Wetlands (2022) 42: 46
https://doi.org/10.1007/s13157-022-01562-6

RAMSAR

Securing the Environmental Water Requirements of Seasonally Ponding Wetlands: Partnering Science and Management through Benefit Sharing

Stefano Barchiesi[1] · **Antonio Camacho**[2] · **Eva Hernández**[3] · **Anis Guelmami**[4] · **Flavio Monti**[5] · **Alessio Satta**[5] · **Osvaldo Jordán**[6] · **Christine Angelini**[7]

Received: 28 December 2021 / Accepted: 28 April 2022 / Published online: 30 May 2022

Abstract

Although environmental flow regime assessments are becoming increasingly holistic, they rarely provoke water managers to enact the adaptive water reallocation mechanisms required to secure environmental water for wetlands. The conditions that cause science-based environmental flow assessments to succeed or fail in informing the management of environmental water requirements remain unclear. To begin to resolve these conditions, we used process tracing to deconstruct the sequence of activities required to manage environmental water in four case studies of seasonally ponding wetlands in Mediterranean and Mesoamerican watersheds. We hypothesized that, when the flexibility and equitability of the socioeconomic system do not match the complexity of the biophysical system, this leads to a failure of managers to integrate scientific guidance in their allocation of environmental water. Diagnostic evidence gathered indicates that science-management partnerships are essential to align institutional flexibility and socioeconomic equitability with the system's ecohydrological complexity, and thus move from determination to reallocation of environmental water. These results confirm that institutions e.g., river basin organizations need to be supplemented by motivated actors with experience and skill to negotiate allocation and adaptive management of environmental water. These institutional-actor synergies are likely to be especially important in water scarce regions when the need to accommodate extreme hydrological conditions is not met by national governance capacity. We conclude by focusing on benefit sharing as a means to better describe the conditions for successful science-based environmental flow assessments that realize productive efficiency in environmental water allocation i.e., recognition of multiple values for both people and ecosystems.

Keywords Environmental flows · Water allocation · Mediterranean · Mesoamerica · Process tracing · Ramsar convention

✉ Stefano Barchiesi
barchiesis@ufl.edu

Antonio Camacho
antonio.camacho@uv.es

Eva Hernández
ehernandez@wwf.es

Anis Guelmami
guelmami@tourduvalat.org

Flavio Monti
monti@medwet.org

Alessio Satta
satta@medwet.org

Osvaldo Jordán
ojordan@creho.org

Christine Angelini
c.angelini@ufl.edu

1 School of Natural Resources and Environment, University of Florida, Gainesville, FL, USA

2 Cavanilles Institute for Biodiversity and Evolutionary Biology, University of Valencia, Paterna, Spain

3 Living European Rivers Initiative, WWF Netherlands, Zeist, Netherlands

4 Mediterranean Wetlands Observatory, Tour du Valat, Le Sambuc, Arles, France

5 The Mediterranean Wetlands Initiative, Le Sambuc, Arles, France

6 Ramsar Regional Center for Training and Research for the Western Hemisphere (CREHO), City of Knowledge, Panama City, Panama

7 Department of Environmental Engineering Sciences, Engineering School of Sustainable Infrastructure and Environment, University of Florida, Gainesville, FL, USA

Resumen

Aunque las evaluaciones del régimen de caudales ambientales son cada vez más holísticas, las administraciones del agua rara vez implementan los mecanismos adaptativos de reasignación de agua necesarios para asegurar los requerimientos hídricos de los humedales. Las condiciones que hacen que las evaluaciones de científicas de dichos requerimientos sean o no tenidas en cuenta siguen sin estar claras. Para comenzar a resolver estas condiciones, utilizamos una metodología basada en el rastreo de procesos para deconstruir la secuencia de actividades requeridas para gestionar los requerimientos hídricos de los humedales en cuatro estudios de caso de humedales estacionales en cuencas hidrográficas del Mediterráneo y Mesoamérica. Suponemos que, cuando la flexibilidad y la equidad del sistema socioeconómico no coinciden con la complejidad del sistema biofísico, esto lleva a que los administradores no integren la orientación científica para realizar las asignaciones hídricas ambientales. La evidencia recopilada con este diagnóstico indica que las alianzas entre ciencia y gestión son esenciales para alinear la flexibilidad institucional y la equidad socioeconómica con la complejidad ecohidrológica del sistema. Estos resultados confirman que las instituciones deben complementarse con actores motivados, con experiencia y habilidad para negociar la asignación y la gestión adaptativa de los requerimientos hídricos de los ecosistemas. Concluimos enfocándonos en la distribución de beneficios como un medio para describir mejor las condiciones para evaluaciones exitosas de los caudales ambientales que logran la eficiencia productiva en la asignación ambiental del agua, es decir, el reconocimiento de múltiples valores tanto para las personas como para los ecosistemas.

Introduction

Wetlands of any size and character play a key role for society, not only because they sustain levels of biodiversity that are disproportionately high relative to the area they cover (Garcia-Moreno et al. 2014), but also because of the ecosystem services they provide (Mitsch et al. 2015), including their enhancement of water security and delivery of other interlinked products such as food and energy (Vörösmarty et al. 2010; Boelee 2011; Hülsmann et al. 2019). In turn, the environmental water requirements of a wetland (*sensu* Ramsar Convention)[1] have been consensually defined[2] and increasingly legislated (Horne et al. 2017; Arthington et al. 2018a) as the adequate amount and quality of freshwater at the right time to sustain a wetland's biodiversity and processes as well as its provisioning of water-related ecosystem services for people (e.g., replenishment, storage, purification, and flow regulation)[3] and other benefits to human well-being that span ecological, economic, sociocultural, and intrinsic values (Russi et al. 2013; Tickner et al. 2017). The concept of environmental water or flows applies similarly to both running and standing waters, meaning the water needs[4] of epicontinental aquatic ecosystems, including to maintain their ecological integrity and capacity to offer ecosystem services. However, despite the progress made over the last decade in environment flows science and policy, implementation of this ecological restoration approach for wetlands – i.e., environmental water releases – in water resources management has been limited (Arthington et al. 2018a). Although environmental flow regime assessments have become increasingly holistic, they rarely provoke water managers to enact the adaptive water reallocation mechanisms required to secure the environmental water requirements of wetlands (Horne et al. 2017). With climate change worsening drought conditions in water scarce areas, reallocating environmental water to wetlands to maintain adequate levels for both people and ecosystems remains a socially divisive undertaking, particularly in locations

[1] The Convention on Wetlands of International Importance, also known as the Ramsar Convention, defines wetlands as "[…] areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres" (Ramsar Convention on Wetlands 2016).

[2] The original definition of environmental flows is "[…] the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems" (Brisbane Declaration 2007). This definition was later expanded to describe "[…] the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being" (Arthington et al. 2018b).

[3] See Grizzetti et al. (2016) for a more comprehensive review of the different definitions of water-related, water, or hydrological secosystem services.

[4] As per Ramsar Convention's definition of wetlands, these water needs include any balance among inflows of fresh, brackish, and saltwater from both surface and groundwater depending on the location of the aquatic ecosystem on the continent.

where water supplies are fully allocated to consumptive uses (Webb et al. 2010).

Beyond the challenging task of determining the adequate amount, quality, and timing of environmental water to reallocate to wetlands, environmental flow regime implementation, and ecological restoration more generally, continue to be constrained by the additional need for such investments to demonstrate multiple benefits from the same environmental water for both people and ecosystems over time (Yang et al. 2016). To reduce competition among wetlands and more direct human uses, a broader suite of benefits delivered by wetlands other than for biodiversity need to be demonstrated to existing water users and decision-makers. These stakeholders are likely to have differing priorities, expectations and responsibilities and thus seek to achieve distinct combinations and timeframes for accrual of the ecosystem services being pursued. A significant challenge is therefore to build science-management collaborations involving multiple partners that support long-term, landscape-scale monitoring and translation of monitoring information into adaptive decision-making, a process that must extend beyond the initial environmental flow assessment (Webb et al. 2010). Due to a general lack of such sustained, multi-sector partnerships, the effectiveness of ecological restoration and management tools such as environmental flows in increasing provision of both biodiversity and ecosystem services is rarely assessed through routine programs (Rey-Benayas et al. 2009).

Meta-analyses of relevant experimental studies have shown that synergies between priorities and expectations can be achieved at the various scales at which restoration actions are deployed but that these synergies depend on a shared design of the restorative actions (Meli et al. 2014). In the many cases where partnership agreements that establish clear roles and strategies for adaptive water allocation between the scientific and the water managers' communities are not in place, each community's set of challenges inherently obstructs environmental flow implementation. Specifically, the scientific community faces challenges related to the uncertainty around prescribed flow-ecology relationships that are often considered to be stationary in implementation frameworks but are, in reality, shifting in response to a changing climate (Poff and Matthews 2013). Scientists are also challenged by the need to integrate the water quality requirement into the prescribed flow-ecology relationship, a task that is difficult to achieve without sophisticated understanding of sediment dynamics, temperature variability, and other water quality variables (Acreman et al. 2014). In turn, water managers often face challenges in implementing environmental flow regimes that have been informed by prescribed flow-ecology relationships due to operational and infrastructure constraints e.g., dam operation schedules (Poff et al. 2016). Finally, both communities are challenged by the need for more socially robust environmental science to increase its understanding, legitimacy, and relevance to decision-making (Hickey et al. 2013).

