme [10] reviewed over 200 different methods used to estimate how much water to retain in a river after new developments, or to mitigate the detrimental effects of flow alteration attributable to human use of freshwater systems. The methods used to assess EFRs have developed over time from simple hydrological rule-of-thumb methods largely aimed at preserving the habitats of commercially important fish species, to more holistic frameworks that encompass many more species, habitats and ecosystem processes (both aquatic and riparian in some frameworks). Sometimes methods also assess social and economic consequences, but usually they do not.

Simple and more qualitative hydrological methods provide quick results with limited resources, but usually with low resolution and low levels of confidence they will meet desired environmental outcomes. Flow standards are typically calculated using fixed percentages of the flow [21,22]. These simplistic, incomplete, and primarily static approaches ignore the complexity and variability inherent in the natural system, and are rarely based on empirical research [13,23,24]. Therefore, several methods have been developed which are more comprehensive and typically tailored to local needs (e.g. the 'recruitment box' method [14]). The Downstream Response to Imposed Flow Transformation (DRIFT) procedure from South Africa [25,26] is at this point in time one of few

methods that explicitly consider societal consequences of flow alteration as part of the assessment [10].

Given the resource intensity of current state-of-the-art interdisciplinary methods, Poff *et al.* [27<sup>••</sup>] argue that a river-by-river or project-specific assessment of EFRs cannot occur at the pace needed to provide timely global coverage. They accordingly propose a regional framework, termed the Ecological Limits of Hydrologic Alteration ('ELOHA'), approach (similar to the well-established regionalization methods in hydrology) allowing EFR determinations to be rigorously scaled up. The framework builds on the notion that river ecological processes and patterns are predominantly shaped by a few key flow variables. The different combinations of these variables across biogeographic and climatic gradients generate 'classes' of stream and river types (e.g. snowmelt, arid-land types) that exhibit similar ecological conditions and likely responses to flow regime change, thus they can be treated as 'management units'. Established flow-ecology relationships can then be used to predict ecological responses to particular types of flow alterations (e.g. reduced minima, modified timing of peaks), and therefore guide how flow regimes need to be managed to achieve societally desired ecological endpoints. In the absence of detailed ecological information, alteration of key hydrological parameters beyond that observed for a particular class of river type can be used as an initial indication of likely flow stress [27<sup>••</sup>]. This framework was developed in part because existing empirical data from the literature are inconsistently reported and inadequate for establishing general, transferable quantitative relationships between flow alteration and ecological response [5]. The ELOHA framework was designed to allow flexibility in its application to a particular situation depending on scientific capacity, availability of suitable hydrological records, background ecological understanding and data, types and degrees of hydrological alteration (e.g. by dams, groundwater abstraction or land-use change) and governance structure. It is now being implemented in various forms by several state agencies and stakeholder groups in the U.S.A [28] and is being tested in Spain [29], China [30], Australia [31], and South America (e.g. Colombia and México, Tharme 2013, personal communication). Each trial has produced innovations around the original ELOHA framework, including the addition of a module to incorporate indigenous values [32]. Regional-scale ELOHA studies in Australia are guiding the Murray-Darling Basin Plan and water resource management in northern Australia and south-east Queensland. In summary, ELOHA offers an ecological science based and empirically testable framework using existing eco-hydrological knowledge and hydrologic modelling tools to develop regional flow management guidelines for ecological sustainability [27<sup>••</sup>]. However, an important (critical) missing element is the societal context in which such EFRs are developed and

implemented. The ELOHA framework acknowledged the need for socially determined ecological endpoints, but the social process of how this is accomplished has yet to be developed [32]. We make an important contribution in this paper to close this gap (section 'Towards an integrative framework').

### The role of global water assessments in addressing EFRs

Global water (scarcity) assessments complement regional analyses by capturing large-scale developments and global trends [4<sup>••</sup>]. Such assessments typically calculate water availabilities and water demands at pixel (usually 0.5 degree) or subcatchment scale, and then aggregate these values to basins, countries or regions [4<sup>••</sup>,33–35]. So far, EFRs have been handled in a very simplistic manner in global water assessments, or not at all. The WaterGap model, for example, has been used to assess EFRs by classifying rivers according to the natural variability of their flow regimes [22]. The assumption in this approach is that aquatic ecosystems in basins with relatively stable flow regimes will be less resilient and hence require higher minimum flows. WaterGap uses the Q90 (the flow equalled or exceeded 90% of the time) as a low flow measure to represent mean annual EFRs, but not intra-annual variability. The H08 model has been used to assess monthly EFRs [36], also classifying basins according to their hydrological conditions (their dryness/wetness and flow variability). The rules for classifying basins are based on case studies from dry lands and densely populated regions. Total global EFRs according to this study are of the order of 30% of total runoff. In a basin-scale analysis of global water scarcity, Hoekstra *et al.* [37] incorporate a presumptive environmental flow standard, based on the Sustainability Boundary approach [38]. This assumes that alteration (augmentation or depletion) beyond 20% in a river's natural flow regime increases the risk of moderate to major changes to ecosystem services and health.

Most of these approaches are pragmatic and not based on ecological theory or informed analyses, due to the lack of globally consistent information, in terms of flow and water use, the flow requirements of aquatic ecosystems, and the socio-economic conditions and vulnerabilities to water scarcity.

### Summary of limitations of current approaches and major knowledge gaps

- Prevalence of case specific approaches in the field of environmental flow assessments, with the consequence that the majority of EFR determinations and results are not readily transferable.
- Lack of consistent information on flow regime, water use and the state of aquatic ecosystems in basins that vary with respect to their socio-environmental context.

