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# Comparative analysis of hybridised solutions to water resources management in Burkina Faso, India and Peru

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**Abstract**

Hybridisation of 'green' and engineered infrastructure, informed by protecting or restoring catchment processes, can resolve interconnected demands on catchment ecosystems, potentially also reversing historic degradation of socio-ecological systems. Pressures are acute in water-scarce, developing regions with episodic rainfall, exacerbated by historic presumptions favouring engineered management. Comparing conditions, histories and emerging approaches in contrasting regions – the Central Plateau of Burkina Faso, Rajasthan State (India) and Ayacucho Region (Peru) – reveals similar yet distinct approaches reflecting different starting regimes. Transferrable learning about hybridising localised, nature-based solutions and engineered technology informs the necessary transition towards a sustainable approach these and other regions.

**Keywords**

sustainable water management; nature-based solutions; adaptation; India; Burkina Faso; Peru

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**Introduction**

International discourse amongst water experts and multilateral funders has, in a transition commencing in the 1990s, begun to diverge from a narrowly technocentric 'hard'-engineered paradigm. Shifts are occurring towards a 'soft path' in which there is increasing emphasis on ecological values (Gleick, 2000) including growing interest in nature-based solutions (NBS) to address a range of water-related challenges (Cohen-Shacham et al., 2016; Abell et al., 2017; UN Environment – DHI et al., 2018; UN Water, 2018). NBS is defined by the IUCN as "…actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g. climate change, food and water security or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016). NBS is closely allied to the concept of 'green infrastructure', defined by the European Commission (2015) as "…a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings". The concept of 'green infrastructure' reflects application of NBS within more developed urban and rural landscapes (for example Grant, 2012). The paradigm of NBS, recognising the value of protected, restored or emulated ecosystems and their processes, improves ecosystem services and resilience, lowering costs, and delivering value to management of water and other natural resources (Nesshöver et al., 2017; Hartig and Kahn, 2016). A nature-based approach is shaping development strategies in both rural and urban areas. Practical implementation of NBS includes emerging approaches for natural coastal/river/urban storm and flood management and erosion control (Parliamentary Office of Science and Technology, 2011; IUCN, 2017; UN Environment – DHI et al., 2017). It is also evident in multiple global applications of integrated water resource and soil protection, applied at both highly localized and landscape scales (as reviewed by Everard, 2018, and UN Water, 2018).

Integrated Water Resources Management (IWRM) has increasingly become a framing construct for water policy reform, requiring cross-sectoral water management in which public participation plays a key role due to multiple, complex interdependencies between people and ecosystems (GWP-TAC, 2000). However, many researchers have highlighted the limitations of IWRM in practice (see for example Biswas, 2004). In relation to NBS in particular, Everard (2019) highlights that, focussed primarily on different dimensions of water extraction and decision-making, the four 'Dublin Principles' of IWRM (IRC, 1992) omit the fundamental need to emphasise foundation ecosystem processes, including rebalancing water resource recharge with exploitation across scales. Everard (2019) therefore proposed evolution towards Integrated Water Resources Stewardship (IWRS) by addition of a fifth stewardship 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*". This necessitates a primary focus on maintaining ecosystem viability and processes underpinning how different mixes of water management solutions are evaluated, deployed and integrated across catchments.

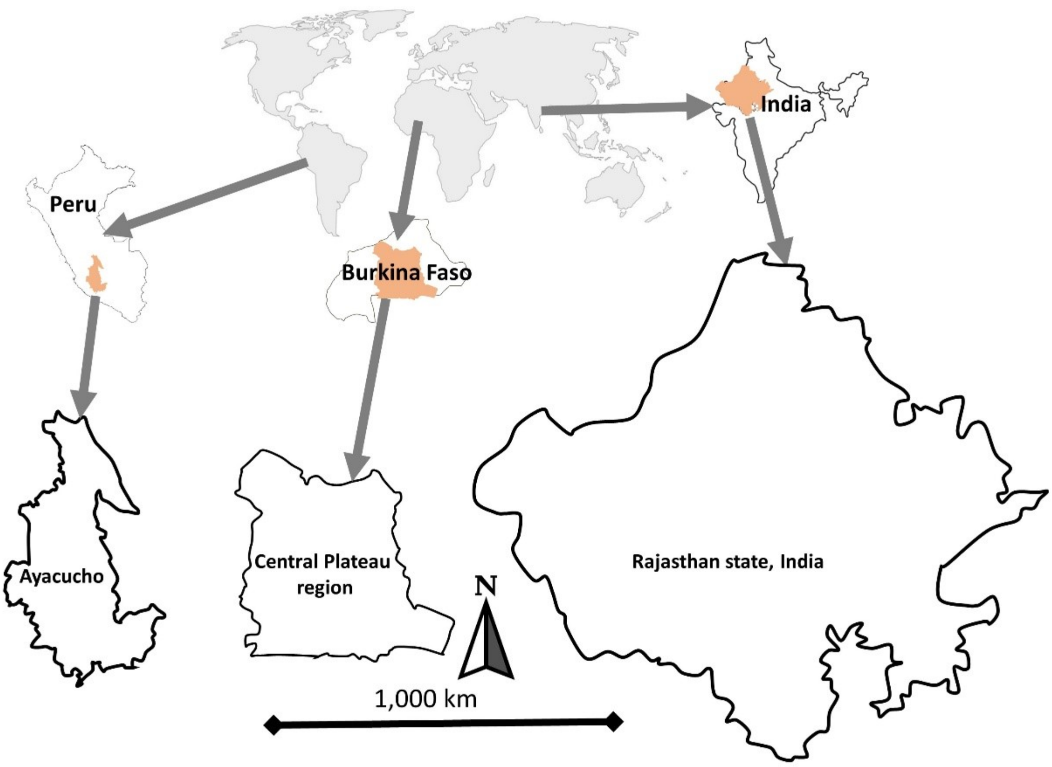
NBS acceptance, design and performance is highly influenced by local ecological, social and political conditions (European Commission, 2015). Uniform approaches to NBS might not provide the most suitable solution in every situation, given that natural and human systems are inherently heterogeneous, not only across the world but also across individual catchments. However, in some localities, locally adapted NBSs may represent the most beneficial or viable solution to water resource management challenges, addressing issues related to water quantity, quality and risks simultaneously, whilst building overall system resilience and reducing environmental pressures or rebuilding ecosystem functions (Cohen-Shacham et al., 2016; Abell et al., 2017; UN Environment – DHI et al, 2018; UN Water, 2018). Furthermore, NBS may be more sustainable and cost-effective than hard engineering solutions, certainly when applied to localised solutions but also, as in the case of natural flood management, as a more systemic, catchment-scale solution (UN Water, 2018).

Despite the potential local efficacy of NBSs, some water-related challenges, such as the storing water for hydroelectric power generation and piped distribution of water supply to intensive centres of water use (urban areas, industry and large-scale irrigation), require hard engineering (or 'grey infrastructure') solutions. A recent report by the World Bank and World Resource Institute (Browder et al., 2019) emphasises the importance of hybridisation of localised water capture, aquifer recharge and efficient use strategies, including both physical infrastructure and community governance arrangements, with engineered approaches installed to serve the needs of heterogeneous communities including intensive water users. Approaches that best serve human needs on a sustainable basis are likely to be those where NBS and 'hard engineering' infrastructure are used together in a hybridised solution that is both efficient and cost-effective, meeting the needs of service users whilst also maintaining (or rebuilding) ecosystems (Abell et al., 2017; UN Water, 2018; Browder et al., 2019). Such an approach is advocated, for example, in serving the currently conflicting demands of local and intensive water users in the Banas catchment in India's Rajasthan state (Everard *et al*., 2018), and more generically in rebalancing the functioning of water-storing ecosystems with human needs at catchment scale (Rockström, 2004).