Assessing environmental water requirements is further challenging for ecosystems shifting in time and space between aquatic and terrestrial phases. These dynamic environments, such as temporary streams and seasonal lakes and wetlands that can transition from flowing (or flooding for lentic ecosystems) to dry through a ponded phase, create a mosaic of habitats and an alternation of ecosystem services (Stubbington et al. 2020). The correct delineation of these transitory wetlands is further complicated by the need to exclude occasional flooding over non-wetland habitats as well as long-term changes in inter-annual variability (Perennou et al. 2018). Although intermittent rivers, ephemeral streams, and temporal lakes, were little studied historically, they have been gaining traction in freshwater research and regional water policies with an expanded new focus (Datry et al. 2017; Arthington et al. 2018b). This is due to increasing disruptions to water resources causing previously perennial systems to become seasonal or intermittent as a result of development, land use and climate change (Leigh et al. 2016), but also due to the recognition of the value of these non-perennial systems as providers of ecosystem services that differ from those produced by perennial systems (Stubbington et al. 2020). This perception is more pronounced in dry regions with developing economies due to the greater reliance of people's livelihoods on temporary streams and ponds for public water supply (e.g., Stubbington et al. 2020). Regions of the world that developed or are developing within an environment of water scarcity tend to already have different infrastructure, institutions, and societal attitudes that equip them to cope with high variability in available water (Gleick 2010), including for protected wetland management (e.g., Downard et al. 2014). For example, such regions often invest in increased water storage for public water supply and crop irrigation but also leverage assessment methods, monitoring technologies, and policies aimed at reducing water use, controlling salinization, and maintaining ecosystems (Davies et al. 2016). Such strategies are often more prevalent in water-scarce regions located within countries of sufficient wealth to offset the cost of unpredictable water availability with institutional reforms and water infrastructure investments (Grey and Sadoff 2007; Vörösmarty et al. 2010). The institutional transaction costs of forming a more complex governance system are therefore higher for water-scarce regions because they require flexible mechanisms to cope with equally high variability in environmental water requirements (Horne et al. 2018). Lessons from partnerships formed under these circumstances can shed light on how existing institutions, and other actor-driven processes (e.g., facilitation by nature conservation organizations), can create bridges between the scientific and water management communities. An example of such partnerships for sustainable wetland governance are the voluntary environmental contracts being used in the European side of the Mediterranean region (Ernoul et al. 2021). Even when falling short of a full connection between scientific and management communities, lessons can help address the research gap in understanding what ultimately governs equitable allocation and effective management of environmental water (Horne et al. 2017) and thus inform amendment of existing policies in line with the integration of scientific progress into the policy-making process (Quevauviller et al. 2005).

To address this research gap, we brought together evidence describing how the process of knowledge generation in ecohydrology science translates into mutual learning and uptake by the science-management partnerships needed to implement environmental water management. Our goal was to identify how environmental water requirements for seasonally ponding wetlands[5] are determined, which institutional entities or other actors (e.g., a wetland conservation project with a stakeholder engagement component) initiate this determination, and which other actors, in turn, need to be involved in the knowledge generation and knowledge uptake processes to support future allocation and management decisions. We used process tracing as a method to gather diagnostic evidence from four case studies in the Mediterranean and the Mesoamerican regions. We compared the significance of that evidence in linking the processes of knowledge generation and knowledge uptake for select wetlands that benefit from a level of protection generated through their designation as Ramsar Sites under the Ramsar Convention on Wetlands of International Importance (Ramsar Convention on Wetlands 2016). The two pairs of case studies (Pair one: Mexico and Costa Rica, and Pair two: Spain and Morocco) represent a combination of regional water scarcity conditions and different levels of institutional development for nature conservation and water agencies in the respective countries. Conscious that trade-offs and synergies between ecosystem services are scale and location dependent (Martínez-Harms and Balvanera 2012), we focused on the common precondition but differentiated outcome of the science-management collaboration across the case studies. We hypothesized the common precondition to be the presence of nature conservation and water agencies but the differentiated outcome of more effective environmental water management to depend on the level and type of institutional development (e.g., policy cohesion between nature conservation and water agencies' mandates, presence of river basin organization) required to enable science-management partnerships. We further expand upon this hypothesis at the end of the analytical framework section of our methods below. In bringing together the ecohydrological and socioeconomic perspectives underpinned by the two sides of these science-management partnerships, we also highlight interconnected processes that could contribute to science-policy integration nationally and, if replicated, accelerate progress in the field of environmental water management worldwide.

[5] We define seasonally ponding wetlands to include the following functional groups of the Lakes, and Palustrine wetlands biomes as per Global Ecosystem Typology (Keith et al. 2020): F2.3 Seasonal freshwater lakes, F2.5 Ephemeral freshwater lakes, F2.7 Ephemeral salt lakes, and TF1.4 Seasonal floodplain marshes.

Methods

Analytical Framework

Process Tracing

We employed process tracing (Beach and Pedersen 2013) as a qualitative research method to evaluate how determining highly variable environmental water requirements of seasonally ponding wetlands (i.e., knowledge generation) translates into potential allocation of environmental water under different allocation mechanisms that may exist in disparate water policy environments (i.e., knowledge uptake and practice). Process tracing is used to evaluate claims of causal inference within a single case i.e., the theory behind the *how* and the *why* change has occurred in a particular context rather than the *if*, including after the events being studied have concluded and in the absence of a control group (Punton and Welle 2015). This theory of change is formulated for each case study by: a) careful description of how the sequence of events have unfolded for various entities, and b) a hypothesis of which intervention is likely to have influenced the key outcome, each activity and intermediate outcome in the sequence of events or activities at the time if necessary (Beach and Pedersen 2013).

Empirical tests are then used to assess the strength of the evidence collected to support the causal sequence and hypothesis while rejecting alternatives (Collier 2011). To generalize our findings, we tested the hypothesis across four case studies for which we were able to identify documentary evidence connected to a particular stage in the causal sequence. The evidence is used to run four increasingly inferential tests that are either necessary or sufficient to accept or reject the hypothesis: 'straw in the wind' (low uniqueness and low certainty of evidence; neither necessary nor sufficient), 'hoops' (high certainty; necessary to accept either the hypothesis or the counterhypothesis), 'smoking gun' (high uniqueness, sufficient to accept the hypothesis), and 'double decisive' (high certainty and high uniqueness of evidence; both necessary and sufficient) (Punton and Welle 2015).

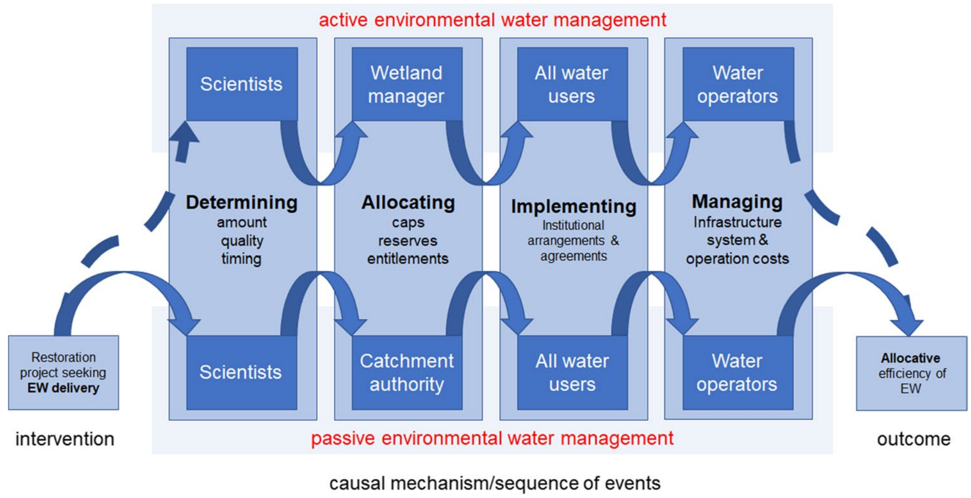

Fig. 1 Deconstructing the sequence of causal events in environmental water (EW) management based on Horne et al. (2018) for the purpose of process tracing analysis. The main difference between the active management pathway (top), which has emerged more recently as an allocation mechanism, and the passive management pathway (bottom) is in a wetland manager as an independent legal entity deciding on how to allocate environmental water as opposed to the catchment authority

The Causal Sequence: Environmental Water Management

To deconstruct the distinct activities that make up environmental water management through process tracing, we followed the categorization proposed by Horne et al. (2018). Accordingly, the sequence of processes is: i) determining, ii) allocating, iii) implementing, and iv) managing environmental water (Fig. 1). In this context, the overall intervention examined is any wetland restoration or conservation project (whether in isolation or as part of a river basin-wide initiative to restore or maintain key aquatic ecosystems) seeking delivery of environmental water and the outcome sought is an efficient allocation of environmental water, which generally means reallocation of some water in a catchment from other human uses to environmental flows for wetlands. Another distinction made by Horne et al. (2018) that we adopted is between 'active' management i.e., when decisions as to where and how to recover and use environmental water are continuously made on the basis of periodically reassessed ecological objectives by an independent legal entity (e.g., a park service or conservancy acting on behalf of the wetland), and 'passive' management i.e., when water is allocated according to rules that have been defined by planning or regulatory instruments by the water management district or river basin authority, even though these rules may provide for a negotiated decision on ecological objectives among all water users at the beginning of the process. In the broader context of governing the commons (*sensu* Ostrom 1990), passive management is generally associated with relatively stable institutions in charge of maintaining common-pool resources for a variety of well-established water-using sectors. By contrast, active management often requires the presence of supporting actors from underrepresented sectors e.g., a local environmental organization to take up the interests of the wetland in question. These actors create a need for more decision-making space around the relatively fixed centers of decision-making represented by institutions (Carlisle and Gruby 2019). This additional decision-making can however be increasingly transitory in nature (e.g., a participatory forum, a collaboration, or a consultation) depending on the standing i.e., the individual legal rights of who is representing the wetland, among other factors (Williams 2010; O'Donnell and Talbot-Jones 2018).

Because of the dichotomy between active and passive management observed by Horne et al. (2018), and how passive management is associated with the role of institutions and active management with the role of actors as discussed above, we analyzed cases studies through the lens of two complementary organizational and social science theories, namely institutional theory and actor-network theory (Modell et al. 2017). According to these theories, institutions rely on the stability of rules whereas actor networks rely on constant change and flexibility from human agency to fulfill agendas. In dealing with the same issue, institutions therefore rely on mandates such as water supply or environmental protection while actors are driven by interest e.g., economic returns from productive water use but also ecosystem health. In our analysis, we differentiate between formal institutions (e.g., state agencies) and supporting actors (e.g., NGOs with focal interest in nature conservation) to best define entities involved in the environmental water management activities and therefore identify adequate evidence for process tracing (Beach and Pedersen 2013). Evidence that an institution has fulfilled its mandate i.e., the institutional performance (*sensu* Saleth and Dinar 2004) may depend on organizational variables measuring decentralization such as nestedness and incentives for local government, and the complementarity or conflict of mandates (Bartley et al. 2008). In contrast, evidence that change has been actor-driven can be evaluated through behavioral variables such as capability, motivation, and opportunity (Koleros et al. 2020). In practice, however, the actions of institutions and actor networks often blend, for example when decentralization is leveraged to ensure effective participation (Pahl-Wostl 2009). Therefore, it can be difficult to discern to which implementation pathway (i.e., active or passive management) any given environmental water allocation decision belongs from simply knowing if the water policy environment supports individual rights for a wetland manager – be it a park service, an environmental organization, or a private steward. Therefore, in addition to identifying institutions and actors, we also focused on who among these entities defines the ecological objectives for environmental water management and how (including for what outcome) these are defined during the determination phase.

