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A socio-ecological framework supporting catchment-scale water resource stewardship

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Vitae

Dr Mark Everard has long-standing involvement in the development and implementation of ecosystem services, particularly in the context of water and other natural resource management. This includes substantial work in the developing world, as well as on global wetlands (he is a member of the STRP [Science and Technical Review Panel] of the Ramsar Commission). He also worked for 22 years in the public sector, understanding the science-policy interface and its application into management, and is a communicator including 27 books to date, 100+ peer-reviewed papers, 250+ technical and popular magazine articles, and frequent contributions to television and radio.

Abstract

The need to adapt human resource demands to the renewable capacities of ecosystems is widely acknowledged and has been transposed into multiple international and national commitments and strategies. This need is intensified by the contemporary 'full world' and increasing human numbers, urbanisation and climate change. However, resource exploitation models, markets and legacy regulations still tend to perpetuate an 'empty world' model, separating societal demands from environmental capacity.

Water resource management exemplifies many natural resource challenges. Choice of water management technologies still tends to maximise the efficiency of resource extraction and diversion to areas of high demand and economic influence, without necessarily prioritising the sustainability of the foundational natural capital of catchment ecosystems and the multiple benefits they provide to a diversity of co-dependents.

Setting the impacts of technology choices within the conceptual framework of catchment ecosystem services forms a novel basis for recognising the often overlooked or disregarded externalities of differing types of water management techniques. It also provides insights into means to mitigate and sustainably hybridise qualitatively differing water management approaches to safeguard, and ideally to rebuild where degraded, the capacities of catchments to meet human needs on an enduring and equitable basis.

Key words

Catchment; water management; Banas; Rajasthan; community-based; socio-ecological systems

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1. Introduction

Maintenance of ecosystem functioning is axiomatic to meeting human needs sustainably in a 'full world', in which economic activities significantly exploit or exceed the capacities of the natural world (Daly, 2005). Whilst inherently renewable, the finite capacities of semi-closed catchment ecosystems are vulnerable to unsympathetic exploitation. Integrated catchment management is increasingly practiced (Newson, 2008). However, legacy technologies for providing water services, such as dam-and-transfer schemes and the assumptions and markets behind their implementation, still often prioritise technical extraction efficiency over working within the functional limits of, or mitigating impacts upon, catchment ecosystems and their diverse dependents (Everard, 2013).

'Hard engineering' water management technologies, developed to address limitations in the capacity of natural systems to meet the demands of urban centres, industry, intensive irrigated agriculture and other human activities, tend to maximise production of a limited range of desired outputs. Examples include damming of rivers for water supply and hydropower, proliferation of bore holes across the developing world, flood banks, and sewerage and potable water reticulation systems. Whilst efficient in delivering targeted services, important for addressing the demands of dense population centres and water intensive lifestyles particularly in water-scarce environments, these generally mechanical and electro-mechanical engineered solutions nevertheless generate multiple externalities beyond the intended immediate benefit, and thereby tend to undermine catchment functioning generally at disproportionate detriment to marginalised constituencies (World Commission on Dams, 2000).

Alternative 'nature-based solutions' are gaining political and scientific currency, though are also critiqued for lacking a clear definition (Nesshöver et al., 2017). However, reliance on natural ecosystem functioning alone has limitations in meeting intensive water demands, and also through the exclusion of other land uses (as for example in protected water capture areas) that may compromise production of other necessary ecosystem services (Gordon *et al*., 2010).

In practice, rigid distinctions between 'ecosystem-based' and 'hard engineering' solutions represent a false dichotomy. Neither provides a complete solution in isolation, and furthermore engineered solutions (such as dams, drainage systems and flood defences) depend closely upon upstream ecosystem processes such as flow and erosion regulation and physico-chemical water purification processes (Makropoulos and Butler, 2010).

Dominant understandings of water scarcity and supply as technical problems, soluble through centralised engineering works, compromise the security of water resources if ecosystem processes and localised needs are overlooked (Birkenholtz, 2015). Overreliance on extraction-focused engineering, without also addressing resource regeneration, tends to deplete catchments and their associated ecosystem services. For example, proliferation of largely unregulated tube wells is a major contributor to the socio-ecological crisis of declining and degrading groundwater across much of South Asia (Postel, 1999), including India's 'drought below ground' (Goldin, 2016) comprising significant and sustained groundwater depletion over many Indian states (Rodell et al., 2009). Competitive deepening of wells throughout India drives declining water yields, increases energised pumping costs, and accesses deep aquifers that are often geologically contaminated and non-renewable (Shah et al., 2001). Groundwater supplies across India today are consequently more constrained by extensive contamination than depletion, threatening food, water and livelihood security (MacDonald et al., 2016).

