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Managing socio-ecological systems: who, what and how much? The case of the Banas River, Rajasthan, India

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Abstract

Addressing socio-ecological linkages is essential for diagnosing and proposing solutions to complex sustainability challenges, such as river-basin management, climate adaptation and broader sustainability problems. 'Who?' is integral to an inclusive approach, 'What?' dimensions of supportive ecosystems are included, and 'How much?' of the value of ecosystem services informs management decisions? In complex systems, such as catchments, these questions have to be addressed within inclusive governance arrangements, shaping technology choices and affecting societal and ecosystem outcomes.

Historic communal water stewardship in the Banas catchment (Rajasthan, India) balanced the recharge of groundwater from monsoon runoff with its exploitation for irrigation and other uses. However, contemporary mechanised extraction of groundwater, and dam-based and other transfer schemes moving water out-of-catchment to urban, agricultural and other intensive users, now favours influential sectors of society. These intensive water management measures also deplete groundwater, prioritising immediate benefits whilst undermining the vitality and functioning of supporting ecosystems. This creates a degenerative cycle within the socio-ecological system, though this may be reversed with the development of governance systems based on a systemic overview of whole-system functioning. Sustainable stewardship, as practiced historically, needs to be adapted to contemporary conditions by emphasising connections amongst all stakeholders, the foundational capital of overall catchment functioning, and net societal and ecosystem benefits.

Key words

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

1. Introduction

The literature on socio-ecological systems (SESs), substantially initiated by Ostrom (1990) [1], deals with the human dimensions of social and ecological dilemmas. Redman *et al*. (2004, p.163) [2] defined a SES as "A coherent system of biophysical and social factors that regularly interact in

resilient, sustained manner", which may span a range of hierarchically linked scales, is continuously dynamic and in which critical resources are regulated by a combination of ecological and social systems. The concept of SESs is not without its critics. For example, Fabinyi *et al*. (2014) [3] recognised that, notwithstanding its value for promoting interdisciplinary dialogue, there is a risk in attempting to cross disciplines and build a holistic perspective on human–environment relations that a normative approach under-appreciates social diversity, divergent values and power relationships. The differing interests and aspirations of diverse stakeholders require resolution if overall system resilience is to be achieved (Avriel-Avnia and Dick, 2019) [4]. This is particularly so in the field of 'environmental water governance', which relies heavily on the effectiveness of community engagement for its legitimacy (Godden and Ison, 2019) [5].

Nevertheless, the SES concept is helpful for understanding and management of complex systems in which human interactions with nature are inherently systemic and highly interactive through multiple feedback mechanisms [6]. This is particularly relevant for addressing sustainability problems such as river basin modelling, addressing multiple scales and dimensions of environmental problems and the uncertainty of social systems (Cabello *et al*., 2015)[7].

Central to SESs are the three principal, interdependent vectors of sustainable development. The fundamental questions raised by social, environmental and economic dimensions raise three related questions: who is involved; what aspects of ecosystems are considered; and how are the overall economics of the SES conceived? However, these three dimensions have also to be considered within the context of formal and informal governance frameworks within which decisions are made, raising the question "why?", as well as technology choices and their influences on the whole integrated SESs, raising the question "how?"

This paper explores these three fundamental and two contextual questions in the context of the Banas catchment in Rajasthan state, India. The Banas is selected as it is a complex catchment with substantial rural areas in the monsoonal drylands of northern India but also with substantial water diversions to urban centres including the booming city of Jaipur. The interactions between these five questions are assessed in terms of their contribution to making the catchment SES either regenerative (balancing resource regeneration with use and an equitable share of benefits) or alternatively degenerative (in which fundamental ecosystem resources and potential benefits to all co-dependents are in a degrading cycle). The Banas today is a microcosm of a degrading SES cycle, but also one for which there is a vision and some initial steps towards restoring systemic functionality as a wise investment in water security. Consequently, learning from this case is more generically relevant to management of catchment SESs.

