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Abstract: Much of the developing world and areas of the developed world suffer water vulnerability. Engineering solutions enable technically efficient extraction and diversion of water towards areas of demand but, without rebalancing resource regeneration, can generate multiple adverse ecological and human consequences. The Banas River, Rajasthan (India), has been extensively developed for water diversion, particularly from the Bisalpur Dam from which water is appropriated by powerful urban constituencies dispossessing local people. Coincidentally, abandonment of traditional management, including groundwater recharge practices, is leading to increasingly receding and contaminated groundwater. This creates linked vulnerabilities for rural communities, irrigation schemes, urban users, dependent ecosystems and the multiple ecosystem services that they provide, compounded by climate change and population growth. This paper addresses vulnerabilities created by fragmented policy measures between rural development, urban and irrigation water supply and downstream consequences for people and wildlife. Perpetuating narrowly technocentric approaches to resource exploitation is likely only to compound emerging problems. Alternatively, restoration or innovation of groundwater recharge practices, particularly in the upper catchment, can represent a proven, ecosystem-based approach to resource regeneration with linked beneficial socio-ecological benefits. Hybridising an ecosystem-based approach with engineered methods can simultaneously increase the security of rural livelihoods, piped urban and irrigation supplies, and the vitality of river ecosystems and their services to beneficiaries. A renewed policy focus on local-scale water recharge practices balancing water extraction technologies is consistent with emerging Rajasthani policies, particularly Jal Swavlamban Abhiyan ('water self-reliance mission'). Policy reform emphasising recharge can contribute to water security and yield socio-economic outcomes through a

systemic understanding of how the water system functions, and by connecting goals and budgets across multiple, currently fragmented policy areas. The underpinning principles of this necessary paradigm shift are proven and have wider geographic relevance, though context-specific research is required to underpin robust policy and practical implementation.

Response to Reviewers: See detailed responses in the attached 'Response to reviewers' document

Assessing the feasibility of integrating ecosystem-based with engineered water resource governance and management for water security in semi-arid landscapes: a case study in the Banas Catchment, Rajasthan, India

Everard et al.

COVER LETTER

Good afternoon Damia,

Many thanks once again for handling this paper. Your speedy response arrived just after I had logged off for vacation, but I am back today and pleased to see that we are really close.

I have given this paper my highest priority. The 'Response to Reviewers' document details how I have handled specific points, but I have run through the whole paper once again tidying it up in places too.

Many thanks, as ever, for your support.

Best wishes,

Mark

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Response to referee comments for submission STOTEN-D-17-05339R1

This document records responses to referee comments received on 14th August 2017.

Responses to referee comments

Reviewer #1: I have read the revised manuscript with title "Assessing the feasibility of integrating ecosystem-based with engineered water resource governance and management for water security in semi-arid landscapes: a case study in the Banas Catchment, Rajasthan, India" which have revised and covered the majority of reviewer's comments.

- Thank you; I am pleased that the reviewer recognises that the prior revision covers the majority of reviewers' comments.

However, some descriptions/explanations in the manuscript are unclear. In particular, the new section "Implementation in other ecosystems" suffers the main flaws, because some information are not clear and should be better referenced. I highly recommend the authors to revise them.

- I have re-titled the section referred to as 'Implementation in other water –stressed regions' as this is more meaningful in the context of the paper's findings.
- I have though also done a substantial reread and edit of the whole of the Results and Discussion section, adding in a few more references to substantiate points made (this new information does not change any conclusion) and improving clarity of English.

Therefore I suggest publication after minor revisions.

- I hope that the final (??) revision meets with approval and addresses all identified concerns.

Minor points:

1) Page 7 line 270: the author cited (Department of Water Resource, 2000) is not reported in References.

- I have now inserted this reference into the Reference list, with an 'accessed' date of today (24th August 2017) though of course consulted much earlier in the drafting process.

2) Page 8 line 292: the author cited (Government of India, 2007) is not reported in References.

- I have now inserted this reference into the Reference list, with an 'accessed' date of today (24th August 2017) though of course consulted much earlier in the drafting process.

3) Page 13 line 461: the authors cited (Agarwal et al., 1990) are not reported in References.

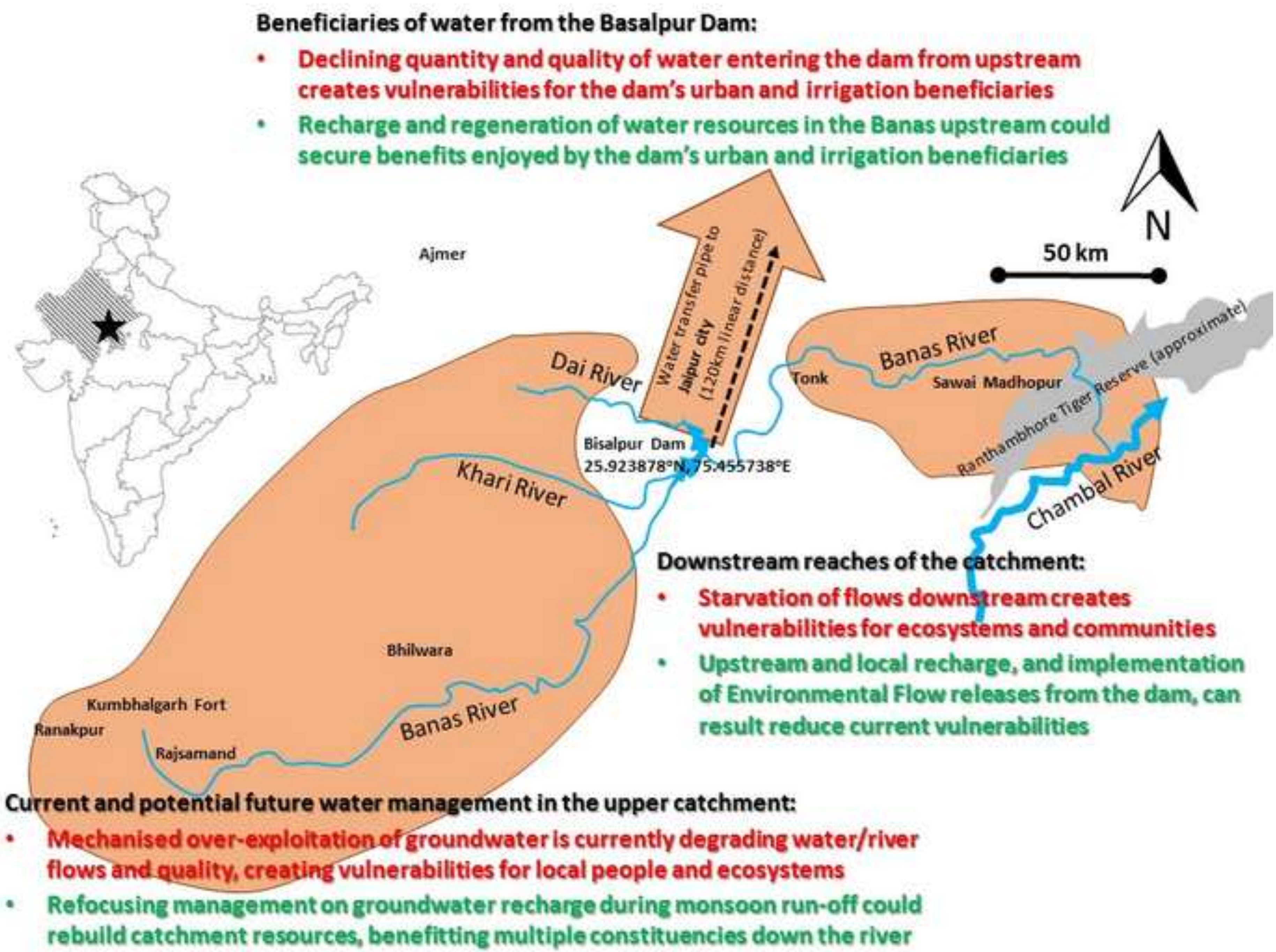
- Apologies, this should have cited the Agarwal et al. (1999) reference, which is included in the Reference list. I have made this correction in the text.

4) References: Agarwal et al. (1999); Dass et al. (2012); Butler et al. (2011); EPW (2006); Everard (2009); Everard (2016); Everard and McInnes (2013) are reported in References, but not in the manuscript.

- See the note above about incorrectly citing this reference as (Agarwal et al., 1999) in the text, an error now rectified.
- Thank you, I have now incorporated the Dass et al. (2012) reference in the correct place in the text.
- Thank you. I had streamlined the text in my last rewrite removing analogies between water resource and flood risk management, but omitted to delete this citations from the Reference list. It is now omitted.

- Thank you. Again, citation of EPW (2006) was omitted in the last revision but inadvertently retained in the Reference list. It is now omitted.
- Thank you. Again, citation of Everard (2009) was omitted in the last revision but inadvertently retained in the Reference list. It is now omitted.
- Thank you. Again, citation of Everard (2016) was ‘cleaned up’ in the last revision but inadvertently retained in the Reference list. It is now omitted.
- The citation of Everard and McInnes (2013) was also ‘cleaned up’ in the last revision but inadvertently retained in the Reference list. However, in my revision of the Results and Discussion section, I have resurrected it and so reinserted it into the Reference list.

*Graphical Abstract



Research highlights

1. Intensive water over-exploitation drives socio-ecological degradation in the Banas
2. Historic and current schemes regenerate water resources from monsoon rains
3. A program refocused on resource recharge can benefit all catchment beneficiaries
4. Rajasthan’s policy environment recognises the need to promote resource recharge
5. A systemic approach to management and investment can guide sustainable development

Assessing the feasibility of integrating ecosystem-based with engineered water resource governance and management for water security in semi-arid landscapes: a case study in the Banas Catchment, Rajasthan, India

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Abstract

Much of the developing world and areas of the developed world suffer water vulnerability. Engineering solutions enable technically efficient extraction and diversion of water towards areas of demand but, without rebalancing resource regeneration, can generate multiple adverse ecological and human consequences. The Banas River, Rajasthan (India), has been extensively developed for water diversion, particularly from the Bisalpur Dam from which water is appropriated by powerful urban constituencies dispossessing local people. Coincidentally, abandonment of traditional management, including groundwater recharge practices, is leading to increasingly receding and contaminated groundwater. This creates linked vulnerabilities for rural communities, irrigation schemes, urban users, dependent ecosystems and the multiple ecosystem services that they provide, compounded by climate change and population growth. This paper addresses vulnerabilities created by fragmented policy measures between rural development, urban and irrigation water supply and downstream consequences for people and wildlife. Perpetuating narrowly technocentric approaches to resource exploitation is likely only to compound emerging problems. Alternatively, restoration or innovation of groundwater recharge practices, particularly in the upper catchment, can represent a proven, ecosystem-based approach to resource regeneration with linked beneficial socio-ecological benefits. Hybridising an ecosystem-based approach with engineered methods can simultaneously increase the security of rural livelihoods, piped urban and irrigation supplies, and the vitality of river ecosystems and their services to beneficiaries. A renewed policy focus on local-scale water recharge practices balancing water extraction technologies is consistent with emerging Rajasthani policies, particularly *Jal Swavlamban Abhiyan* ('water self-reliance mission'). Policy reform emphasising recharge can contribute to water security and yield socio-economic outcomes through a systemic understanding of how the water system functions, and by connecting goals and budgets across multiple, currently fragmented policy areas. The underpinning principles of this necessary paradigm shift are proven and have wider geographic relevance, though context-specific research is required to underpin robust policy and practical implementation.