Refocusing the Outcome: Productive Environmental Water Efficiency and Benefit Sharing

Each pathway to the implementation of environmental water (i.e., active vs. passive management in Fig. 1) incurs different transaction costs associated with setting up the allocation mechanism for environmental water. Where mandated institutions are already well established, these transaction costs may include lock-in costs of changing deeply entrenched practices. In contrast, where the need for more flexibility calls for designing, implementing, and maintaining new arrangements, the transaction costs are first predominantly transition costs, and thereafter new administrative costs (Horne et al. 2018). In water-scarce regions in particular, the institutional costs of flexibility reflect both the limited predictability of ecological demands due to seasonal variability e.g., of wetland flooding for waterfowl (Donnelly et al. 2019), and the need to clearly articulate the wider societal benefits stemming from environmental water for wetlands to a full set of stakeholders (Overton et al. 2014). Despite active environmental water management thus requiring a higher investment, this pathway does not ensure the outcome of allocative efficiency of environmental water. For this outcome to be realized, collaboration needs to prevail over competition among water users. However, collaboration is not a sufficient precondition as making environmental water managers a legal entity and a lawful water right holder has been found to lead to either collaboration or competition depending on other circumstances (O'Donnell 2017). We therefore posit instead that the higher costs of establishing an allocation mechanism for seasonally ponding wetlands are better met (as a cost-effective investment) by framing benefits more broadly from the early stages of the causal sequence of determining, allocating, implementing, and managing environmental water. The determining circumstances for achieving collaboration in environmental water management are then the adoption of a better suited approach that allows setting up and pursuing broader, more inclusive objectives for the reallocation of water uses in a catchment i.e., conserving biodiversity and delivering other ecosystem services at the same time. One such approach is 'benefit sharing', a concept that will hereafter remain a key theme of this study.

Benefit sharing has been used as an approach to broaden the assessment of economic benefits from transboundary rivers to also include indirect and non-use values of water (Sadoff and Grey 2002; Fisher et al. 2005; Arjoon et al. 2016). Although benefit sharing is not explicitly applied in environmental flow implementation, freshwater research has aligned to this perspective by introducing the concepts of demand management for environmental water (Pittock and Lankford 2010) and productive environmental water efficiency (Horne et al. 2018). Productive efficiency requires environmental water to deliver multiple benefits and therefore places equal emphasis on both the biodiversity conservation and ecosystem services component of the assessment, though these components are not easily dissociable as a healthy ecosystem function (i.e., biodiversity) is the basis for service provision. With this revised focus, active management works to reduce the additional uncertainty introduced by the need to monitor the response of both biodiversity and ecosystem services to environmental rewatering by allowing for frequent decision points to reevaluate predictions, with costs depending on the learning needs of stakeholder participation (Williams 2010). Considering environmental water management rarely reaches the implementation phase (Arthington et al. 2018b), we further broke down the process of determining environmental water into: i) recognizing, ii) convening, iii) agreeing, and iv) preparing for allocation (more details in Fig. 2) as four distinct steps or activities within 'determining' to better analyze barriers preventing progress to the next stages. We did so by focusing on benefit sharing as the benchmark approach described by IUCN (2021) because it operationalizes recognition of the multiple values of environmental water for both people and ecosystems. Furthermore, this kind of approach is suitable to introduce the political dimension of water allocation in connection to stakeholders that operate within the formal and informal constraints of institutional structures and a web of power relations (van Gevelt 2020). Also considering the importance of stakeholder (i.e., any water-related ecosystem service beneficiary) participation for understanding and negotiating productive efficiency in environmental flows assessment (Overton et al. 2014; Grizzetti et al. 2016), we focused our analysis on the first activity of 'recognizing' to formulate a hypothesis regarding these expected barriers.

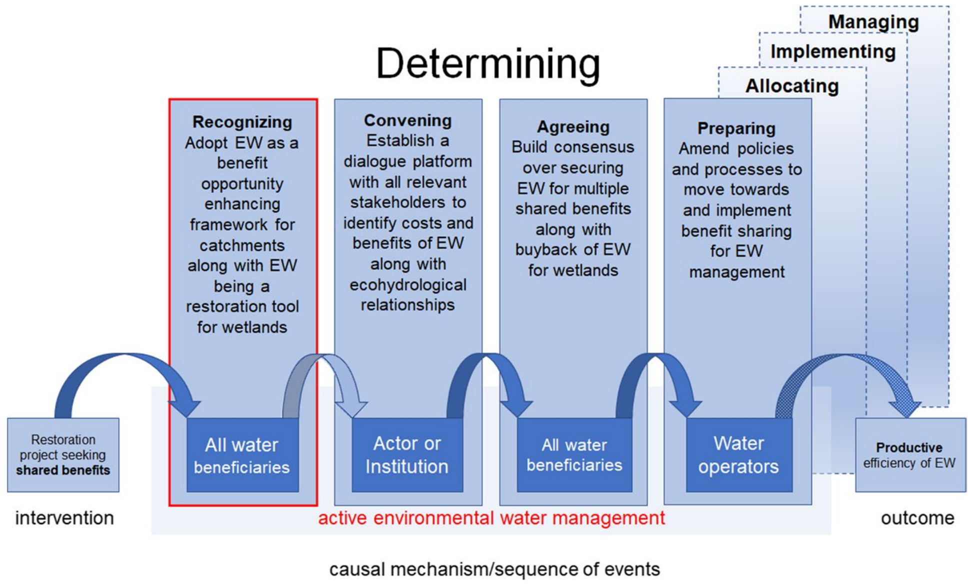

Fig. 2 Deconstructing the sequence of causal events in determining environmental water (EW) based on IUCN (2021) for the purpose of a more focused process tracing analysis of stage #1 in Fig. 1 'Determining'. A key difference with Fig. 1 is that the intervention and outcome have changed from seeking EW delivery and allocative efficiency of EW to seeking shared benefits and productive efficiency of EW based on Horne et al. (2018), respectively. As a result, water users from Fig. 1 have become water beneficiaries in this figure. The first step of 'recognizing' in this more detailed sequence is circled in red to highlight that this is the focus of this study. The arrow leading to the following step of 'convening' is transparent to indicate that the environmental water management process moves on to the next activity if the hypothesis that we formulated accordingly and tested in our analysis is met

The Hypothesis: Science and Management for Complexity Unmatched

To comply with the process-tracing methodology described above, we reformulated the conceptual hypothesis that we outlined in the introduction in terms of preconditions and differentiated outcomes as a procedural hypothesis for moving from the first to the second activity identified in Fig. 2 as follows: the process of recognizing the principles of productive environmental water efficiency, which includes raising the awareness of and reaching a full understanding of the values of the allocation for all environmental water beneficiaries, leads to the process of convening a truly holistic environmental water assessment. This is because the flexibility and equitability of the socioeconomic system has then become sufficient for (and therefore match) the complexity of the biophysical system created through step 1 (recognizing the principles), which in turn leads to sufficient coupling of scientific and managerial expertise in step 2 (convening of the environmental water assessment as a dialogue platform). The main hypothesis for this study can therefore be formulated as a two-part set of conditions:

- An environmental water assessment process for seasonally ponding wetlands is effective when:
  - the institutional flexibility and socioeconomic equitability in the watershed[6] match its biophysical complexity in terms of both ecology and hydrology, and
  - the assessment is holistic and convened following the principles of productive environmental water efficiency such as in a benefit-sharing approach.

To accept or reject this main hypothesis as per process tracing method, we compiled documentary evidence for each case study that we used to run the four (when possible, based on available evidence) increasingly inferential tests. In practice, then, the coupling of scientific and managerial expertise manifests in the type (e.g., whether it incorporates both ecological and hydrological complexity) and source (e.g., whether it originates from an institution or through other supporting actors) of the request to conduct an environmental water assessment. This request needs to characterize the environmental water both in terms of ecological outcomes and the resource supporting the cultural, social, and economic values of the wider community, including less tangible

[6] The exceptions to the watershed as the most relevant management unit being the cases of inter-basin water transfers and groundwater resources not following the watershed boundaries.

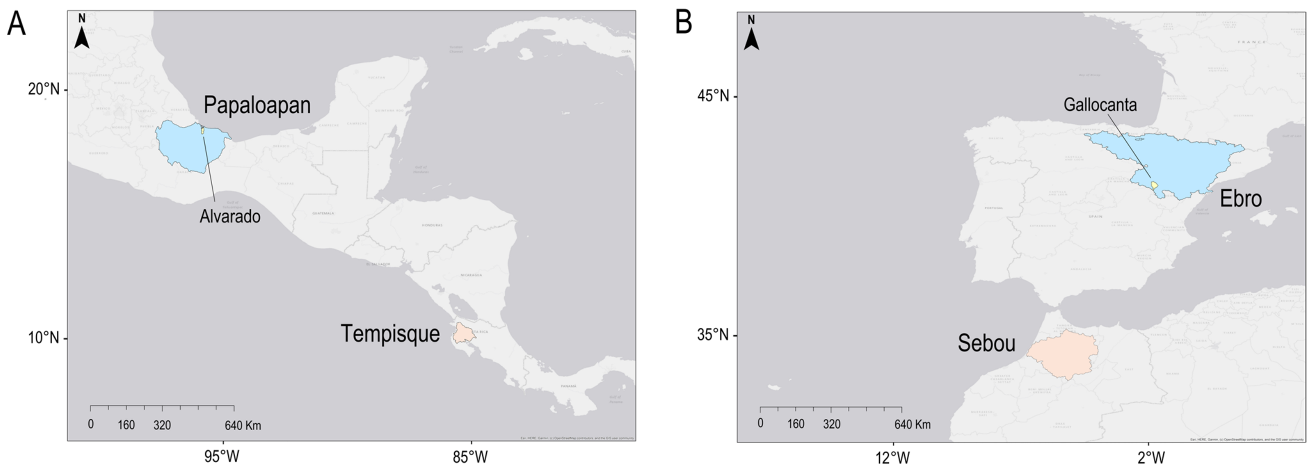

Fig. 3 Location of the hydrographic units where the four seasonally ponding wetlands are found in the respective Mesoamerican (**A**) and Mediterranean (**B**) regions. Two of these have their own hydrographic sub-unit i.e., Sistema Lagunar Alvarado and Laguna de Gallocanta. The territory of the countries with the relatively higher GDP is in blue while that of the countries with the relatively lower GDP are in red

benefits such as the flexibility and legal security of the allocation mechanism itself (Horne et al. 2018). The related guiding questions that we used to gather documentary evidence to test the hypothesis are in Annex I of the Supplementary Material.