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- Use of simplistic hydrological analyses to include EFRs in global water assessments and models due to absence of broadly applicable more sophisticated methods and data.
- Limited robust, mechanistic understanding of the relationships between flow modifications and impacts on ecosystem structure, functioning and related services due to lack of data and difficulty to unravel effects of flow alteration from other stressors such as land-use changes.
- Lack of a widely accepted classification scheme for eco-hydro-climatic and socio-economic types of river basins as a basis for testing concepts and developing transferable flow rules.

### Governance of environmental flows and associated ecosystem services

Despite increased attention to environmental flows in ecological research, and their environmental and water policy importance, little scientific research has been conducted to date to identify requirements for effective policies. Table 1 summarizes results of a search of scientific publications on selected topics in the SCOPUS data base. These show clearly the emergence of environmental flows as a research topic, and their association with implementation or management. Research on the link between environmental flows and governance issues or ecosystem services has, however, remained very limited. Developments in related fields are represented as well as reference.

### How to implement EFRs in policy and water management practice

Experience from implementation shows that critical bottlenecks in the process of developing and implementing EFR policies lie in the dialogue between scientists, policy-makers and water managers and users, and in the appropriateness of governance structures [17,19,22,27<sup>••</sup>,39<sup>•</sup>]. A recent report produced by The Nature Conservancy and World Wildlife Fund compiled expert assessments on the basis of international reviews, and experience from case studies on the implementation of EFRs, concluded: *'Governments and water management authorities across the world have made significant and wide-spread progress in developing policies and laws to recognize EFRs. Despite this significant policy development, in the majority of cases environmental flow provisions remain at the stage of policy and debate rather than implementation.'* [18]. This report identified as major implementation challenges: first, the lack of political will and stakeholder support, second, insufficient resources and capacity, third, institutional barriers, and fourth, conflicts of interest. Presently, this represents an uncommon example of comparative work on this topic, though the lack of conceptual underpinnings from the social sciences results in

certain omissions — for example, on deficiencies in policies themselves.

Unfortunately, systematic comparative research on water governance systems is not only largely absent in the field of analysing EFR policies [40<sup>••</sup>]. Idealized design principles based on institutional and technological panaceas have been applied to water issues without long-term monitoring of their performance and effectiveness, and without revision and critical reflection on practice [41–43]. We are still some distance from having an adequate knowledge base on the determinants of the dynamics and performance trends of water governance and management systems in different socio-economic and environmental contexts [41,42].

Given the bottlenecks in implementation of EFR policies, research is needed on both structural characteristics of the governance system to support implementation and on characteristics of the implementation processes themselves. Critical governance challenges to be addressed include: setting of strategic goals, conflict resolution and negotiation, resource mobilization, identification of operational targets and monitoring indicators, development and implementation of an adaptive implementation process.

Meeting these challenges requires having appropriate institutions<sup>1</sup> in place. Institutions (e.g. laws, societal norms) determine who sets targets, what they are, how they are monitored, and the assessment of the consequences of outcomes. In contrast to legal frameworks, societal norms are not changed by purposeful design, but they change during processes of societal learning. However, formal and informal rules are not independent of each other [44,45]. The content of laws may reflect societal norms and value structures. Informal settings support innovation but may also be an impediment for change (e.g. patronage networks).

Regarding regulatory frameworks, environmental policy has for a long time relied on a command and control approach to prescribing environmental targets. This worked reasonably well for issues relating to water quality where many conflicts can be overcome through technical solutions. However, often costly end-of-pipe solutions have been chosen to deal with individual problems in isolation. Allocating water to different uses and users is a more difficult problem, since conflicts over water and land use can be overcome by technical means to only a limited extent, in particular in times of extreme water scarcity. The paradigm shift towards more integrated approaches

<sup>1</sup> We use 'institutions' here in the tradition of scholarly work in the broad field of institutional analysis, to refer to the rules (formal and informal) which shape the behavior of actors, including legal frameworks, operational rules and practices, and social and cultural norms.

Table 1

## SCOPUS analysis of number of publications on selected topics

Search terms	2000	2005	2008	2010	2011	2012
'Environmental flow'	17	45	73	111	115	123
'Environmental flow' AND 'implementation' OR 'management'	3	20	35	59	71	70
'Environmental flow' AND 'policy'	0	6	10	18	13	15
'Environmental flow' AND 'governance'	0	3	0	1	4	3
'Environmental flow' AND 'ecosystem service'	0	0	2	5	6	2
'Environmental flow' AND 'stakeholder'	0	1	1	4	3	4
'Ecosystem service' AND 'governance'	1	1	7	31	38	52
'Water' AND 'governance'	18	58	153	232	288	327
'Ecosystem service'	36	123	401	841	1018	1199

Number of publications (choice for search space in category 'article or review') with search terms in title, abstract or keywords. Date of research: 31.05.2013.

and the explicit recognition of complexity and uncertainty also demand far more flexible and adaptive institutions. Modern regulatory frameworks (e.g. the European Water Framework Directive (WFD)) abstain from narrow prescriptions of specific environmental targets and adopt a more inclusive and integrated approach (e.g. a 'good state' for European waters as goal in the WFD).

However, as shown by Pahl-Wostl et al. [40<sup>••</sup>], innovative legal frameworks are a necessary, but not sufficient condition for dealing effectively with water related management problems. In this first comprehensive comparative analysis of complex water governance and management systems in national river basins, the implementation of policies was found to be a critical bottleneck [40<sup>••</sup>] and, in some cases, the capacity for implementation (knowledge and resources) was missing. Another important factor is lack of general effectiveness of formal institutions. If effectiveness is low, laws and management plans may exist on paper but are not applied in practice. Furthermore, the study by Pahl-Wostl et al. [40<sup>••</sup>] supports the view that development often focuses on economic benefits and leads to fulfilling needs for human populations at the expense of the environment [4<sup>••</sup>]. Similarly, central government incentives for economic growth in China have driven inter-province competition, which in turn has marginalized attention to water quality, especially in trans-provincial rivers [46]. This suggests that economic development needs to be in balance with institutional development and capacity building and leadership at different levels to lead to sustainable practice.