Key words

Banas; Bisalpur; community-based recharge; water resources; vulnerability, ecosystem services

Research highlights

1. Intensive water over-exploitation drives socio-ecological degradation in the Banas
2. Historic and current schemes regenerate water resources from monsoon rains
3. A program refocused on resource recharge can benefit all catchment beneficiaries
4. Rajasthan's policy environment recognises the need to promote resource recharge
5. A systemic approach to management and investment can guide sustainable development

1. Introduction

Industrial growth, technological development and capital accumulation during the nineteenth century triggered economic thinking and consequent management and technology choices that overlooked the importance of ecological processes and their contributions to public and business welfare (Braat and de Groot, 2012). Across multiple policy spheres, broader spatial and temporal negative externalities resulting from narrow framing of both problems and solutions consequently result not from bad intent but from lack of systemic perspective. Technology choices for the provision of water to urban centres, industry and irrigation exemplify this utilitarian approach, overlooking wider ramifications for the water cycle and its dependent ecosystems and livelihoods downstream of abstracted surface and groundwater resources (World Commission on Dams, 2000). Lack of systemic thinking is also contributory to state-led dispossession of water rights from rural people as a supply-side solution to support industrial and urban economic growth (Birkenholtz, 2016). Technocentric policy presumptions tend to drive engineered solutions, for example 'dam and transfer' schemes and energised groundwater abstraction, maximising a subset of uses of piped water and energy favouring influential beneficiaries whilst overlooking many linked ecosystem services and their beneficiaries (World Commission on Dams, 2000; Everard, 2013).

The integral connections between urban, rural, industrial, agricultural and nature conservation benefits provided by catchment ecosystems have often been overlooked in former management paradigms (Newson, 2008). Integrated Water Resources Management (IWRM) has been advanced as a response to meeting competing needs and uses at catchment scale (Calder, 1999), including addressing the growing problem of water scarcity in the developing world (Shah and van Koppen, 2014). Practical implementation of the principles of IWRM across extensive and diverse landscapes in developing world situations is however frequently limited by knowledge and data gaps, regulatory and scientific capacities, and power asymmetries (Ioris, 2008).

Everard (2013) identified the need and opportunities for increasing synergy between ecosystem-based and engineered water management solutions. Neither paradigm represents a panacea in mixed urban-rural landscapes, in which engineered management is far more interdependent with ecosystem processes than is conventionally recognised. Large-scale cases of landscape management for improving raw water quality, for example serving water supply to New York City (Committee to Review the New York City Watershed Management Strategy *et al*., 2000), the Upstream Thinking programme in south west England (McGonigle *et al*., 2012) and to protect natural spring water sources in France (Perrot-Maître, 2006), demonstrate substantial economic and input efficiencies relative to conventional electromechanical treatment of more contaminated water, also producing multiple ecosystem service co-benefits.

In India, recent policy presumptions favour advanced engineering solutions that may not work in sympathy with local geography and culture, and hence may not be sustainable in the long term. These include substantial investment in large-scale 'dam and transfer' schemes, diverting water from areas of perceived excess towards urban economies and intensive irrigation centres of high demand. India's National Informatics Centre (2017) lists 4,877 completed 'large dams' (as defined by the International Commission on Large Dams, ICOLD) with a further 313 large dams under construction across the country, impounding virtually all large rivers systems. The needs of people and ecosystems in donor catchments are poorly reflected in management decisions, though ramifications of physical impoundments, redirection of flows and changes in catchment ecosystem services may be profound (World Commission on Dams, 2000). Severe problems stemming from over-exploitation of groundwater have long been recognised, including depletion of water tables, saltwater encroachment, drying of aquifers, groundwater pollution, and soil waterlogging and salinisation (Singh and Singh, 2002) and local risk of subsidence (Rodriguez and Lira, 2008). Nevertheless, India's policy environment still favours energised tube well abstraction of receding and increasingly geologically contaminated groundwater to promote short-term agricultural profitability (FAO, 2011). This is leading to abandonment of centuries-long, geographically and culturally sensitive practices and loss of associated traditional wisdom balancing water access with recharge from episodic monsoon rainfall (Das, 2015; Raju, 2015).

This paper addresses vulnerabilities created by fragmented policy measures between rural development, urban and irrigation water supply, and downstream consequences for people and wildlife. Water vulnerability is a multi-factorial issue, comprising water scarcity, generally assessed on a volumetric basis, and water stress which includes factors such as water quality, accessibility and the commonly underestimated influence of governance arrangements and other social factors (Plummer *et al*., 2012). Water vulnerability is therefore a dynamic concept integrating geographical and climatic factors with demand, infrastructural conditions and prevailing institutional arrangements, economic policy, planning and management approaches (FAO, 2012). Essentially, the concept of water vulnerability is interpreted in this paper as relating to risks arising from availability of water of adequate quality and quantity to secure the wellbeing of humans and ecosystems.

This study focuses on the Banas catchment in Rajasthan state, India. The question addressed by this paper is how restoration of the Banas water system can be achieved at catchment scale, seeking mutual benefits for rural, urban, irrigation and wildlife co-dependents. This is addressed by the objectives of: characterising trends in the Banas catchment; identifying vulnerabilities for co-dependents; proposing systemic solutions to reverse degradation of the catchment socio-ecological system (SES); and identifying research and development priorities to achieve linked urban and rural livelihood and ecosystem security. These objectives are addressed by targeted visits, including empirical observations and semi-structured interviews at sites in upper, middle and lower river reaches, literature review, and identification and testing of proposed solutions within the cross-sectoral co-author community. Although the case study is geographically specific, underlying principles are of generic geographical relevance across water-stressed areas of the world.

2. Methods

Evidence-gathering for this study took the form of literature review and site visits to the upper, middle and lower Banas catchment including semi-structured interviews with key stakeholders active.

2.1 Literature review

Literature review took account of a diversity of peer-reviewed sources but also, by necessity, of technical reports (particularly by Government institutions in Rajasthan and at national level in India) and relevant media sources to assemble evidence where peer-reviewed literature was lacking. This diversity of published sources was used to characterise and document transitions in infrastructure development in the catchment. Learning from ecosystem-based catchment restoration solutions implemented elsewhere in Rajasthan was included in the review.

2.2 Site visits and semi-structured interviews

Site visits were conducted in three distinct zones of the Banas catchment: the headwater locations; the Bisalpur Dam mid-way down the river system; and Amblidha where the Banas transects the Ranthambhore Tiger Reserve. At these different locations, some interviews were prearranged whilst others were opportunistic. Interviewees included a range of Forest Officers in the upper and lower catchments, village gatherings, the Junior Site Engineer at the Bisalpur Dam, local people operating water infrastructure, and staff of NGOs. Given the heterogeneity of sites and the wide diversity of geographical and cultural perspectives of interviewees, it was neither feasible nor useful to undertake a uniform structured interview. Interviews were therefore of necessity semi-structured, building around how the five dimensions of the STEEP framework (social, technological, environmental, economic and political) manifested in the local setting. Observations and interviews at all field sites were recorded in writing at the time of the visit. Prompting questions from interviewers were structured around social arrangements, technology choice, environmental context including flows of ecosystem services, economic aspects, and political context (multi-scale governance, not just the formal policy environment). In order not to restrict the flow of information, interviewees were allowed to expand freely on answers to prompts, with key points of their feedback recorded for later dissociation around STEEP elements. Once all aspects of the STEEP framework were exhausted in conversations, interviews were concluded with thanks and a request to use this information for research purposes.

A two-day visit in June 2017 was undertaken in vicinity of the headwaters of the Banas system. This visit included the source of the South Banas (also known as the Katar) which rises in the grounds of a temple at Berokamath. The source of the North Banas (also known as the Gomti or Gomati) at Sevantri as also visited. Various river sites, including the first major impoundment of the South Banas at Bagara Dam, were also part of this visit. Invited meetings also took place with five local men from Bawara village situated on the banks of the South Banas upstream of the Bagara Dam, and a village community meeting at Kesar village in hill country between the sources of the two Banas headwaters. Opportunist discussions also occurred with people at small impoundments or operating water infrastructure at sites on the North Banas River.

A site visit was undertaken to the Bisalpur Dam in April 2017. This entailed observations of the dam infrastructure and locality, and in particular a semi-structured interview with Dharmendra Kaushik, Junior Site Engineer, who had been involved in the planning and building phase of the Bisalpur Dam between 1987 and commissioning in 2002 and had subsequently continuously held the role of Junior Site Engineer.

Visits to the lower Banas in Amblidha where it transects the Ranthambhore Tiger Reserve are documented in Everard *et al*. (2017). Visits by the senior author took place in April 2016 and April 2017, with other co-authors (in particular Khandal and Sahu) visiting and working in communities and habitat throughout the lower river reach on a routine basis.

Additional information is provided from the literature, and also the direct working experiences in the Banas of Forest Department and NGO co-authors. The spectrum of expert and interviewee input is listed in Table A1 in the Annex. It is recognised that this is a sparse sampling regime enforced by time and budgetary limitations relative to the size and heterogeneity of the catchment. However, attention has been paid to trends in water use and resources at key upstream, mid-river/dam and downstream locations to build an overview.

3. Results and Discussion

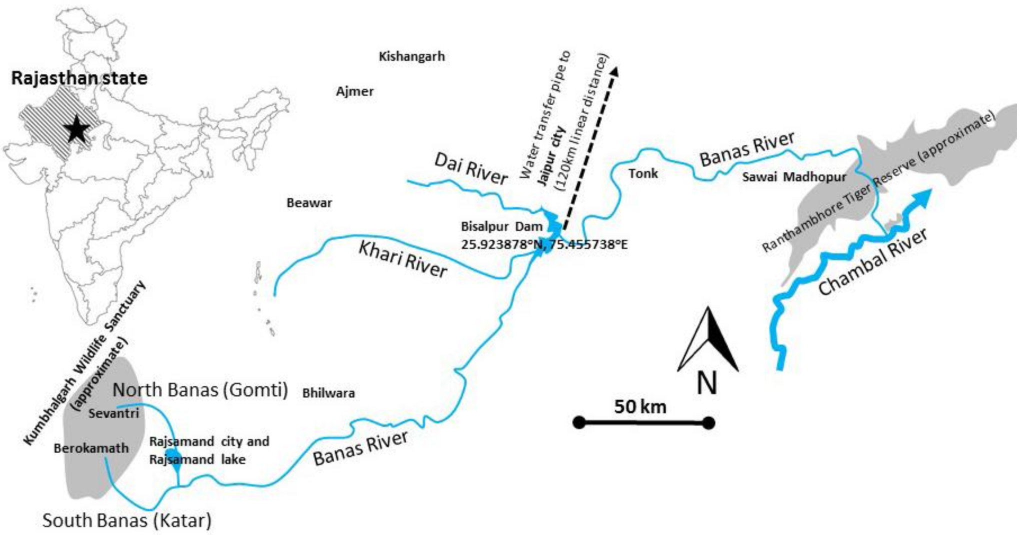
This Results and Discussion section draws on the evidence-gathering methods to characterise the Banas River and associated uses, including the Bisalpur Dam, then turning to explore socio-economic and ecological vulnerabilities across the Banas-Bisalpur nexus. Initiatives that have been successful in recharging shallow groundwater and catchments elsewhere in Rajasthan are also reviewed. This provides information ~~for~~ supporting the consideration of options for a more systemic approach to catchment management.

3.1 Physical characteristics of the Banas catchment

The Banas is the only river with its entire course in the state of Rajasthan. The two headwaters of the main stem of the Banas River rise in the Kumbhalgarh Wildlife Sanctuary in the Khamnor Hills. The South Banas (Katar) rises at Berokamath in the hilly District of Udaipur. The North Banas rises at Sevantri in the relatively dry (average 556.1mm per annum rainfall, Table 1) District of Rajsamand District but which, in the vicinity of the headwaters and upper river, shares more of the hilly topography of the relatively moister Udaipur District (632.7mm per annum rainfall, Table 1). These two principal headwaters join approximately 10km to the east of the town of Rajsamand, the combined Banas subsequently flowing through Bhilwara, Tonk and Sawai Madhopur Districts before combining with the Chambal River which forms the border with Madhya Pradesh state near the village of Rameshwar in Sawai Madhopur District (Bhatt, 2005). In total, the Banas River is 512 km in length, with a catchment area of 45,833 km^2 (Department of Water Resources, 2000; Upadhyay and Rai, 2013). 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). There is a pronounced seasonal flow regime in the river system responding to episodic monsoon rainfall that typically peaks in July and August.