Power relations between societal sectors also privilege urban water demand over the legitimate needs and rights of rural communities and ecosystems (Romero-Lankao et al., 2017), ultimately depleting the common resource supporting rural and urban beneficiaries alike. Barraqué et al. (2008, page 1156) recognised a "civil engineering paradigm" wherein, as cities grow, an engineering-based approach characterised as "taking more from further" dominates resource exploitation, potentially generating conflicts with communities denied access to their local resources. This narrowly technocentric model is exemplified by solutions implemented throughout the twentieth century to serve the booming demands of the city of Jaipur (Rajasthan state, India) (Figure 1; Table 1). Pervasive tube well proliferation generally serving individual or family demands from groundwater resources is leading to abandonment of traditional communal water harvesting techniques to recharge local aquifers, breaking down necessary governance structures and community cohesion. This common occurrence across India is exemplified in Rajasthan's Banas catchment system, compromising inflows from the upper river system to the Bisalpur Dam, from which water is extracted and pumped 120km to the north-east to meet much of the demands of the city of Jaipur, so creating linked vulnerabilities for urban and rural dependents (Gupta et al., 2014). Flörke et al. (2018) identified Jaipur as the second out of 482 of the world's largest cities most at risk from urban surface water deficit, further compounded by climate change and population growth, limiting socio-economic development and potentially generating conflict between urban and agricultural sectors in catchments from which water is diverted. This urban/rural power and resource use disparity is significant in Rajasthan given the dense human population (68.5 million) of which 75.1% is urban (www.rajasthan.gov.in, accessed 31st July 2018).

Figure 1: Map of the Banas catchment, Rajasthan (India) (adapted from Everard et al., 2018)

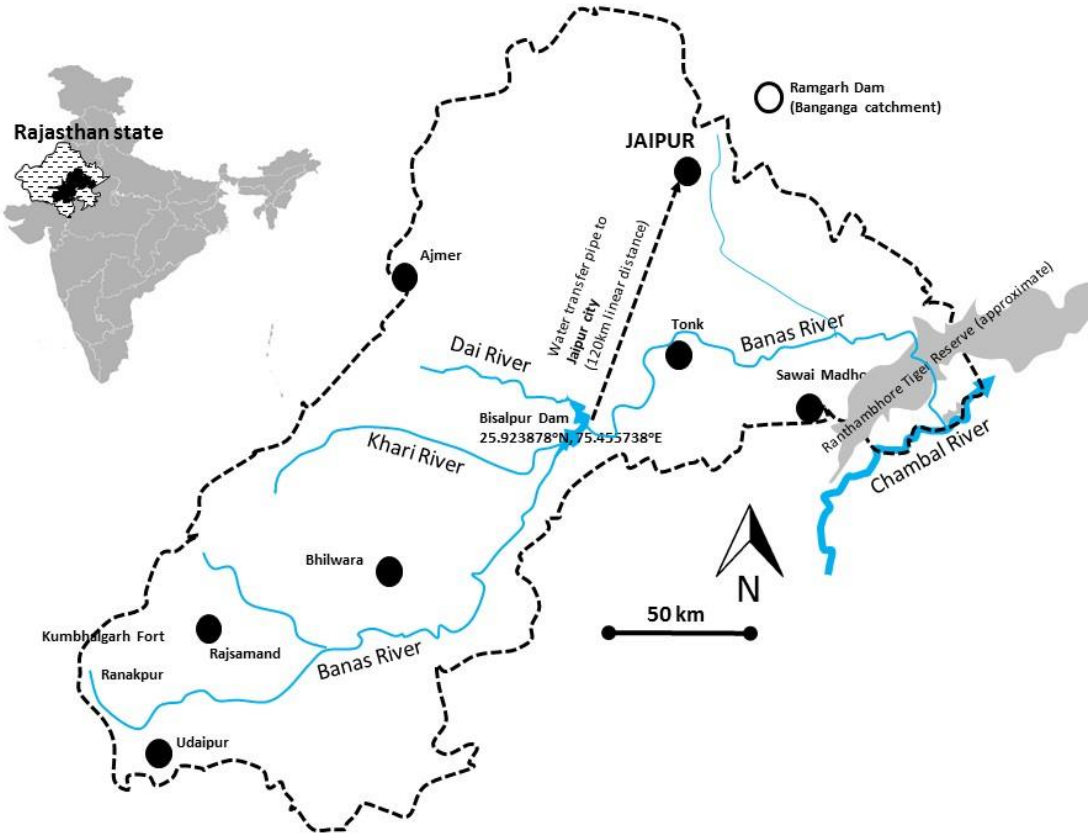


Table 1: A recent history of water supply solutions to serve Jaipur's booming demands

Date	Problems and solution implemented (from review by Everard et al., 2018).
Beginning of the 20th Century	Jaipur is fed from local groundwater and water-harvesting tanks (reservoirs), with some wells dug to augment groundwater recharge from monsoon run-off
Mid-20th century	Declining groundwater levels and water quality become evident to city water resource managers
1952	Jaipur City appropriates the out-of-catchment resources of the Ramgarh Dam, 32km to the north-east of Jaipur, filling from 1903 to provide local water supply, irrigation and fishery benefits and also hosting rowing events during the 1982 Asian Games
1987	The Bisalpur Dam is built on the Banas river system, 120km to the south-west of Jaipur City, to serve the water resource demands of local cities and irrigation schemes
2000	The Ramgarh Reservoir is dried out due to demands from Jaipur City and also by development encroachment around the reservoir periphery
Late 1990s to 2000	Water resources from the Bisalpur Dam are progressively appropriated by Jaipur City, transported by a network of pipes and pumping stations, in the face of strong local opposition (including violent protests involving civil fatalities). No compensatory investment is made in catchment recharge to maintain water quality and quantity in the Bisalpur Reservoir, and there are no planned releases from the dam to maintain the viability of the lower catchment and its dependents
2014	Evidence emerges from studies showing that water quantity and quality are declining in the Bisalpur Dam, threatening water security for Jaipur and other cities abstracting water
2018	Government of Rajasthan makes preparations a river-interlinking project to divert flows from the substantially more distant Chambal and Brahmani rivers into Bisalpur dam to meet drinking water and irrigation demands including those of Jaipur city (Saini, 2017)

All forms of water management technology have multiple implications for ecosystem processes, services and distributional outcomes for dependent beneficiaries (World Commission on Dams, 2000). There is therefore a need to understand the functions, benefits and potential impacts on catchment ecosystem functioning of different types of infrastructure. Ecosystem services provide a conceptual framework to explore these implications, and how combinations of water management techniques can be deployed to provide water services whilst protecting or rebuilding catchment capacities.