Case Studies

To analyze the first stage in the causal sequence of determining environmental water and keep with the broader goals for the study, we chose two pairs of regional case studies in a watershed/river basin location containing a seasonally ponding wetland that is also designated as a Ramsar Site of International Importance and for which a request to conduct an environmental flow assessment had been made. The first pair of case studies from the Mesoamerican region (Fig. 3A) includes:

- Sistema Lagunar Alvarado[7] and Laguna La Popotera,[8] found in the Papaloapan watersheds of Mexico,[9] and
- Palo Verde,[10] found in the Tempisque-Bebedero watersheds of Costa Rica.[11]

The second pair of case studies located in the Mediterranean region (Fig. 3B) includes:

- Laguna de Gallocanta,[12] found in the Ebro River Basin of Spain,[13] and
- Lacs d'Imouzzer du Kandar,[14] found in the Sebou River Basin of Morocco.[15]

To control for similar circumstances of water scarcity as much as possible, the two pairs of national-level case studies are found in comparable water stressed watersheds/river basins[16] and comparatively drier climate sub-types within their respective regions, namely the tropical savanna climate (Aw) for the Papaloapan and Tempisque-Bebedero watersheds, the Cold semi-arid climate (BSk) for the Ebro River Basin (on the cusp with a continental climate with warm summers and cold winters for Laguna de Gallocanta), and the Hot-summer Mediterranean climate (Csa) for the Sebou River Basin according to the Köppen-Geiger climate classification for the present time (Beck et al. 2018). While the four countries also have different levels of legal and institutional development for environmental water management, the

7 https://rsis.ramsar.org/ris/1355
8 https://rsis.ramsar.org/ris/1462
9 http://sina.conagua.gob.mx
10 https://rsis.ramsar.org/ris/540
11 https://www.snitcr.go.cr
12 https://rsis.ramsar.org/ris/655
13 http://www.chebro.es
14 https://rsis.ramsar.org/ris/2374
15 http://www.abhsebou.ma
16 http://aqueduct.wri.org

differences in resources between pairs are comparable as the ratio between Mexico's and Costa Rica's GDP is 1.7, and the ratio between Spain's and Morocco's GDP is 1.1 (World Bank 2020). Notably, Laguna de Gallocanta in Spain, as an endorheic system, and Sistema Lagunar Alvarado in Mexico, as a coastal lagoon-delta complex with numerous freshwater floodplain marshes associated such as Laguna La Popotera originally, are considered separate hydrographic units as assessed by Lehner et al. (2008). While the four case studies can be grouped into pairs based on geoclimatic and development classifications, we first analyzed each case study individually as presented in detail in Annex II of the Supplementary Material and summarized below.

Results

Documentary evidence that is neither necessary nor sufficient to firmly prove the hypothesis, but it is nonetheless useful to increase its plausibility, was used to pass the 'straw in the wind' test for all case studies, namely Mexico, Costa Rica, Spain, and Morocco. This evidence is linked to the record of past initiatives to determine environmental water requirements within at least the watershed or river basin where the seasonally ponding wetland of interest is found. Other supporting evidence that is instead necessary to keep the hypothesis under consideration was used to pass the 'hoops' test for all four case studies again. This evidence is about the level of sectoral participation achieved during the determination of the environmental water requirements. This evidence is necessary because it is the minimum requirement to operationalize recognition of the multiple values of environmental water for both people and ecosystems as per benefit-sharing approach. Other more compelling evidence to consider the hypothesis acceptable was used to run the 'shooting gun' test, which only Mexico and Spain were able to pass. This evidence pertains to the setting up of monitoring networks and research-driven systems to assess the productivity of the environmental water and thus guarantee its adaptive management. This evidence is more compelling because it follows all the principles of productive environmental water efficiency such as in a benefit-sharing approach. Finally, the strongest evidence to fully validate or counter the hypothesis was used to run the 'double decisive' test, which no case study was able to pass. This last piece of supporting evidence, if found, would have been tying the determination of the environmental water to its actual allocation beyond the definition of the allocation mechanism.

Discussion

This study provides a renewed perspective on how to secure environmental water by looking at a subset of inland aquatic ecosystems (i.e., seasonally ponding wetlands) for which the high institutional transaction costs to cope with natural variability in water availability create a distinctive need to connect the processes of knowledge generation and knowledge uptake for more effective adaptive management. Our study further breaks down the analysis conducted by Horne et al. (2018) on maximizing benefits and minimizing the costs of environmental water use and management and focuses on benefit sharing as a benchmark approach for realizing environmental water efficiency through the recognition of its multiple values for both people and ecosystems. Whereas numerus studies have confirmed the importance of stakeholder participation in the governance of water resources since Pahl-Wostl (2009), we used the process tracing method to conduct a more detailed analysis of the specific sets of institutions and actors involved in the management of four seasonally ponding wetlands.

More broadly, our analysis provides useful guidance on how to implement science-management partnerships for effective environmental water outcomes by highlighting a set of three challenges that need to be overcome to that effect (Fig. 4). The first challenge relates to science and is imposed by the combination of hydrological and ecological complexity of seasonally ponding wetlands. The second challenge relates to management and is imposed by the lack of institutional flexibility and socioeconomic equitability. Third, and finally, there is a challenge imposed by the need to match and connect scientific and managerial expertise when these exist or are developing, e.g., in water scarce regions, but are not brought together by effective approaches such as the framing of environmental water as a multi-faceted benefit to share within the watershed. The latter challenge likely includes the need to bridge the gap in the awareness of these multi-faceted environmental water beneficiaries through facilitation by nature conservation organizations during e.g., participatory planning platforms and we suggest further research in this area. The different levels of experience and success in overcoming this set of three challenges from our case studies were also the basis for recommending different avenues for adjustment and replication as part of the current international agenda on ecosystem restoration as discussed below. Because the four seasonally ponding wetlands analyzed are also Ramsar Sites, we focused specific policy recommendations for replication in the context of the Convention.

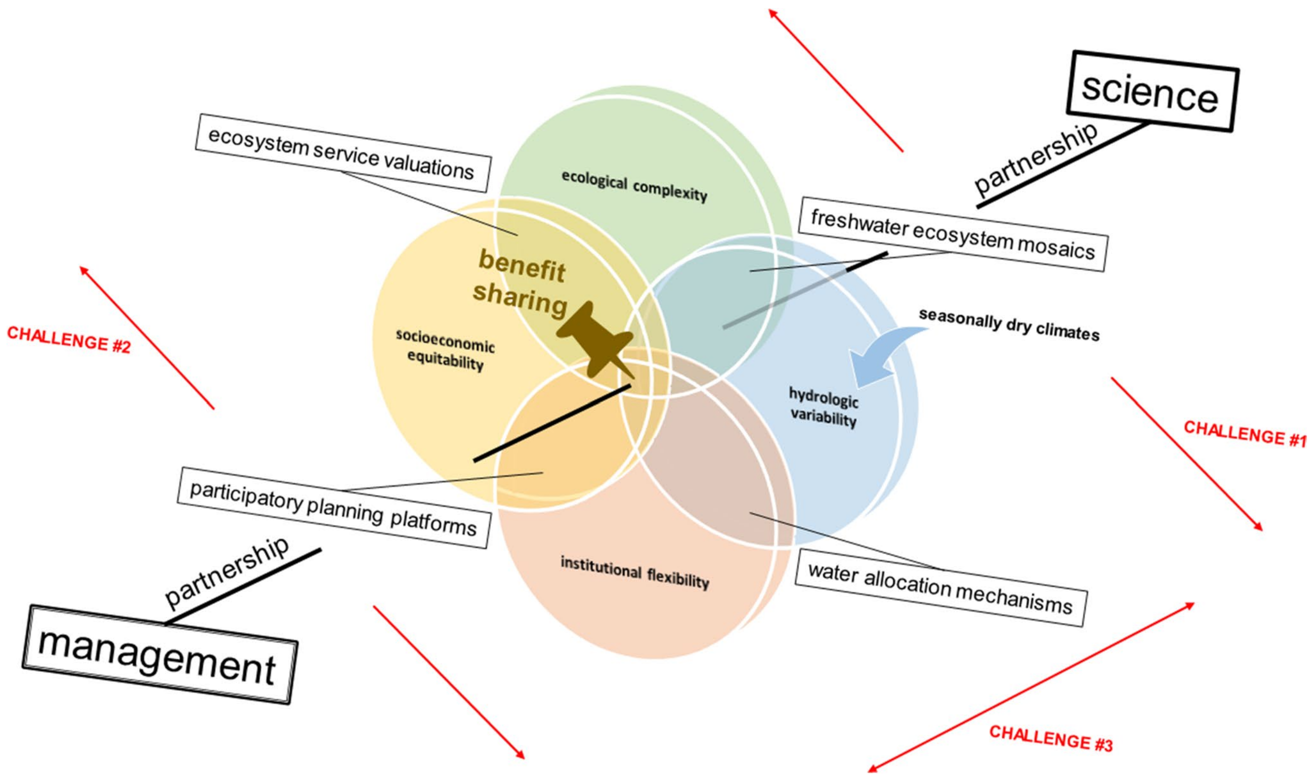

Fig. 4 The three challenges for implementing science-management partnerships for effective environmental water management based on productive water allocation efficiency: 1) the challenge for science at the intersection between hydrological variability (made more extreme in seasonally dry climates) and ecological complexity where freshwater ecosystem mosaics occur, 2) the challenge for management at the intersection between institutional flexibility and socioeconomic equitability where facilitation of participatory planning platforms occur, and 3) the challenge for partnering science and management at the intersection between these four elements of the socio-ecological system where benefit-sharing can pin all of them together and help bridge the gap with policy. To that effect, policies such as water allocation mechanisms and ecosystem service valuations also need to occur at the intersection between hydrological variability and institutional flexibility as well as ecological complexity and socioeconomic, respectively