The analyses of Pahl-Wostl et al. [40<sup>••</sup>] showed that adaptive capacity and the ability to respond to challenges from global change is strongly related to polycentric governance which refers to a distribution of power but effective coordination structures. Such polycentric structures balance bottom-up and top-down pathways of influence. Their modular structure supports learning processes and the diffusion of innovation [47]. The driver of change and thus also for development and implementation of EFRs is agency — how actors form coalitions and

networks to move an issue forward, experiment with or promote innovative practices, and interpret and adapt the rules under which they operate. Agency is essential in processes of learning and transformative change. We argue here that transformative change towards more sustainability may be supported by organising stakeholder dialogue around the concept of ecosystem services and the importance of functional ecosystems to deliver them.

The climate change debate has raised awareness on how a range of hitherto largely neglected ecosystem services may enhance adaptive capacity and resilience of social-ecological systems. Investments in natural systems have been promoted as an efficient and effective approach in climate change adaptation, to increase the capacity of social-ecological systems to deal with uncertainty and surprise [48]. Such reframing may also support a more systematic and integrated approach to dealing with EFRs. In water governance and management systems overwhelming emphasis has been given to provisioning<sup>2</sup> services, whereas regulating and supporting services (e.g. storage capacity of riparian landscapes to buffer both against droughts and floods) and requirements for their maintenance have been largely ignored. Provisioning services, such as water supply for irrigation, arguably are often perceived to provide the most direct socio-economic benefits. Correspondingly, governance and management have evolved around exploiting and guaranteeing access to these provisioning services. Ineffective governance systems and the ignorance of complex feedbacks have often led to ineffective use and overexploitation of some services, to the detriment of the overall

<sup>2</sup> This typology for ecosystem services was introduced by the Millennium Ecosystem Assessment [49], which makes a distinction between: *provisioning services* such as food, water or energy, *regulating services* such as climate regulation, waste decomposition, purification of water and air or pest and disease control, *supporting services* such as nutrient dispersal and cycling, seed dispersal or primary production and *cultural services* such as cultural and spiritual inspiration, recreational experiences and scientific discovery.

integrity of ecological systems and long-term negative consequences for human well-being [49,50,51\*].

### **Ecosystem services to support implementation in an adaptive management approach**

The definition of ecological objectives and monitoring targets for river basin management constitutes a societal choice. A promising approach not yet fully explored in relation to EFRs is the concept of ecosystem services. Ecosystem services describe the benefits derived for human well-being from terrestrial and aquatic ecosystems. The ecosystem services concept allows evaluation of trade-offs and synergies amongst different services, and can assess the implications of choice quantitatively and in a spatial context (e.g. [49]). Economic methods for the monetary valuation of ecosystem services are being developed [52,53], but valuation should and must not be limited to monetary approaches to make the ecosystem services concept operational. Methods of multi-criteria analysis and the combination of quantitative and qualitative approaches can raise awareness about the multiple roles and values of ecosystem services [54,55]. This can support deliberative processes and help to identify and negotiate complex trade-offs between different water demands, including those of aquatic ecosystems [56].

The importance of combining different governance approaches has also been shown in the implementation of water markets, which have been promoted as one solution to achieve efficient water allocation and redistribution of water to meet environmental targets [57]. A crucial step in formal water trading is the initial allocation of tradable water rights, in order to include a share for the environment [58]. The considerable experience of Australia with water markets has shown that formal regulation, participatory approaches and market-based instruments need to be combined to achieve efficient and effective water allocation which can cope with increasing uncertainty and conflict, for example caused by climate change [59,60].

One constraint in using the ecosystem services concept to determine sustainable EFRs is the weakness of quantitative relationships between river flows, ecosystem state and service functions [61]. However, the application of the concept to assess the impacts of flow alterations does not require, and will never be based on, perfect predictive knowledge. Given the complexity of human-environment feedbacks, it is rare to find linear causal patterns of the linkages between ecosystems — ecosystem services — human well-being — human response — and feedbacks to drivers of change [62,63]. Knowledge gaps may be overcome by an adaptive management approach, which can act as a meta-framework to allow management action under situations of incomplete and uncertain knowledge of flow-ecology relationships, conflicts between competing uses, and conditions of high uncertainty

due to global and climate change [20,64–67]. Experimental approaches also help to manage adaptive response to trade-offs between human and ecosystem water demands. For example, where engineered water management already exists, but EFRs include occasional high flows to mobilize spawning gravels for fish or create new geomorphological surfaces to reset riparian plant successions, experimental reservoir flow releases, with measured ecological response to this manipulation [6], can lead to ecologically beneficial re-design of reservoir operating rules [16]. It is important to point out that implementing adaptive management requires enabling institutional frameworks that provide guidance for transparent and flexible processes at different levels, from the redesign of operational management rules to a re-allocation of water shares. The importance of, and requirements for, adaptive management needs to be addressed at the stage of policy design.

### **Summary of major research and implementation gaps:**

- Scant research on the governance of environmental flows, in particular, institutional settings, use of scientific and local knowledge and dealing with uncertainty, decision-making processes and policy implementation.
- Limited transferability of insights, due to the prevalence of case study specific analyses with no comparative analyses across a larger number of cases.
- A lack of research on the applicability of the ecosystem services concept in policy development, trade-off analysis and implementation of EFRs.
- Little research on the economics of environmental flows with regard to short and long-term cost-benefit impact assessments of their implementation.
- Few synthesis efforts and trans-disciplinary approaches (linking science, policy, practice) directed towards the common goal of developing guidelines for effective EFR implementation.