2. Differing types of water management infrastructure

A broad spectrum of water management techniques is deployed to address human needs. This range of approaches is coarsely segregated here into the four categories of: natural infrastructure; traditional solutions; green infrastructure; and hard engineering (see Table 2 for descriptions and examples). Although necessarily coarse, this categorisation emphasises different conceptual approaches for delivery of water services.

Table 2: Categorisation of the broad spectrum of water management infrastructure

Categorisation of water management techniques	Examples of relevant water management techniques
Natural infrastructure	Catchment habitats constitute primary natural infrastructure, providing a diversity of beneficial services (Nesshöver et al., 2017), potentially including as examples: • Unmodified landscapes in areas of low population that store, purify and buffer flows of water; • Protected water capture zones from which other uses are excluded; and • Restored regions or catchments, particularly water capture and storage zones in upper catchments.
Traditional solutions	Traditional water management solutions adapted to local climate, geography and culture are found across the world, reviewed by Pearce (2004) with examples including: • Qanat (and related) downstream tunnel systems found in hilly, porous terrain from Arab nations through Spain and into South America, directing water from groundwater stored within the interior of hills to downstream users; • Interception of subsoil moisture flows over broad landscapes, diverted to promote crop production by Papago Indians in Arizona, with similar systems found in other arid areas such as Israel and Yemen; and • Diverse, globally distributed terracing maximising the capture and efficient use of water, soil and nutrients in dry, sloping landscapes.
Green infrastructure	The term 'green infrastructure' spans diverse techniques emulating natural processes, reconciling environmental needs with economic growth in urban settings (Horwood, 2011), including for example green roofs, street trees, green open spaces, and sustainable drainage systems (SuDS). SuDS themselves encompass a range of techniques (Woods-Ballard et al., 2015) ranging from urban filter drains and pervious pipes, which produce minimal or no ecosystem service benefits beyond local flood regulation, through to constructed wetlands optimally designed to produce a diversity of regulatory and cultural benefits in addition to provide limited habitat for wildlife (supporting services). A progressive example of green infrastructure deployment occurs in the densely populated small island city-state of Singapore. Multiple techniques reintegrate various formerly displaced ecosystem services, contributing to climate resilience, emission reductions, balanced water flows and thermal comfort (Demuzere *et al*., 2014), including rooftop farming to address food security and carbon footprint concerns (Astee and Kishnani, 2017). In rural settings, Rural Sustainable Drainage Systems (RSuDS), implemented to reduce transport of pollutants to watercourses and offset other damage from farmed landscapes (Avery, 2012), include

	for example vegetated riparian strips, swales, interception ponds, buffer zoning, retirement of critical habitat, and wetland protection.
Hard engineering	'Hard engineering' infrastructure spans a breadth of mechanical and electromechanical water management solutions, developed to deliver a limited subset of services with high technical efficiency (Newson, 2008). Examples include dam-and-transfer schemes, engineered flood defences, river bank reinforcement, impermeable urban surfaces, and other forms of habitat conversion to maximise a limited subset of benefits (both urban and rural).

The Millennium Ecosystem Assessment (2005) categorisation of ecosystem services is used to consider the generic impacts of these broad approaches to water management. The Millennium Ecosystem Assessment classification is selected as it explicitly recognises four qualitatively different provisioning (such as food, fresh water and natural medicines), regulating (including water flows and purification, and disease regulation), cultural (for example assembly of fishing and cropping communities, characterising settlements and spiritual resources) and supporting (e.g. habitat for wildlife, water and nutrient cycling, and soil formation) service categories. Although redefined as functions in some subsequent reclassifications (for example TEEB, 2010; Braat and de Groot, 2012) to avoid 'double-counting' of benefits to people, supporting services are retained here as their vital underpinning roles need to be integrated into decision-making contexts to avert undermining the functioning and resilience of ecosystems including their capacities to generate other more directly exploitable services.

2.1 Natural infrastructure

The natural infrastructure of catchment ecosystems generates a mixed suite of provisioning, regulating, cultural and supporting ecosystem services. A range of examples of natural infrastructure is described in Table 2. Whilst the benefits of natural infrastructure can be local in scale, extensive habitat such as global mountain areas provide multiple water-related and other benefits at not only catchment but potentially continental scales (Körner et al., 2005). This spectrum of ecosystem services supported human needs in pre-industrial times and can still support demands today where ecosystem capacities are not exceeded. However, natural infrastructure alone is limited in its capacity to meet the demands for water resources and wastewater purification of increasingly intense human activities (urban and other settlements, industry, intensive irrigation, etc.) Whilst water capture zones are a form of natural infrastructure widely protected in different parts of the world as raw surface and groundwater sources (Zheng et al., 2016), exclusion of other uses from these zones can compromise the meeting of other needs in contemporary landscapes (Haakh, 2002).