Hybridised approaches have been shown to be highly effective at reducing water-related risks and building resilience to climate change, both of which will be highly relevant to the minimisation of human health and livelihood impacts, food and energy security, ecosystem rehabilitation and maintenance, and climate adaptation (European Environment Agency, 2017; Moglia and Cook, 2019). Developing regions and semi-arid lands (SALs) in particular are identified as climate change ´hotspots´ wherein changes in rainfall patterns, floods and droughts are expected to be significant (Huang et al, 2016). Furthermore, the livelihoods of the one billion people that live in these regions globally depend heavily on rain-fed agriculture and pastoralism, rendering them particularly vulnerable to water-related climate change impacts (Campbell et al., 2002). The combination of climate risk and socioeconomic profile means that human populations in SALs will be disproportionately vulnerable to climate change. This in turn threatens attainment of the central commitment underpinning the United Nation´s 2015-2030 sustainable development agenda (UN, 2015) – to 'leave no one behind' – unless action is taken to improve climate resilience and adaption (Gannon et al., 2018).

The development of water management in SALs is substantially shaped by geography, history and culture as well as governance arrangements. In this paper, we compare and contrast the development of differing approaches to water management in SALs across three geographical regions: the Central Plateau region of Burkina Faso; Rajasthan State in India, and the province of Ayacucho in Peru (Figure 1). These regions were selected on the basis that 1) they represent good examples of hybridised water management solutions in SALs; (2) they are within developing nations that are subject to a high degree of poverty; (3) rural people represent a significant proportion of total population; (4) there are known power imbalances between urban/intensive and rural water needs; (5) the research team is familiar with situations in each region; and (6) they span three different continents.

*Figure 1: Locations map of Ayacucho (Peru), the Central Plateau of Burkina Faso and Rajasthan state (India)*




Each of these regions has a different balance between centralised, technocentric management, 'hard engineering' solutions and NBS, shaped by their differing development and political trajectories. However, in all cases, there is a general move towards devolution of management responsibility to stewards of localised water resources, with growing emphasis on NBS and particularly re-evaluation of the nature-based approach embedded in traditional management solutions. Each region is also facing emerging demographic, climate and development challenges for which different water management models are being explored. The contrasting Burkinabe, Indian and Peruvian examples selected for this research share a vision of accommodating localised, devolved governance in catchment-scale planning, including solutions that serve the needs of local communities, simultaneously with supporting increasing urban demands. The contrasting regions start from different starting regimes. This creates opportunities for inter-regional learning from generically similar places with regionally and culturally nuanced physical and governance solutions, informing integrated solutions encompassing both 'green' (nature-based) and 'grey' ('hard engineering') infrastructure (Browder et al., 2019). From these observations, we seek to derive transferrable principles concerning the development of hybridised solutions to sustainable water management of wide relevance to semi-arid regions facing similar challenges.

**Trends in 'green' and 'grey' water management infrastructure**

NBS is an umbrella concept that describes a range of approaches recognizing the contribution that ecosystems and ecosystem services can make to global societal challenges, including water resources management, commonly entailing community governance (Cohen-Shacham et al., 2016; UN Environment – DHI et al., 2018; UN Water, 2018). Traditional and indigenous approaches, particularly those innovated prior to mechanisation that work instead to augment natural resource recharge processes and enable access to water at a sustainable pace, often embrace more natural approaches to water resources management (UN Water, 2018). Recognising the close dependence on governance arrangements, Ostrom (1990) applied and popularised the term 'Common Property Resources' (CPR) in a review of many such community-governed natural resources across the world. These governance arrangements tend to form by 'institutional bricolage': a process through which people, consciously and non-consciously, assemble or reshape institutional arrangements, drawing on whatever materials and resources are available, regardless of their original purpose (Cleaver and de Koning, 2015). Pearce (2004) and Everard (2013) review a diversity of traditional water management solutions adapted to local climate, geography and culture across the world. The term 'green infrastructure' reflects application of these nature-based principles within more developed urban and rural landscapes (for example Grant, 2012). These approaches recognise the interdependence of people with supporting ecosystems, including water resources. This highlights the need for a more balanced approach to water management that relies less on presumptions in favour of technocentric solutions but instead blends hard engineering with NBS approaches (UN Water, 2018).

Natural limitations inherent in both natural infrastructure and locally controlled NBS may constrain the potential volume of water available to supply the needs of large-scale users (cities, large-scale irrigation, industry), and so may hold back those aspects of development. However, overreliance on heavy engineering solutions, such as dam-and-transfer schemes or energised pumping of often receding groundwater, tends to not only favour already-economically privileged and politically influential (particularly urban) areas at the expense of rural and other communities. Overreliance on mechanised solutions also tends simultaneously to deplete catchment water resources through a primary focus on technically efficient extraction for immediate gains (World Commission on Dams, 2000). Examples of this technocentricity are seen in all three study regions, such exploitation of the waters in Burkina Faso´s Ziga Dam, Rajasthan's Bisalpur Dam and the demands of the Peruvian city of Lima.

Over-reliance on technically efficient, extraction- and transfer-based solutions is one of the drivers of a tendency to search increasingly remotely for perceived surplus water resources, appropriating and often ultimately depleting them, whilst also marginalising communities in donor catchments with the potential for fomenting civil unrest. Barraqué *et al*. (2008, p.1156) recognised this tendency as a "civil engineering paradigm" in which a narrowly engineering-based approach to addressing the water demands of growing cities drives and repeats a cycle of "taking more from further". Sustainable solutions lie not so much in reversion to either engineering or nature-based approaches, but in their context-specific hybridisation supporting local, rural needs whilst replenishing ecosystems from which large-scale water resources are withdrawn (Everard, 2019).

Whilst there is general agreement that hybridised solutions encompassing both NBS and 'grey infrastructure' are likely to constitute the most sustainable water management strategy for both urban and rural areas, determination of the right mix between both remains unclear as a result of a lack of tools, technical guidelines and approaches (UN Water, 2018). In addition, decision-makers often lack information and metrics to adequately evaluate and compare green infrastructure options to conventional grey approaches regarding technical specifications, costs and benefits (Browder *et al*., 2019). Everard (2019) also recognized the lack of a shared conceptual model of the systemic impacts of all technology choices on catchment dynamics, offering an ecosystem service-based approach to address this gap by explicitly recognising both the benefits and the externalities of different approaches and highlighting the need and means to mitigate the externalities. Adoption of ecosystem service-based systemic analysis can also overcome the current lack of coherent understanding in the literature as to what constitutes NBS or hybrid solutions, including the extent to which purportedly engineered solutions are in fact closely reliant on upstream ecosystem processes such as flow buffering, erosion regulation and physicochemical purification. Consequently, the term 'green infrastructure' is often used to describe what might otherwise be considered a hybrid approach (Kabisch et al., 2017). In this paper, we make a clear distinction between systems that rely solely on natural or ecosystem functions (green infrastructure), and where there processes of natural systems serve as a fundamental resource exploited by built infrastructure or technology (grey infrastructure), ideally constituting a hybridised model. Such hybridised models are emerging in water supply schemes in south west England under the 'Upstream Thinking' programme, in north west England under the SCaMP (Sustainable Catchment Management Programme) and in water resource supplies to New York City. These catchment-based approaches target protection of raw water quality at source, reducing risks and treatment costs to urban users, some based on 'payment for ecosystem services' (PES) arrangements (all reviewed by Everard, 2013).