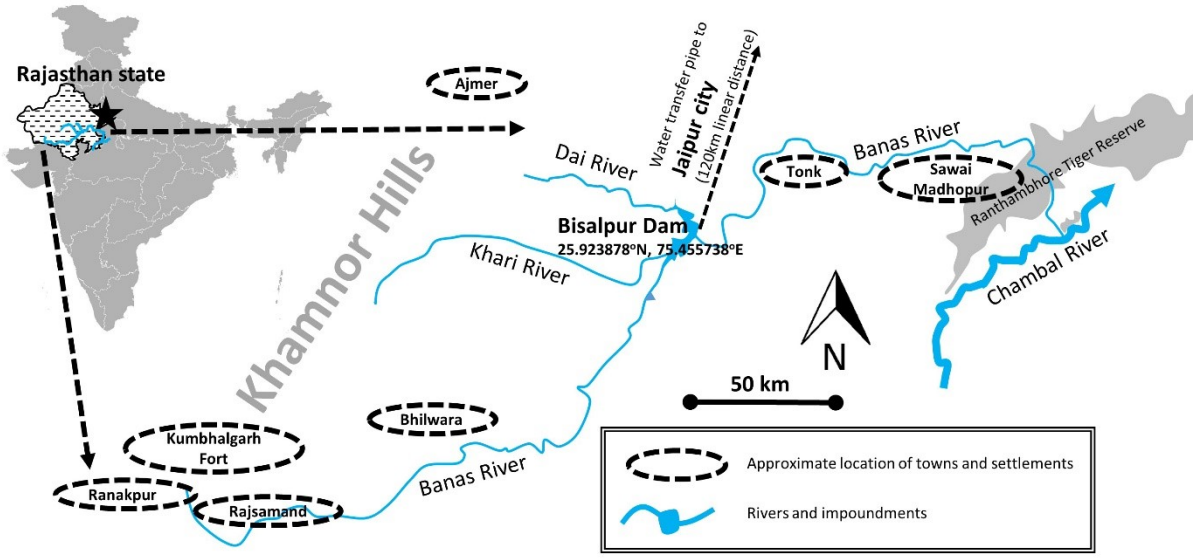
2. Overview of the Banas case study catchment SES

India has millennia of innovations in water management reflecting adaptations to the monsoonal climate, frequently with arid or semi-arid conditions outside of the rainy season. Diverse local traditions of the management of water, together with its political significance and cultural meaning, tend to occur across Deccan (peninsular) India (Mosse, 2003) [8]. Innovative water harvesting and

stewardship systems are encountered pervasively across India, attuned to local terrain, meteorology 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 [9]. Despite their widespread abandonment in recent years, there is now growing awareness about the importance of replenishing aquifers in western and southern parts of India most effectively enacted by rejuvenation or adaptation of traditional water management practices at local scale [10].

The main stem of the Banas river has a total length of 512km, rising from two headwaters in the Kumbhalgarh Wildlife Sanctuary in the Khamnor Hills, collecting a number of major tributaries across a total catchment area of 45,833 km^2 [11][12]. The Banas discharges into the Chambal River to the east of the city of Sawai Madhopur. The whole river course runs within the state of Rajasthan, the only major river system entirely within the state. The Banas Basin as a whole falls under the tropical grassy plains, semi-arid and hot, category of the climate classification of Köppen and Wegener (1924) [13], producing a pronounced seasonal flow regime responding to episodic monsoon rainfall that typically peaks in July and August.

Figure 1: Overview of the main stem of the Banas River, Rajasthan



Historically, the Banas catchment has been the beneficiary of a long tradition of a diversity communal, nature-based water stewardship, particularly pertaining to the harvesting and generally underground storage of monsoon run-off adapted elegantly to the highly varied local geographical and cultural conditions [14]. However, abandonment of these communal practices in favour of competitive, mechanised extraction and water transfers is today threatening water quantity and quality, in particular depressing groundwater levels. Across north-western India, as indeed India in general, dominant policies relating to promotion of mechanised water extraction are contributing to ongoing groundwater depletion, a result of oversight of longer-term consequences with multiple adverse consequences including rendering traditional approaches to extraction of shallow groundwater ineffective in accessing the receding water table [15], depriving people lacking resources for deep pumping, and exposing abstractors to health risks where water is extracted from

geologically contaminated deeper aquifers. Outmigration from villages, particularly by young men seeking greater material opportunities in cities, but also even including village abandonment, are commonplace throughout rural Rajasthan.