Where development demands or land use pressures have degraded natural infrastructure and its associated services, mitigation measures may include protection or restoration of regions of high functioning within catchments (Palomo et al., 2013). Addressing the likely benefits of targeted re-establishment of forests, urban green spaces, wetlands and some other habitats, the UK's Natural Capital Committee (2015) concluded that these investments were likely to provide beneficial ecosystem services yielding at least as great an economic return as investment in traditional engineered infrastructure. Everard (2018) collates examples from a variety of countries and development contexts across the world where restoration of ecosystems has rejuvenated ecosystems and their capacities to support human wellbeing, reversing prior cycles of socio-ecological degradation including raising beneficiaries out of poverty. Novel water-sensitive and

other forms of agriculture and catchment uses sensitive to the functions and broader services produced in a context-sensitive way, as for examples enshrined under the Ramsar Convention's 'Wise Use' concept for wetlands (Ramsar Convention Secretariat, 2010), can also protect or rebuild the functioning of natural infrastructure.

2.2 Traditional solutions

Across the world, communities have innovated what have become traditional solutions to work with natural processes, including enhancement of supplies of water and linked ecosystem services in their unique geographic settings (see examples in Table 2). As one widespread and diverse set of examples, water harvesting systems adapted to differing terrains occur across India, attuned to local geography and culture to enhance natural groundwater recharge processes with run-off from scant, episodic monsoon rains and representing long-term adaptation to extreme and changing climates enabling local communities to thrive throughout millennia (Pandey et al., 2003). Social infrastructure supporting maintenance and equitable allocation of water and linked ecosystem services is as essential as physical structures (Ostrom, 1990; Everard, 2015). Restoration of traditional solutions, including modern adaptations based on their operational principles, has supported regeneration of rural sub-catchments in north Rajasthan in catchments formerly aridified by abandonment of traditional community-based water stewardship practices (Sinha et al., 2015; Everard, 2015). There is growing awareness in Indian groundwater management policies concerning the importance of replenishing aquifers in western and southern parts of India that is best enacted at local scale by rejuvenation or adaptation of traditional water management practices (Soumendra et al., 2017). Groundwater replenishment, rather than simple storage, is likely to support a linked set of ecosystem services in addition to enhancing water security.

However, many of India's traditional water management solutions are today in decline along with groundwater levels and water quality, as extraction by tube wells and other mechanised means undermines resource recharge and societal collaboration (Birkenholtz, 2015; Everard, 2015). Restoration of traditional practices, and adaptation of their underpinning principles appropriate to contemporary lifestyles and population levels, could constitute important mitigation strategies to arrest or reverse this decline. Whilst traditional solutions have generally addressed benefits at a local scale, pervasive implementation across landscapes can potentially regenerate catchment ecosystems, securing resources for intensive water users downstream (Everard et al., 2018). Whilst some authors, such as Gupta (2011), argue that traditional water management solutions are romanticised in modern-day Rajasthan, and it also true that anicuts (low dams across streams or drainage lines) and some other traditional methods are engineered solutions, the distinction is that they operate effectively on a local scale to replenish groundwater resources and store some surface water, helping to secure the livelihoods of communities by local collaboration, although they may also have a cumulate impact on the restoration of water resources and soil fertility at river basin scale (Sinha et al., 2015).

2.3 'Green infrastructure'

'Green infrastructure' spans diverse techniques, a number of them described in Table 2. Green infrastructure emulates natural processes to replace some of the ecosystem services lost through development. Green infrastructure solutions are generally designed as mitigation for selected regulatory services (hydrological, water and air quality and others), some cultural services (such as amenity areas) and limited supporting services (particularly habitat for wildlife) with only minor

potential contributions to provisioning services (such as rooftop gardening in Singapore), albeit that constructed wetlands can be designed for multiple beneficial outcomes. Though often considered novel, green infrastructure such as street trees, grassed verges and green spaces were historically widespread in urban areas, albeit today declining under the pressure of neoliberal urban development (Tappert et al., 2018). In rural settings, RSuDS (Rural Sustainable Drainage Systems) emulate natural processes lost to intensive farming. Green infrastructure in both urban and rural contexts mitigates the impacts of intensive development ('hard engineering') to reincorporate a subset of lost ecosystem services. However, even in as progressive and extensive an urban deployment of green infrastructure as occurs in Singapore, outcomes span a narrower range of ecosystem services than those provided by natural and traditional solutions.

Further integration of 'green infrastructure' into the mainstream of development plans requires valuation of all ecosystem services on a par with other planned benefits, both in new developments and as retrofit. For example, the UK's Natural Capital Committee (2015) examined the potential benefits of creation of urban green spaces, concluding that they were likely to provide multiple beneficial ecosystem services cumulatively making economic returns on investments at a scale at least as great as investment in traditional engineered infrastructure. Recognition and valuation of the benefits of ecosystem services provides a case for inclusion of green infrastructure approaches in both urban and rural settings to minimise or mitigate the negative impacts of development.