## Methodology

*STEEP framework*

The STEEP (social, technological, ecological, economic, political) model, initially developed to help businesses assess global change issues (Morrison and Wilson, 1996), has been applied to analyse systemic relationships in different domains of human activity including meeting sustainability goals (Steward and Kuska, 2011) and integrating different types of knowledge (Aretano *et al*., 2013). STEEP has been developed and applied as a systems model exploring interlinkages between its constituent elements in the deployment of technologies and associated governance systems for management of water, ecosystem service flows and development issues in South Africa, Europe and India (Everard *et al*. 2012; Everard 2013 and 2015). Key to its systemic application is exploring interlinkages between the five constituent domains: the functioning of socio-ecological systems within complex political, economic and technology deployment situations. STEEP is used here as a basis for examining how ecosystem services can be managed within a modern societal decision-making context accounting for systemic relationships between interlinked domains of human activity and interest in the three contrasting regions.

*Introduction of case studies*

Differing water management histories between the three case study regions are represented against an illustrative timeline in Figure 2. All regions have a longer-term history of localised, community-based water management. However, pathways diverged throughout the twentieth century. Civil unrest in Ayacucho, particularly through the 1980s and 1990s, inhibited development and significant urbanisation. Over the course of the twentieth century, in the late colonial era and following Indian independence (1947), Rajasthan as part of a general trend across India followed a pathway of political centralisation and an increasingly technocentric approach to water management (Sathyamurthy, 1996). Since gaining independence as the Republic of Upper Volta in 1960, a focus of development aid in Burkina Faso has led to rapid increases in the provision of improved water supply and sanitation in urban areas, but access to basic water sources and sanitation in rural areas, where three-quarters of the population live, remains relatively low. An overview of the main characteristics of each case study is provided in Table 1, with more detailed information included in the following paragraphs.

*Figure 2: Illustrative representation of changes in water management paradigm over time in Ayacucho, Burkina Faso and Rajasthan*

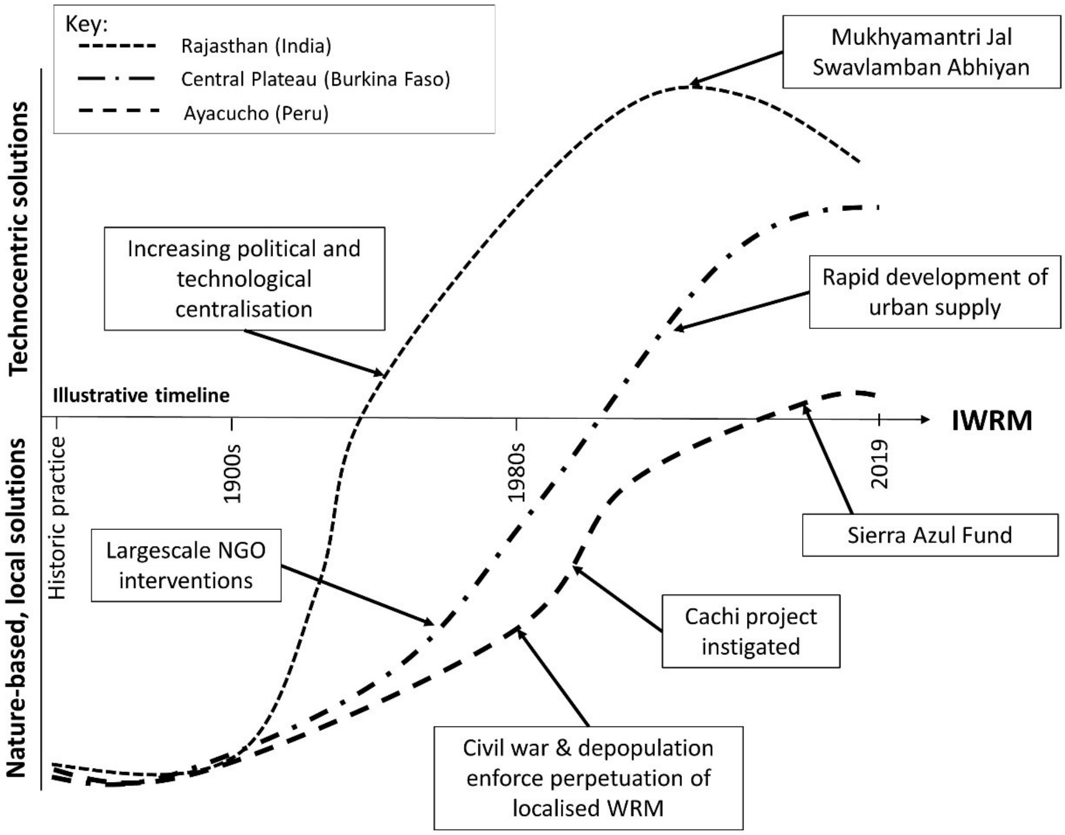



*Table 1: Main characteristics of the three case study sites in Burkina Faso, India and Peru*

| | Plateau Central (Burkina Faso) | Rajasthan (India) | Ayacucho (Peru) |
|---|---|---|---|
| **Area** | 94,000 km$^2$ | 342,239 km$^2$ | 43,821 km$^2$ |
| **Population** | 8,700,000 | 68,500,00 | 703,628 |
| **Annual rainfall** | 300-900 mm | 100-650 mm | 5-1,500 mm |
| **National HDI (Human Development Index) Ranking (UNDP, 2019)** | 182 | 129 | 82= |
| **Current green infrastructure (summarised from Case Studies below)** | Soil and water conservation (e.g. planting pits, grass strips, stone lines) to reduce land degradation and increase water supply for rain-fed agriculture. | Diverse local solutions to recharge shallow groundwater, local storage in ponds (naadi), contour trenches, loose stone check dams | Surface water storage, groundwater recharge (e.g. *amunas*) and soil and water conservation (e.g. pasture closure). Supply for agriculture and drinking water. |
| **Current grey infrastructure (summarised from Case** | Large-scale dams and reservoirs (e.g. Ziga and Bagré) for hydropower and water supply to | Diversion of water from increasingly remote dams/catchment to serve urban demands | Cachi Project, which transfers water from the Chicllarazo, Apacheta and Choccoro rivers to the |

| | | | |
|---|---|---|---|
| **Studies below)** | Ouagadougou. Smaller scale dams and reservoirs for local water supply and irrigation. | | Cuchoquesera dam (water supply and power generation) |
| **Aspirations (summarised from Case Studies below)** | Development of a new model of water management balancing technologically advanced with nature-based and localised solutions to water management | | |

*Data collection and analysis*

Information on the history and nature of water management in the target SAL regions was primarily collated from literature sources. The main sources of literature for the case of the Central Plateau area of Burkina Faso are Petit and Baron, (2009), Critchley and Gowing (2013) and Newborne and Tucker (2015). Reviews by Everard (2015), Tiwari et al. (2015), Varua *et al*. (2016), Everard *et al*. (2018) and Dashora et al. (2019) are principal sources for the situation in Rajasthan State, India. Assessing the situations in the Ayacucho region of Peru, we draw extensively from reviews by Mills-Novoa and Taboada Hermoza (2017) and Oré and Rap (2009). All sources are substantially augmented by wider literature, together with various national policy documents.

As a means to assess both disconnections and successes, the situation in each arid/semi-arid region was stratified against the STEEP framework.