### **Towards an integrative framework**

Given the knowledge gaps identified, we conclude that there is a need to develop an integrative framework to guide the establishment of a sound knowledge base on EFRs and their associated water governance and management needs. However, simply developing a scientific knowledge base cannot overcome a lack of political will or stakeholder engagement. Knowledge co-production needs to be closely linked to policy processes. Therefore, the framework should support both scientific analysis and practical implementation, implying a systematic compilation, sharing and evaluation of experiences from riverine systems around the globe. Such a framework would not ignore complexities and differences among basins, but would enable differences to be taken into account in a systematic way [44,68].

An integral part of such a framework is a consistent classification system across different climates, aquatic and riparian ecosystems, societal water needs, levels and types of anthropogenic modification (e.g. reservoir and dam constructions, abstractions, return flows, changes in water quality), and management goals. We do not seek to explain the full details of such a classification system in this brief review, but rather, present a research agenda by identifying its essential dimensions:

- Societal and environmental context refers to external factors of influence, including economic and institutional development, culture, climate regime and expected trends of climate change impact; these cannot be changed by interventions at the level of water governance or management;
- The environmental system in a river basin is characterized by its current state of aquatic and riparian ecosystems, hydrologic regimes, trends of anthropogenic modification;
- The governance system can be classified according to institutions, actors, multi-level structures, existing EFR policies, and implementation of good governance principles;
- The interface between human and environmental systems is characterized by ecosystem services, which includes the availability, valuation, resilience and use of ecosystem services (including biodiversity!), and observed trade-offs or synergies between services;
- Management options and goals refer to strategies guiding ecosystem management in general. These include conservation (i.e. preserving the relatively intact state), mitigation (e.g. avoiding future negative impacts), restoration (e.g. restore heavily modified system towards a more natural state), and intervention (adaptive intervention to achieve predefined functional state) approaches.

These five dimensions and  $n$  attributes for each dimension are not meant to result in a five multiplied by  $n$  classification space. The goal is to develop a few classes combining attributes along each of the five dimensions and then combine some dimensions to develop types. Initially this will require identification of types of environmental and types of governance and management systems. Ultimately it could be desirable to develop types of coupled social-ecological systems (e.g. heavily modified in arid climate with low economic and institutional development). However, we consider that an initial separation of dimensions, as suggested above, will be more fruitful in synthesizing existing concepts and knowledge and identifying inter-relationships, and will lead to more robust results.

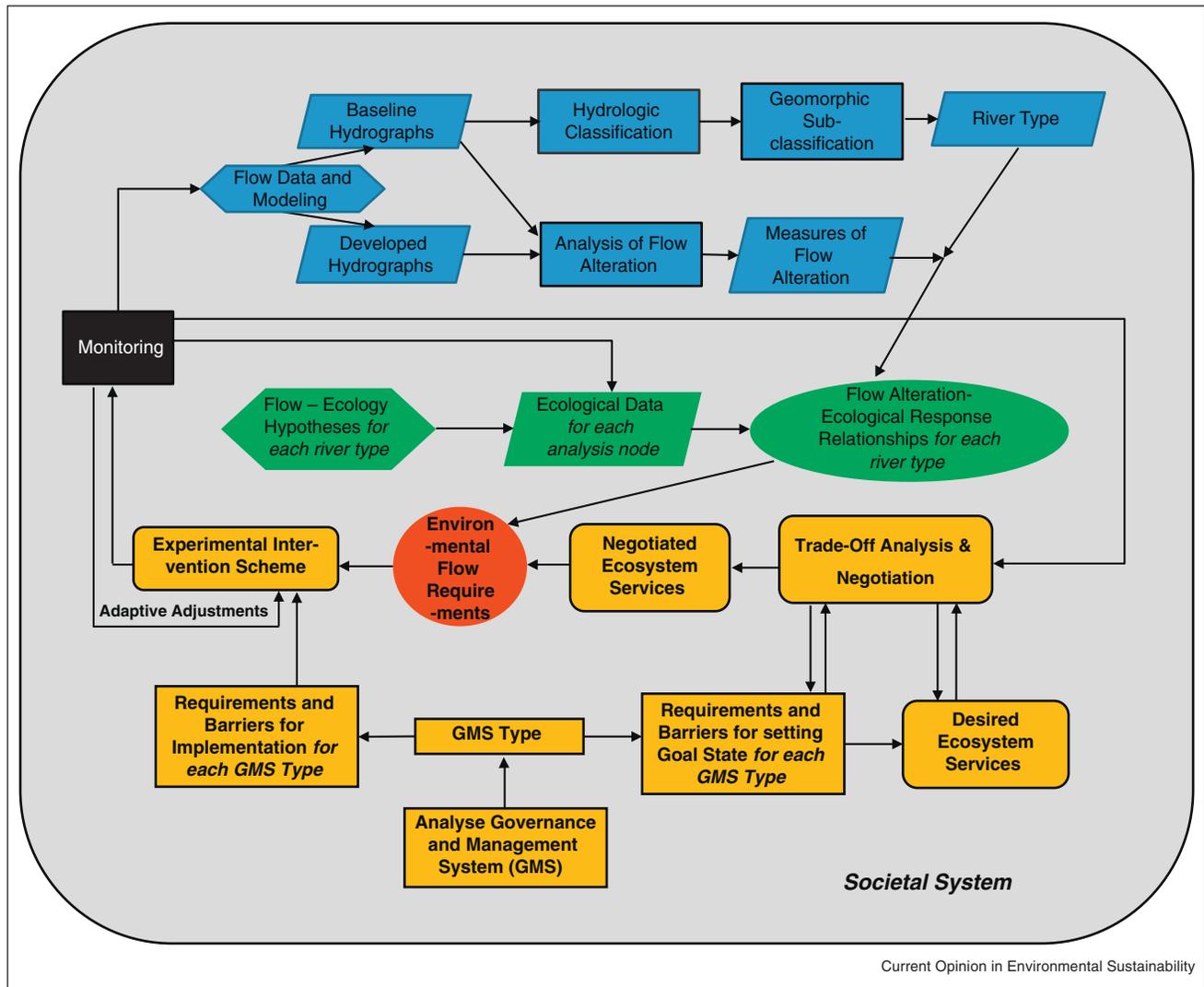
Our expectation is that research that is linked with ongoing policy processes will lead to more meaningful insights that address the needs of stakeholders while also