2.4 'Hard engineering' infrastructure

'Hard engineering' infrastructure for water management spans a breadth of mechanical and electromechanical solutions such as dam-and-transfer schemes, engineered flood defences, river bank reinforcement, and residential and industrial spaces delivering a limited subset of services with high technical efficiency. Intensive agriculture, maximising production of selected provisioning services rewarded by markets but displacing a broader range of natural processes affecting water systems, can be regarded as common with 'hard engineering' of catchments. (See further examples in Table 2.) Whilst generalisations across the broad expanse of built and rural applications are crude, the primary purpose of these forms of engineered management solutions is the efficient, targeted delivery of a limited subset of provisioning and some regulatory services such as water supply, wastewater treatment, defence of assets from flooding, and the production of food and other farmed commodities. In populated landscapes, hard engineering solutions such as sewerage systems alleviate pressures from development through severe pollution and other 'downstream' threats to ecosystems by artificial maximisation of regulatory water purification processes. Supporting services are not key design features of engineered techniques for water storage, abstraction or reticulation, beyond limited mitigation measures such as fish passes, constructed nesting sites, or modification of dam releases to emulate natural hydrographs reducing some undesirable ecological and social impacts (Chen and Olden, 2017). Some large structures may become culturally appreciated (such as major dams or the architecture of London's Victorian sewers), though their construction does displace pre-existing cultural services.

Consequently, whilst 'hard engineering' solutions provide a limited subset of water services supporting densely developed society, a net consequence is displacement of a wider range of other, commonly disregarded ecosystem services. These marginalised or expunged services could be beneficially mitigated or restored by alternative management techniques, generally elsewhere within drainage basins, to protect the overall supportive capacities of catchment ecosystems and thereby to contribute to the flows of benefits (water availability and quality, flood and drought buffering, etc.) supplied to the beneficiaries of hard engineering solutions. When the balance of

services enhanced and degraded are considered in a balanced way, automatic presumptions in favour of engineered solutions may be reassessed and potentially challenged where other approaches might not only yield the desired benefits but also work more sympathetically with catchment ecosystem processes.

2.5 Towards the sustainable hybridisation of water management approaches

All technological approaches have strengths and limitations. Natural infrastructure produces a diversity of services, though with limited capacity, whilst conversely 'hard engineering' solutions efficiently serve intensive uses of a limited subset of services but with inevitable externalities for non-targeted services. There is early recognition of the potential for hybridisation of differing approaches. These include as two examples the increasing use of catchment management to protect raw water quality reducing investment in 'hard engineering' for the treatment for potable supply (Postel and Thompson, 2005; Smith and Porter, 2010), and also emerging natural flood management strategies reducing downstream and coastal defensive 'hard engineering' coincidentally providing multiple linked co-beneficial ecosystem services (Parliamentary Office of Science and Technology, 2010; Costanza et al., 2006). Watershed protection is the most mature global sector for implementation of payment for ecosystem services (PES) schemes supporting a diversity of markets, including protection of raw water quality and flood risk, amenity and a range of other benefits often valued through costs averted 'downstream' by upstream catchment stewardship (Salzman et al., 2018). Whilst the developed world has historically tended to increase its reliance on hard engineering approaches, presumptions in favour of engineered solutions should be revisited in the light of insights about the achievement of desirable outcomes from other, more ecosystem-centred approaches (natural, traditional and green infrastructure) that also tend to generate fewer externalities on non-target ecosystem services. A view of catchment dynamics that takes account of the potential benefits of more ecosystem-centred approaches may potentially reduce the need for investment in hard engineering where protected or emulated ecosystem processes safeguard the quality and/or quantity and may also buffer flows of water.

Potential synergies between differing water management approaches warrant further exploration as part of a more integrated approach founded on overall catchment functioning and capacities, rather than perpetuating resource exploitation for immediate and narrowly framed benefits. This can, for example, build upon norms that may well be underappreciated, such as the dependence of 'hard engineering' solutions such as treatment works and piped drainage systems on the hydrological buffering, erosion regulation, and water purification and storage processes of upstream natural infrastructure. Understanding the potential for hybridisation of these different management approaches may not only ensure efficient and potentially more cost-effective service delivery to people, but also has the potential to maintain, or to rebuild where degraded, the supportive capacities of drainage basins as a necessary underpinning to the sustainability of socio-ecological systems.

The key issue here is not to seek to achieve some notional model of a catchment in a fully 'natural' state, functioning and delivering services as it would in the absence of human interventions. Such an aspiration would be unattainable given current levels of human population and demand. Rather, it is to recognise the strengths and externalities of differing management approaches, and to use this insight to identify contextually attuned combinations such that overall ecosystem integrity and functioning is preserved. Synergies between techniques at catchment scale can not only protect overall catchment ecosystem service capacity, but also potentially deliver economic efficiencies by minimising or mitigating externalities. Table 3 summarises observations in the preceding overviews

of the key strengths of each qualitatively differing water management approach, including mitigation measures for potentially degraded ecosystem services.