**Results**

*Case Study 1 – Central Plateau, Burkina Faso*

For the purposes of this research, the Central Plateau region of Burkina Faso is considered as the area roughly equivalent to the central third of the country (West et al., 2008), comprising the contemporary administrative regions of Nord, Centre-Nord, Centre-Est, Centre-South, Centre, Plateau-Central and Centre-Ouest (excluding the provinces of Sanguié and Sissili). Nature-based soil and water conservation techniques to restore degraded land (*zipele*) and/or increase agricultural production, including for example small planting pits known locally as *zaï*, have been traditionally used by small-scale farmers in the north of the Central Plateau where rainfall is lower and more highly variable compared to further south (Kaboré and Reij, 2004). Large-scale promotion and implementation of these and other similar nature-based water management techniques in the north of the Central Plateau began during the 1960s and 1970s, with support from both the national Government and international non-governmental organizations (NGOs) as a response to the severe droughts that occurred during this period (Kabore-Sawadogo et al., 2013). In the following decades, the potential of these techniques to reduce the vulnerability of poor small-scale farmers from the impacts of increasingly unpredictable and highly variable rainfall across the Central Plateau region was recognized by national Government and International Organizations. This led to implementation of several large projects, such as PATECORE (*Projet Aménagement des Terroirs et Conservation des Ressources)*, implemented in 400 villages in the Bam province (PATECORE, 2004). The active promotion of NBS for water management continues (Douxchamps et al., 2012; Critchley and

Gowing, 2013), and further expansion of their use forms part of the Government's current National Adaptation Plan (NAP) (GoBF, 2015a) and Intended Nationally Determined Contributions (INDC) (GoBF, 2015b). Detention and storage of surface flow in naturally low-lying areas (*bas-fonds*) during the rainy season is another traditional technique that represented a key coping mechanism to the water deficits experienced during the 1970s and 80s (Sally et al., 2011). These and other small reservoirs (*retenues d'eau*) are still used widely across the Central Plateau today, primarily for livestock watering and the irrigation of small plots comprising markets gardens, with a total of 790 across the country (GoBF, 2018). Both types of nature-based structure also serve to recharge groundwater (Newborne and Gansaonré, 2017; Koïta *et al*., 2018).

The repair and construction of both small and large-scale dams and reservoirs forms a major part of Burkina Faso´s strategy to increase access to water, not just for small-scale farmers but for many different types of water users (GoBF, 2018). Aside from the impacts of climate change, water resources in the Central Plateau region are under severe stress due to competing demands for water. In the central region, there is an increasing demand for water supply from the growing urban population in the Burkinabé capital, Ouagadougou. Approximately 70% of Ouagadougou's water supply is currently diverted from out-of-catchment from the Ziga reservoir retained by the Ziga dam, located along the Nakambé River (White Volta) approximately 50 kilometres east-north-east of the capital (GoBF, 2013 in Newborne and Tucker, 2015). The Ziga project (phase I and II) is designed to meet the capital´s water needs until 2030 (Newborne and Gansaoré, 2017). However, due to the rapid rates of population increase, there is growing pressure for water to be released from Bagré dam, also out of catchment and impounding the Nakambe River 146 km to the south-east, which would reduce the water supply available for hydropower and irrigation (Newborne and Tucker, 2015). Notwithstanding the current trend of urbanisation across the region (and the country as a whole), farming populations will remain high and agriculture will continue to represent a key vehicle of both poverty reduction and facilitation of the structural transformation of the economy, as outlined in the National Plan for Social and Economic Development (PNDES) 2016-2020 (GoBF, 2016). The priority of the Burkinabé government (with donor backing) is to support special agricultural zones, known as 'agro-poles', where agricultural investment and activity is to be concentrated in the development of modern large-scale irrigation systems, one of which is located at Bagré (Newborne and Gansaonré, 2017).

Although the Government presents both urban and rural areas as equal priorities in the promotion of poverty reduction and economic development in their various policy documents, in practice, urban areas (in particular, Ouagadougou) have much greater power to plan and implement water-related investments. This problem is amplified by the fact that on-the-ground implementation of localised level water management institutions that form an important part of the Government´s IWRM approach (triggered by a highly water-stressed context and need for an evidence-based approach to water management) has been limited since the Burkinabé water sector was reformed in the early 2000s (Petit and Baron, 2009). For example, evidence suggests that rural populations located along the banks and upstream of the Ziga reservoir have been inadequately compensated for losing access to water supplies that they previously used for small-scale irrigation and cattle watering, and which is now reserved solely for use of water supply for Ouagadougou (Newborne and Gansaonré, 2017).

These diversions of water from the Ziga Reservoir, and current pressures also to exploit water from the Bagré dam, are consistent with the "civil engineering paradigm" described by Barraqué *et al*. (2008), with associated rural dispossession and linked issues of ecological and socio-economic disadvantage in donor catchments.

Burkinabé Government recognizes and has stated policies seeking to promote the value of both green and grey infrastructure for water management (MEFR, 2015; GoBF, 2018), and is actively engaging with international partners in a bid to improve their integration (Crawford et al., 2016). One example of this is the recent IUCN project ´WISE-UP to Climate', which tested and developed integrated approaches to optimizing built infrastructure and NBS for water resources management in the Volta River basin (Crawford et al., 2016). Nonetheless, more needs to be done to ensure truly integrated water resources management by the Government, and to increase understanding of the potential impacts and trade-offs between different potential portfolios of nature-based and engineered solutions (Newborne and Tucker, 2015). Key aspects of the Burkinabé situation are summarised in Table 2 in accordance with the STEEP framework.

*Table 2: Commentary on STEEP (social, technological, environmental, economic, political) elements observed in current and recent water management in the Central Plateau, Burkina Faso*

| STEEP element | Relevant aspects relating the STEEP element to the system as a whole |
|---|---|
| Social | • Conflict between an increasingly urbanized population that requires growing levels of water supply, and a rural population seeking to increase both rain-fed and irrigated crop production.<br>• A historic culture of strong hierarchical relationships limits the implementation of the participatory principles of IWRM (Traore, 2002, in Petit and Baron, 2009). |
| Technological | • The increasingly urbanized population drives the construction of dams and reservoirs, so that water can be collected, stored and transferred to the capital, as well as used for irrigation and generation of energy.<br>• Advances in irrigation technology and a focus on smart agriculture, particularly in designated larger-scale farming development areas ('agro-poles´) are focused on the development of modern irrigation systems.<br>• A focus on more ´crop per drop´ drives adoption of green infrastructure, particularly by small-scale farmers, as well as modern irrigation systems. |
| Environmental | • Recurrent drought and increasingly variable rainfall combined with an increasing population density drives soils over-exploitation and land degradation on the Central Plateau, an increasingly severe issue (Kabore-Sawadogo et al., 2013).<br>• The aim of reducing vulnerability to climate variability drives efforts to both increase water storage and adoption of nature-based soil and water conservation.<br>• Objectives of food security and poverty reduction take precedence over environmental protection (Petit and Baron, 2009), overlooking their inherent interdependencies. |

| | |
|---|---|
| Economic | • A high dependence on agriculture persists, with 90% of the population engaged in the sector. The government's ambition is to increase the contribution of irrigated agriculture to national agricultural production to 25% by 2020 (GoBF, 2016) with a focus on 'agro-poles'.<br>• The national development strategy gives equal importance to both urban and rural areas for the promotion of economic growth. |
| Political (governance) | • Government policy (both IWRM-related, as well as broader rural development, climate change and sustainable land management adaptation policy) is directed at the expansion of NBS for climate change adaptation and resilience building, together with the construction of a range of grey infrastructure to ensure the provision of water for irrigation, hydropower generation and domestic water supply<br>• On the ground implementation of local level water management institutions and their functions is limited (although some examples of success stories do exist: see Petit and Baron, 2009). |