leading to scholarly advances [69,70]. For practical implementation of an integrative approach to EFR assessments, and as a guide for engaged research, we have developed the SUMHA (Sustainable Management of Hydrological Alterations) framework presented in Figure 1. This framework adopts the Ecological Limits of Hydrological Alteration (ELOHA) framework as the starting point. The ELOHA framework makes a clear distinction between social and scientific processes, but details only the hydro-ecological science underlying the setting of environmental flows. The SUMHA framework introduces the social sciences as an essential part of an assessment, and, by while advocating engaged research it does not make a strict distinction between scientific and social processes. Governance and management systems (GMS) are classified according to different types. These types determine requirements and barriers for negotiations about setting targets for EFRs and for their implementation. To do so SUMHA adopts the classification scheme described above.

The SUMHA framework (like ELOHA) does not assume that 'natural flow conditions' should be identified for different river types as the most desirable states from an ecological perspective; it is not 'reference-based', but rather, is 'objective-based' [71]. It suggests expressing desirable goals in terms of ecosystem state, of bundles of ecosystem services, which need to be negotiated in participatory settings. This implies negotiating target use patterns of those ecosystem services expected to meet criteria for economic, environmental and social sustainability, and designing adaptive implementation strategies to achieve negotiated targets. Applying such a framework cannot overcome existing gaps in our understanding of how environmental flows affect ecosystem functions and thus ecosystem services. However, data requirements can be assessed from the perspective of the decision-making process [72]. A lack of data should not imply inaction. SUMHA advocates an adaptive management framework where the knowledge base is improved during the implementation process.

The nature of the participatory process, and the kinds of management strategies and types of EFRs that might be the most promising to implement in particular cases, will depend on the general characteristics of the governance regime, and on the river type. In the SUMHA framework, the governance regime characteristics will be typical of certain classes of governance systems as represented in the classification scheme. Having identified the class of governance regime, it will be possible to draw on the global experience to identify the best available practices in comparable situations. The classification system thus supports various steps of the assessment by providing guidance and a systematic approach that builds on knowledge accumulated across various social-ecological settings. We therefore expect the SUMHA framework to

Figure 1



The Sustainable Management of Hydrological Alterations (SUMHA) Framework. The SUMHA Framework builds on the ELOHA Framework. SUMHA framework introduces the social sciences as essential part of an assessment, and while advocating engaged research it does not make a strict distinction between scientific and social processes as ELOHA does. SUMHA includes a process of analyzing governance and management systems (orange squares) which interact with design and implementation of policy and management processes (orange rounded squares). The description of hydrological analysis and classification (blue) and the analysis of flow alteration–ecological response relationships (green) were adopted from the ELOHA framework [24].

be used for supporting the implementation process in individual cases, and to allow the mapping of experience from a large number of cases in a consistent structure, for the purpose of comparative analyses to seek generalization.

## Conclusions

Building on recent advances in environmental flow science, water governance and management, we have identified a clear need for a more systematic approach to EFR analysis on both the natural and social science fronts and, in particular, on the interaction between

social/political and environmental systems. Neither simplistic approaches that ignore differences between cases, nor approaches that assume each case to be unique, offer appropriate ways to proceed. A unifying framework, as sketched in this paper, is essential for the assessment and implementation of sustainable EFRs in national water policy, in IWRM plans for river basins, and in global environmental water assessments. It is essential to overcome limitations and knowledge gaps to build a knowledge base and to develop transferable insights on flow rules and strategies for effective implementation which take into account both (needs for

change in) the governance context and the design of the implementation process itself. A link to ecosystem services is expected to raise awareness for the importance of ecosystem functions for the resilience of social-ecological systems, to support negotiations about trade-offs and develop strategies for adaptive implementation. Experience in implementation of EFR policies provides evidence for an engaged research approach, where research is not detached from its practical use on the ground. We advocate strongly for such engagement as the only way forward to build the foundations for sustainable management of water uses.

Our conclusions concur with the new research agenda proposed for global change science under the umbrella of Future Earth (cf. [www.icsu.org/future-earth](http://www.icsu.org/future-earth)). Interdisciplinary collaboration between natural and social sciences and co-production of knowledge by actors from science and policy are essential for tackling complex issues in the sustainable management of environmental resources.

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## References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- of special interest
- of outstanding interest

1. Cook C, Bakker K: **Water security: debating an emerging paradigm**. *Global Environ Change* 2012, **22(1)**:94-102 <http://dx.doi.org/10.1016/j.gloenvcha.2011.10.011>.
- Comprehensive and insightful review of the concept of water security, the different meanings and interpretations of the concept in the natural and social sciences, the increasing popularity of the concept in the scientific and policy literatures.
2. Nilsson C, Reidy CA, Dynesius M, Revenga C: **Fragmentation and flow regulation of the world's large river systems**. *Science* 2005, **308**:405-408 <http://dx.doi.org/10.1126/science.1107887>.
3. Palmer MA, Reidy-Liermann C, Nilsson C, Florke M, Alcamo J, Lake PS, Bond N: **Climate change and world's river basins: anticipating management options**. *Front Ecol Environ* 2008, **6(2)**:81-89 <http://dx.doi.org/10.1890/060148>.
4. Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Reidy Liermann C, Davies PM: **Global threats to human water security and river biodiversity**. *Nature* 2010, **467**:555-561 <http://dx.doi.org/10.1038/nature09440>.
- Highly cited diagnostic analysis of implications of threats to water security. Analyses provided evidence that increasing water security for humans is achieved to the expense of water security for the environment.
5. Poff NL, Zimmerman JKH: **Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows**. *Freshw Biol* 2010, **55(1)**:194-205 <http://dx.doi.org/10.1111/j.1365-2427.2009.02272.x>.
6. Konrad CP, Olden JD, Lytle DA, Melis TS, Schmidt JC, Bray EN, Freeman MC, Guido KB, Hemphill NP, Kennard MJ et al.: **Large-scale flow experiments for managing river systems**. *BioScience* 2011, **61(11)**:948-959 <http://dx.doi.org/10.1525/bio.2011.61.12.5>.