Table 3: Strengths (🡅) and mitigation measures (✚) to address shortfalls (🡇) of ecosystem service provision by different types of water management infrastructure

Type of infrastructure	**Strengths and mitigation measures relating to ecosystem service provision**	
Natural	🡅 *Provides multiple, linked ecosystem services suiting low demand* 🡇 *Can be over-ridden with increasing demand*	✚ *Protect, restore or recreate critical habitat to retain or regenerate services*
Traditional	🡅 *Works with natural processes to augment supply of water and related ecosystem services* 🡇 *May require substantial land area, and lack of innovation may not adequately address contemporary lifestyles*	✚ *Reverse current trends towards abandonment of traditional practices* ✚ *Innovate novel methods to apply traditional wisdom in modern contexts*
'Green'	🡅 *Emulates natural processes to offset shortfalls in developed environments* 🡇 *Limited opportunities for retrofitting, and needs recognition of the value of services in new build*	✚ *Requires recognition of the value of ecosystem services on a par with built assets in urban and industrial planning and development*
'Hard'	🡅 *Provides efficient delivery of a limited set of services for dense populations* 🡇 *Tends to create many negative externalities*	✚ *Narrow presumptions in favour of 'hard' engineering solutions need to be challenged, considering how alternative approaches may provide more sustainable solutions* ✚ *Where 'hard engineering' solutions best serve identified needs, mitigation can be achieved by looking upstream to restore catchment-scale processes compensating for lost or degraded ecosystem services*

2.6 Relevance to the Banas catchment

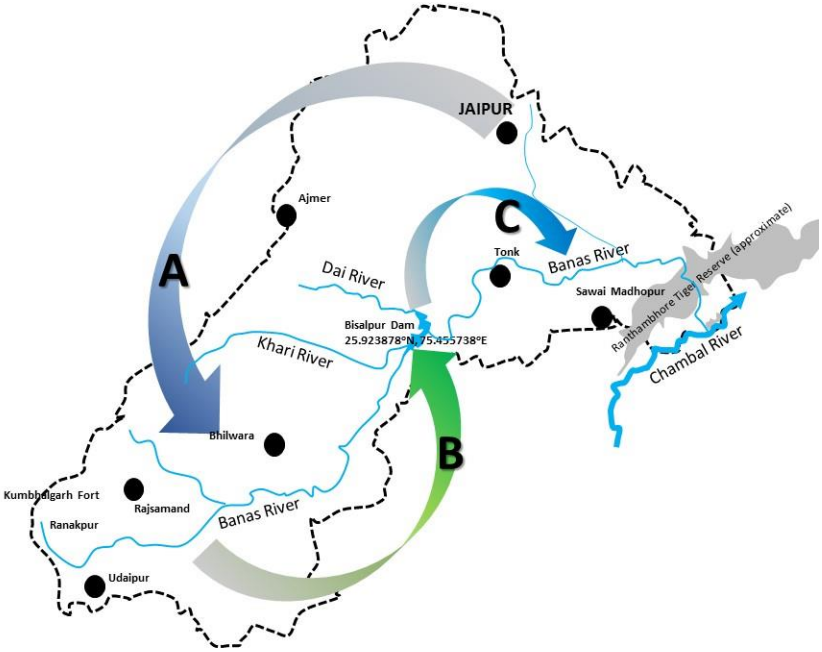
Restoration of traditional practices to regenerate catchment hydrology, productivity and socio-economic wellbeing, reversing formerly degrading cycles in socio-ecological systems by community collaboration and governance, has been achieved in small, rural catchments in Alwar District of Rajasthan (Sinha *et al.*, 2015; Everard, 2015). The challenge is to expand this to larger, complex catchments.

The Banas River system is one such large catchment, lying entirely within the arid/semi-arid Indian state of Rajasthan. The main stem of the Banas River is 512km in overall river length from its source in the Khamour Hills in Rajsamand district to its confluence with the Chambal River in Sawai Madhopur district, and is joined by many major tributaries draining a total basin area of 45,833 km². The Banas system is subject to multiple demands and pressures from fragmented urban and rural users who are largely unaware of their co-dependence, implementing locally beneficial solutions yet cumulatively degrading the catchment ecosystem leading to interconnected vulnerabilities (Everard et al., 2018). Illustratively (see Figure 2), there is a need for urban beneficiaries of 'hard engineering' water transfer schemes from the Banas system to (A) invest in upstream recharge solutions as a mitigation measure to contribute to water security. (B) Investment recirculated co-beneficially to rural upper catchment populations can promote traditional solutions and the adaptation of traditional knowledge into modern innovations to improve water security locally and as a contribution to catchment-scale restoration, improving the quantity and quality of flows to the Bisalpur Dam underwriting urban water security. With adequate recharge, (C) dam releases may then be possible to provide 'environmental flows' mitigating impacts from 'hard engineering'

infrastructure including water diversion, reanimating downstream ecosystems and communities currently suffering from the urban appropriation of water.

Water efficiency, reuse and accountability must also be promoted in both urban and rural areas to ensure that diverted resources are not simply wasted. This may be achieved through routine implementation of urban measures, such as rooftop water harvesting and greywater reuse, and efficient rural water uses as for example trickle irrigation (Sharma et al., 2018). Working in synergy with ecosystem processes regenerating resources at catchment scale confers optimal means to underwrite water security across the whole linked socio-ecological system, simultaneously benefitting both rural and urban dependents. Otherwise, continuing catchment aridification and further extension of the failed "taking more from further" paradigm to draw upon ever more remote and increasingly contested resources are inevitable prognoses.