*Case Study 2 - Rajasthan, India*

Governance systems in India are nested, reflecting the sheer physical size and the geographical and cultural heterogeneity of the country, particularly as instituted under the Panchayat Raj system (Hardgrave and Kochanek, 2008). 'Top down' legislation and decision-making at national and state level delivered at the level of Development Blocks and enforced by District Collectors links with community-based 'bottom up' governance arrangements from village-scale Gram Panchayats or Gram Sabha through Gila Panchayats at the Development Block level, supported by a diversity of NGOs at national down to local levels. Communities in the arid Thar Desert and semi-arid regions of the state of Rajasthan have innovated a diversity of NBSs, backed up by community-based governance, enabling them to thrive throughout a four-and-a-half thousand year history (Sharma *et al*., 2018). However, India's water management strategy throughout much of the latter half of the twentieth century has followed a familiar pathway of increasing uptake of and dependence on technocentric, large-scale and energized water infrastructure, including appropriation of water resource ownership by the state and exploitation by politically powerful users. This kind of centralisation, of policy, water ownership and technology, is as much a political strategy of nation-building and supremacy over water scarcity and other natural limitations as a solution addressing the needs of all in society (Wittfogel, 1957; Worster, 1985; Reisner, 1986; Swyngedouw, 2007; Molle *et al*., 2009). In a rural setting, the pervasion of tube wells has compounded this situation, cumulatively depleting water resources, accessing geologically contaminated and potentially non-renewable groundwater, breaking down community collaboration and contributing to a cycle of socio-ecological breakdown (Chinnasamy and Agoramoorthy, 2016).

Risks of capture of water resources by elites using heavy engineering techniques is well-known across India (Birkenholtz, 2016). This includes appropriation under considerable local opposition by the City of Jaipur of water from the Bisalpur Dam. The Bisalpur Dam was initially constructed for local purposes (as reviewed by Everard *et al*., 2018). Appropriation of the Bisalpur Dam's water to serve the city of Jaipur was resisted by protests from local people, sometimes turning violent with some farmers shot dead (Birkenholtz, 2016). Key aspects stratified by the STEEP framework are summarised in Table 3, addressing the linked vulnerabilities of inherently interconnected rural, urban, wildlife and irrigation beneficiaries of water resources from the Banas catchment in Rajasthan.

*Table 3: Commentary on STEEP (social, technological, environmental, economic, political) elements observed in current and recent water management in Rajasthan, India*

| STEEP element | Relevant aspects relating the STEEP element to the system as a whole |
|---|---|
| Social | • The asymmetric power of municipalities and other intensive water users tends to appropriate increasingly remote water resources, to the detriment of less advantage stakeholder groups (Birkenholtz, 2016; Everard *et al*., 2018).<br>• Whereas community collaboration has been foundational to subsistence on limited water resources throughout millennia, tube wells and other energised solutions are leading to individualised, competitive extraction without regard to community cohesion and the rights of other users of common resources (Chinnasamy and Agoramoorthy, 2016).<br>• There is little (though recently increasing) regard across catchments of how water extraction by influential stakeholder groups affects access to water by other groups (Everard *et al*., 2018). |
| Technological | • Whereas historic approaches were founded on technologies balancing resource recharge from monsoon rains with sustainable extraction and efficient use, contemporary energised extraction and water transfer schemes are selected on the basis of technically efficient extraction without regard to resource renewability (Sharma *et al*., 2018).<br>• There is recent recognition of the importance of reinstatement of innovation of localised rural solutions as a basis for self-sufficiency, for example under the Government of Rajasthan's flagship *Mukhya Mantri Jal Swavlamban Abhiyan* programme (Government of Rajasthan, 2018). |
| Environmental | • Contrary to historic approaches embedding significant local knowledge and traditional wisdom, the overall carrying capacity of local aquifers and catchment resources are overlooked in contemporary mechanised water exploitation resulting in a cycle of degradation of ecosystems, their services and the security of their dependents at all scales (Sharma *et al*., 2018).<br>• Wider-scale interactions between local water-harvesting and use and the dynamics of wider catchments, including inputs to reservoirs and other reserves exploited by intensive users, are not well understood, representing a significant research gap (Everard, 2019). |
| Economic | • In contemporary Rajasthan, contrary to its longer-term history, the diverse values of all ecosystem services and their distribution across society are substantially overlooked in a narrowly neoliberal exploitative approach to water extraction (Everard *et al*., 2018).<br>• Systemic ramifications of solutions for costs and benefits across all ecosystem services and their associated beneficiaries are significantly |

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| | overlooked under the contemporary exploitation model (Everard, 2019). |
| Political (governance) | • Despite long-standing multi-scalar governance, there is little practical connection between different tiers of informal and formal governance in decisions on water allocation and exploitation, as a result of power asymmetries and also disconnections between different government departments (Birkenholtz, 2016). |

In recent times, declining groundwater and increasing geological contamination and water scarcity have forced a rethink of policy directions in Rajasthan. International programmes such as 'more crop per drop' (FAO, 2003) and the Government of Rajasthan's flagship *Mukhya Mantri Jal Swavlamban Abhiyan* (MJSA: 'Chief Minister's Water Self-sufficiency Mission) programme have refocussed attention on local stewardship of water, including localised groundwater recharge and its efficient and equitable use as part of a vision to find long-term solutions for a water-sustainable Rajasthan (Government of Rajasthan, 2018). This is necessarily a transformative process in India, given the backdrop of the previous century of progressive centralisation of legislation and reliance on engineering solutions, and their legacy in regulations, technocentric culture and increasing drought vulnerability.

Everard et al. (2018) set out a vision of the sustainable hybridisation of the technologies serving these integrated recipients of water-related services. This vision regards the Banas catchment as an integrated unit, with recommendation for the recycling of money, mirroring the water cycle in the catchment. In this ideal economic cycle, urban and other intensive users of water piped from a major dam on the river would pay for water, with revenues recirculated to rural communities in the upper catchment. These subsidies can support self-beneficial construction and maintenance of water-harvesting and water-efficient practices that combine at catchment scale to improve flows of water of improved quality into the Bisalpur Dam. A payment for ecosystem services (PES) approach is recommended, though there is no current appropriate legislative basis for achievement of this catchment-scale integrated approach. However, the MJSA programme has some similarities with the general aims and principles of PES by recirculating taxpayer revenues (purchase of services by government on behalf of public beneficiaries) into rural self-sufficiency projects that potentially contribute to overall catchment regeneration (service providers). Everard (2019) progresses this thinking by using an ecosystem services framework to assess the strengths but also limitations and externalities of different water management solutions: natural infrastructure, traditional NBS, 'green infrastructure' and heavy engineering. This insight forms a conceptual basis for hybridisation of nature-based with technocentric approaches to work with catchment processes, including the mitigation of explicitly recognised externalities, as a foundation for restoring ecosystem viability supporting all water users in the Banas catchment.