The Banas River comprises ten major sub-catchments including the river's main stem (Department of Water Resources, 2014): the Berach and Menali on the right bank, and the Kothari, Khari, Dai, Dheel, Sohadara, Morel and Kalisil on the left bank (Singh *et al*., 2007). Three principal tributaries comprise the upper river system upstream of the Bisalpur Dam: the Khari; the Dai; and the Banas which is the largest reaching a width of 900m above the Dam and that is itself broken into North and South forks in its headwaters. There are impoundments of varying sizes, mainly small, upstream on many of the smaller tributaries of the Banas, Khari and Dai. (See Figure 1.)

Figure 1: Location map of the Banas catchment, Bisalpur Dam and key cities, towns and other landmarks



3.2 Water availability and quality in the Banas catchment

The episodic nature of monsoon rains and the generally hot climate combine to result in groundwater supporting over 85% of India's rural domestic water requirements, 50% of urban and industrial water needs, and nearly 55% of irrigation demand (Government of India, 2007). 88% of India's extractions of groundwater are used for irrigation with 137% withdrawal of available groundwater (Central Ground Water Board, 2014). There has been a pronounced trend towards using deeper groundwater, accessed by mechanised pumping from tube wells. Between 1960-61 and 2010-11, the main sources of irrigation across India changed radically with an exponential rise from 0 to nearly 30 million hectares irrigated with water extracted from tube wells, twice as much as from any other source (Ministry of Agriculture, 2014). Increasing groundwater exploitation has been amplified by excessive and wasteful water usage due to low power tariffs, collectively contributing to a sharp fall in water tables (Planning Commission, 2007).

Rajasthan is India's second largest state with nearly 5% of the country's total population (^{c}69 million), but with only 1% of its water resources (Government of Rajasthan, 2010). The arid/semi-arid climate of Rajasthan and its paucity of surface water resources results in a high dependency on groundwater for irrigation and drinking water, exacerbating its depletion and risks associated with lack of alternative sources (Directorate of Economics and Statistics, 2011). More than 80% of water supply schemes in Rajasthan State depend on groundwater exploited via tube wells, open wells and hand pumps (Jain and Singh, 2014). Analysis of trends in water levels in wells in Rajasthan during pre-monsoon (May) and post-monsoon (November) periods between 1989 to 2014, also in relation to withdrawal rates from groundwater and water levels predicted from rainfall, reveal declining groundwater levels in both hard rock areas and tapping alluvial aquifers related to increasing groundwater draft (Central Ground Water Board, 2016a). In the pre-monsoon 2016 period, over 37% of Rajasthan's wells were accessing water 20-40 metres below ground level, with 19.09% reaching more than 40 metres (Central Ground Water Board, 2016b).

Exposure to geologically enriched water is exacerbated in regions of groundwater depletion, as deeper resources with longer residence times are extracted. In regions such as Rajasthan where the rate of groundwater extraction exceeds that of its renewal, geological contamination is an increasing problem (particularly salinity in western Rajasthan and fluoride in the southern part) as well as declining water yields and increasing pumping costs arising from competitive deepening of wells (Shah *et al*., 2001). 218 (90%) of the 243 blocks (administrative units within Districts) comprising the state of Rajasthan are declared 'dark zones', signifying groundwater depletion or degraded chemical quality particularly due to excessive fluoride, nitrate, chloride and total dissolved solids concentrations (Jain and Singh, 2014). Geological contamination of groundwater, particularly by fluoride, is an increasing issue with serious public health implications in Rajasthan (Brindha and Elango, 2011). Well depth and anion data for Districts of Rajasthan traversed by the Banas (Central Ground Water Board, 2016a) are reproduced in Table 1. The World Health Organization (2010) recognises excess fluoride as a major global public health concern stimulating tooth enamel and skeletal fluorosis following prolonged exposure to high concentrations, with an elevated risk of skeletal effects at fluoride intake rise above 6 mg/day, though fluoride can also be a cellular poison and can form hydrofluoric acid in the gut. The primary ingestion pathway is consumption of groundwater originating in regions with an abundance of the minerals fluorspar, fluorapatite and cryolite (IPCS, 2002) or crops taking up fluoride from high-fluoride irrigation water. Agrawal *et al*. (1997) recognise high fluoride concentrations in groundwater resources as one of the most important health-related geo-environmental issues in India, and in particular Rajasthan where high fluoride groundwater is distributed in all 31 of its Districts with three million (in 1997) people consuming water with excess fluoride. Dental and skeletal fluorosis associated with consumption of contaminated groundwater is a pervasive problem as a well as a locally acute issue in Rajasthan (Meena *et al*., 2011).

Table 1: Rainfall, well depth and anion data for selected Districts of Rajasthan (Central Ground Water Board, 2016a)

District	Annual average rainfall (1901-1970) in mm	Premonsoon well depth in metres below ground level), May 2014	Sites exceeding permissible limit (2014-15)		
			Fluoride (1.5 mg l^{-1})	Nitrate (45 mg l^{-1})	Chloride (1,000 mg l^{-1})
Udaipur	632.7	2.25 to 22.85	15% (4/27)	37% (10/27)	0% (0/27)
Rajsamand	556.1	4.53 to 21.19	23% (3/13)	77% (10/13)	0% (0/13)
Bhilwara	603.3	3.4 to 21.1	52% (13/25)	44% (11/25)	12% (3/25)
Tonk	598.2	2.05 to 31.45	35% (6/17)	53% (9/17)	18% (3/17)
Sawai Madhopur	655.8	2.75 to 12.75	30% (6/20)	50% (10/20)	0% (0/20)
Rajasthan state	549.1	0.02 to 112.85	28% (154/561)	43% (240/561)	11% (59/561)

Data to substantiate reported trends in abandonment of traditional water recharge practices are elusive, though a growing literature asserts that their restoration could be significant in rebalancing water resource recharge with demands on receding groundwater (for example Shah and Raju, 2002; Pandey *et al*., 2003; Rathore, 2005; Narain *et al*., 2005; Everard, 2015). Increasing numbers of tube wells suggest a proportionate decline in traditional water management techniques, though the lack of licencing of mechanised extraction provides no authoritative record of how many pumps are in operation or the depth at which they are extracting water. One unsubstantiated estimate by the Junior Site Engineer at Bisalpur Dam was that only 1-2% of villages in the catchment upstream of the dam retain traditional rainwater harvesting infrastructure, with most now reverting to energised tube well abstraction of groundwater without any contribution to its recharge (Dharmendra Kaushik, Personal Communication). A Central Ground Water Board (2013a) assessment of Rajsamand District, where much of the main stem of the upper Banas rises and flows and which hosts 1,037 villages, recorded an overall 126.73% over-development of groundwater exploitation leading to declining and frequently critical levels with diverse forms of wells from 8-203 m depth accessing water with an electrical conductivity 300 to 3,440 µS cm^{-1} (at 25°C). The main stem of the Banas flows next through Bhilwara District, hosting 1,834 villages experiencing a 135.55% (over)exploitation of groundwater with high salinity (35-2453 mg Cl l^{-1}), fluoride (0.24 -7.24 mg F l^{-1}) and nitrate (5.2-749 mg NO_3 l^{-1}) contents and an overall scarcity of water (Central Ground Water Board, 2013b). There are no Environmental-flow (E-flow) requirements in place in the upper Banas River (Gupta *et al*., 2014).

The implications for groundwater storage of increasing groundwater withdrawals through rapid proliferation of tube wells in India has not been well studied, though negative trends have been observed in West Bengal (Chinnasamy and Agoramoorthy, 2016). Simplistic assumptions about recharge versus use also tend to overlook the complexities of groundwater system dynamics at regional and district levels, most monitoring by India's Central Ground Water Board relating to shallow, unconfined aquifers with only 5% of Rajasthan's monitoring wells reaching the deep, confined aquifers that are tapped by many irrigation wells (Chinnasamy *et al*., 2015). The dynamics, recharge rates and potentially substantial residence times of these deep aquifers are barely understood, raising significant questions about the sustainability of their use for purposes other than as emergency reserves (Dragoni and Sukhija, 2008).

Declining levels and pervasive and rising geological contamination of water in wells, and the questionable quality and sustainability of increasingly exploited deeper, confined aquifers, suggest that a renewed focus on recharge and use of shallow, renewable unconfined aquifers presents a more precautionary and sustainable pathway of water resource development. Stewardship and sustainable exploitation of renewable elements of the water resource are the focus of traditional water stewardship techniques found across Rajasthan (Sharma and Everard, 2017). The need to reorient water resource development on a more sustainable path is made more urgent by Rajasthan's increasing human population, including disproportionately rapid growth in urban areas (Table 2). This may increase pressure for continued dispossession of water rights from rural people as a supply-side solution to support industrial and urban economic growth identified by Birkenholtz (2016). Birkenholtz (2012) reports that the Government of Rajasthan's Water Resources Department declared 27,000 anicuts in the Banas River basin upstream of Bisalpur Reservoir illegal in April 2010, arguing that they inhibited filling of the reservoir, demonstrating not merely rural-urban power asymmetries in water resource appropriation but also naivety about the role of water retention and infiltration in the upper catchment as a net contribution to catchment water storage and groundwater recharge.

Table 2: Population growth in Rajasthan and selected Districts (Directorate of Census Operations Rajasthan, 2011)

State or District	Total population growth, 2001-2011	Urban population growth, 2001-2011
Rajsamand	17.7%	42.8%
Bhilwara	19.2%	23.6%
Tonk	17.3%	25.5%
Sawai Madhopur	19.6%	25.3%
Rajasthan state	21%	29%

3.3 Water exploitation in the headwaters of the Banas

Evidence about water use and trends from villages in the Khamnor Hills, from which the two main headwaters of the Banas rise, was primarily derived from the visit in June 2017 and relevant literature. This included field observations from river sites including the source springs of both the North and South Banas as well as interviews with village groups, Forest Officers and opportunistic meetings from people at sites on both sub-catchments. Evidence from semi-structured interviews is collated using the STEEP framework in Table A2 of the Annex.

On the basis of this evidence, water vulnerabilities in the upper Banas were observed to relate significantly to technological changes, particularly increasing use of mechanised pumps that are progressively displacing traditional water management systems such as harens, open wells and rehats (Figure 2). This trend appears to be in a positive feedback loop, with water levels in the formerly better watered Khamnor Hills now receding under intensive pumping and consequently becoming inaccessible by traditional means. This in turn makes maintenance of bullocks to power traditional technologies economically non-viable. Disconnection of extraction rates from natural renewal rates also appears to be creating vulnerabilities relating to water quality, a trend that is recognised at village scale but for which no solutions are in place due at least in part to a lack of alternative water sources. There is also a concern that traditional knowledge relating to locally attuned water management is being lost. Rising populations and the economic non-viability of declining farm sizes compound these problems, with rural communities dependent on other income – principally local labour and emigration of younger men to cities – to supplement subsistence needs. The long-term prognosis arising from increasingly mechanically intensive water extraction practices, compounded by the demands of increasing resort developments supporting a tourism industry that does not operate in sympathy with village-scale water governance, are serious for the viability of local communities for whom water rather than land area is a limiting factor for food production. Many of these problems are not soluble by village-level governance alone. However, there is at present a lack of catchment-scale planning.