7. Richards KS, Brasington J, Hughes F: **Geomorphic dynamics of floodplains: ecological implications and a potential modelling strategy**. *Freshw Biol* 2002, **47(4)**:559-579 <http://dx.doi.org/10.1046/j.1365-2427.2002.00920.x>.
8. Naiman RJ, Bunn SE, Nilsson C, Petts GE, Pinay G, Thompson LC: **Legitimizing fluvial ecosystems as users of water: an overview**. *Environ Manage* 2002, **30(4)**:455-467 <http://dx.doi.org/10.1007/s00267-002-2734-3>.
9. Brisbane Declaration 2007. [http://www.eflownet.org/download\\_documents/brisbane-declaration-english.pdf](http://www.eflownet.org/download_documents/brisbane-declaration-english.pdf).
10. Tharme RE: **A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers**. *River Res Appl* 2003, **19(5-6)**:397-441 <http://dx.doi.org/10.1002/rra.736>.
11. Postel SL, Richter BD: *Rivers For Life: Managing Water for People and Nature*. Island Press; 2003.
12. Hill M, Platts WS: **Ecological and geomorphological concepts for instream and out-of-channel flow requirements**. *Rivers* 1991, **2**:319-343.
13. Poff NL, Allan JD, Bain MB, Karr JR, Prestegard KL, Richter BD, Sparks RE, Stromberg JC: **The natural flow regime: a paradigm for river conservation and restoration**. *BioScience* 1997, **47(11)**:769-784 <http://dx.doi.org/10.2307/1313099>.
14. Mahoney JM, Rood SB: **Streamflow requirements for cottonwood seedling recruitment — an integrative model**. *Wetlands* 1998, **18(4)**:634-645 <http://dx.doi.org/10.1007/BF03161678>.
15. Bunn SE, Arthington AH: **Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity**. *Environ Manage* 2002, **30(4)**:492-507 <http://dx.doi.org/10.1007/s00267-002-2737-0>.
16. Richter BD, Thomas GA: **Restoring environmental flows by modifying dam operations**. *Ecol Soc* 2007, **12(1)**:12 In: <http://www.ecologyandsociety.org/vol12/iss1/art12/>.
17. Dyson M, Bergkamp G, Scanlon J (Eds): *Flow — The Essentials of Environmental Flows*, edn 2. IUCN; 2008. Reprint, IUCN <http://data.iucn.org/dbtw-wpd/edocs/2003-021.pdf>.
18. Le Quesne T, Kendy E, Weston D. *The implementation challenge. Taking stock of government policies to protect and restore environmental flows*. The Nature Conservancy and WWF Report. WWF; 2010. [http://awsassets.panda.org/downloads/the\\_implementation\\_challenge.pdf](http://awsassets.panda.org/downloads/the_implementation_challenge.pdf).
19. King JM, Pienaar H (Eds): *Sustainable Use of South Africa's Inland Waters: A Situation Assessment of Resource Directed Measures 12 Years After the 1998 National Water Act*. WRC Report No. TT 491/11. South Africa: Water Research Commission, Pretoria; 2011 In: [www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=9519](http://www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=9519).
20. Poff NL, Allan JD, Palmer MA, Hart DD, Richter BD, Arthington AH, Meyer JL, Stanford JA, Rogers KH: **River flows and water wars? Emerging science for environmental decision making**. *Front Ecol Environ* 2003, **1(6)**:298-306.
21. Cullen P: **The future of flow restoration in Australia**. *Water Shed* 2001:1-2.
22. Smakhtin V, Revenga C, Döll P: **A pilot global assessment of environmental water requirements and scarcity**. *Water Int* 2004, **29(3)**:307-317 <http://dx.doi.org/10.1080/02508060408691785>.
23. Richter BD, Baumgartner JV, Powell J, Braun DP: **A method for assessing hydrologic alteration within ecosystems**. *Conserv Biol* 1996, **10(4)**:1163-1174 <http://dx.doi.org/10.1046/j.1523-1739.1996.10041163.x>.
24. Arthington AH, Bunn SE, Poff LN, Naiman RJ: **The challenge of providing environmental flow rules to sustain river ecosystems**. *Ecol Appl* 2006, **16(4)**:1311-1318 In: <http://www.jstor.org/stable/40062003>.
25. King JM, Tharme RE, de Villiers MS (Eds): *Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology*. Updated Edition. WRC Report No. TT 354/08.