Figure 2: Potential flows to mitigate and generate ecosystem processes underlining water security in the Banas catchment: (A) mitigation through compensatory investment from mainly urban beneficiaries of 'hard' engineering in natural and traditional the upper catchment regenerating resources; (B) enhanced flows of fresh water replenishing the catchment, dam and associated ecosystem services; and (C) potential for excess water enabling 'environmental flow' releases mitigating downstream impacts of water diversion



2.7 Broader global examples

A 'full world' conception of sustainable development needs to go beyond simply reducing human pressures, instead seeking regeneration of damaged ecosystems as a vital resource for continuing human security and opportunity. Pioneering solutions rebuilding ecosystem capacities for poverty alleviation and future socio-economic security across the world include regeneration of green cover through methods such as terracing, tree planting and exclusion of grazing from high-slope areas, reversing degradation of the erosive Ethiopian Highlands (Hurni et al., 2010) and Loess Plateau of China (World Bank, 2007), and recent uptake of Managed Aquifer Recharge in Australia, USA and

Europe for the cost-efficient recycling of storm run-off or treated effluent for potential beneficial reuse integrating engineered treatment systems with enhanced aquifer recharge (Dillon et al., 2010). Further progress is seen in agricultural practices aimed at multiple potential beneficial outcomes (clean water, biocontrol, biodiversity benefits, climate stabilisation and long-term soil fertility) using novel practices as part of profitable agricultural practices (Foley et al., 2011; Robertson *et al*., 2014).

These examples represent potential contributions to the 'Half-Earth' vision (Wilson, 2016), granting half of the earth's ecosystems to nature to rebuild lost capacity. Catchment systems are logical, geographically bounded units for considering the rebalancing for protection or rehabilitation of ecosystem processes with the multiple, interlinked and competing pressures of human demands (Newson, 2008). The ramifications of water management technology choices, and the potential for mitigation and hybridisation with other approaches to meet human needs whilst also ensuring continuation of vital catchment processes, can constitute a significant component of visioning and planning for regenerative socio-ecological catchment systems.

2.8 Integrated water resource stewardship (IWRS)

The Dublin Statement on Water and Sustainable Development recognises increasing scarcity of water resulting from completing uses and overuse of water (WMO, 1992). Beyond the largely economic formulation of the four 'Dublin Principles' for integrated water resources management (see Table 4), the UN Human Rights Council (2010) passed Resolution A/HRC/15/L.14 reaffirming access to safe, clean drinking water and sanitation as a human right. However, these definitions are incomplete, focusing on exploitation of water rather than stewardship of its quality, quantity and role in wider ecosystem processes and services, and in particular the need to ensure or promote replenishment of water resources to meet the burgeoning demands of a 'full world'.

For these reasons, a paradigm of integrated water resource stewardship (IWRS) is proposed, adding a fifth stewardship principle: "5. Sustainable stewardship of fresh water systems includes protection or enhancement of resource regeneration processes, safeguarding or increasing the resilience and capacities of integrated socio-ecological systems" (see Table 4). This evolution towards a stewardship and resource replenishment model, augmenting managed and equitable exploitation, is not only appropriate but essential to rebuilt depleted ecosystem service capacity in a 'full world'.

Table 4: The four 'Dublin Principles' of integrated water resource management (WMO, 1992), with proposed additional fifth resource replenishment and stewardship principle (underlined)

1. Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment
2. Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels
3. Women play a central part in the provision, management and safeguarding of water
4. Water has an economic value in all its competing uses and should be recognized as an economic good

5. Sustainable stewardship of fresh water systems includes protection or enhancement of resource regeneration processes, safeguarding or increasing the resilience and capacities of integrated socio-ecological systems

2.9 Governance considerations

A narrow focus on technically efficient water resource extraction and diversion to meet the needs of fragmented users across (and sometimes outside of) catchments is currently leading to degrading socio-ecological cycles in many drier, developing world catchments. Consequently, there is a pressing need in the Banas system, and elsewhere where water resources are constrained or contested, to make progress towards an overall management framework predicated on stewardship of whole-catchment resource for equitable benefit-sharing. However, this acknowledgement, already well accepted under the principles of integrated water resource management (IWRM), is insufficient of itself to broker change towards more collaborative governance.

Rather, a common understanding of the consequences of water management strategies needs to inform decisions across all stakeholder groups sharing the resources of a catchment, leading to more informed and transparent decision-making. In common with many predominantly rural developing regions, India has an interconnected system of 'top down' policy and 'bottom up' community-centred governance institutions (see Table 5). India's community-based panchayat (or panchayat raj) system is a uniquely South Asian political system found also in Pakistan, Bangladesh, Sri Lanka and Nepal dating back to around 250AD. However, this South Asian system of intersecting state and community institutions has parallels across the developing world as a means to adapt high-level strategies to highly heterogeneous geographical and cultural contexts. It is necessary to develop and share a common vision of landscape hydrology and the influence of technological interventions, a perspective that is today largely lacking, to inform potential 'win-win' solutions that serve local needs whilst working with natural processes at catchment scale. This resembles common-pool resource problems (Ostrom, 1990), albeit at a greater and more complex scale.

Table 5: Intersecting 'top' down' and 'bottom up' governance institutions in India

'Top down' state institutions	**'Bottom up' community-based institutions**
National: Strategies, legislation and associated budgets are set nationally by the Government of India. Some perceived national priorities (hydropower, defence, etc.) are enforced by central government.	Numerous NGOs interface with government at all levels to influence policies.
State: National mandates are modified by state-level governments, which also have considerable autonomy. Currently, the demands of urban centred and other politically and economically influential groups (such as large industry and irrigated farming enterprises) tend to skew decision-making about water resource management and allocation.	