Approximately mid-way along the river's course, the Banas is impounded by the Bisalpur Dam constructed in 1987 for the benefit of local irrigators and cities. However, increasingly from the late 1990s up to 2000, water from the Bisalpur Reservoir has been substantially appropriated by the city of Jaipur some 120km to the north, in the face of violent opposition from local people in which protestors were killed [16]. Jaipur had formerly subsisted on water captured from monsoon episodes and stored in lakes and groundwater, though this resource is now substantially depleted and polluted. In 1952, municipal authorities reached out 32km to the north-east to appropriate water from the Ramgarh Dam, originally also built for local uses on completion in 1903, though the Ramgarh Reservoir had dried completely by 2000 due to over-abstraction and encroachment. This led on to decisions to appropriate water from the Bisalpur Dam.

Systemic connections between the upper and middle catchments of the Banas River, including the people using this water and the technologies that they deploy, are compromising the quantity and quality of inflows to the Bisalpur Dam, creating linked vulnerabilities for both urban and rural dependents [17]. In 2017, the Government of Rajasthan made preparations under a river-interlinking project to divert flows from the substantially more distant Chambal and Brahmani rivers into the Bisalpur Dam to meet growing drinking water and irrigation demands, including those of Jaipur city [18]. In essence, this apparently endless pursuit of perceived 'excess' water from increasingly further afield replicates the broken "civil engineering paradigm" observed globally as cities develop following a "taking more from further" habit [19]. Implicit in this paradigm is that there are always remote sources with perceived surplus water, and for which the rights of local people and ecosystems can be overlooked or disregarded.

There are no environmental flow releases from the Bisalpur Dam, compromising the viability of the whole lower river. This threatens river ecology, riparian settlements and livelihoods, and resources available for wildlife particularly as the lower Banas flows past the Ranthambhore Tiger Reserve and into the Chambal River immediately above the National Gharial Sanctuary. Water security for the city of Sawai Madhopur in the lower Banas catchment is also compromised, water no longer reliably extractable from the bed of the Banas River but instead pumped from groundwater around the periphery of the Ranthambhore Tiger Reserve.

Urban/rural power relationships and resource use disparities are significant in Rajasthan, given the dense human population (68.5 million) of which 75.1% is urban [20]. As a system, the Banas catchment is being over-exploited by a limited sector of users (who?), extracting a limited set of ecosystem services to the exclusion of others (what?) with substantial net disparities in benefit (how much?), now and into the future as the supporting ecosystem and its multiple services to dependent beneficiaries degrades. This fractured contemporary use of the system results in a cycle of degradation, from which the perceived (albeit flawed) solution is to look even further afield for resources from increasingly remote catchments that, in a crowded and growing nation, are likely to be increasingly contested and degraded.

Recent initiatives driven by the Government of Rajasthan include the flagship Mukhya Mantri Jal Swavlamban Abhiyan programme (MJSA) [21]. MJSA stimulates reinstatement or innovation of localised rural solutions as a basis for self-sufficiency, recognising their importance for reversing systemic degradation driven by overreliance on technically efficient extraction, population growth and urbanisation. Climate change modelling of the Banas catchment suggests a significant increase in annual number of warm days and nights, a decreasing trend in the annual number of cool days and nights, and a significant decrease in the total annual precipitation [22] indicating increasing water stresses. MJSA builds on grassroots movements driven by NGOs to enhance local, rural water security through restoration of traditional methods and wisdoms in the sustainable management of water (for example [23], [24] and [14]).

3. The current situation of the Banas catchment SES

Literature specifically on the Banas system is relatively scant, and included in the above overview. Knowledge from this overview is used to inform the foundational and framing questions about the current state of the Banas SES in the sub-sections below.

3.1 Who wins and loses under contemporary use and management of the Banas system?

Advancing a common pool resources (CPR) model based on empirical observations of community stewardship of shared environmental resources, Ostrom [25] and [26] concluded that communities or groups have a higher probability of succeeding in the sustainable management of common resources if they are small, homogenous, possess substantial social capital including a strong sense of community with mutual trust, and are willing to forego immediate benefits in exchange for longer-term rewards. However, in an increasingly populated world with competing sectoral interests in natural resource use, exemplified by large and heterogeneous catchment systems, the diversity of and competition between different interconnected sectors creates great complexity.