Science-Management Partnerships

Challenge for Science: Hydrological Variability and Ecological Complexity

In both temperate and tropical climates with a distinct dry season such as the Mediterranean and Central American savannas (Beck et al. 2018), both intra- and inter-annual variability but also vulnerability to overall climate change are key determinants of seasonally ponding wetland ecosystems (Osland et al. 2011; Lefebvre et al. 2019). Following the natural patterns imposed by these climatic conditions, many ecological features depend on the hydrology of each wetland's typology i.e., whether a lotic (i.e., running waters), lentic (i.e., standing waters), or marine-process dominated coastal (e.g., estuaries) ecosystems (UN Environment 2018). In lentic ecosystems such as the seasonally ponding wetlands we took into consideration, the flooding regime i.e., when, where, and how much the wetland is inundated, is the main bio-physical factor influencing all other abiotic variables e.g., salinity (Camacho et al. 2009). These in turn co-determine the composition of the biological communities and ecosystem functioning (Camacho et al. 2016) as in the case of Laguna de Gallocanta (see Annex II of the Supplementary Material). Due to these climatic and hydrological characteristics, a mosaic of permanent and temporary wetland typologies coexist in the same landscape (Stubbington et al. 2020). Latitudinal and longitudinal gradients of local geomorphological factors (Ward 1989) play a role in the seasonality of flooding patterns, and therefore of the environmental water requirements to be recommended when designing and managing allocations. As a result of these gradients, highly variable hydrological connectivity may control the flow between isolated wetlands and the more permanent stream network as for the cases of Palo Verde, Laguna de Popotera, or even Lacs d'Imouzzer du Kandar if we include underground connectivity via a shared aquifer (see Annex II of the Supplementary Material).

The variability-adapted ecology of these systems makes it such that a regime of minimum flows (even when partially mimicking natural flow patterns) is not expected to ensure ecological integrity for lentic ecosystems in the medium and long run when it has not worked to reverse hydrological alterations for lotic ecosystems (e.g., Mezger et al. 2021). It also makes it challenging for science to design active adaptive management protocols for the incremental averaging of ecological models and responses as experimental environmental water is released, which tends to require more collaborative monitoring frameworks (Williams 2010). Based on the evidence we collected, scientist that worked to determine the environmental water requirements for Sistema Lagunar Alvarado in Mexico and Laguna de Gallocanta in Spain were largely able to overcome these challenges whereas in Palo Verde, in Costa Rica, and Lacs d'Imouzzer du Kandar, in Morocco, were not, although a variety of supplementary efforts that reflect on good management are taking place in the respective watersheds. In summary, the differences in the scientific contributions to an environmental water determination of the seasonally ponding wetlands across case studies suggest that the lack of these capabilities may be the limiting factor for legitimizing such an assessment and subsequently considering a water reallocation within the existing institutional frameworks. At the same time, the lack of an explicit and complete request for such an assessment from managing (water and/or nature conservation) institutions suggests a thwarting effect on scientific efforts as discussed in the next section.

Challenge for Management: Institutional Flexibility and Socioeconomic Equitability

In the face of the ecohydrological challenges above, we hypothesized that the common precondition for effective environmental water management to be realized was the presence of nature conservation and water agencies. By contrast, we hypothesized that the differentiated outcomes for this effective management of environmental water to depend on the level and type of institutional development required to enable science-management partnerships. From the legal perspective of agency mandates, certain types of standing waters may be more challenging than water courses to protect. Water legislation may not explicitly complement sustainable water resources management with the conservation of important aquatic habitats and species as management rules for rivers have often only been linked directly to human uses such as abstractions or navigation (Perry et al. 2021), but those rules only secondarily benefitted habitats and species present in e.g., seasonally connected floodplain wetlands. The physical and biological nexus between a pond or a marsh and its adjacent stream network can be difficult to demonstrate when this nexus is disconnected, however temporarily, or variably dependent on an aquifer (McLaughlin et al. 2014). Specific examples of the type of institutional development required to enable science-management partnerships in the case of our inland aquatic ecosystems of analysis are the capacity to integrate wetland conservation into sectoral water allocation and dealing with highly variable availability in water scarce environments.

The blueprint for the proficient conservation of Laguna de Gallocanta is in the application of the combined provisions of the EU Birds and Habitats Directives (BHD) and Water Framework Directive (WFD). The BHD aims to safeguard any water-dependent site designated because of 'Natura 2000' listed habitat or species from allocating water to other uses such as agriculture (see Annex II of the Supplementary Material). The WFD, for its part, aims at reaching the good status of all water bodies in the EU, and not to further deteriorate them. The determination of all hydromorphological elements (i.e., environmental flows and connections to groundwater) that support both the requirements of the qualifying habitat or species of Natura 2000 sites and those of good ecological status under the WFD is a desirable yet elective assessment program that Spain, among other EU member countries, has undertaken. This type of assessment implies protection from adequate water allocation for wetlands like Laguna de Gallocanta. Similarly, the Mexican Environmental Flow Standard (see Annex II of the Supplementary Material) does away with minimum flow approaches that have little relevance in highly seasonal climates and recognizes natural variability as a better paradigm for assessments, if not according to holistic methods that consider tradeoffs between ecological conservation and water use yet (Gómez-Balandra et al. 2014). However, not all countries make the link between wetland conservation and environmental water allocation explicit in their legislation, and not all wetlands are designated as water bodies entitled to protection in the first place, typically leaving out the smallest and temporary wetlands from river basin management plans (RBMPs in the WFD, PAMICs in Mexico). It is therefore difficult to expect a good level of protection for wetlands, especially if isolated, in the absence of at least a designation as protected area including under an international treaty such as the Ramsar Convention. The extent of the vulnerability of wetlands as a scattered ecosystem has been revealed by Bastin et al. (2019), who found that only 15% of inland surface waters globally are protected, or by Paragamian et al. (2017), who found that the number and state of small wetlands e.g., on the Greek islands was not even known.

Water scarcity can also hinder institutional development and flexibility to conduct negotiated agreements for environmental water allocation and management when ecosystem services are not framed as part of the solution to achieving socioeconomic equitability. The socioeconomic context in water-scarce regions is one of recurrent and prolonged drought, demand seasonally exceeding supply, and unequal allocation hampering resilience of social-ecological systems despite any well-intentioned regulation. In the Mediterranean Region, for example, a steady drop in the flow of rivers has been coupling with a massive increase in dam storage capacity to a level 1.5 times the annual volume of freshwater discharged into the Mediterranean Sea (MWO 2018). This steady drop in the flow of rivers between 1960 and 2000, from 25% to 70%, reaching 80% for the River Cetina (Croatia) or 65% for the Nile River, has strongly affected water requirements of wetlands. The reductions in flow, combined with other phenomena like reduction of minimum flows and the increased frequency of flash flooding, when water cannot be retained, have contributed to make water resources available for wetlands increasingly scarce throughout the Mediterranean region (MWO 2018). In the Mesoamerican Region, the dry corridor within the isthmus running from Mexico to Panama has been described as a poverty trap where the link between climate change and ecosystem degradation is exacerbated and is a known source of both concern and cooperation (Gotlieb et al. 2019). Although situations of crisis or endemic deficiency can contribute to reducing conflict and promoting negotiation, these situations usually bring about additional resources in the form of international finance that is attached to increased water storage solutions. In the Sebou river basin of Morocco, the Green Climate Fund (GCF) is investing in what they consider as "improving the climate resilience of agricultural systems" of the central Saïss Plain by a water transfer and irrigation scheme among other measures.[17] In the Tempisque-Bebedero watersheds of Costa Rica, the Central American Bank for Economic Integration (BCIE) is financing the water supply program for Guanacaste (PIAAG) that hinges on the creation of a new reservoir.[18]

By contrast, the institutions and actors involved in the determination of the environmental water requirements for Sistema Lagunar Alvarado in Mexico and Laguna de Gallocanta in Spain were largely able to overcome the challenges for management imposed by the lack of flexibility and equitability with a clear, and somewhat cohesive, mandate for water agencies and nature conservation agencies alike. In Palo Verde and Lacs d'Imouzzer du Kandar, the level of cohesion was hindered by the lack (Costa Rica) or early stage of implementation (Morocco) of a water law linking watershed management to wetland conservation. This suggests that international finance also flows more sectorally in countries where the integration between the management of water resources and wetlands (as connected features of the landscape that may or may not be protected at a varying level from indirect uses) is lacking. The sectoral nature of international finance is evidenced by multilateral investments going towards initiatives focusing on wetland biodiversity or their climate change mitigation potential but not as a piece of natural infrastructure or a nature-based solution contributing to water security.

Challenge for Partnering Science and Management: Benefit-Sharing as a Potential Solution to Also Achieving Productive Environmental Water Efficiency

In the face of both ecohydrological and socioeconomic challenges above, we further hypothesized that enabling effective science-management partnerships would require an environmental water assessment that is holistic and convened following the principles of productive environmental water efficiency as in benefit-sharing. The failure to meet this last condition is best shown by the example of Mexico. The level and type of institutional development in Mexico were such that the environmental water requirements determined for the wetlands of the Papaloapan watersheds could be secured. This was possible owing to a clear mandate from river basin organizations that were also strengthened by the need to comply with international biodiversity and climate change commitments and compounded by water scarcity. Although realistic and mindful of existing water availability and water rights, the ecological objectives for those environmental water determinations were not entirely linked to socioeconomic values in practice through, for example, ecosystem service assessments that included water users' participation in addition to experts' opinion, however representative. Therefore, the environmental water efficiency achieved was only productive on paper and future conflict and competition were thus not necessarily prevented. This is even more noteworthy considering that the Mexican watersheds for which environmental water reserves were determined had been identified for their high biological richness and conservation values but also identified as unique given the relatively low demand from current water users (CONAGUA 2011). These watersheds and their environmental water reserves have since been integrated into broader water resources management planning (CONAGUA 2019).