Development Block: State programmes, including associated development funds, are delivered at the level of development blocks. (These 'blocks' spanning clusters of districts are the lowest state administrative unit.)	**Panchayat samiti** ('samiti' means 'committee') represent groups of panchayats, interfacing with government at development block level.
District Collector: Although not formulating policy, a secondary level of administration occurs at district level (Indian states are divided into multiple districts) headed by a District Collector (also referred to as the District Magistrate) in charge of revenue collection and administration, including local arbitration.	**Panchayats** (literally "assemblies of five" elders) are selected to represent communities, often spanning multiple smaller villages and Gram Sabha. In heavily forested regions, particularly in the Himalayan state of Uttarakhand, **van panchayats** (forest panchayats) govern community use of forests within village boundaries including water resources. The Government of Odissa (2002), subsequently renamed Odisha, also instituted an experimental system of **pani panchayats** ("Water panchayats") to facilitate the engagement of farmers in irrigation matters.
	Gram Sabha (village councils) comprise elected representatives promoting village development needs, including local-scale water management. They may bid for government block-level funding via Panchayats and panchayat samite.

The principal contribution of this study has been to develop insights into the wider ecosystem service implications of qualitatively differing approaches to water management, providing a foundation for dialogue, policy formulation and decision-making informing a more connected approach to water use and sharing through the hybridisation of different management approaches. Successes achieved in restoration of linked societal and ecosystem restoration in small rural catchments in Alwar District highlight that success is possible. The strategic challenge of extending this type of collaborative success to broader landscapes spanning different constituencies and their associated power relationships can be supported by insights into the benefits, externalities and potential mitigation measures pertaining to different water management approaches.

Common understandings of the interdependencies of water management approaches across multi-scale governance institutions can provide a conceptual basis for the achievement of collaborative governance, in which state and non-state stakeholders undertake collective, consensual decision-making around the management public assets (Ansell and Gash, 2007).

3. Discussion

The need to reintegrate ecosystems and their services into societal policies and practices as core but finite resources supporting continuing socio-ecological resilience and progress is internationally accepted, albeit yet requiring substantial societal transformation to shape mainstream practice (Millennium Ecosystem Assessment, 2005). Stewardship of currently degraded water and other ecological resources is emerging as a priority in a 'full world' (Roa-García, 2014), challenging historic

management approaches founded primarily on efficient exploitation rather than resource regeneration. Consideration of the range of benefits and externalities of differing types of water management techniques, using the ecosystem services framework, can illuminate the strengths and weaknesses of different approaches including their ramifications for other dependent catchment stakeholders. This insight may inform sustainable hybridisation of solutions across basins to balance the provision of benefits to people with conservation or regeneration of ecosystem services sustaining catchment-scale socio-ecological systems.

Reversion to living purely off natural infrastructure is not an option given the substantially degraded current state of ecosystems, and limitations in their capacity to support contemporary population levels and water demands in a 'full world'. Conversely, an approach premised narrowly on efficient extraction without rebalancing replenishment raises questions about ecological sustainability, human equity, and long-term distributional costs and benefits. Living within the renewable capacities of catchment systems therefore requires broader thinking across spatial and temporal scales and between societal sectors (particularly rural and urban) to identify how most sustainably to hybridise different water management techniques, cognisant and accountable for their distributional impacts and cumulative contributions to safeguarding or rebuilding the breadth of ecosystem services upon which ecosystem resilience, service production and human wellbeing depend.

Transition to a functional and stewardship-based view of the world faces the conflict of established and assumed rights founded substantially on privately held physical property (land, water and their uses) with reprioritisation of predominantly publicly beneficial catchment ecosystem services (Graham, 2014; Everard, 2017). Solutions to these challenges are far more than technological, requiring wider consideration of supporting ecosystem processes and the reengineering of a social, economic and policy infrastructure upon which the sustainable stewardship and sharing of resources can be envisaged and developed for the long-term security and opportunity of all beneficiaries of catchment ecosystem services. Consequently, social learning may be as important as physical infrastructure recommendations for the formulation of practical and accepted solutions (Blackmore et al., 2007), benefitting from an iterative approach linking science to policy and societal actors (Sarkki et al., 2015). Whilst some form of consensual or enforced guidance based on an overview of catchment functions and service production may conflict with established neoliberal world views predicated on maximisation of (generally private) short-term profit overlooking potential externalities, it is however essential for continuing water security, long-term sustainability and the meeting of interlinked human needs.

An effectively linked, nested framework of governance is essential to guide societal transition to a stewardship-based approach to water management. However, governance mechanisms alone are insufficient in the absence of a shared understanding of water systems and the systemic impacts of management technologies upon them. The principal contribution of this paper is development of insights about the systemic ramification of qualitatively differing approaches to water management, forming a common understanding that may be shared between nested governance institutions as a basis for reversing the current presumption in favour of decision-making founded on narrowly sectoral demands. Knowledge-sharing about the benefits and externalities of water management choices across these governance institutions is essential to manage power relationships particularly between rural and urban constituencies, interactions between upstream and downstream dependents, and frame decisions and innovations aimed to safeguard or rebuild the capacities of catchments to support integrated socio-ecological systems on a sustainable basis. Details of governance transformations are beyond the scope of this paper, the principal contribution of which is to develop insights into the systemic consequences for catchment ecosystem functioning of different types of water management infrastructure to inform future decision-making.

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