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Figure 2: A rehat, or Persian wheel, in operation, a central wheel driven by bullocks to turn a chain of pots drawing water up from ann adjacent open well (June 2017, image © Dr Mark Everard) – Low resolution version of image Fig 6 – Rehat in operation.JPG inserted to aid reviewers

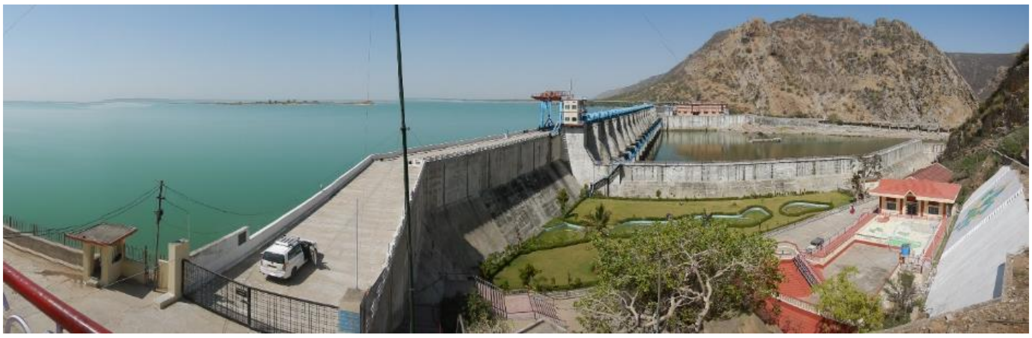
3.4 Water management and diversion at the Bisalpur Dam

Construction of the Bisalpur Dam-reservoir complex (25.924790^{o}N, 75.456060^{o}E, altitude 831 m asl) was completed between 1995 and 1999 as a project of the Government of Rajasthan, located at a rock gorge 255 km river distance downstream from the head of the Banas River immediately downstream of the confluence of the Khari and Dai river systems, for the purpose of providing drinking water, irrigation of a command area of 81,800 hectares and fishery co-benefits (Government of India, 2013; Government of Rajasthan, 2014). The Bisalpur Dam had a height of 39.5 m above deepest foundation, 574 m total dam length, with an effective storage capacity of over 1.1 km^3 (National Informatics Centre, 2017). The Bisalpur Dam qualifies as a 'large dam' under ICOLD criteria (above 15 metres in height from the lowest point of foundation to top of dam and retaining a reservoir of more than 1 million m^3) warranting inclusion on the World Register of Dams (ICOLD, 2017). The Bisalpur Dam has 18 spillways to release water during high monsoon flows (Figure 3).

Prior to dam construction, local communities drew water from approximately 60 tube wells. Dam construction and filling submerged and displaced significant numbers of villages and inhabitants, resulting in substantial protests against perceived unjust provisions under the state government's rehabilitation and resettlement policy

(Agarwal *et al*., 19990), culminating in many displaced people becoming landless and/or homeless (Mathur, 2013).

Figure 3: The Bisalpur Dam (April 2017, image © Dr Mark Everard) – *Low resolution version of image Fig 2 – Bisalpur Dam.JPG inserted to aid reviewers*



The Bisalpur Dam has since been substantially increased in height and capacity over two phases. The primary purpose of these redevelopments was to provide drinking water for the city of Jaipur some 120 km to the north (Central Water Commission, undated). Jaipur City and its environs had exhausted viable local potable water supplies, firstly from overexploitation of its local groundwater sources and subsequently of the resources of the Ramgarh Reservoir (see Box 1).

Box 1: Water supply to Jaipur City, Rajasthan state, India

Jaipur, located in the semi-arid zone of the Indian state of Rajasthan, is India's 10th largest city with a population of over 3.1 million people and is expected to grow to 4.21 million by 2025 (UN Habitat, 2013). Water demands were initially served by local open wells, regenerated by capture of periodic monsoon rains. Development of the water supply system is now around 100 years old, with initial supply augmentation in 1918 via a series of 16 large-diameter open wells with limited piped water supply (Jain, undated).

The Ramgarh Reservoir had been constructed some 32 km to the north east of Jaipur by damming the Banganga River in 1897, with reservoir filling commencing in 1903 for local water supply and irrigation but also providing a valuable fishery (Sugunan, 1995).

In 1952, Jaipur City turned northwards to appropriate water from the Ramgarh Reservoir to complement its insufficient local resources, raising the Ramgarh Dam to increase the volume of Ramgarh Lake to provide 7.0 megalitres of water per day (MLD) to the city. Ramgarh Dam was raised once more in the late 1960s and again in 1982 to augment supply, at its peak area the lake spanning 15.5 km^2 in the wet season. However, encroachment by urban development around the lake has since resulted in cessation of free flows of water into the lake, which has now been dry since 2000 (Sunny, 2000). Aside from implications for Jaipur City, an important source of drinking water, irrigation and fish was lost, and the rights of local people dispossessed. Long before this formerly valued wildlife and amenity area dried completely, limitations on the availability of surface water were being realised. Tube well drilling was introduced in late 1960s, tapping into groundwater below and adjacent to Jaipur City.

As a larger and more reliable source, work began extending the Bisalpur Dam on the Banas River some 120km to the south of Jaipur in 2006, with water reaching Jaipur from the dam in 2009. Jaipur city is outside of the natural catchment of the Banas River, the flow and linked ecosystems of which are compromised by large-scale impoundment and water transfers. Design demand from the Bisalpur system has since been increased in stages, water transfer pumping stations transferring water to the south of Jaipur City. Canals transporting the water have high leakage and evaporation rates, causing further problems through wastage. Tanker transportation of water serves un-piped areas of Jaipur city throughout the year.

Jaipur's water supply is still augmented by pumping from tube wells, although groundwater in Jaipur City is overdrawn by a calculated 600% with no more land area available to enhance recharge to meet the demands of rapid continuing urbanisation. Groundwater under the city is not only retreating to around 400 feet (122 metres) but is increasingly contaminated from geological and anthropogenic sources (Yadav and Garg, 2011). Tatawat and Singh Chandal (2008) surveyed water from hand pumps around the city measuring conductivities from 345-2,550 $\mu S\ cm^{-1}$ (at 25°C) with a World Health Organization (2011) maximum limit of 1,400 $\mu S\ cm^{-1}$, total dissolved solids from 239.6-1,435 mg l^{-1} (maximum limit 500 mg l^{-1}) and chloride from 32.49-624.81 mg l^{-1} (against a recommended maximum of 250 mg/l but without formal health guideline). Fluoride is a major cause for concern, with 40% of groundwater samples from Jaipur exceeding a permissible limit of 1.5 mg l^{-1} (Central Pollution Control Board, 2008; World Health Organization, 2011).

There is an increasing rate of tube well failures due to the declining water table. In addition to municipal wells, a large number of additional tube wells drilled by private owners exploit water indiscriminately, further depleting the water table and adversely affecting water quality. Jaipur is increasingly dependent upon the Bisalpur Dam, and so is vulnerable to the declining quantity and quality of water in the Banas-Bisalpur system (Dass *et al*., 2012).

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The Bisalpur Dam had been providing water to the towns of Ajmer, Beawar and Kishangarh since 1994, but a major project of the Government of Rajasthan's Water Resources Department increased dam capacity to begin serving the City of Jaipur and en route villages from December 2008 (Government of Rajasthan, 2014). The Bisalpur-Jaipur Water Supply Project (BWSP) was instigated by the Government of Rajasthan in 2005 to deliver water from the existing Bisalpur Dam headworks to the south edge of Jaipur City. Phase I of the BWSP included provision for 360 MLD to Jaipur City and 40 MLD for rural areas, with Phase II increasing these volumes to 540MLD and 60MLD respectively, with potable water from Bisalpur Dam reaching Jaipur from March 2009 (RUIDP, 2017). Subsequent dam raising has not been without vigorous dispute, with 10 protesting farmers shot of which 5 were killed in

2005 as the dam was raised to achieve a storage of 38.7 tmcft (over 10^8 Ml) by 2007 (Bhaduri, 2015; Shiva, 2015).

There are further proposals to transfer an additional 300 mm^3 $year^{-1}$ of water from the Anas River in the Mahi Basin to the Berach River in the Banas Basin to augment the Bisalpur Dam (Department of Water Resources, 2014). There are also reports (with quotes from senior staff though at the time of writing no official announcements) of the Government of Rajasthan's Public Health Engineering Department (PHED) proposing a second phase of the Bisalpur project to be completed in 2019 increasing the allocation of water to Jaipur City from 600 to 930 MLD (Joseph, 2016).

Under operational targets at the time of the site visit to the Bisalpur Dam in April 2017, the cities of Jaipur, Ajmer and Tonk receive significant water from the Bisalpur Dam headworks, with a further extensive area irrigated for agriculture in Tonk District via two canals on each bank of the river and substantial estimated annual evaporation from the Reservoir surface. Data in Table 3 is derived from an operational manual *Rajasthan Water Resources, Bisalpur Dam* published by the Department of Water Resources, Government of Rajasthan, shared during the site visit by the Junior Site Engineer but regrettably not published online. Though these values are not peer-reviewed, if treated cautiously they are at least indicative of the substantial quantities of water diverted or evaporated from the Bisalpur Reservoir that are lost to the Banas system.

Table 3: Approximate water diversion and loss from the Bisalpur Dam (Department of Water Resources operational manual: 'Rajasthan Water Resources, Bisalpur Dam')

Water diverted or lost	Reported tmcft annually	Recalculated values	
		Average Mld	%
To Jaipur city	11	853	34%
To Ajmer city	5	388	15%
To Tonk city	0.5	39	1.5%
To 88,000 ha land irrigated in Tonk District	8	620	25%
Loss through evaporation from reservoir surface	8	620	25%
Required releases to the downstream river	0	0	0%
TOTALS	32.5	2,520	100%

There are no planned releases to the Banas River downstream of the Dam, as the river has not been assigned an Environmental Flow requirement (Gupta *et al*., 2014), largely on the assumption the river is seasonal and dry outside of the monsoon season (Dharmendra Kaushik, Personal Communication). There is no hydroelectric generation at the Bisalpur Dam, the primary purpose of which is water storage and diversion for urban and irrigation uses. The Dam also lacks any form of fish passage. Migratory fish species, particularly mahseer (*Tor* spp.), have been long known from the Chambal River (TWFT, 1984; Desai, 2003) and the reach of the lower Banas running through the Ranthambhore Tiger Reserve (Everard *et al*., 2017) as well as sampled from Bagara Dam and an upstream section of the South Banas

(Katar) river Bawara village during the June 2017 site visit (Figure 4). The mahseer species *Tor tor* is known from the Chambal river and is of conservation concern (Pinder and Raghavan, 2013), classified as Near Threatened (NT) in the IUCN Red List (IUCN, 2017). However, mahseer are reported as absent from the Bisalpur Dam and adjacent river (Dharmendra Kaushik, Personal Communication). The Dam therefore appears to have eliminated mahseer, and by implication probably other riverine fishes, further skewing the distributional benefits and costs of management across the catchment. Annual dam management and maintenance of ₹900 crore is effectively recouped from the ₹1,000 crore gross charges for irrigation water, though individual charges to farmers per hectare per crop are affordable (Dharmendra Kaushik, Personal Communication); no mention was made in interviews or in the literature of charges levied on urban beneficiaries of water diverted from the Bisalpur Dam beyond transmission and distribution costs.