*Case Study 3 - Ayacucho, Peru*

Located on the centre-south of Peru, the region of Ayacucho has a population working predominantly in the agricultural sector (Banco Central de Reserva del Perú, 2015). Historic and a significant part of current rural water demand has been or is substantially met by upland wetlands as well as *Bofedales*, *qochas* and *amunas*. (*Bofedales* comprise naturally occurring depressions in the flat, treeless uplands, many of which have been increased in size and connected by people over thousands of years to enhance vegetation and water supply. *Qochas* constitute small-scale water storage basins developed for local use. Amunas comprise water-collecting systems used since pre-Hispanic times comprising ditches with permeable walls to collect and divert water to artificial springs (Barúa, 2017).) Lane (2009) reviews research dating back to the Late Intermediate Period (AD 1000–1480) in the north-central Andes, revealing sophisticated social organization of water management through devolved power and development of a complex suite of hydraulic technologies including silt dams and silt reservoirs.Peru instigated the Cachi Project in 1987 following implementation of many large-scale irrigation projects during the 1970s. Larger-scale regional agriculture and drinking water supplies for Ayacucho city now depend upon the Cachi Project as their principal infrastructure. The Cachi Project transfers water from the Chicllarazo, Choccoro and Apacheta rivers to the Cuchoquesera Dam, also fed by wetland ecosystems as well as *bofedales*. This represents a mix of NBS supporting the filling of engineered dams and water transfer schemes. As a result of the fragile condition of this semi-arid upland ecosystem, there is a high susceptibility to climate change, in particular to irregular water availability in lagoons, lakes and rivers (the average annual precipitation oscillates between 5mm to 1,500 mm).

Similar to India, water governance systems in Peru are nested, with strongly technical centralised institutions interacting with ‘bottom up’ social organizations that have conserved or recovered ancestral knowledge for water management. The Cachi Project was considered as the lever for the "self-sustainable development" of the region, the basis of agricultural development and a key factor in reducing rural migration during a period of internal armed conflict, with the progressive threat of drug trafficking (Corporación de Fomento y Desarrollo Económico Social de Ayacucho, 1983). However, there was a lag-phase of twenty years from the first designs and studies to completion of the Cuchoquesera Dam. Planned works under the Cachi Project have not yet been completed, and many sections of infrastructure are deteriorating. Nevertheless, the Cachi Project remains a central political banner of Ayacucho elites to provide for the needs of the city and for irrigation, effectively centralising benefits for the already privileged at the expense of rural development (Gilvonio and Zeisser, 2015).

Away from the city, in the Andean region of Ayacucho, where 62% of agriculture is rain-fed, NBSs continue to be developed by communities highly dependent on natural resources as an adaptation to increasing climatic variability. State-promoted projects related to NBS date back to the 1980s in Peru. These include projects such as the National Watershed Management and Soil Conservation Program (PRONAMACHCS), the Natural Resources Management Project in the Southern Highlands (MARENAS), the Sustainable Water and Soils Management Project in Laderas (MASAL), and the Adaptation to Climate Change Program (PACC Peru), implemented by state agencies with international cooperation.

In the case of Ayacucho, the work of two local NGOs, Bartolomé Aripaylla Association (ABA) and the Centre for Agricultural Development (CEDAP), was key to resumption of traditional practices of sowing and harvesting water (Asociación Bartolomé Aripaylla, 2014). A particularly important solution was the construction of *qochas*, many of which had been abandoned due to migration of people consequent from the civil war. The recognition of this work raised the possibility of scaling-up these types of nature-based and locally beneficial interventions through a public fund at the national level and a legal framework for promotion. A complicating factor in some regions of Ayacucho is enrichment of water by metals and other pollutants arising from historic and artisanal mining (Loredo *et al*., 2009). Consequently, the Sierra Azul Fund was created in 2017 (previously called "Mi Riego" Fund) as a technical and political response from the public sector to the problems affecting the water security of families farming in the Andes, with the purpose of executing viable public investments in water harvesting projects. This re-localisation of water control and management techniques rebalances some of the intended and unintended consequences of centralisation seen under the Cachi Project, supporting local uses as well as contributing to adaptation and development of small-scale agriculture. At this point, a recent impact evaluation of the Sierra Azul Fund reveals that small-scale interventions improved agricultural productivity, though profitability and income have not increased (Zegarra, 2019). Nonetheless, this fund generates improved livelihood expectations in rural areas, as in Ayacucho where more than 53 *qochas* will be constructed by the end of 2019 (Ministerio de Agricultura y Riego, nd).

The linkage between upstream water storage and contributions to catchment flow compensation is recognised in Peru under the Water Law of 2009 and the Compensation Mechanisms for Ecosystem Services Law[1] of 2014. Both legal tools essentially seek to balance the needs of local, rural people with the demands of intensive irrigation and urban users. Elsewhere in Peru, such as the major city of Lima (with a population of almost 10 million), power asymmetries mean that demands are met at the perceived expense of rural inhabitants in the catchment (Hommes and Boelens, 2017), much as they are perceived to be in Rajasthan and throughout India (Birkenholtz, 2016) and in Burkina Faso (Newborne and Tucker, 2015). In Ayacucho, the breach of agreements to the detriment of the communities surrounding the Cuchoquesera Dam has generated discontent, leading the communities to request hearings with the Regional Government of Ayacucho to determine compensation measures (CONDESAN, 2014). At the end of 2018, SUNASS (National Superintendence of Services and Sanitation) announced the implementation of a compensation mechanism for ecosystem services, including projects in Ayacucho, specifically in the Challhuamayo and Quichcahuasi microbasins within the Cachi basin headwater, which may help to address some of the communities' demands. Financial measures may, as proposed for the Banas catchment in Rajasthan, have a role to play in Ayacucho, where these compensation mechanisms may be used to recirculate payments from *retribuyentes* (beneficiaries) to *contribuyentes* (providers) promoting implementation of NBS projects. Overall, the goal of these interventions is to simultaneously recover or improve flows of ecosystem services and enhance the wellbeing of communities in upland basins. Finally, the recent Law on Climate Change (Government of Peru, 2018) attempts to promote the implementation of adaptation and mitigation measures addressing climate change, considering the contribution of traditional knowledge, the hydrological cycle and the ecosystem-based adaptation approach. A summary of the situation in Ayacucho, stratified by the STEEP framework, is provided in Table 4.

[1] We use the term 'compensation' as the translation of *retribución*. According to the Law, compensation mechanisms for ecosystem services are "schemes or tools to generate, transfer or invest economic resources for the conservation, recovery and sustainable use of ecosystem service sources".

*Table 4: Commentary on STEEP (social, technological, environmental, economic, political) elements observed in current and recent water management in Ayacucho, Peru*

| STEEP element | Relevant aspects relating the STEEP element to the system as a whole |
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| Social | • Increasing (social) recognition of the needs of all users are beginning to shape IWRM implementation, countering the power asymmetries of former prioritisation of large-scale irrigation projects (Corporación de Fomento y Desarrollo Económico Social de Ayacucho, 1983).<br>• The demand for water and sanitation services in a growing city is seen as an opportunity to implement NBS that compensate for past 'ecological injustices' perceived by communities located in the upper basin (Corporación de Fomento y Desarrollo Económico Social de Ayacucho, 1983).<br>• Nevertheless, power asymmetries remain between societal sectors favouring the demands of influential communities at the perceived expense of rural inhabitants (Hommes and Boelens, 2017), |
| Technological | • Former presumption in favour of technocentric solutions based on procuring supply to intensive users, often by diversion from remote regions, is currently being reassessed in terms of better understanding of solutions that work with the hydrological cycle to provide a wider distribution of benefits (soil moisture, humidity, rain, infiltration) (Zegarra, 2019).<br>• There is greater openness to integrate traditional knowledge (water sowing and harvesting) with more technical and intensive approaches as part of blended solutions promoted by the state (Government of Peru, 2018). |
| Environmental | • The hydrometeorological trend is towards increases in dry period indices (consecutive days without rain), which affects families reliant upon rain-fed agriculture and the recovery of degraded ecosystems (Gobierno Regional de Ayacucho, 2015).<br>• Natural processes occurring in the headwaters, such as leaching of mineral-rich rocks (including from historic and artisanal mining) and consequent mobilization of metals and acidity, may impair water quality downstream and ecosystem services (Loredo *et al*., 2009). |
| Economic | • More than 50% of the population of Ayacucho has an occupation linked to agriculture, so NBS proposals to improve this sector and the income of the population are key for the development of the region (Government of Peru, 2018).<br>• Water service and sanitation companies are key players in the financing of NBS aimed at improving ecosystem services for this sector. Because the collection for this service is low, it is expected that other actors from the private sector may join the recently created compensation mechanism (Compensation Mechanisms for Ecosystem Services Law of 2014). |
| Political (governance) | • NBS are part of numerous officially recognized strategies and policies, such as the National Agrarian Policy, the Plan of Risk Management and Adaptation to Climate Change in the Agricultural Sector, with the National Policy and Strategy on Water Resources, |