## 10 Open issue 2013

- Pretoria, South Africa: Water Research Commission; 2008 In: [www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=3675](http://www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=3675).
26. Brown CA, Pemberton CW, Greyling AJ, King JM: *DRIFT user manual volume 1: biophysical module for predicting overall river condition in small to medium sized rivers with predictable flow regimes. WRC Report No. 1404/1/05*. Pretoria, South Africa: Water Research Commission; 2005, .: [www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=7056](http://www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=7056).
  27. Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E, ●● Acreman M, Apse C, Bledsoe BP, Freeman MC *et al.*: **The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards**. *Freshw Biol* 2010, **55(1)**:147-170 <http://dx.doi.org/10.1111/j.1365-2427.2009.02204.x>.  
 Framework to assess the implications of flow alterations on riverine ecosystems in a more systematic way by using a classification scheme to assign rivers to different types. Practical stepwise guidance for a scientifically based implementation of environmental flow requirements.
  28. Kendy E, Apse C, Blann K: **A practical guide to environmental flows for policy and planning**. *Nat Conserv* 2012 In: <http://conserveonline.org/workspaces/eloha/documents/practical-guide-to-environmental-flows-for-policy>.
  29. Belmar O, Velasco J, Martínez-Capel F: **Hydrological classification of natural flow regimes to support environmental flow assessments in intensively regulated rivers, Segura River Basin Spain**. *Environ Manage* 2011, **47**:992-1004.
  30. Zhang Y, Arthington AH, Bunn SE, Mackay XiaJ, Kennard M: **Classification of flow regimes for environmental flow assessment in regulated rivers: the Huai River Basin, China**. *River Res Appl* 2012, **28**:989-1005.
  31. Arthington AH, Mackay SJ, James CS, Rolls RJ, Sternberg D, Barnes A, Capon SJ: *Ecological limits of hydrologic alteration: a test of the ELOHA framework in south-east Queensland. Waterlines Report Series No. 75*. Canberra, Australia: National Water Commission; 2012, . Available at: In: [www.nwc.gov.au/publications/waterlines/75](http://www.nwc.gov.au/publications/waterlines/75).
  32. Finn M, Jackson S: **Protecting indigenous values in water management: a challenge to conventional environmental flow assessments**. *Ecosystems* 2011, **14(8)**:1232-1248 <http://dx.doi.org/10.1007/s10021-011-9476-0>.
  33. Meigh J, Folwell S, Sullivan C: **Linking water resources and global change in West Africa: options for assessment**. In *Regional Hydrological Impacts of Climatic Change: Impact assessment and Decision Making*, vol. 295. Edited by Wagener T, Franks SW. IASH Pub; 2005:297-306.
  34. Widen-Nilsson E, Halldin S, Chong-Yu X: **Global water-balance modelling with WASMOD-M: parameter estimation and regionalisation**. *J Hydrol* 2007, **340(1-2)**:105-118 <http://dx.doi.org/10.1016/j.jhydrol.2007.04.002>.
  35. Hoff H, Falkenmark M, Gerten D, Gordon L, Karlberg L, Rockström J: **Greening the global water system**. *J Hydrol* 2010, **384(3-4)**:177-186 <http://dx.doi.org/10.1016/j.jhydrol.2009.06.026>.
  36. Hanasaki N, Kanae S, Oki T, Masuda K, Motoya K, Shirakawa N, Shen Y, Tanaka K: **An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing**. *HESS* 2008, **12**:1007-1025 <http://dx.doi.org/10.5194/hess-12-1007-2008>.
  37. Hoekstra AY, Mekonnen MM, Chapagain AK, Mathews RE, Richter BD: **Global monthly water scarcity: blue water footprints versus blue water availability**. *PLoS ONE* 2012, **7(2)**:e32688 In: <http://dx.doi.org/10.1371/journal.pone.0032688>.
  38. Richter BD, Davis MM, Apse C, Konrad C: **A presumptive standard for environmental flow protection**. *River Res Appl* 2011, **28(8)**:1312-1321 <http://dx.doi.org/10.1002/rra.1511>.
  39. Arthington AH, Naiman RJ, McClain ME, Nilsson C: **Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities**. *Freshw Biol* 2010, **55(1)**:1-16 <http://dx.doi.org/10.1111/j.1365-2427.2009.02340.x>.  
 Insightful and comprehensive summary of major insights and recommendations derived from a special issue in Freshwater Biology on environmental flows — ecological data, new methods and analytical framework (ELOHA), individual case studies.
  40. Pahl-Wostl C, Lebel L, Knieper C, Nikitina E: **From applying panaceas to mastering complexity: toward adaptive governance in river basins**. *Environ Sci Pol* 2012, **23**:24-34 <http://dx.doi.org/10.1016/j.envsci.2012.07.014>.  
 First comprehensive comparative analyses of complex governance and managements systems in national river basins to identify how the characteristics of a governance regime affect its performance in different contextual conditions.
  41. Meinzen-Dick R: **Beyond panaceas in water institutions**. *Proc Natl Acad Sci USA* 2007, **104**:15200-15205.
  42. Ingram H: **Beyond universal remedies for good water governance: a political and contextual approach**. In *Water for Food in a Changing World*. Edited by Garrido A, Ingram H. Routledge; 2007:241-261.
  43. Gleick P: **Global freshwater resources: soft-path solutions for the 21st century**. *Science* 2003, **302**:1524-1528.
  44. Pahl-Wostl C: **A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes**. *Global Environ Change* 2009, **19(3)**:354-365 <http://dx.doi.org/10.1016/j.gloenvcha.2009.06.001>.
  45. Ostrom E: *Understanding Institutional Diversity*. Princeton University Press; 2005.
  46. Silveira A: **China's Political System, Economic Reform and the Governance of Water Quality: the case of the Pearl River Basin**. In *Water Security and Federal Rivers*. Edited by Connell D, Garrick D, Anderson G, Pittock J. Cheltenham: Edward Elgar; December 2013.
  47. Ostrom E: **Polycentric systems for coping with collective action and global environmental change**. *Global Environ Change* 2010, **20**:550-557.
  48. Smith DM, Barchiesi S: **Environment as infrastructure: Resilience to climate change impacts on water through investments in nature**. In *Perspectives on water and climate change adaptation*. Edited by International Union for Conservation of Nature (IUCN); 2009:1-10. [http://www.worldwatercouncil.org/fileadmin/wwc/Library/Publications\\_and\\_reports/Climate\\_Change/PersPap\\_02\\_Environment\\_as\\_Infrastructure.pdf](http://www.worldwatercouncil.org/fileadmin/wwc/Library/Publications_and_reports/Climate_Change/PersPap_02_Environment_as_Infrastructure.pdf).
  49. MEA [Millennium Ecosystem Assessment]: *Introduction and conceptual framework. Ecosystems and human well-being: a framework for assessment*. Millennium Ecosystem Assessment; 2005.
  50. Butchart SHM, Walpole M, Collen B *et al.*: **Global biodiversity indicators of recent declines**. *Science* 2010, **328**:1164-1168 <http://dx.doi.org/10.1126/science.1187512>.
  51. Naiman RJ, Dudgeon D: **Global alteration of freshwaters: influences on human and environmental well-being**. *Ecol Res* 2011, **26**:865-873.  
 Synthesis article which highlights the global dimension of environmental flows, decline of freshwater ecosystems and global responsibility to deal with the challenges.
  52. EEA [European Environmental Agency]: *Scaling up ecosystem benefits. A contribution to The Economics of Ecosystems and Biodiversity (TEEB) study*. European Environmental Agency, Report No. 4/2010. 2010 <http://dx.doi.org/10.2800/41295>.
  53. Puhspam K (Ed): *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*. Routledge; 2012.
  54. Busch M, La Notte A, Laporte V, Erhard M: **Potentials of quantitative and qualitative approaches to assessing ecosystem services**. *Ecol Indic* 2012, **21**:89-103.
  55. Chan KMA, Satterfield T, Goldstein J: **Rethinking ecosystem services to better address and navigate cultural values**. *Ecol Econ* 2012, **74**:8-18.
  56. ESAWADI: *ESAWADI. Utilizing the Ecosystem Services Approach for the Water Framework Directive Implementation. Framework of Analysis*. ESAWADI; 2011. [http://www.esawadi.eu/IMG/pdf/ESAWADI-Framework\\_of\\_Analysis-vf.pdf](http://www.esawadi.eu/IMG/pdf/ESAWADI-Framework_of_Analysis-vf.pdf).