Figure 4: A mahseer, genus Tor*, sampled from the Bagara Dam (April 2017, image © Dr Mark Everard) – Low resolution version of image Fig 3 – Tor species from Bagara Dam.JPG inserted to aid reviewers*

Bisalpur Lake and the cities and irrigated land that its water serves are vulnerable to both declining quantity and quality of water. The Central Pollution Control Board (2015) has recognised the Banas River, including the vicinity of the Bisalpur Dam, as amongst the highest priority rivers for pollution control action largely on the basis of biochemical oxygen demand (BOD) in the range of 4.2-39.9 mg l^{-1}. Between 2002 and April 2017, the lake had only completely filled nine times and had completely dried out in 2006 prior to the July rains, during which time the needs of Jaipur were met from six tube wells tapping into groundwater 100 feet deep around the dam area (Dharmendra Kaushik, Personal Communication). Gupta *et al*. (2014) chart the declining trend of water inflow into the Bisalpur Reservoir by comparing theoretical yield based on rainfall data from 1981-2012 with actual inflow, noting a slight increase in rainfall yet a fall in actual inflow ascribed to upstream development including construction of extensive anicuts, population growth and inter-annual variations in rainfall contributing to both episodic and chronic shortages in water supplies and irrigation facilities. Gupta *et al*. (2014) conclude that the Bisalpur Dam

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Increasing dependence of Jaipur and other cities on the waters of the Bisalpur Dam, originally built for local drinking water and irrigation purpose, therefore perpetuates a this pattern of urban appropriation and rural dispossession observed in Jaipur's history of water management and more widely across the developing world. The observed declining flows and quality of water entering the Bisalpur Reservoir, and observations that the dam operates substantially below its design dependability, puts at significant risk the urban centres and irrigated command areas that the Banas-Bisalpur scheme supplies. It also raises additional civil vulnerabilities, with a history of protest by affected local people dispossessed and disadvantaged by perceived political asymmetries favouring remote urban and industrial economic activities. Further vulnerabilities arise from the substantial amount of water (25%) lost to the system through evaporation from the reservoir surface, a vulnerability potentially averted if more water could be stored as an underground resource across the catchment rather than accumulating the surface behind the dam.

3.5 The Banas catchment below the Bisalpur Dam

Downstream of the Bisalpur Dam, the river is starved of flows beyond those limited periods when the dam overtops (noting that the dam only filled completely nine times between 2002 and 2017), reportedly as the lower river is assumed to be seasonal. Historic and observational evidence highlights that the river was formerly a significant source of year-round water, and that many stretches still hold perennial water. Above-ground and underground flows in the Banas River were the primary source of water to the city of Sawai Madhopur until the 1980s (Y K Sahu, Field Director, Ranthambhore Tiger Reserve, Personal Communication). 8.0 MLD of water is now supplied to Sawai Madhopur from surface and groundwater supply sources including 78 tube wells and 10 open wells adjacent to the city, though with some water still lifted from an open well connected to an intake constructed on the banks of Banas River (Local Self Government Department, 2008). Photographic evidence of permanent water in the lower Banas River taken in notably dry periods (Figures 5 and 6) further endorses that the lower Banas can not be assumed to be a naturally dry river outside of monsoon season. Low flows in the downstream section of the Banas outside of the monsoon season are further compounded today by largely illegal and extensive sand and gravel mining destroying the structure of the exposed river bed, further suppressing the groundwater table (ISET and CEDSJ,

2011) and impacting on the availability of fish spawning and other habitat. These water losses starve the river of dry weather flows outside of the monsoon season. This has potentially significant ramifications for riparian communities and their livelihoods.

Figure 5: Large pool on the Banas River running through the Ranthambhore Tiger Reserve during a severe drought including two 'missed' monsoons (April 2016, image © Dr Mark Everard) – Low resolution version of image Fig 4 - Banas at Amblidha.JPG inserted to aid reviewers

Figure 6: The lower Banas River viewed downstream from National Highway 1, 20km north of Sawai Madhopur, carrying substantial water in summer, the driest time of year, in a notably dry year (April 2017, image © Dr Mark Everard) – Low resolution version of image Fig 5 - Banas from NH1 20km north of Sawai Madhopur.JPG inserted to aid reviewers

Everard *et al*. (2017) record the concerns of village people from the of Amlidha region buffer zone of the Ranthambhore Tiger Reserve about livelihood implications arising from diminishing flows in the Banas River. These people now mostly obtain water for domestic use from pumped tube wells close to villages, with some water also pumped from the Banas River and transported in small quantities by women or in larger quantities by vehicles. Secondary impacts include the exploitation of other alternative resources such as tube wells situated around Sawai Madhopur, potentially negatively impacting wider ecosystems and human opportunities. River drying due to diversion of flows therefore has long spatial-range impacts on people. It also has potentially significant impacts on wildlife, both terrestrial and aquatic, with declining flows from the Banas now limiting water availability in Ranthambhore Tiger Reserve and well as reaching the Chambal National Gharial Sanctuary downstream of the confluence of the Banas. Pressures can arise directly from declining water availability, but also as secondary impacts through degradation of complex riparian habitat at Ranthambhore (Forest Department, 1990) and in contributing to potential wildlife-human conflicts (Everard *et al*., 2017).

Locally, the The Banas River is referred to as *Van Ki Asha* (‘Hope of forest’) for its important role in bringing water across the state as well as the “…*lifeline of central Rajasthan*” yet, given the depleting state of the river and almost complete diversion of its waters in the middle of its course, that service is now almost completely compromised. Current alternative surface reservoir and groundwater development closer to the city of Sawai Madhopur therefore places greater pressure on local resources. Declining river flows also compromise the capacities of downstream communities to meet their needs, reduce water flows through and into globally significant tiger and gharial reserves, and may contribute to increasing wildlife-human conflict for limited resources. These downstream vulnerabilities are compounded by climate change and also by extensive sand mining in the bed of the Banas River that further depresses the water table (ISET and CEDSJ, 2011).

3.6 The potential role of water harvesting in catchment restoration

India has a long history of localised innovations intercepting monsoon run-off to recharge groundwater, where water is protected from high evaporative rates and accessible throughout the year (Pandey *et al*., 2003). There is a growing literature asserting that traditional knowledge, currently being lost through village abandonment and conversion to mechanised techniques, can play significant roles in rebalancing water resource recharge with demands on receding groundwater if appropriately supported by reformed policies and investment (for example Shah and Raju, 2002; Pandey *et al*., 2003; Rathore, 2005; Narain *et al*., 2005; Everard, 2015).

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Watershed management programmes promoting the distributed restoration of small-scale water harvesting have resulted in significant impacts on catchment hydrology and downstream water availability in Andhra Pradesh and other parts of India (FAO, 2012). Significant groundwater rises are reported where community-based participatory methods have been developed at benchmark sites in several Indian states/provinces amongst a wide range of experimental watersheds across Asia (Wani *et al*., 2003, 2005, 2006 and 2009). There are commonalities between the diverse traditional methods to accelerate the natural recharge of soil moisture and groundwater in India with those observed across Africa, Asia, the Americas and the wider drier tropical world (Pearce, 2004; Everard, 2013, Mati, 2007).

Successes brokered by the NGO Tarun Bharat Sangh, largely across Alwar District of Rajasthan since the mid-1980s working with communities to reinstate or innovate traditional water-harvesting structures (WHSs) and associated local governance mechanisms, have driven substantial socio-economic and ecological regeneration at village scale. These successes have subsequently been elevated in scale by formation of *Pad Yatra* (catchment-scale 'water parliaments') to foster collaboration, resulting in regeneration of whole catchment systems including reappearance of perennial water bodies after decades of channels drying outside of the monsoon season (reviewed by Kumar and Kandpal, 2003; Sinha *et al*., 2013; Everard, 2015). Regeneration of catchments has brought ecological and socio-economic uplift, but also restored ecosystems of medicinal, spiritual and other cultural values (Everard, 2016), as well as resilience for wildlife and livelihoods (Torri, 2009). These trends are confirmed by remote sensing, within the spatial and spectral limitations of time series datasets (Davies *et al*., 2016).

This evidence supports the view that beneficial outcomes for the socio-ecological system of the Banas river could arise from a concerted and targeted programme of catchment regeneration, founded on management regimes favouring recharge of resources from monsoon run-off that has been a key feature of water management throughout Rajasthan prior to mechanisation~~, would be of beneficial~~. It is not merely the local people, who are its primary actors, who would benefit from greater water security. If integrated across sub-catchments, regeneration of hydrology across the basin may play a role in more secure water access and ecosystem vitality, also reducing geological contamination from deep groundwater. This type of connected, ecosystems-based approach to water resource restoration could result in win-win-win outcomes for these three linked upstream, dam-dependent and downstream components of the river system. If a comprehensive programme can be implemented, working from the upper reaches of the Banas system, these benefits can then potentially cascade down to the Bisalpur Reservoir, and hence play a strategic role in safeguarding the quality and quantity of water available for urban and agricultural exploitation as well as providing headroom for releases to the lower river as relief for affected ecosystems and communities. None of these potential benefits are thus far quantified in the Banas, though evidence from catchment regeneration in Alwar District suggests a high likelihood of success if ~~they~~ this integrated approach can be scaled up and connected between villages along river systems.

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3.7 Opportunities to improve the sustainability of the Banas system

Reappraising the Banas-Bisalpur complex in a joined-up way, with management framed by ecosystem processes rather than immediate utility, thereby raises options for reversing the cycle of degradation currently gripping the Banas-Bisalpur system and its beneficiaries. The STEEP framework (social, technological, environmental, economic and political) has already been used to organise feedback from semi-structured interviews. STEEP has previously been applied to addressing sustainability goals (Steward and Kuska, 2011), including as a systems model addressing technology choices and governance systems in the management of water, ecosystem service flows and dependent development issues in South Africa (Everard, 2013), Europe (Everard *et al*., 2012) and India (Everard, 2015). STEEP is used here to explore opportunities to improve the sustainability of the Banas system, addressing the significant, linked vulnerabilities identified for its rural, urban, agricultural and wildlife dependents.

From the social perspective, the demands that people place on water resources in the river ultimately depresses groundwater levels and associated livelihood opportunities, as water is the primary limiting factor of food production. Traditional knowledge is being lost as younger people abandon village life for improved economic opportunity in cities, promoting greater reliance on mechanised water extraction techniques that may ultimately limit future livelihood opportunities. Across the Banas catchment as a whole, there is also a repeating pattern of resource dispossession as the needs of remote urban people are served in preference to those in the lower catchment by diversion of substantial volumes of water from the Bisalpur Dam. Overall, modern, technocentric and water-hungry lifestyles are supplanting traditional livelihoods generally evolved in balance with the capacities and vagaries of localised climate, culture and water systems.

Technologically, the proliferation of mechanised water extraction and diversion technologies has already been described as driving a positive feedback loop, in which mechanised pumping techniques become necessary to access receding groundwater levels depressed by high extraction rates. Traditional water extraction practices such as open wells and rehats, still widespread but in decline around the upper catchment, automatically limited extraction rates to the replenishment of open wells from shallow groundwater. By contrast, electric or diesel pumps attached to tube wells have no such limits and also withdraw water from deeper underground, including tapping into deeper and potentially confined aquifers which tend to be more geologically contaminated and may not be renewable. Large-scale water diversions out of the Banas catchment from the Bisalpur Dam without regard for the needs of people and ecosystems in the lower catchment also reflect a blinkered technological approach.

Environmental processes recharging shallow, unconfined groundwater and surface waters are consequently being overridden. There was no evidence that the dynamics of deeper aquifers, and their connections with shallower, unconfined groundwater, are understood. Current vulnerabilities across the whole Banas-Bisalpur socio-ecological system stemming from declining water quantity and quality could, however, be addressed by a renewed focus on processes regenerating water resources and the limitation of extraction to rates commensurate with replenishment of shallow groundwater. In the case of the Kesar village meeting, opportunities were identified with the community for adoption of water-efficient irrigation as well as opportunities for recharging the shallow groundwater, which may save significant volumes of water relieving some impending pressures. The World Health Organization (2011) recognises well-designed and managed rainwater harvesting at both household and larger community scales as providing an important source of drinking water with very low health risk, which can also be blended with water from other sources to reduce the levels of contaminants of health concern including fluoride. A range of NGOs is working with communities to recognise, restore or innovate water harvesting practices to improve livelihood security, which have in several cases cumulatively had the effect of regenerating catchment hydrology, ecosystems and livelihoods. A range of water-wise solutions from Rajasthan, including water recharge, access and efficient usage, are documented by Sharma and Everard (2017) including description of their purposes, geographical suitability, and construction and maintenance requirements.