When turning to Spain, the same analysis of whether this final precondition had been met revealed that the environmental water determination for Laguna de Gallocanta came short of securing the reallocation from farmers' groundwater abstractions and ecosystem services were only assessed partially i.e., for tourism. In Morocco, the process appeared to have stopped even earlier. Embedding the procedures for

[17] https://www.greenclimate.fund/project/fp043

[18] http://www.senara.or.cr/proyectos/paacume/Paacume.aspx

environmental water determination within the Sebou river basin organization's was a top-down provision that did not lead to replicating it for the Lacs d'Imouzzer du Kandar but has now spurred other initiatives such the water fund that can sponsor the application of holistic approaches with ecosystem services assessments. In Costa Rica, the bottom-up compliance to the requirement for the Palo Verde wetlands to have a management plan as a protected area was valuable in planning an assessment of water-dependent ecological objectives, but still fell short in terms of determining socioeconomic values because of either the duplication or lack of representation in fora where these are discussed and negotiated, i.e. conservation area councils, interinstitutional watershed commissions and water infrastructure development project steering committees. In other words, the level of scientific knowledge about the Palo Verde wetlands was not convened with equal footing to the managerial expertise within water (infrastructure) institutions focusing on water storage and delivery against scarcity.

Recommendations for Replicating Experiences with Science-Management Partnerships

In bringing together the ecohydrological and socioeconomic perspectives underpinned by the two sides of a science-management partnership, our goal was also to highlight any interconnected process that, if replicated, could accelerate progress in the field of environmental water management as part of a renewed call to protect and restore inland aquatic ecosystems (Tickner et al. 2020). Key avenues for extending and replicating experiences with science-management partnership have been paved by the recently revised global ecosystem restoration agenda. We summarize the main global and regional policy efforts to heed this call to protect and restore inland aquatic ecosystems with environmental water allocations in Annex III of the Supplementary Material. To describe a key mechanism for replicating science-management partnerships in the specific context of Ramsar Sites and the types of actions and policy rationale for managing environmental water for wetlands more broadly (Barchiesi et al. 2018), we also provide details of the two relevant Ramsar Regional Initiatives[19] for the four cases in this study in Annex III of the Supplementary Material.

The interconnected process that we identified from the Mexican and Spanish case studies is the role of cost-benefit analyses. This emerged as a vital tool for clarifying sectoral interests in the longer term and for tipping the scale in favor of repeated applications of environmental water allocations in the future, despite the many uncertainties inherent to the process (Magdaleno 2017; Salinas-Rodríguez et al. 2018). While the tradeoffs between water using sectors and environmental flows in water-scarce river basins have been assessed in terms of the productive efficiency of water in general, including in the Ebro River Basin (Crespo et al. 2019), full appreciation of these tradeoffs would only come from also including the productive efficiency of environmental water (Horne et al. 2018). Setting up monitoring programs for environmental flow releases that largely exist in Mexico with RedMORA (Salinas-Rodríguez et al. 2021) but are currently still under development in Spain (Mezger et al. 2019) could enable active adaptive management protocols designed to incrementally average ecological models and responses (Williams 2010) and be assisted by already codified benefit-sharing approaches (e.g., IUCN 2021) in terms of facilitating the science-management partnership. Another key interconnected process for scientists, wetland managers and water operators alike is the development of Ramsar Site management plans. These site-level plans have limitations in terms of operational definitions for the assessment of allowable uses, economic benefits, and stakeholder engagement opportunities (Munguía and Heinen 2021). However, they can be a key anchor for river basin management plans and other sustainable watershed management practices even where multiple nature conservation agencies exist for one site (Palo Verde) or multiple, non-adjacent locations exist for one site that is however connected underground (Lacs d'Imouzzer du Kandar).

Conclusions

In conclusion, this study supports engaging academia, non-governmental and civil society organizations in the conservation sector, water managers and protected area managers in governmental agencies as well as water user associations and other forms of sectoral representation at any relevant administrative level in science-management partnerships for effective environmental water management. This is to overcome the challenges with effective implementation encountered at the early phase of the environmental water management process when determination of environmental water requirements needs to be translated into a formal mechanism for (re)allocation. Our findings suggest that where institutions, such as river basin organizations are mandated by law, these institutions need to be supplemented by motivated actors with experience and skill to negotiate allocation and adaptive management of environmental water, especially in water scarce regions where extreme conditions are not met by national capabilities. Therefore, matching scientific, managerial and facilitation expertise achieves the

[19] A particularly relevant mechanism for sharing lessons on securing the environmental water requirements of wetlands are the regional initiatives endorsed by the Ramsar Convention (Ramsar Convention on Wetlands 2016).

dual advantages of a) adopting a benefit-sharing and productive efficiency approach for reframing determination of environmental water to include both biodiversity and ecosystem service values, and b) connecting the regulatory and planning processes at a practical level. This way, after developing and implementing a legal basis for regulating water use that includes an environmental water allocation as well as an assessment methodology to ensure the both ecosystem and people's needs are met, governmental programs or public-private partnerships have a better chance to protect and restore wetlands that also support, wherever possible, the achievement of water, energy, food, and other security objectives.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13157-022-01562-6.

Acknowledgements We acknowledge the Specialist Group on Water of the Scientific and Technical Network of the Mediterranean Wetlands Initiative (MedWet STN) for originally convening several of these authors to work on this research topic as well as Stefano Barchiesi's PhD Supervisory Committee for providing additional feedback.

Author Contributions Stefano Barchiesi and Flavio Monti proposed the research topic. All authors, including Antonio Camacho, Eva Hernández, Anis Guelmami, Alessio Satta and Osvaldo Jordán, contributed to the study conception or sources of information for the case studies. Stefano Barchiesi designed the research methodology and analytical framework and performed the case study analysis. The first draft of the manuscript was written by Stefano Barchiesi and edited by Christine Angelini. All authors commented on previous versions of the manuscript and read and approved the final manuscript.

Funding Partial support for Stefano Barchiesi's research was provided by the University of Florida (UF) Water Institute Graduate Fellowship (WIGF) Program and the School of Natural Resources and Environment (SNRE). Christine Angelini was supported by NSF CAREER Award (#1652628). Antonio Camacho was supported by the project CLIMAWET-CONS (PID2019-104742RB-I00), funded by the Spanish Research Agency.

Data Availability Data are all derived from public sources that are duly cited.

Declarations

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Acreman M, Arthington A, Colloff M, Couch C, Crossman N, Dyer F, Overton I, Pollino C, Stewardson M, Young W (2014) Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. Frontiers in Ecology and the Environment 12:466–473

Arjoon D, Tilmant A, Herrmann M (2016) Sharing water and benefits in transboundary river basins. Hydrology and Earth System Sciences 20:2135–2150

Arthington AH, Kennen JG, Stein ED, Webb JA (2018*a*) Recent advances in environmental flows science and water management – innovation in the Anthropocene. Freshwater Biology 63:1022–1034

Arthington AH, Bhaduri A, Bunn SE, Jackson SE, Tharme RE, Tickner D, Young B, Acreman M, Baker N, Capon S, Horne AC, Kendy E, McClain ME, Poff NL, Richter BD, Ward S (2018b) The Brisbane Declaration and global action agenda on environmental flows. Frontiers in Environmental Science 6:45

Astorga-Espeleta Y (2016) Gestión del recurso hídrico en Costa Rica. Ambientico 260:17–24

Barchiesi S, Davies PE, Kulindwa KAA, Lei G, del Río LMR (2018) Implementing environmental flows with benefits for society and different wetland ecosystems in river systems. Ramsar policy brief no. 4. Ramsar Convention Secretariat, Gland, Switzerland. Retrieved September 17, 2021 from https://www.ramsar.org/

Barrios-Ordóñez JE, Salinas-Rodríguez SA, Martínez-Pacheco A, López-Pérez M, Villón-Bracamonte RA, Rosales-Ángeles F, Guerra Gilbert A, Sánchez Navarro R (2015) National water reserves program in Mexico. Experiences with environmental flows and the allocation of water for the Environment. In: De la Peña ME, Ramírez G, Alcalá C (eds) Technical note BID-TN-864. Interamerican development Bank, water and sanitation division, Mexico City, Mexico

Bartley T, Andersson K, Jagger P, van Laerhoven F (2008) The contribution of institutional theories to explaining decentralization of natural resource governance. Society and Natural Resources 21:160–174

Bastin L, Gorelick N, Saura S, Bertzky B, Dubois G, Fortin M-J, Pekel J-F (2019) Inland surface waters in protected areas globally: current coverage and 30-year trends. PLoS ONE 14:e0210496

Beach D, Pedersen RB (2013) Process-tracing methods: foundations and guidelines. University of Michigan Press, Ann Arbor, Michigan

Beck MW, Bokde N, Ascencio-Cort'es G, Kulat K (2018) R package imputeTestbench to compare imputation methods for Univarite time series. The R Journal 10:218–233

Bello-Pineda J, Ortiz-Lozano L, Ramírez-Chávez E, Aquino-Juárez R, Castillo-Domínguez S (2009) Sitio piloto Río Papaloapan-Laguna de Alvarado. In: Buenfil-Friedman J (ed) Adaptación a los impactos del cambio climático en los humedales costeros de México. Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT) and Instituto Nacional de Ecología (INA), Mexico City, Mexico

Boelee E (ed) (2011) Ecosystems for water and food security. Background paper. United Nations Environment Programme (UNEP), Nairobi, Kenya Colombo, Sri Lanka: International Water Management Institute (IWMI)

Brisbane Declaration (2007) “Environmental flows are essential for freshwater ecosystem health and human well-being,” in 10th International River Symposium and International Environmental Flows Conference (Brisbane, QLD). Retrieved September 17, 2021 from https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/ELOHA/Pages/Brisbane-Declaration.aspx

Cabestany G (2018) Modificaciones legislativas recientes en torno al aprovechamiento del agua en México. Temas Estratégicos, No. 62. Instituto Belisario Domínguez, Senado de la República, México, Mexico City, Mexico