Communities making use of the water resources of the Banas catchment are geographically distributed and diverse in livelihoods and intensity of use. There is a stark division of water demand by distributed rural communities and the more influential and still fast-growing urban centres that today exert asymmetric power over resource appropriation creating issues of distributional inequity. Inequities are particularly inflicted on downstream communities deprived by diversion of water from the river system to urban centres. This includes both those denied direct use of the water as well as beneficiaries of a diversity of water-vectored ecosystem services, both rural but also the residents of the booming city of Sawai Madhopur and subsistence and tourism interests dependent on the ecosystems of the lower catchment.

Abandonment of the long tradition of communal, nature-based water stewardship, observed in the Banas system but also more pervasively across India, is part of a social transition from collaborative to competitive behaviours. Aside from breakdown of community structures that have evolved over millennia as an adaptation to local geographic conditions, competitive, mechanised extraction and

water transfers also pose health threats though declining water availability, particularly for those with limited resources for pumping, as well as increasing exposure to geologically contaminated water. Village outmigration, particularly by young men who perceive reduced lifestyle expectations due to resource degradation, further compounds social breakdown and opportunities for collaborative water management.

3.2 What aspects of ecosystems are considered in the contemporary Banas system?

The 'what?' question pertains to aspects of supporting ecosystems that are factored into management of SESs. In this regard, the field of ecosystem services is particularly helpful. Ecosystem services are defined as "*The benefits that people obtain from ecosystems*" by the Millennium Ecosystem Assessment (2005) [27]. The Millennium Ecosystem Assessment (MA) also classified services into the four distinct categories of provisioning, regulating, cultural and supporting services, reflecting qualitatively different societal benefits and associated value systems. Some subsequent reclassifications have been advanced, some redefining supporting services as ecosystem processes rather than services as they are not directly consumed so risking economic 'double counting' [28] [29]. However, supporting services remain vital considerations in management decisions as they underpin the functioning and resilience of ecosystems and their capacities to provide more directly consumed services [30]. The evolving framework of ecosystem-derived 'Intrinsic values', 'Instrumental values' and 'Relational values' under development by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [31] departs from this general structure, mining deeper into the inherent values of nature in addition to expanding upon the differing ways in which humanity benefits from them. However, regardless of the specific classification scheme, central principles remain that all services are systemically interconnected and therefore highly interdependent. A systemic approach is therefore essential for sustainable decision-making, as use and management of natural resources affects ecosystem structure and functions with potentially serious consequences for system resilience and interdependent human interests [32]. Interdisciplinary, mixed method approaches are consequently required to maintain system resilience as a basis for reducing risks to human and environmental wellbeing in system management [33].

Historic water management across rural areas of the Banas catchment, as well as within the city of Jaipur and other rural centres, has relied on an innovative range of locally adapted nature-based solutions to harvest, store and access water falling predominantly during the limited monsoon period. However, technological transitions favouring efficient water extraction rather than regard for the renewability of accessible subsurface aquifers is depressing groundwater levels and degrading the supportive capacities of ecosystems. Not only is this also reducing the environmental quality of extracted water due to geological contamination but it also degrades other water-vectored ecosystem service benefits such as retention of soil moisture and support for ecosystems. Mid-way along the course of the main stem of Banas river, the Bisalpur Dam also diverts substantial amounts of water for urban and intensive irrigation uses. The lack of environmental flow releases from the Bisalpur Dam compromises the viability of downstream ecosystems and services, degrading the overall supportive capacities of the catchment SES.

3.3 How much? What values are considered in the contemporary Banas system?

Management of an SES can be predicated on benefits to a narrow subset of services and/or beneficiaries, with unvalued or undervalued services and their associated beneficiaries tending to become marginalised from decision-making undermining the integrity of the SES. Conversely, SES management may be inclusive of a wider or alternative range of benefits conferred upon a broader swathe of society, a more inclusive approach accounting for the diversity of values and value systems enjoyed by society and so tending to contribute to more equitable decisions that also highlight the importance of maintaining the resilience of foundational ecosystems supporting the SES. Unstable and ultimately degenerating catchment SESs are exemplified when interests in immediate exploitation of water override the maintenance of catchment resources and their diverse beneficial processes, and by the commonplace externalisation of the needs of future generations.