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| | and recently in the Framework Law on Climate Change, among others (Government of Peru, 2018).<br>• Peasant communities are key to the success of these types of solutions, their governance institutions operate closer to the population and so are capable of monitoring compliance with agreements at the local level. In addition, because NBS usually involve part of their territories, their effective participation in the acceptance and execution of proposals is required in order to guarantee the sustainability of NBS (Asociación Bartolomé Aripaylla, 2014). |

The current situation in Ayacucho is framed by a highly localised and community-based approach enforced by historic conflict and failed attempts of development through the Cachi Project. However, in the national scenario, current development aspirations recognize the need for more intensive, large-scale management solutions. Significantly, as the balance changes between traditional and local solutions towards engineered and basin-scale management serving the needs of increasingly populated urban centres, traditional practices for water security and associated rights are protected, at least theoretically, in legislation. Nevertheless, transposition of these intents into practical operational practices is facing conflicts.

While the official narrative of the Water Law in Peru is 'soft path'-oriented in congruence with the IWRM paradigm (French, 2016), emphasizing demand control, 4 large-scale irrigations projects are being prioritized as catalysts for regional and national economic development (Ministerio de Economía y Finanzas, 2019). In addition, Del Castillo Pinto (2011) identifies some shortcomings in the Water Law including degree of participation of the private sector in hydraulic infrastructure without clear regulatory controls. Nevertheless, there is also a growing revaluation of traditional knowledge and practices as a major contributor to water security (Ochoa-Tocachi et al, 2019). In this way, 'green' solutions are being recovered and recognized as a complement to 'grey' infrastructure development, which should work as a hybridised approach to alleviating water stress.

**Discussion**

Stratifying water management challenges in Ayacucho, Rajasthan and the Central Plateau of Burkina Faso according to the STEEP reveals many commonalities. Social disparities in power relations have favoured large urban and other intensive users, skewing technology choice and economic benefits in their favour to the exclusion of less privileged sectors, undermining ecosystem capacities yet at the same time depending upon ecosystem processes. Nonetheless, there is emerging recognition in all three study regions that governance arrangements require reform to take account of distributional outcomes and the resilience of water systems. Thus, systemic interdependencies between STEEP elements are apparent, yet also evidently have not featured centrally in many former phases of management arrangements.

The close interdependence of intensive technological solutions, such as dam-and-transfer schemes and large diversion for irrigation and other uses, and water use in upstream catchment uses, is evident in all three case study areas. However, whilst Government of Rajasthan leadership is occurring under the MJSA scheme, power asymmetries from fast-growing urban centres remain, along with a persistent presumption towards the "civil engineering paradigm". The same situation is apparent in Burkina Faso, where aspirations to draw water from the relatively distant Bagré Dam run counter to concerns about the integration of NBS as a more sustainable alternative to increasingly remote water transfers. So too in Ayacucho, where re-localisation of water management techniques and control under the Sierra Azul fund is counterbalanced with continuing government commitment to centralisation and appropriation under the Cachi Project, albeit that this trajectory has been delayed by the recent history of civil conflict.

Thus, each region is facing common but locally nuanced emerging demographic, climate and development challenges for which different water management models are being explored and emerging government initiatives are taking shape, though not yet fully integrated with or overturning former technocentric presumptions. Transitions in technology from heavy engineering towards more integrated NBS do not appear to be limited by lack of traditional and novel ecosystem- and community-based solutions. However, inefficiencies in the design, assessment and implementation of green and grey infrastructure projects may have emerged from a lack of systemic thinking about outcomes. This may be an institutional failure, as well as due to scarcity of understanding and data informing green designs in different geographies, perpetuating automatic presumptions in favour of the kinds of mechanised solutions that profitable engineering consultancies are keen to promote (World Commission on Dams, 2000).

Everard *et al*. (2016) describe how the significance of issues perceived initially as 'environmental' tend only to become more widely recognised and institutionalised when their ramifications, or 'ripples', are expressed in other components of the STEEP framework, for example, as matters of economic, health or distributional equity concern. This 'ripple effect' would seem also to apply in the case of water management. Recognition of the often overlooked systemic implications of narrow technocentric presumptions behind the "civil engineering paradigm", as well as the benefits of a hybridised approach, across the whole STEEP framework can then provide the basis for a communication strategy to promote transition to a more integrated and sustainable approach to water management. We use the STEEP framework to identify common themes across the three comparative regions, the consequences of the "civil engineering paradigm", and the benefits of a more integrated approach hybridising nature-based with engineered solutions (see Table 5).

*Table 5: A summary of (a) common themes across study areas, (b) consequences of the "civil engineering paradigm", and (c) benefits of a more integrated approach hybridising nature-based with engineered solution, based on the STEEP (social, technological, environmental, economic, political) framework.*

| **STEEP element** | **Common themes across study regions, and likely outcomes of a narrow engineering-focus compared with hybridised solutions linking NBS with engineering** |
|---|---|

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| Social | a) Social disparities in power relationships have favoured large urban and other intensive users. At local rural scale, NBS have been informed by locally articulated needs integrating the views of multiple stakeholders including their traditional knowledge with NGOs playing key integrative roles. The needs of urban/intensive and rural communities have often been poorly integrated in decision-making.<br>b) Large-scale engineering solutions tend to favour intensive users, and so too reinforce power asymmetries and distributional outcomes across society.<br>c) Localised solutions related to local needs, integrated with engineered solutions fed by ecosystem flows and serving intensive centres of demand, can work with catchment processes for win-win outcomes. |
| Technological | a) Technology choice has often formerly been shaped by power asymmetries in society, with poor rural communities generally losing out to those in more developed areas, though there is emerging recognition of the value of locally effective solutions responding to ecosystem processes and community needs.<br>b) A large-scale engineering presumption tends to impose uniform, 'top down' solutions that undermine ecosystem processes and marginalise small-scale dependants.<br>c) Localised solutions addressing local needs and natural processes, commonly based on as well as adapting, traditional knowledge and technologies, can regenerate catchment processes essential for enhancing water resources simultaneously supporting local needs and engineered solutions. |
| Environmental | a) Ecosystem processes and capacities tend to be undermined unless there is a commitment to stewardship that balances resources recharge with exploitation ('withdrawal-to-availability'), evidenced for example by the depletion of Rajasthan's Banas River system through removal of water from the Bisalpur Dam and by deep tube well extraction throughout the catching undermining river system vitality and its many ecosystem services.<br>b) A large-scale engineering presumption tends to undermine ecosystem processes, focusing on exploitation without balancing recharge.<br>c) Linking localised NBS can address local needs simultaneously with regenerating catchment capacity to provide inputs to engineered solutions adopted to serve centres of intensive demand. |
| Economic | a) As water diverted for productive uses from rural to urban areas is a common feature in the three case study areas, associated economic benefits will also have tended to be skewed towards urban and other intensive users of water. This implicitly is to the detriment of security for rural and small-scale water users, as well as undermining the capacities of supporting ecosystems and the many service benefits they provide, both representing major market failures.<br>b) The large-scale engineering presumption based on the utility of water overlooks its many values both as a resource for distributed small-scale users but also as a vector of a range of valuable ecosystem services. |