Camacho A, Borja C, Valero-Garcés B, Sahuquillo M, Cirujano S, Soria JM, Rico JE, de la Hera A, Santamans AC, de Domingo AG, Chicote A, Gosálvez RU (2009) Standing waters. Inland lentic ecosystems. In: Bases ecológicas preliminares para la conservación de los tipos de hábitat de interés comunitario en España. Ministerio de Medio Ambiente, y Medio Rural y Marino, Madrid, Spain

Camacho A, Murueta N, Blasco E, Santamans AC, Picazo A (2016) Hydrology-driven macrophyte dynamics determines the ecological functioning of a model Mediterranean temporary lake. Hydrobiologia 774:93–107

Camacho A, Picazo A, Rochera C, Santamans AC, Morant D, Miralles-Lorenzo J, Castillo-Escrivà A (2017) Methane emissions in Spanish saline lakes: current rates, temperature and salinity responses, and evolution under different climate change scenarios. Water 9:659

Carlisle K, Gruby R (2019) Polycentric Systems of Governance: a theoretical model for the commons: polycentric Systems of Governance in the commons. Policy Stud J 47:927–952

Castañeda C, Gracia F, Conesa J, Latorre B (2020) Geomorphological control of habitat distribution in an intermittent shallow saline lake, Gallocanta Lake, NE Spain. Science of the Total Environment 726:138601

Collier D (2011) Understanding process tracing. Political Science & Politics 44:823–830

Comín F, Cabrera M, Rodó X (1999) Saline lakes: integrating ecology into their management future. Hydrobiologia 395-396:241–251

Comisión Nacional del Agua (CONAGUA) (2011) Identificación de reservas potenciales de agua para el ambiente en México. Secretaría de Medio Ambiente y Recursos Naturales, Mexico City, Mexico

Comisión Nacional del Agua (CONAGUA) (2018) Análisis Costo-Beneficio para el decreto de reservas de agua para el ambiente en las cuencas Río Actopan y Río La Antigua, pertenecientes a la Región Hidrológica Papaloapan. Secretaría de Medio Ambiente y Recursos Naturales, Mexico City, Mexico

Comisión Nacional del Agua (CONAGUA) (2019) Lineamientos para incluir volúmenes no comprometidos de aguas nacionales superficiales en los 10 decretos de reserva de agua, publicados el 6 de junio de 2018 a través de la Programación Hídrica. Secretaría de Medio Ambiente y Recursos Naturales, Mexico City, Mexico

Comisión Nacional del Agua (CONAGUA) (2020) Programa Nacional Hídrico 2020–2024. Secretaría de Medio Ambiente y Recursos Naturales, Mexico City, Mexico

Crase L, Cooper B (2017) The political economy of drought: legacy and lessons from Australia's millennium drought. Economic Papers: a journal of applied economics and policy 36:289–299

Crespo D, Albiac J, Kahil T, Esteban E, Baccour S (2019) Tradeoffs between water uses and environmental flows: a hydroeconomic analysis in the Ebro Basin. Water Resources Management 33:2301–2317

Datry T, Bonada N, Boulton A (2017) Intermittent rivers and ephemeral streams. Ecology and management. Academic Press, London, UK

Davies J, Barchiesi S, Ogali CJ, Welling R, Dalton J, Laban P (2016) Water in drylands: adapting to scarcity through integrated management. IUCN, Gland, Switzerland

Dirección de Agua (DA) (2019) Guía de selección de metodologías para la estimación del caudal ambiental en Costa Rica. Comisión de Caudal Ambiental. Retrieved September 17, 2021 from http://www.da.go.cr/

Donnelly P, Naugle D, Collins D, Dugger B, Allred B, Tack J, Dreitz V (2019) Synchronizing conservation to seasonal wetland hydrology and waterbird migration in semi-arid landscapes. Ecosphere 10:e02758

Downard R, Endter-Wada J, Kettenring KM (2014) Adaptive wetland management in an uncertain and changing arid environment. Ecology and Society 19:23

El Madani M, Strosser P (2008) Evaluation de l’importance socioéconomique des usages de l’eau dans le bassin du Sebou. Rapport final du projet Ec’Eau Sebou. Retrieved September 17, 2021 from http://www.abhatoo.net.ma/maalama-textuelle/developpement-economique-et-social/developpement-economique/agriculture/ressources-en-eau-et-lutte-contre-la-secheresse/evaluation-de-l-importance-socioeconomique-des-usages-de-l-eau-dans-le-bassin-du-sebou-rapport-final-du-projet-ec-eau-sebou

Ernoul L, Vera P, Gusmaroli G, Muccitelli S, Pozzi C, Magaudda S, Horvat KP, Smrekar A, Satta A, Monti F (2021) Use of voluntary environmental contracts for wetland governance in the European Mediterranean region. Mar Freshw Res. https://doi.org/10.1071/MF21109

European Commission (2013) Interpretation manual of European Union habitats - EUR28. Brussels, Belgium: European Commission, DG Environment, nature ENV B.3. Retrieved Septmeber 17, 2021 from https://ec.europa.eu/environment/nature/

Fisher, F., L. Annette, A. Ilan, S.-S. Arlosoroff, Z. Eckstein, M. Haddadin, H. Salem, G. Jarrar, A. Jayyousi, U. Shamir, W. Hans, A. Salman, and E. Al-Karablieh. 2005. Liquid assets: an economic approach for water management and conflict resolution in the Middle East and beyond. Milton Park, Abingdon-on-Thames, Oxfordshire, UK: Routledge

Garcia-Moreno J, Harrison I, Dudgeon D, Clausnitzer V, Darwall W, Farrell T, Savy C, Tockner K, Tubbs N (2014) Sustaining freshwater biodiversity in the Anthropocene. Springer Water, Cham, Switzerland

van Gevelt T (2020) The water – energy – food nexus: bridging the science – policy divide. Current Opinion in Environmental Science and Health 13:6–10

Gleick P (2010) Roadmap for sustainable water resources in southwestern North America. Proceedings of the National Academy of Sciences of the United States of America 107:21300–21305

Gómez-Balandra MA, Saldaña P, Martinez-Jiménez M (2014) The Mexican environmental flow standard: scope, application and implementation. Journal of Environmental Protection 5:71–79

Gotlieb Y, Pérez-Briceño P, Hidalgo H, Alfaro E (2019) The central American dry corridor: a consensus statement and its background. Revista Yu’am 3:42–51

Government of Aragon (2019) Memoria de gestión de la Reserva Natural Dirigida de la Laguna Gallocanta 2018. Retrieved September 17, 2021 from https://www.aragon.es/-/reserva-natural-de-la-laguna-de-gallocanta

Government of Aragon (2020) Plan de Seguimiento Ecológico de la Reserva Natural Dirigida de la Laguna de Gallocanta. 2020–2024. Retrieved September 17, 2021 from https://www.aragon.es/-/reserva-natural-de-la-laguna-de-gallocanta

Grey D, Sadoff C (2007) Sink or swim? Water security for growth and development. Water Policy 9:545–571

Grizzetti B, Lanzanova D, Liquete M, Reynaud A, Cardoso AC (2016) Assessing water ecosystem services for water resource management. Environmental Science and Policy 61:194–203

Hickey GM, Forest P, Sandall JL, Lalor BM, Keenan RJ (2013) Managing the environmental science-policy nexus in government: perspectives from public servants in Canada and Australia. Science and Public Policy 40:529–543

Horne AC, Webb JA, O'Donnell E, Arthington AH, McClain M, Bond N, Acreman M, Hart B, Stewardson MJ, Richter B, Poff NL (2017) Research priorities to improve future environmental water outcomes. Frontiers in Environmental Science 5:89

Horne AC, O'Donnell EL, Loch AJ, Adamson DC, Hart B, Freebairn J (2018) Environmental water efficiency: maximizing benefits and minimizing costs of environmental water use and management. WIREs Water 5:e1285

Hülsmann S, Sušnik J, Rinke K, Langan S, van Wijk D, Janssen ABG, Mooij WM (2019) Integrated modelling and management of water resources: the ecosystem perspective on the nexus approach. Current Opinion in Environmental Sustainability 40:14–20

International Union for the Conservation of Nature (IUCN) (2021) Sharing the benefits from river basin management. A practitioner's guide. IUCN, Gland, Switzerland

Jiménez J, Calvo-Alvarado J, Pizarro F, González E (2005) Conceptualization of environmental flow in Costa Rica: preliminary determination for the Tempisque river. IUCN, San José, Costa Rica

Keith DA, Ferrer-Paris JR, Nicholson E, Kingsford RT (eds) (2020) The IUCN global ecosystem typology 2.0: descriptive profiles for biomes and ecosystem functional groups. IUCN, Gland, Switzerland

Koleros A, Mulkerne S, Oldenbeuving M, Stein D (2020) The actor-based change framework: a pragmatic approach to developing program theory for interventions in complex systems. American Journal of Evaluation 41:34–53

Kuhn NJ, Baumhauer R, Schütt B (2011) Managing the impact of climate change on the hydrology of the Gallocanta Basin, NE-Spain. Journal of Environmental Management 92:275–283

Lefebvre G, Redmond L, Germain C, Palazzi E, Terzago S, Willm L, Poulin B (2019) Predicting the vulnerability of seasonally-flooded wetlands to climate change across the Mediterranean Basin. Science of the Total Environment 692:546–555

Lehner B, Verdin K, Jarvis A (2008) New global hydrography derived from spaceborne elevation data. EOS. Transactions of the American Geophysical Union 89:93–94

Leigh C, Boulton AJ, Courtwright JL, Fritz K, May CL, Walker RH, Datry T (2016) Ecological research and management of intermittent rivers: an historical review and future directions. Freshw Biol 61:1181–1199

Magaña V, Gómez L, Neri C, Landa R, León C, Ávila B (eds) (2011) Medidas de adaptación al cambio climático en humedales del Golfo de México. Instituto Nacional de Ecología (INE), Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), World Bank (WB), Government of Japan, Universidad Nacional Autónoma de México (UNAM), Universidad Autónoma Metropolitana (UAM), and Centro de Especialistas en Gestión Ambiental (CEGAM), Mexico City, Mexico

Magdaleno F (2017) Experimental floods: a new era for Spanish and Mediterranean rivers. Environmental Science and Policy 75:10–18

Martínez-Harms MJ, Balvanera P (2012) Methods for mapping ecosystem service supply: a review. Int J Biodivers Sci Ecosyst Serv Manag 8:17–25