The preceding overview of the contemporary situation of the Banas catchment reveals a recent emphasis on technically efficient water abstraction and transfer from the system, overlooking wider benefits stemming from maintaining system integrity and the diversity of ecosystem services resulting from abandonment of locally nuanced water stewardship. Dominant policies promoting mechanised water extraction contribute not only to ongoing groundwater depletion, but also oversight of many linked ecosystem service benefits. This is particularly so in the case of diversion of most of the flows of the Banas system from the Bisalpur Dam, denying its benefits to local and downstream constituencies and ecosystems though marginalisation of all services other than the provisioning service of immediate water supplies. Ongoing apparent faith in the "civil engineering paradigm", seeking increasingly remote resources from which to appropriate water, reinforces the perception that the dominant contemporary narrative of water management still overlooks the diversity of ecosystem services and their beneficiaries in the narrow pursuit of meeting urban demands

3.4 Governance

The principles underpinning CPRs as advanced by Ostrom [25] include explicit recognition of a social infrastructure comprising tiered, consensual rules in communities that incorporate monitoring of members' behaviour with associated graduated sanctions and dispute resolution for violators. Examples of CPR observed across the world exhibit these common principles, governing sustainable and egalitarian exploitation of the benefits of communal ecosystems. The idealised situations addressed as principal case studies by Ostrom [1] and [26] tend to focus on small, homogenous communities with strong mutual trust with a high level of self-governance. However, in addressing large and more internally contested systems, institutions and mechanisms for solving conflicts among local participants over how to divide the costs and benefits of using common resources needs to be explicitly factored into decision-making processes (Eggertsson, 2014) [34]. This has high relevance to complex catchments subject to competing demands, such as the Banas system.

The longer-term history of rural water stewardship in dryland Rajasthan, entailing close community collaboration at local scales in groundwater recharge and equitable distribution and use throughout the year, is substantially consistent with Ostrom's CPR model. Cumulatively, these localised practices have also maintained catchment-scale processes. However, technologically driven changes in social attitudes, essentially moving from a collaborative to a competitive model enabled by energised tube well extraction without either formal or informal sanctions nor even a register of tube wells, departs from simplistic application of the CPR model in rural settings whilst undermining the wider water resources of the catchment system. Asymmetric power relationships across, and large-scale energised water diversion from, the Banas system for urban use also departs from participatory governance ideals, skewing benefits to politically and economic influential constituencies (particularly municipalities and large-scale irrigators), and overlooking the interests of powerless and less favoured sectors of society co-dependent on common catchment resources. Lack of catchment-scale oversight progressively undermines ecosystem processes at catchment scale, ultimately undermining benefits to all competitive interests as groundwater recedes also exposing users to increasingly geological contaminated layers whilst also compromising the quantity and quality of water filling the Bisalpur Reservoir upon which urban constituencies have become increasingly dependent.

The lack of an integrated approach to catchment management in the Banas system, across Rajasthan and indeed in India in general, overlooks issues of maintaining overall catchment carrying capacity and of the protection of benefits to all constituencies. (Literature searches reveal no relevant references to catchment management in the Banas system and in Rajasthan, and few sources for India as a whole beyond largely conceptual overviews.) Appropriation of water by Jaipur city in the face of civil opposition reveals the imposition of power asymmetries without due consideration or recompense of the rights of local people and the needs of supporting ecosystems. These lacunae of governance contribute to the current degrading state of the Banas SES.

3.5 Technological solutions in the contemporary Banas system

All uses of a system ultimately affect system structure, resilience and function. In the case of the pre-mechanised Banas catchment, benign techniques such as localised groundwater recharge measures working to enhance natural processes of resource regeneration during monsoon rains represented a technical approach inherently sympathetic with the overall resilience of the catchment SES. By contrast, contemporary individualistic competitive behaviours in rural water extraction using boreholes, and the hegemony of influential sectors diverting water away from the catchment denying access to local and downstream users, represents the importance of technology choice in shaping the sustainability, or otherwise, of catchment systems. It also emphasises how governance systems shape technology choice, which may either enhance or undermine the sustainability of the linked social, ecological and economic dimensions of the SES.