The economics of water management in the Banas are currently short-term and utilitarian. This includes investment in increasingly efficient extraction technologies that, though yielding immediate returns through irrigation, appear to be depleting the quantity and quality of accessible water and may in the longer term result in village livelihoods becoming non-viable. Perhaps the more pressing utilitarian issue is the resource dispossession from the Banas catchment and its predominantly rural dependents to serve the demands of remote urban and industrial economies, a form of economic hegemony replicated frequently in the developing world. Both mechanical extraction and diversion are progressively depleting water, the core resource of the Banas system and its dependent human population and wildlife on the current trajectory of declining flows and water quality. On the basis that this appropriation strategy without regard for resource regeneration replicates former exploitation patterns that have ultimately depleted water resources, it may also ultimately limit economic opportunity in urban areas to which water is now diverted. A wise investment for the longer term would be on resource recharge for the security of the whole connected socio-ecological system.

Overall, governance of water resources in the Banas is highly fragmented. There is no watershed-level planning. Water exploitation is instead driven by local and immediate demand. The lack of clear overview and potential regulation of what is happening to the catchment water system is not helped by the lack of requirements for licences to sink tube wells, except in 'dark zones' designated where groundwater is significantly overexploited (Press Information Bureau, 2013). Reform of water management based on an overview of the catchment, incentivising resource recharge and balancing extraction with replenishment, presents a major stepping stone towards sustainable development. India already has de facto commitments to taking this systemic approach to water planning based on ecosystem processes as a contracting party under the Convention on Biological Diversity (Convention on Biological Diversity, undated) and the Ramsar Convention, and its aspirations to adopt an integrated water resource management (IWRM) approach.

The need for a systemic approach to the Banas-Bisalpur nexus reflecting the value of protecting or enhancing regenerative ecosystem processes is far more than a matter of altruistic concern. It is the means by which the currently degrading socio-ecological cycle, including repetition of Jaipur City's historic pattern of depletion of its local resources and the Ramgarh Dam, can be effectively reversed. Placing the regeneration of underpinning hydrological processes at the heart of future strategies is fundamental for a more sustainable approach to resource exploitation and conservation. It changes the emphasis from exploitation of resources in the immediate term using the most efficient technological means, towards an emphasis on the ecosystem processes constituting the primary natural infrastructure upon which extractive uses depend. This can result in potential win-win-win outcomes for the whole socio-ecological system in the upstream sector, the Bisalpur Dam and beneficiaries of its diverted water, and downstream reaches. Importantly, taking account of the upstream-to-downstream cascade of hydrological, chemical and ecosystem service flows, self-beneficial ecosystem-based interventions need to start at the top of the catchment.

3.8 Power asymmetries

A frequent observation through this Results and Discussion section has been instances of urban economies dispossessing water management schemes (the Ramgarh Dam and the Bisalpur Dam) and water rights of rural communities, with the needs of wildlife and communities largely excluded from decision-making and consequently dependent upon residual natural resources~~ largely excluded from decision-making~~. This general trend of power asymmetries leading to skewed outcomes favouring the already most privileged ~~, a~~is observed more widely in water management practices ~~by~~ (World Commission on Dams, 2000; Everard, ~~(~~2013; ~~)~~ ~~and~~ Birkenholtz, ~~(~~2016). Further power asymmetries arise where local people have access to mechanised tube wells, enabling them to competitively pump water thereby not merely degrading and depressing groundwater levels but also breaking down the bonds of community participation in water management even to the extent ~~s~~of threatening the viability of food production and other livelihood needs in the longer-term future. The shift in perception of water from community resource towards utilitarian and economic commodity further drives incentives for mechanically efficient extraction, rather than seeking to balance exploitation with recharge rates. The net effect is one of declining community stewardship of resource quality and quantity, favouring competitive exploitation and a void of governance relating to resource sustainability and equity at catchment scale.

Further asymmetries in distribution of ~~shares of~~ benefits and costs of water management arise from disruption of the longitudinal continuity of the river by the impassable barrier of the Bisalpur Dam, reducing flows of water and fragmenting wildlife. Mahseer fishes (genus *Tor*) sampled from the upper South Banas, possibly from a relic population stranded by downstream disconnection, and reported from the lower river provide evidence of these~~is~~ generally migratory fishes having formerly occupied more of the river. This is indicative of prospects for other wildlife and the flows of ecosystem services to which it contributes.

Risks stemming from these asymmetric water vulnerability and resource access include biophysical wellbeing including food security and human health, the viability of community economic activities, and of the ecosystems they depend on, as well as the potential for civil disruption.

Viewed on a systemic basis, an ecosystem-based approach to water resource management across the Banas system is as advantageous for more powerful urban beneficiaries as it is to rural communities whose livelihoods would be secured by refocusing on local-scale recharge of water resources. Without such an eco-centric and 'bottom up' strategy, increasing water vulnerability for all linked constituencies benefitting from the ~~water~~ resources of the Banas system is the only likely outcomes.

3.9 Policy fit and practical implementation

Global society is emerging from a model of management for narrowly framed problems and solutions, largely blind to wider ramifications, into a paradigm of systemic awareness informed by interconnections between ecosystem services and their associated beneficiaries (Everard, 2017). Legacy water resource exploitation policies and practices founded on technical extraction efficiency, without regard for balancing resource regeneration rates and their broader and longer-term socio-ecological consequences, are~~s~~ evident ~~in~~ across India over recent times ~~in~~ for example in the form of stimuli for improving agricultural profitability in the short term though ironically threatening food security in the long term (Zaveri *et al*., 2016).

In Rajasthan, there is growing recognition that recent historic over-emphasis on water exploitation without balancing recharge needs to be redressed. *Jal Swavlamban Abhiyan* ('water self-reliance mission') is a significant Rajasthan Government strategy implemented from early 2016 that emphasises and invests in decentralised water management for self-sufficiency (The Hindu, 2015). At the launch of the second phase, Rajasthan's Chief Minister, Vasundhara Raje, said that the first phase of *Mukhyamantri Jal Swavlamban Abhiyan* (MJSA) benefitted 42 lakh (4.2 million) people and 45 lakh (4.5 million) livestock and brought 25 blocks across Rajasthan into a 'safe' water security condition, with the second phase intended to cover 4,200 villages and 66 townships (Times of India, 2016). These figures are not substantiated, and superficially appear optimistic (heavy rains in August 2016 broke a two-year severe drought possibly skewing perceived outcomes) but indicate clear political intent to restore or promote groundwater recharge practices. This ~~, an~~ intent ~~that~~ is being echoed in other water-limited Indian states, for example in Gujarat (Shah, 2014). Catchment regeneration also contributes to the UN Sustainable Development Goals (SDGs: United Nations, 2015), particularly 6 of the 8 targets under SDG6 (clean water and sanitation). Common understanding and consensus is now required across government departments, NGOs, village and local communities and other interests to convert far-sighted political intent into practical policies and effective tools to promote practical outcomes.

The Banas system presents a focused case study of both problems created by fragmented exploitation and the potential for systemic solutions. In particular, the direct linkage between declining water levels and quality from the headwaters ramify not merely as vulnerabilities for local people but also downstream to diverse beneficiaries throughout the catchment. From an economic perspective, the most substantial values are associated with urban beneficiaries of water diverted from the Bisalpur Dam, dispossessing the perceived lower priorities of local people, irrigation and wildlife in the lower river. Costs associated with vulnerabilities to these economically privileged constituencies are substantial, and will escalate dramatically on current trends if overexploitation of the Banas follows the same trajectory as the now depleted Ramgarh Dam and local groundwater resources around Jaipur. Construction, upgrades to, and ongoing maintenance and operation of the Bisalpur Dam already entail significant investment, apparently with most maintenance costs paid by irrigation beneficiaries rather than the urban users of most of the water. Further, presumably substantial, costs will also be associated with reported proposals to transfer additional water from the Anas River that, in essence, replicates former failed or failing models of resource appropriation and dispossession for assumed water security.

A systemic perspective recognises that recharge and stewardship of the resource, a central feature of traditional geographically adapted water management innovations, is at least as important as water abstraction technologies. Recent Indian policy has overlooked this important element of the system. Rural areas of the Banas present an underexploited opportunity for promoting uptake of water-harvesting structures (WHSs) for the benefit of the wider catchment and its dependents as "…*the status of villages in the catchment is very poor because of no involvement of government and non-government organizations*…" (Upadhyay and Rai, 2013, p.~~-~~91). Where a variety of WHSs have been installed, they have helped regenerate vegetation and also given villagers resilience against drought as compared to parts of the Banas catchment where these structures are absent (Upadhyay and Rai, 2013). Successes in Alwar District of Rajasthan illustrate the potential for self-beneficial but also integrated restoration of water harvesting to regenerate the soci~~a~~o-ecological system of whole small catchments. Although villagers in the Banas system were found to know the importance of water conservation, there is currently a lack of formal and informal institutions offering training for further improvement of soil and water conservation techniques (Upadhyay and Rai, 2013). Replication of successful regeneration schemes with appropriate geographical and cultural adaptations in the Banas catchment, particularly focused initially in the upper river enabling benefits to ~~flow~~ cascade downstream, appears to present a significant opportunity to contribute to increased resilience for all of the river system's rural, urban, irrigation and wildlife beneficiaries.

Assigning some form of economic value to water resources and ecosystem services represents a powerful tool to embed their conservation into the policy environment (Daily *et al*., 2009). Payments for ecosystem services (PES) is an established and now globally widespread model for bringing the values of often formerly overlooked ecosystem services into mutually beneficial markets (OECD, 2010). PES solutions have proven effective for protecting water quantity and quality for downstream uses. UK, US and French examples cited previously constitute a small subset of higher-profile examples of operational water-related PES schemes globally (Everard, 2013; Schomers and Matzdorf, 2013). PES therefore represents one of many potential tools that can make use of existing investments to provide an economically efficient means to improve water security simultaneously in the upper Banas catchment, for users of water impounded by the Bisalpur Dam, and for communities and ecosystems downstream of the Dam. A proportion of the substantial planning, development and ongoing expenses incurred by beneficiaries of technological solutions at the Bisalpur Dam, including fair payments by beneficiaries who currently do not pay, could be diverted under formal PES arrangements to promote recharge and efficient use practices in communities in the upper catchment ('providers' in PES terms but also net beneficiaries of water-wise solutions) for the benefit of enhanced water security. Enhanced payback could result through improved security of water ~~a~~ quantity and quality in the system as a whole, and reduced likelihood of civil disruption and costs averted from further water appropriation schemes. Furthermore, if these water resource investments were integrated with existing rural development, public health and other budgets, a highly efficient mechanism to deliver multiple, simultaneous socio-ecological system benefits could ensue both locally and at catchment scale from strategic, multi-beneficial interventions in the spirit of 'systemic solutions' (*sensu* Everard and McInnes, 2013). PES is not the only feasible economic instrument to generate investment in 'bottom-up' recharge of the Banas system, for example with instruments such as 'green bonds' – be they sovereign or private – playing roles in ecosystem and community regeneration elsewhere across the world (Hall *et al*., 2017)

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Implementation of a wide-scale programme of water resource regeneration and efficient use for self-beneficial purposes, with the potential for cumulative impact on restoring shallow groundwater and surface flows in the river system, may most effectively be delivered by the existing network of community-facing NGOs already active across Rajasthan, ideally in a targeted pilot sub-catchment to demonstrate efficacy as a stepping stone towards upscaling the approach. Many effective and proven techniques are known, and documentation (such as Sharma and Everard, 2017) exists to expedite the uptake of locally appropriate solutions attuned to local geography, needs and culture.

It is recognised that there are many knowledge gaps to be filled in progressing this shift in policy and practical implementation, hence the precautionary language of the previous paragraphs. However, this is best approached as a matter of ‘action research’: taking an adaptive, learning approach based on practical action to reverse the degrading condition of water systems and dependent ecosystems and livelihoods. There is certainly an urgency to reversing the current degrading cycle if the integrated rural, urban, irrigated and wildlife elements of the Banas-Bisalpur complex are to remain viable in the longer term.