McLaughlin DL, Kaplan DA, Cohen MJ (2014) A significant Nexus: geographically isolated wetlands influence landscape hydrology. Water Resources Research 50:7153–7166

Mediterranean Wetlands Observatory (MWO) (2018) Mediterranean Wetlands Outlook 2: solutions for sustainable Mediterranean wetlands. Tour du Valat, France

Meli P, Rey Benayas JM, Balvanera P, Martínez Ramos M (2014) Restoration enhances wetland biodiversity and ecosystem service supply, but results are context-dependent: a meta-analysis. PLoS ONE 9:e93507

Mezger G, De Stefano L, González del Tánago M (2019) Assessing the establishment and implementation of environmental flows in Spain. Environmental Management 64:721–735

Mezger G, González del Tánago M, De Stefano L (2021) Environmental flows and the mitigation of hydrological alteration downstream from dams: the Spanish case. Journal of Hydrology 598:125732

Mitsch WJ, Bernal B, Hernandez ME (2015) Ecosystem services of wetlands. International Journal of Biodiversity Science, Ecosystem Services and Management 11:1–4

Modell S, Vinnari E, Lukka K (2017) On the virtues and vices of combining theories: the case of institutional and actor-network theories in accounting research. Accounting, Organizations and Society 60:62–78

Morant D, Picazo A, Rochera C, Santamans AC, Miralles-Lorenzo J, Camacho-Santamans A, Ibañez C, Martínez-Eixarch M, Camacho A (2020) Carbon metabolic rates and GHG emissions in different wetland types of the Ebro Delta. PLoS ONE 15:e0231713

Munguía S, Heinen J (2021) Assessing protected area management effectiveness: the need for a wetland-specific evaluation tool. Environmental Management 267:1527

Navarro A, Vargas-Alpízar P, Arce R, Quirós M, Zeledón J, Veas Ayala N, Acuña-Piedra J (2017) Estado de los humedales 2017: nuevos desafíos para su gestión. Programa Estado de la Nación, San José, Costa Rica

O'Donnell E (2017) Competition or collaboration? Using legal persons to manager water for the environment in Australia and the United States. Environmental and Planning Law Journal 34:503–521

O'Donnell EL, Talbot-Jones J (2018) Creating legal rights for rivers: lessons from Australia, New Zealand, and India. Ecology and Society 23:7

Osland MJ, González E, Richardson CJ, C. J. (2011) Coastal freshwater wetland plant community response to seasonal drought and flooding in northwestern Costa Rica. Wetlands 31:641–652

Ostrom E (1990) Governing the commons: the evolution of institutions for collective action. Cambridge University Press, Cambridge, UK

Overton IC, Smith DM, Dalton J, Barchiesi S, Acreman MC, Stromberg J, Kirby JM (2014) Implementing environmental flows in integrated water resources management and the ecosystem approach. Hydrological Sciences Journal 59:860–877

Pahl-Wostl C (2009) A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. Global Environmental Change 19:354–365

Paragamian K, Giannakakis T, Georgiadis N, Catsadorakis G, Poursanidis D, Kardamak A, Noidou M, Vrettou F, Tziritis E, Pediaditi E (2017) Island wetlands of Greece – from ignorance to international recognition. Proceedings of the 12th Society of Wetlands Scientists Europe Chapter Meeting, 4th – 6th May 2017. Retrieved on September 17, 2021 from https://lifecharcos.lpn.pt/downloads/paginas/956/anexos/charcosabstractbookfinalmay1.pdf

Perennou C, Guelmami A, Paganini M, Philipson P, Poulin B, Strauch A, Tottrup C, Truckenbrodt J, Geijzendorffer I (2018) Mapping Mediterranean wetlands with remote sensing: a good-looking map is not always a good map. Advances in Ecological Research 58:243–277

Perry D, Harrison I, Fernandes S, Burnham S, Nichols A (2021) Global analysis of durable policies for free-Flowing River protections. Sustainability 13:2347

Pittock J, Lankford BA (2010) Environmental water requirements: demand management in an era of water scarcity. Journal of Integrative Environmental Sciences 7:75–93

Poff NL, Matthews JH (2013) Environmental flows in the Anthropocene: past progress and future prospects. Current Opinion in Environmental Sustainability 5:667–675

Poff NL, Brown CM, Grantham TE, Matthews JH, Palmer MA, Spence CM, Wilby RL, Haasnoot M, Mendoza GF, Dominique KC, Baeza A (2016) Sustainable water management under future uncertainty with eco-engineering decision scaling. Nature Climate Change 6:25–34

Punton M, Welle K (2015) Straws-in-the-wind, hoops andSmoking guns: what can process tracing offer to impact evaluation? Centre for Development Impact – CDI paper #10. Institute of Development Studies, Brighton, UK

Quevauviller P, Balabanis P, Fragakis C, Weydert M, Oliver M, Kaschl A, Arnold G, Kroll A, Galbiati L, Zaldivar JM, Bidoglio G (2005) Science-policy integration needs in support of the implementation of the EU water framework directive. Environmental Science and Policy 8:203–211

Ramsar Convention on Wetlands (2016) An introduction to the convention on wetlands (previously the Ramsar convention manual). Ramsar Convention Secretariat, Gland, Switzerland

Rey-Benayas JM, Newton AC, Diaz A, Bullock JM (2009) Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. Science 325:1121–1124

Russi D, ten Brink P, Farmer A, Badura T, Coates D, Förster J, Kumar R, Davidson N (2013) The economics of ecosystems and biodiversity for water and wetlands. IEEP, London, UK and Brussels, Belgium Gland, Switzerland: Ramsar Secretariat

Sadoff C, Grey D (2002) Beyond the river: the benefits of cooperation on international rivers. Water Policy 4:389–403

Saleth RM, Dinar A (2004) The institutional economics of water – a cross-country analysis of institutions and performance. World Bank, Washington, DC, USA Cheltenham, UK: Edward Elgar Publishing and The World Bank

Salinas-Rodríguez SA, Barrios-Ordóñez JE, Sánchez-Navarro R, Wickel AJ (2018) Environmental flows and water reserves: principles, strategies, and contributions to water and conservation policies in Mexico. River Research and Applications 34:1057–1084

Salinas-Rodríguez SA, Barba-Macías E, Infante Mata D, Nava-López MZ, Neri-Flores I, Domínguez Varela R, González Mora ID (2021) What do environmental flows mean for long-term freshwater ecosystems' protection? Assessment of the Mexican water reserves for the Environment program. Sustainability 13:1240

Sánchez Navarro R (2016) Estudio de las necesidades hídricas de humedales españoles: condicionantes legales y posibilidades metodológicas. Unpublished doctoral dissertation. Universitat Politècnica de València. Retrieved on September 17, 2021 from https://doi.org/10.4995/Thesis/10251/62197

Sistema Nacional de Áreas de Conservación (SINAC) (2017) Valoración de los servicios ecosistémicos que ofrecen siete de los humedales protegidos de importancia internacional en Costa Rica: Palo Verde, Caribe Noreste, Caño Negro, Gandoca-Manzanillo, Maquenque, Térraba-Sierpe y Las Baulas. San José, Costa Rica: Sistema Nacional de Áreas de Conservación (SINAC), Centro Internacional de Política Económica – Universidad Nacional de Costa Rica (CINPE-UNA), Programa de las Naciones Unidas para el Desarrollo (PNUD)

Sistema Nacional de Áreas de Conservación (SINAC) (2018) Inventario Nacional de Humedales Costa Rica. San José, Costa Rica: Proyecto Humedales de SINAC-PNUD-GEF. San José, Costa Rica: Áreas de Conservación (SINAC), Programa de las Naciones Unidas para el Desarrollo (PNUD), Global Environment Facility (GEF). Retrieved on June 24, 2020 from http://www.sinac.go.cr/ES/docu/Paginas/pnhumed.aspx

Stubbington R, Acreman M, Acuña V, Boon PJ, Boulton AJ, England J, Gilvear D, Sykes T, Wood PJ (2020) Ecosystem services of temporary stream differ between wet and dry phases in regions with contrasting climates and economies. People and Nature 2:660–677

Tickner D, Parker H, Moncrieff C, Oates N, Ludi E, Acreman M (2017) Managing Rivers for multiple benefits–a coherent approach to research, policy and planning. Frontiers in Environmental Science 5:4

Tickner D, Opperman JJ, Abell R, Acreman M, Arthington AH, Bunn SE, Cooke SJ, Dalton J, Darwall W, Edwards G, Harrison I, Hughes K, Jones T, Leclère D, Lynch AJ, Leonard P, McClain ME, Muruven D, Olden JD et al (2020) Bending the curve of global freshwater biodiversity loss: an emergency recovery plan. BioScience 70:330–342

UN Environment (2018) A framework for freshwater ecosystem management. Volume 4: scientific background. Retrieved September 17, 2021 from https://wedocs.unep.org/

Vörösmarty C, McIntyre P, Gessner M, Dudgeon D, Proussevitch A, Green P, Glidden S, Stanley S, Bunn CS, Liermann CR, Davies P (2010) Global threats to human water security and river biodiversity. Nature 468:334

Ward JV (1989) The four-dimensional nature of lotic ecosystems. Journal of the North American Benthological Society 8:2–8

Webb JA, Stewardson MJ, Chee YE, Schreiber ESG, Sharpe AK, Jensz MC (2010) Negotiating the turbulent boundary: the challenges of building a science-management collaboration for landscape-scale monitoring of environmental flows. Marine and Freshwater Research 61:798–807

Williams B (2010) Passive and active adaptive management: approaches and an example. Journal of Environmental Management 92:1371–1378

World Bank (2020) World development indicators. GDP (current US$). Retrieved September 17, 2021 from https://data.worldbank.org/indicator/NY.GDP.MKTP.CD

World Wide Fund for Nature (WWF) (2019) Débit ecologique dans le Sebou. Cas du barrage Allal El Fassi. WWF, Casablanca, Morocco. Retrieved September 17, 2021 from https://wwfafrica.awsassets.panda.org/downloads/rapport_debit_ecologique.pdf?33163/Rapport-Debit-Ecologique

Yang W, Sun T, Yang Z (2016) Does the implementation of environmental flows improve wetland ecosystem services and biodiversity? A literature review. Restoration Ecology 24:731–742