3.6 A systemic perspective of contemporary conditions in the Banas catchment

The former, pre-mechanised conditions in both rural areas of the Banas catchment and the City of Jaipur, reliant on local resources the regeneration of which had been enhanced by innovative and

locally nuanced nature-based measures, represented an inherently regenerative SES. By contrast, contemporary trends under which asymmetric power relationships between urban and rural water users, favouring energised tube well extraction accessing increasingly deeper and more geologically contaminated groundwater resources with proportionate abandonment of traditional communal recharge practices as well as large-scale water diversion, ultimately undermines the common resource upon which the long-term wellbeing of all catchment co-dependents. Though systemically connected, communities and the ecosystem of the Banas SES find themselves today in a detrimentally degenerative cycle. Everard *et al*. (2018)[35] describe how these trends in the Banas system are resulting in linked degradation and growing risks for rural and urban water security, irrigation capacity, wildlife and associated ecotourism. Systemic connections between the upper, middle and lower reaches of the catchment, and between communities co-dependent on the common catchment resource, are fragmented by a lack of an overall governance framework focused on protection of the foundational ecosystem processes upon which ongoing human security, equity and opportunity potentially depends. Instead, technical solutions favouring immediate benefits to their proponents override systemic integrity, with the asymmetrical power exerted by urban constituencies dispossessing rural and ecological needs.

4.0 Vision of a regenerative SES cycle in the Banas catchment

There is a pressing need to reverse the degrading cycle of the Banas SES, both for its inherent value but also the security of its ecosystems and millions of human dependents. Everard *et al*. (2018)[35] presented a vision of a regenerative Banas catchment founded on rebalancing demands with the capacities of the foundational resource, through wiser policies and choices reflecting the interests of all catchment co-dependents and working with natural processes to enhance the system's supportive capacities. The following sub-sections explore this vision though the lens of the three framing questions – "who", "what" and "how much"? – set within the framing contexts of "why?" (governance) and "how?" (technological implementation).

4.1 Who should be considered in progress towards a sustainable Banas SES?

Interactions with the diverse communities and livelihoods across the 45,833 km^2 catchment area of the Banas system, including other urban areas receiving diverted water, are not today reflected in decisions pertaining to water resource exploitation or retention of the functioning and supportive capacities of the overall catchment. The large scale and heterogeneity of the Banas catchment is beyond simplistic application of the CPR model, necessitating structured governance arrangements to recognise and manage competing needs and demands. The former model of localised community collaboration needs, essentially, to be upscaled to deal with the greater complexity of contemporary conditions.

4.2 What should be considered in progress towards a sustainable Banas SES?

What appears to be almost entirely overlooked under the contemporary water extraction and diversion paradigm is the functioning of the overall ecosystem, its connections throughout the catchment, and the diversity of ecosystem services that flow from it. A refocusing of management to address system capacities, including the recharge of foundational groundwater and surface resources to balance exploitation and provision of other required services, is an essential underpinning for reversing the current degrading condition of the SES. This requires catchment-scale appreciation of ecosystem processes under a vision that goes beyond traditional river restoration approaches that, though still evolving, often lack convincing examples of maintaining ecosystem-level benefits particularly for larger rivers [36]. Indigenous communities are increasingly taking a lead in river restoration, re-engage socio-culturally and politically with their rivers to expand dimensions of river restoration that to date have been substantially underreported in ecological and social science literatures [37]. A focus on distributed measures that not only address local needs but that cumulatively restore river functioning is essential if the resource is to sustain the needs of its heterogeneous dependent population into the future.

4.3 How should values be considered in progress towards a sustainable Banas SES?

Failure to invest in the sustainability of catchment resources from which longer-term, wider-scale benefits accrue represents a major market failure. A significant measure identified to address this market failure pertains to charging for water diverted from the Bisalpur Dam, the City of Jaipur paying currently for the technology to divert the water but not for the water itself. In summary, this vision reflects that money, like the water it exploits, should be regarded as cyclic in terms of investment into the state of the natural capital yielding a return on investment of beneficial flows. The hidden costs of failure to invest in the renewability of the water itself include the substantial sums currently being considered for tapping ever more distant resource under the failing and inequitable 'more from further' model.