3.10 Research and development needs

The preceding discussion of vulnerabilities, potential solutions, and policy and implementation options are supported in principle~~,~~ by available evidence. However, they lack quantification in this specific context. It is necessary to quantify likely outcomes to identify and justify options for reform of policies and ~~,~~ management practices and redirection of associated investment. Furthermore, although the multiple authorship of this paper represents an initial consortium of common interest sharing ideas to shift the management paradigm for net increased socio-ecological security and opportunity, further common understanding and consensus is required across all relevant government departments and other interested institutions (particularly municipality, community leaders, and government Irrigation and Water Services Departments). It will also be important to engage local community representatives to build on local needs and traditional knowledge, to test proposals in a local context, and to assure their legitimacy. Key research questions highlighted by the above discussion include:

- How does the catchment function naturally? A comprehensive catchment GIS that, importantly, includes the dynamics and interactions of different strata of the groundwater system, built from new data and relevant existing datasets (such as water flows, quality flow, climate, land cover, abandonment of WHSs, remote sensing and other relevant metrics) would enable analysis of longer-term trends in the catchment, and between sub-catchments, and also serve as a model for scenario-testing.
- What water management options – traditional, engineered, novel or combinations – can balance recharge of ground and surface waters with their use to support sustainable livelihoods in the diverse villages and towns of the catchment, taking account of geological and cultural differences and interdependencies?

- What is the most effective mechanism to promote sustainable water management practices across the catchment, or a pilot sub-catchment, mediating high-level aspirations for water self-sufficiency with operational acceptance and implementation? This research question is optimally addressed through action research in partnership with government bodies, local delivery NGOs, and academic and citizen monitoring of outcomes for water quantity and quality in pilot sub-catchment(s).
- What are the costs and benefits of an ecosystem-centred approach as compared to the current narrowly technocentric development model? In broad terms, this research will underpin assessment of the potential for a PES scheme to promote management options likely to optimise multi-beneficial outcomes. Distributional equity issues relating to historic and potential future schemes should be taken into account.
- What governance arrangements, including reform of policies and refocusing of different strands of municipal and public funds, can most effectively bring about this shift in paradigm? This research strand would be enacted in direct collaboration with government partners tasked with leading *Jal Swavlamban*, addressing the SDGs, and other programmes relevant to water security.
- Is an Environmental Flow standard necessary for the lower Banas River, and if so what is the most socially and ecologically beneficial regime for releases from the Bisalpur Dam? This will be informed by historic records (e.g. former extraction of water from the lower river to supply Sawai Madhopur), modelling of an un-impounded river, consideration of the needs of downstream ecosystems and communities, and also consideration of the benefits likely to accrue from establishing Environmental Flows and installing a fish pass in the Dam.
- How is an integrated programme best targeted to ensure maximum benefits for all integrated rural, urban, irrigation and wildlife beneficiaries of catchment processes, noting that hydrological functions run from upstream to downstream? This research stage is about an optimal approach to up-scaling a catchment regeneration programme, potentially with detailed design of a pilot sub-catchment scheme but including lessons for wider uptake in Rajasthan and beyond.

3.11 Implementation in other water-stressed regions~~ecosystems~~

Many regions of the developing world are subject to similar issues water vulnerability, driven by rising populations, a changing climate, and technological and economic/policy focus of water extraction without balancing recharge (UNESCO, 2006). Many of the attributes of this locally focused research have wider generic applicability across India, as well as tropical Africa elsewhere in Asia and the central and southern Americas. The growing global population and supporting natural resources base makes this challenge as germane to many regions currently considered more water-secure (Vörösmarty *et al*., 2000).

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The underlying principle of refocusing on ecosystem processes and enhanced resource recharge to rebuild primary natural capital securing socio-ecological systems is as relevant in these other environments (Millennium Ecosystem

Assessment, 2005)~~,~~. However, they ~~but~~ need to be attuned to local geography and culture, ~~(~~much as the heterogeneous schemes observed across the Indian state of Rajasthan are themselves diverse and locally adapted~~)~~. STEEP represents a systemic framework ~~to~~ helpful for consideration of how local adaptation can be achieved, accounting ~~of~~ for tightly interconnected social contexts and needs, ~~technologies~~ appropriate technologies~~to local context~~, environmental conditions both regionally and locally, economic needs and incentives, and the wider formal and informal policy environment including opportunities and areas for reform.

4. Conclusions

The Banas catchment is in a cycle of linked ecosystem and socio-economic degradation as a result of intensifying water exploitation practices that are out of balance with natural or enhanced water resource regeneration. Communities in the upper river, the many millions of people now almost wholly reliant on piped supplies from the Bisalpur Dam, downstream communities, and the ecology of the river and the many beneficial ecosystem services it provides are all subject to increasing vulnerabilities. Perpetuating a serially failing ~~failed~~ technocentric resource appropriation model will not result in sustainability.

Rebalancing resource recharge with exploitation across the Banas-Bisalpur nexus could yield multiple co-benefits for all affected communities and ecosystems. Regeneration of the socio-ecological vitality of Rajasthani river systems has been demonstrated in Alwar District and elsewhere across India and the arid developing world, and could be achieved in the Banas catchment were resources and capacity-building available to promote a concerted and targeted programme of rehabilitation or innovation of traditional water management practices.

A paradigm shift towards an ecosystem-based approach has associated costs, but the benefits are substantial and particularly when risk of failure of water supply to a major city are taken into account~~ed~~. There is also significant potential for overall cost efficiencies when benefits to all linked rural, urban, irrigation and wildlife constituencies are ~~taken into account~~considered, together with the potential for pooling diverse, currently fragmented rural development, water resource, wildlife and other budgets into strategic water resource interventions yielding multi-beneficial outcomes.

There is political recognition, significantly through the Rajasthan's *Jal Swavlamban Abhiyan* programme, of the need to rebalance water management towards recharge rather than solely efficient engineered extraction of declining and increasingly contaminated resources. Rajasthan also has an active network of well-established, community-facing NGOs that could serve as extension workers and locally trusted brokers to work with distributed rural communities towards local and catchment-scale socio-ecological regeneration.

Research needs are identified to underpin robust policy, practice and redirection of investment. Although quantification of details is necessary, the basic principle of refocusing effort on recharge as a more sustainable and approach to water security is established.

Achievement of water security is a growing challenge across the developing world, and also increasingly in the already developed world. Basic principles of ensuring that resource exploitation is balanced with recharge remain important, including technology choice and appropriateness to geographical and cultural contexts and how this is shaped by economic and policy environments.

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Annex: Raw source of information used in this paper

Table A1: Key experts and interviewees and their interests

Informant and role • **Perspective**
Academic sector
University of the West of England (author team) • Expertise in ecosystem services and sustainable water management, particularly community-based water management and their integration with engineered systems
JK Lakshmipat University, Jaipur (author team) • Expertise in sustainable water management, and water quality/chemistry
IIT Delhi (author team) • Expertise and interest in community development
Government sector
Dharmendra Kaushik (dharmendrakaushik1964@gmail.com), Junior Site Engineer, Bisalpur Dam (interviewee) • Involved in the building phase of the Bisalpur Dam between 1987 and commission in 2002, and continuously held the role of Junior Site Engineer of the Bisalpur Dam from 2002 to the time of interview (April 2017)
Forest Department, Ranthambhore Tiger Reserve (author team) • Concerned with wildlife conservation and interested in ecosystem service delivery to local communities including averting and redressing wildlife-human conflict, focused on the downstream sector of Ranthambhore Tiger Reserve
Forest Department, Upper Banas (author team and also other Forest Officers coordinating the visit) • Concerned with wildlife conservation and interested in ecosystem service delivery to local communities, focused on the Banas catchment headwater area including Kumbhalgarh Wildlife Reserve
NGO sector
Wells for India (author team) • Promotes community-based collaboration on water harvesting, water management and sanitation solutions
Tiger Watch (author team) • Focused on tiger conservation, nationally but with a particular focus on the Ranthambhore Tiger Reserve, concerned with wildlife conservation also with interests in the National Gharial Sanctuary. Interested also in ecosystem service delivery from the Reserve, and averting and redressing wildlife-human conflict
Wetlands International (author team) • A broad remit of wetland and aquatic ecosystem conservation interests for inherent and societal benefits
Mahseer Trust (author team) • Focused on the conservation of mahseer (fishes) and the rivers that support populations for their many societal values, from subsistence and recreational to spiritual and associated ecosystem services
WWF-India (author team)

• A broad remit of wildlife conservation interests for inherent and societal benefits
Local communities
• Village meeting in Kesar • Meeting with male elders in Bagara village • Meeting at Sevantri and guidance to sites in the Gomti • Meetings with villagers in Amlidha • Opportunist conversations with rural inhabitants and water users in both the upper Banas and Amlidha

Table A2: Evidence on water use and trends from the upper Banas stratified by STEEP criteria

Key points from interview with officer in charge of the Bagara Dam on the South Banas River (2nd June 2017). • Social factors: The Bagara Dam was constructed by the Forest Department to provide drinking water for 224 villages downstream. • Technological factors: The Bagara Dam is the first impoundment from source of the South Banas, constructed at 660m above sea level with a height of 32 feet (nearly 10 metres) to crest. • Environmental factors: In the hilly country of the upper Banas (both South and North), the water table is generally high and the quality of the water is generally good due to natural water capture by the vegetated hills. Many traditional WHSs are still operated in the upper Banas system. However, water availability for villages declines as the South Banas flows downstream into flatter lands, with receding water levels and declining quality. Udaipur District has no dark zones as it is in hilly with good vegetation and water capture, but the downstream Districts of Rajsamand and Bhilwara have many dark zones Of the 243 Blocks (a 'Community development block' is the administrative sub-division below the tehsil, or sub-District) within a state) comprising the state of Rajasthan, 197 (81%) are over-exploited. Mahseer and a range of other cyprinid fishes are present in the Bagara Reservoir, and were sampled for taxonomic analysis during the visit to dam. • Economic factors: A licenced fishery is based on the shore of the Bagara Reservoir. • Political factors: Dams/anicuts are built by the Forest Department or by the Soil Conservation Department, depending on whose land they lie, with the exception of large dams that are built by the Water Resources Department. Water exploitation is by local demand, not watershed planning. No licences are required to sink tube wells, except in 'dark zones' (areas of depleted or contaminated groundwater).
Collated points from semi-structured interview (2nd June 2017) with five men from Bawara Village, Udaipur District, situated on the banks of the South Banas river

upstream of the Bagara Dam, invited to share their views at the nearby Forest Department nursery.

- Social factors: Bawara Village is small, comprising scattered households across the river valley. There is little population growth, but a principal problem is the decreasing size of individual landholdings as inheritance passes to multiple children. Some better-off families have their own wells. There are also some wells open to the community. However, most water supply derives from small shared wells typically serving 8-10 families.
- Technological factors: There is a high continuing reliance on traditional water methods of water access, with tube wells rare. Water from many wells is accessed by rehats (Persian wheels in which animal power drives a chain of buckets lifting water from an open well) mostly driven by bullock power, though bullock numbers are reducing with increasing mechanised (electric and diesel) pumping from open wells and river beds. Bullocks would no longer be maintained if rehats fell into decline. There is also increasing use of tractors, displacing the need for animal power. Irrigation of winter crops also makes use of haren (gravity-based systems in which water intercepted and diverted by check dams is diverted via channels to irrigate fields over distances of up to 10km). There are concerns that the more rapid rates of water extraction through mechanised pumping are exceeding resource renewal rates, leading to declines in water levels in wells and the river rendering traditional access methods ineffective.
- Environmental factors: Water is perceived as of good quality. Water is not yet limiting, proximity to the river contributing to a high water table. However, though declines in levels due to mechanised pumping are recognised. The natural resources of the landscape still sustain people's needs including the recycling of organic fertilisers and harvesting of wild food (including fruits such as custard apples), dead wood, and leaves for feeding livestock. Though the diet is predominantly vegetarian, some people eat small fish from the river. Sampling during the visit resulted in capture of mahseer (a fin clip was taken for DNA analysis) and other small unidentified cyprinid species.
- Economic factors: The non-viability of increasingly small land-holdings is a significant economic concern, with significant outmigration of younger men into cities as landholdings are often insufficient even for subsistence agriculture. Older men and others remaining in the village have to supplement their incomes from local labour (such as construction and road repairs).
- Political (governance) factors: Most decision-making in the village, including that germane to water management, still relies on traditional local governance structures such as *Gram sabha* though wealthier families can act autonomously, for example in the construction of their own wells.