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| | c) Localised solutions addressing local needs and working with natural processes can regenerate catchment processes essential for enhancing water resources for engineered solutions, yielding substantial net benefits and greater distributional equity including for the diversity of water-vectored ecosystem services and the long-term resilience of the catchment system. |
| Political (governance) | a) Disparities in power relationships have formerly dominated governance arrangements, which require reform to better address the continued viability of supporting ecosystem and the equitable distribution of benefits across all in society.<br>b) Presumptions in favour of large-scale engineering solutions tend to reinforce 'top down' governance arrangements favouring privileged sectors of society, inadvertently undermining ecosystems and the needs of their diverse dependents.<br>c) Conversely, greater synergies between local and 'bottom up' governance arrangements can better recognise the distributional benefits and disbenefits of different management options, allow for innovation of mitigation measures to conserve the foundational resource of catchment processes and services, and hence recognise the potential benefits of linking nature-based with engineered solutions across catchments for greater sustainability and distributional equity. |
| Systemic connections | a) Historically localised solutions were inherently connected across the elements of STEEP.<br>b) Interconnections have substantially disintegrated with technology options and choice governed by short-term financial advantage, breaking down community cohesion and degrading supporting environments.<br>c) A more systemically connected approach across all elements of the STEEP framework is required to achieve sustainable, hybridised solutions, informed by social, economic and ecological aspects of technology choice and governance arrangements. |

Greater integration of governance and decision-making is required across scales to ensure that a shared conceptual understanding of the ramifications of all technology choices, both 'green' and 'grey', are hybridised to produce an optimally beneficial outcome for all connected communities and the ecosystems that support their needs, so returning the socio-ecological system into a regenerative cycle. This will entail explicit recognition of the strengths but also the limitations, the often formerly overlooked externalities and potential mitigation measures that may be applied under different technological approaches. This is summarised in Table 6 (adapted from Everard, 2019, with some examples from the three case study regions).

*Table 6: Strengths, limitations and externalities, and potential mitigation measures of different technological approaches relating to development of hybridised water management solutions (adapted from Everard, 2019) with examples from the three case study regions*

| | **Type of infrastructure** | |
|---|---|---|
| | **Nature-based solutions/'Green infrastructure'** | **Hard engineering/'grey infrastructure'** |

| | | |
|---|---|---|
| **Strengths** | • Provides multiple, linked ecosystem services suiting low demand and adapted to local environments and needs<br>• Emulates natural processes that augment supply of water and related ecosystem services to offset shortfalls in developed environments (e.g. zaï pits in Burkina Faso) | • Provides efficient delivery of a limited set of services for dense populations |
| **Limitations/ externalities** | • Can be over-ridden with increasing demand<br>• May require substantial land area, and lack of innovation may not adequately address contemporary lifestyles<br>• Limited opportunities for retrofitting, and needs recognition of the value of services in new build | • Tends to create many negative externalities (e.g. catchment depletion under the Cachi Project in Peru perceived by highland communities) |
| **Mitigation measures** | • Protect, restore or recreate critical habitat to retain or regenerate services<br>• Reverse current trends towards abandonment of traditional NBS (e.g. under the Sierra Azul fund in Peru)<br>• Innovate novel methods to apply traditional wisdom in modern contexts<br>• Requires recognition of the value of ecosystem services on a par with built assets in urban and industrial planning and development (e.g. as reflected in Rajasthan´s Government investment in the MJSA programme to support rural development). | • Narrow presumptions in favour of 'hard' engineering solutions need to be challenged (e.g. dam-and transfer schemes in all three study regions), considering how alternative approaches may provide more sustainable solutions<br>• 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 (e.g. the potential to reverse declining water quality and low rate of filling of the Bisalpur Dam through catchment-based solutions as a contribution to increasing water security for Jaipur City). |

In all localities, as indeed throughout much of the water-stressed world, sustainable solutions lie not in uniform adherence to either engineering and nature-based approaches, but rather their hybridisation. Through the context-sensitive implementation and integration of these different paradigms, solutions can be developed that simultaneously support local, rural needs whilst replenishing the catchment-scale ecosystems from which large-scale water resources are withdrawn. This call for a 'pervasive localism' approach, in which local communities work with ecosystems to support their needs whilst contributing to hydrological processes at landscape scale supporting the demands of intensive users, has been made previously by Everard (2016 and 2018), and specifically so in the case of Rajasthan's Banas catchment by Everard *et al*. (2018). Making this transition from current trajectories and their underpinning paradigms requires systemic thinking and integration across disciplines and policy areas (UN Water, 2018).

By outlining both the 'ripples' (wider systemic ramifications) of the "civil engineering paradigm" together with the benefits of a hybridised approach (Table 5), and the potential for hybridisation of water management approaches to balance out formerly often overlooked externalities at catchment scale (Table 6), decision-makers are armed with a framework for transparently taking better account of the needs of all societal beneficiaries and actors, and the catchment ecosystems supporting their needs. This can then inform practical delivery of the vision and stated aspiration of sustainable hybridisation of nature-based and engineered solutions to address common problems in contrasting geographic regions.

**Conclusions**

- In all three semi-arid landscape study regions, nature-based and localised water management approaches served communities over longer-scale history. However, recent centralisation and mechanisation trends have to varying degrees degraded foundational natural processes and capacities often to the disadvantage of the least influential and privileged sectors of society.
- There is growing recognition of the need to integrate localised, nature-based approaches with mechanised water extraction as a basis for water security, manifesting to differing degrees and using different legislative, financial and management approaches between the three study regions.
- A catchment-scale approach is required, ecosystem processes necessarily informing technology assessment, deployment and management, and the integration of different nature-based and mechanised solutions to work in greater synergy with each other and with catchment processes.
- Hybridisation of ‘green’ and ´grey´ engineered infrastructure informed by protecting or restoring catchment processes can simultaneously serve the disparate but interconnected demands of rural and urban communities by focusing on the viability of their common supportive ecosystems.
- Power relations have to be addressed in all study regions. All stakeholders play significant roles as actual or potential users, financiers, or other forms of actor in the protection or restoration of catchment processes. Collaboration in decision-making is essential to underpin the needs of all people sharing catchment water resources.
- Reform of regulatory regimes, including financial instruments (both deterrents and inducements such as under ‘payment for ecosystem services’ schemes), have important roles to play in driving progress towards the sustainability of catchment-scale processes and resources.
- Further research is required to quantify interdependencies and potential synergies between different management approaches and how they can be integrated to fully mitigate externalities from technology choice. For this, the future infrastructure model needs also to be informed by systemic perspectives, rather than simply maximising short-term exploitation of water, with a systemic approach to long-term social, economic and ecosystem viability and equity.
- Learning from this study is transferrable to these and other arid and semi-arid regions facing similar challenges.

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