57. Le Quesne T, Pegram G, Von Der Heyden C: **Allocating scarce water. A WWF primer on water allocation, water rights and water markets, WWF Water Security Series 1.** WWF 2007 In: [http://assets.wwf.org.uk/downloads/scarce\\_water.pdf](http://assets.wwf.org.uk/downloads/scarce_water.pdf).
58. Walter T, Kloos J, Tsegai D: **Options for improving water use efficiency under worsening scarcity: Evidence from the Middle Olifants sub-basin in South Africa.** *Water SA* 2011, **37(3)**:357-370 In: [www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=9078](http://www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=9078).
59. Bell S, Park A: **The problematic metagovernance of networks: the politics of water reform in New South Wales.** *J Public Pol* 2006, **26(1)**:63-83 <http://dx.doi.org/10.1017/S0143814X06000432>.
60. Bell S, Quiggin J: **The limits of markets: the politics of water management in rural Australia.** *Environ Polit* 2008, **17(5)**:712-729 <http://dx.doi.org/10.1080/09644010802421448>.
61. Palmer MA, Filoso S: **Restoration of ecosystem services for environmental markets.** *Science* 2009, **325**:575-576.
62. Pahl-Wostl C: **The implications of complexity for integrated resources management.** *Environ Model Softw* 2007, **22(5)**:561-569 <http://dx.doi.org/10.1016/j.envsoft.2005.12.024>.
63. Carpenter SR, Mooney HA, Agard J, Capistrano D, DeFries RS, Diaz S, Dietz T, Duraipappah AK, Oteng-Yeboah A, Pereira HM et al.: **Science for managing ecosystem services: beyond the millennium ecosystem assessment.** *Proc Natl Acad Sci USA* 2009, **106(5)**:1305-1312 <http://dx.doi.org/10.1073/pnas.0808772106>.
64. Richter BD, Warner AT, Meyer JL, Lutz K: **A collaborative and adaptive process for developing environmental flow recommendations.** *River Res Appl* 2006, **22(3)**:297-318 <http://dx.doi.org/10.1002/rra.892>.
65. O'Keefe J, Le Quesne T: **Keeping rivers alive. A primer on environmental flows and their assessment.** WWF Water Security Series 2. WWF; 2009 In: [http://assets.wwf.org.uk/downloads/keeping\\_rivers\\_alive.pdf](http://assets.wwf.org.uk/downloads/keeping_rivers_alive.pdf).
66. Pahl-Wostl C: **The importance of social learning in restoring the multifunctionality of rivers and floodplains.** *Ecol Soc* 2006, **11(1)**:10 In: <http://www.ecologyandsociety.org/vol11/iss1/art10/>.
67. Pahl-Wostl C, Sendzimir J, Jeffrey JP, Aerts J, Berkamp G, Cross K: **Managing change toward adaptive water management through social learning.** *Ecol Soc* 2007, **12**:30 In: <http://www.ecologyandsociety.org/vol12/iss2/art30/>.
68. Pahl-Wostl C, Holtz G, Kastens B, Knieper C: **Analyzing complex water governance regimes: the management and transition framework.** *Environ Sci Pol* 2010, **13(7)**:571-581 <http://dx.doi.org/10.1016/j.envsci.2010.08.006>.
69. Palmer MA: **Socio-environmental sustainability and actionable science.** *BioScience* 2012, **62**:5-6.
70. Pahl-Wostl C, Giupponi C, Richards K, Binder C, de Sherbinin A, Sprinz D, Toonen T, van Bers C: **Building the foundations for dealing with the challenges arising from global change requirements for methodologies, methods, data and knowledge.** *Environ Sci Pol* 2013, **28**:36-47.
71. Dufour S, Piégay H: **From the myth of a lost Paradise to targeted river restoration: forget natural references and focus on human benefits.** *River Res Appl* 2009, **25(5)**:568-581 <http://dx.doi.org/10.1002/rra.1239>.
72. Meijer KS, van Beek E: **A framework for the quantification of the importance of environmental flows for human well-being.** *Soc Nat Resour* 2011, **24**:1252-1269.