If investment from intensive water users benefitting from the provisioning service of fresh water supply were to be recycled to support improved water stewardship practices in the upper catchment, greater water security will be enjoyed by all linked beneficiaries by focusing on supporting catchment processes rather than competitive extraction for immediate benefit [35]. Basing management and investment decisions on protecting or restoring the supportive capacities of the whole catchment systems can thereby contribute to both improved water quantity and safer water quality, achieved by avoiding dependence on geologically contaminated, deeper and currently receding resources. At rural scale, greater emphasis on the multiple values of water in the ecosystem, including food production through enhanced soil moisture and support for the ecosystems upon which tourism and subsistence harvesting of fish and other provisioning benefits are founded, could safeguard values for a broader swathe of society.

4.4 What governance arrangements can propel progress towards a sustainable Banas SES?

Consideration of who benefits or not, what facets of ecosystem services are considered and net societal value might become implicit in management of CPRs at localised scales amongst largely homogenous communities. However, structured governance arrangements at bigger scales and in more complex systems, for enforcement of rules and enabling participatory dialogue to address competing demands, may be required where coherent social capital, mutual trust and shared long-term goals tend to be lacking. A comprehensive governance system, that may comprise both formal inducements (such as MJSA) and sanctions as well as devolved informal governance, requires an inclusive but ideally statutory approach accounting for the diversity of values and value systems enjoyed by society and so tending to contribute to more equitable decisions that also highlight the importance of maintaining the resilience of foundational ecosystems supporting the SES.

4.5 How can technology choice drive progress towards a sustainable Banas SES?

Decisions shaping technology choice, its distributional impacts and the overall functioning of the catchment system tended to be synergistic in pre-mechanised times, focused on resource recharge and sustainable access at local scales but distributed across the catchment. However, introduction of energised technologies in both rural areas and applied to meet the demands of the contemporary populous and urbanised situation create conflicts between users including the needs and viability of the ecosystem itself.

Everard (2019)[38] used the Banas system as a case study of how technological approaches can by hybridised to address impacts on catchment processes. Crudely stratifying water management infrastructure into four groups – natural, traditional solutions, 'green infrastructure' and heavy engineering – a progressive increase in efficiency of delivery of a narrow subset of desired services along this spectrum was observed, but also a decreasing departure from solutions that work in synergy with natural processes and which address the disparate needs of dependent communities. All techniques have their externalities, natural and traditional solutions working at small scale but unable to service concentrated centres of demand whereas heavy engineering solutions (such as the Bisalpur dam and water diversion schemes from it) tend to work against natural processes and to liquidate overlooked ecosystem services. The proposed solution is not simply overreliance on any one type of solution, but to explicitly recognise the externalities of each approach using the ecosystem services framework, and to invest in a hybridised set of solutions that protect or restore natural processes and the benefits that flow from them. In the case of the Banas, this would entail solutions such as the recycling of money from intensive water users, reliant on heavy engineering techniques, into support for a dispersed water capture and recharge approach modified from traditional practices in small-scale communities across the catchment, incentivising self-beneficial recharge of local groundwater that can cumulatively restore the quantity and quality of water available for abstraction from the Bisalpur Reservoir. A further co-benefit could include sufficient water available to allow for environmental flow releases from the dam, reanimating the ecosystems and dependent livelihoods of the lower catchment that are today largely disregarded.

As a SES, extraction within the Banas catchment could then be balanced with recharge engaging and providing benefits for all users ('who?'), addressing the maintenance of restoration of a broader

suite of ecosystem services ('what?') with greater distribution of benefits ('how much?'). Thus, the currently fractured and degrading catchment system can be returned to a positive, regenerative SES cycle, rebuilding the foundational capital of natural processes as an underpinning for socio-economic security, and averting the substantial costs and short-termism of constantly pursuing "more from further".

4. Discussion

The systemic nature of both ecosystem services and the SES approach is vital for understanding and management of complex systems. Whilst inherently renewable, the finite capacities of semi-closed catchment ecosystems are vulnerable to unsympathetic exploitation, necessitating a fully integrated management approach [39]. Uses and management of any landscape or waterscape has systemic consequences can may create either degenerative of regenerative SES cycles [40]. The distinction is the extent to which management practices and technology deployment work in sympathy with natural processes, ensuring the resilience and continued functioning of the system and hence its capacity to continue to provide beneficial ecosystem services, or conversely that undermine ecosystem properties and processes ultimately sending the whole interdependent socio-ecological system into a degrading cycle. The former, regenerative model is consistent with global needs to achieved ecosystem regeneration supporting continuing human wellbeing.

In less populated and more socially cohesive conditions, CPR principles could be enacted on the basis of substantial social capital and a long-term perspective, contemporary pressures of population and urbanisation create greater contest for short-term resource exploitation. However, the complexity of contemporary catchments and the contest for resources between stakeholders making use of catchment water resources means that the three strands of environmental process, social inclusivity and the plurality of benefits need to be considered within the additional contexts of governance frameworks and technology choice. Omission of any of the five strands can result in inequities, degradation of foundational ecosystem processes and erosion of overall societal value, often shaped by fragmentation of governance and dependence on technological approaches that erode system integrity and the wellbeing of all dependent constituencies. This accords with the concept of a 'full world', advanced by Daly (2005)[41], in which economic activities significantly exploit or exceed the capacities of the natural world, and the consequent need to maintain ecosystem functioning as a foundation for meeting human needs sustainably. In a world where the mass of humans is an order of magnitude higher than that of all wild mammals combined, with profound historical impacts of humanity on the global biomass of prominent taxa [42], the necessity of seeking a regenerative approach to the ways that SESs are constituted and exploited is an urgent priority.

Reversing ecosystem degradation is a major challenge threating livelihood security on a global basis, making ecosystem restoration a global imperative, UNEP (2019) [43] declaring 2010-2030 as The UN Decade on Ecosystem Restoration. A step-change is therefore required in restoration science, increasing its engagement with socio-economic research and public engagement so that people engage as conscious beneficiaries and key actors in system restoration, not merely emphasising the biophysical underpinnings of ecosystem service flows but with public perception serving as a key

driver of ecosystem restoration [44]. In the context of catchments, this entails a greater focus on the kind of stewardship of water and linked ecosystem resources that had been a distinctive feature of historic communal water management in Rajasthan, has been substantially abandoned at present, but may underpin a sustainable future albeit with traditional wisdoms adapted into modern conditions.

Stewardship is a vital principle informing the sustainable management and alignment of SESs, balancing resource use with regeneration. This is explicit in maximum sustainable yield (MSY) calculations in forestry and marine fisheries, albeit that MSY is often narrowly economic in focus and may support appropriation of resources rather than their viability and provision of wider suite of linked services [45]. Reflecting on the four 'Dublin Principles' [46] established as a foundation for Integrated Water Resources Management (IWRM), Everard (2019)[38] observed that stewardship was a missing element, the four principles framed as rates of extraction and rights to use and decide. Consequently, a fifth IWRM principle "*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*" was advanced to accompany the four existing principles [38] (Table 1).

Table 1: The four 'Dublin Principles' of integrated water resource management (WMO, 1992)[46], with proposed additional fifth resource replenishment and stewardship principle [38] (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

The Banas system today has suffered the blight of competitive, mechanised extraction with associated linked vulnerabilities. In essence, mechanised extraction of water and the assumed rights by powerful elites, in particular in large urban centres such as Jaipur, create compound pressures resulting in upstream-downstream competition for water, with little or no regard to the viability of the hydrological and other functions of the catchment ultimately providing for the needs of all inherently interdependent stakeholders. A stewardship-based model, in which hybrid technologies focus on the viability of the catchment system whilst addressing competing demands and the externalities resulting from technological deployment to serve them, offers a more sustainable vision. This requires focus on the ecosystem processes and services providing for the needs of all, rather than the current emphasis on competitive extraction from the Banas system and increasingly extending more remotely, in a model of upstream-downstream collaboration rather than competitive trade-off.

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In moving societal preoccupations and assumptions from an inherently degenerative approach favouring short-term and localised benefits from exploitation of resources without balancing regeneration towards a regenerative and sustainable stewardship model, questions of 'who?', 'what?' and 'how much?', transparently assessed and systemically integrated in decision-making and influencing technology choices, is a crucial underpinning. The need for sustainable framed governance systems is exemplified by water management challenges in the Banas system and in Rajasthan more widely, as urban/rural power relationships and resource use disparities are both significant and likely to be exacerbated by population growth and climate change trends. However, these challenges and indicative solutions have wider global relevance.

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