Collated points from semi-structured interview (2nd June 2017) in Kesar Village, situated in hilly Khamnor Hills terrain between the headwaters of the South and North Banas, to which all villagers were invited. (A constantly shifting number of people, estimated as fluctuating between 25 and 50, attended with men only speaking.)

- Social factors: Kesar Village comprises approximately 500 households. The village has almost doubled in population over the past 30-40 years. About 50 open wells serve the needs of the village. The younger men from virtually all households work away in cities. The erosion of traditional water management skills, and the physical strength necessary to operate them, is being lost.
- Technological factors: The water table in this hill country is relatively high, and water from many of the approximately 50 open wells in the village is still commonly accessed using rehats (Persian wheels). However, there has been a significant trend towards motorised pumping and the progressive abandonment of traditional methods: whereas there were 40-50 rehats operational in the village only five years previously accessing water from a depth of about 20 feet (6 metres), at the time of the meeting only 10 rehats remained operational. There is increasing reliance on tube wells, mainly using electric pumps despite the erratic electricity supply, which access groundwater as deep as 200-400 feet (61-122 metres). Declining groundwater levels mean that restoring rehats would not serve people's needs as they can not access deepening groundwater. Opportunities were identified in the meeting for adoption of water-efficient irrigation as well as opportunities for recharging the shallow groundwater, which may save significant volumes of water relieving some impending pressures. However, on current trends, the prognosis of water scarcity over coming decades is that villages such as Kesar may be increasingly abandoned due to insufficient water.
- Environmental factors: The declining water table from its recent high level is a significant cause for concern. So too is the quality of water abstracted from deep groundwater by tube well. The Panchayat (traditional village governance institution) organised water testing, which revealed high fluoride levels. Villagers complained of chronically aching knees and legs, recognising that this was likely a result of fluorosis through increasing use of fluoride-rich water. Though unhappy about this situation, the convenience of accessing water by turning a switch rather than driving bullocks to operate a rehat overrode concerns about long-term health risks. Also, traditional wells and extraction methods become increasingly less viable as groundwater recedes. Access to quantities of water was an over-riding priority as it is water, not land area that limits food production in Kesar. There is also declining reliance on naturally harvested medicinal plants, with increasing use of western pharmaceuticals. There are also occasional conflicts with panther (leopard: *Panthera pardus*) predation of stock and herbivores eating crops.
- Economic factors: there was a polarisation of opinion about the extent of food sufficiency in the village, some growing enough for their own consumption but other villagers pointing out a high dependence on a government ration shop selling wheat imported from outside of the region. To afford sufficient food, many families in Kesar Village depended on income from local labour and

money sent back by emigres working away in cities (predominantly in Bombay). Villagers also noted that keeping bullocks is expensive (around ₹200 per day) so declining agricultural benefits from farming smaller fields was leading to reductions in stock numbers, further driving the trend towards abandoning rehats in favour of mechanised pumps.

- Political (governance) factors: Village governance matters are mainly addressed through the Panchayat. Issues of concern include declining water levels, decreasing water quality with associated health risks and food insufficiency also linked to water access. A positive feedback was noted, mechanised technology depressing well water levels such that rehats become ineffective and bullocks unaffordable, driving increasing need for deeper mechanised wells. There were no current answers to address this worrying trend and is prognosis.

Collated points from semi-structured interview (2nd June 2017) in Sevantri Village, from which the North Banas river rises at an impoundment that is also the site of Sevantri Temple, and other sites down to anicuts approximately 10km downstream from the source. The discussions were predominantly with the proprietor of a hotel at Sevantri accompanying the survey team on its tour of these Gomti river sites, but also with other local people encountered at visited sites on an *ad hoc* basis.

- Social factors: The source of the river is of spiritual importance to the people of Sevantri and its environs. Water is also drawn from the impoundment to meet people's needs. People value anicuts constructed on the Gomti for watering their stock animals.
- Technological factors: The barrage at Sevantri is an engineered structure retaining water for multiple uses. Series of anicuts also retain open water bodies along the upper river.
- Environmental factors: a diversity of biodiversity was observed using the impoundment at Sevantri (fish, reptiles including snakes and terrapins, birds), with diverse aquatic vegetation and fish observed in several downstream anicuts.
- Economic factors: Sevantri itself is a place of pilgrimage, the small hotel demonstrating an aspect of its economic value. Most livelihoods in the upper North Banas are agricultural.
- Political (governance) factors: The religious significance of the impoundment at Sevantri, which is the site of a temple and a place of religious ceremonies, imposes local control of contamination of the water or harm to its biota. Otherwise, the sparse population of people is free to make use of the ecosystem services of the upper river with little or no evident regulated restrictions.

Collated additional points observed by visits to a range of river sites in the upper Banas, and in discussion with a range of Forest Department officers interviewed opportunistically on our tour.

- Social factors: There are no large towns in the Khamnor Hills around the headwaters of the Banas River, the population scattered across the hilly terrain in small villages. The Kumbhalgarh Fort though is a significant tourist attraction, with many resorts being built relatively recently to accommodate the demands of richer tourists and assumed to ump significant volumes of groundwater without licence to maintain green lawns, swimming pools and other tourist luxuries in a semi-arid landscape.
- Technological factors: Many traditional water harvesting and access technologies were observed and reported as in place in the hilly region of the upper Banas. The first major impoundment on the South Banas is the Bagara Dam, noted separately. Proliferation of tube wells is increasing, both for farm use and to support the heavy demands of resorts.
- Environmental factors: The water table and water quality are generally high in the Khamnor Hills due to the hill country intercepting monsoon rains. However, declines in groundwater level are noted with the pervasion of mechanised pumping. Water availability declines as the Banas runs from the hills onto flatter lands: Udaipur District has no Dark Zones (areas where the quantity and/or quality of groundwater is poor) as it is hilly with good vegetation, but the downstream Districts of Rajsamand and Bhilwara are problematic.
- Economic factors: The economy of the region is split between subsistence and cash crop farming, but is substantially subsidised by income from young men working away in cities, local labour and a booming tourist economy.
- Political (governance) factors: Overall governance of water resources in the Banas is highly fragmented. There is no watershed planning. Water exploitation is instead driven by local demand. Dams/anicuts are built by either the Forest Department or the Soil Conservation Department, depending on whose land they are on, with the exception of large dams that are built by the Water Resources Department. No licences are required to sink tube wells, except in ‘dark zones’. Tube wells are proliferating for local and resort uses. Lack of planning based on an overview of the catchment, incentivising resource recharge and balancing extraction with replenishment, presents a major obstacle to sustainable development.

Assessing the feasibility of integrating ecosystem-based with engineered water resource governance and management for water security in semi-arid landscapes: a case study in the Banas Catchment, Rajasthan, India

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Abstract

Much of the developing world and areas of the developed world suffer water vulnerability. Engineering solutions enable technically efficient extraction and diversion of water towards areas of demand but, without rebalancing resource regeneration, can generate multiple adverse ecological and human consequences. The Banas River, Rajasthan (India), has been extensively developed for water diversion, particularly from the Bisalpur Dam from which water is appropriated by powerful urban constituencies dispossessing local people. Coincidentally, abandonment of traditional management, including groundwater recharge practices, is leading to increasingly receding and contaminated groundwater. This creates linked vulnerabilities for rural communities, irrigation schemes, urban users, dependent ecosystems and the multiple ecosystem services that they provide, compounded by climate change and population growth. This paper addresses vulnerabilities created by fragmented policy measures between rural development, urban and irrigation water supply and downstream consequences for people and wildlife. Perpetuating narrowly technocentric approaches to resource exploitation is likely only to compound emerging problems. Alternatively, restoration or innovation of groundwater recharge practices, particularly in the upper catchment, can represent a proven, ecosystem-based approach to resource regeneration with linked beneficial socio-ecological benefits. Hybridising an ecosystem-based approach with engineered methods can simultaneously increase the security of rural livelihoods, piped urban and irrigation supplies, and the vitality of river ecosystems and their services to beneficiaries. A renewed policy focus on local-scale water recharge practices balancing water extraction technologies is consistent with emerging Rajasthani policies, particularly *Jal Swavlamban Abhiyan* ('water self-reliance mission'). Policy reform emphasising recharge can contribute to water security and yield socio-economic outcomes through a systemic understanding of how the water system functions, and by connecting goals and budgets across multiple, currently fragmented policy areas. The underpinning principles of this necessary paradigm shift are proven and have wider geographic relevance, though context-specific research is required to underpin robust policy and practical implementation.

Key words

Banas; Bisalpur; community-based recharge; water resources; vulnerability, ecosystem services

Research highlights

1. Intensive water over-exploitation drives socio-ecological degradation in the Banas
2. Historic and current schemes regenerate water resources from monsoon rains
3. A program refocused on resource recharge can benefit all catchment beneficiaries
4. Rajasthan's policy environment recognises the need to promote resource recharge
5. A systemic approach to management and investment can guide sustainable development

1. Introduction

Industrial growth, technological development and capital accumulation during the nineteenth century triggered economic thinking and consequent management and technology choices that overlooked the importance of ecological processes and their contributions to public and business welfare (Braat and de Groot, 2012). Across multiple policy spheres, broader spatial and temporal negative externalities resulting from narrow framing of both problems and solutions consequently result not from bad intent but from lack of systemic perspective. Technology choices for the provision of water to urban centres, industry and irrigation exemplify this utilitarian approach, overlooking wider ramifications for the water cycle and its dependent ecosystems and livelihoods downstream of abstracted surface and groundwater resources (World Commission on Dams, 2000). Lack of systemic thinking is also contributory to state-led dispossession of water rights from rural people as a supply-side solution to support industrial and urban economic growth (Birkenholtz, 2016). Technocentric policy presumptions tend to drive engineered solutions, for example 'dam and transfer' schemes and energised groundwater abstraction, maximising a subset of uses of piped water and energy favouring influential beneficiaries whilst overlooking many linked ecosystem services and their beneficiaries (World Commission on Dams, 2000; Everard, 2013).

The integral connections between urban, rural, industrial, agricultural and nature conservation benefits provided by catchment ecosystems have often been overlooked in former management paradigms (Newson, 2008). Integrated Water Resources Management (IWRM) has been advanced as a response to meeting competing needs and uses at catchment scale (Calder, 1999), including addressing the growing problem of water scarcity in the developing world (Shah and van Koppen, 2014). Practical implementation of the principles of IWRM across extensive and diverse landscapes in developing world situations is however frequently limited by knowledge and data gaps, regulatory and scientific capacities, and power asymmetries (Ioris, 2008).

Everard (2013) identified the need and opportunities for increasing synergy between ecosystem-based and engineered water management solutions. Neither paradigm represents a panacea in mixed urban-rural landscapes, in which engineered management is far more interdependent with ecosystem processes than is conventionally recognised. Large-scale cases of landscape management for improving raw water quality, for example serving water supply to New York City (Committee to Review the New York City Watershed Management Strategy *et al*., 2000), the Upstream Thinking programme in south west England (McGonigle *et al*., 2012) and to protect natural spring water sources in France (Perrot-Maître, 2006), demonstrate substantial economic and input efficiencies relative to conventional electromechanical treatment of more contaminated water, also producing multiple ecosystem service co-benefits.

In India, recent policy presumptions favour advanced engineering solutions that may not work in sympathy with local geography and culture, and hence may not be sustainable in the long term. These include substantial investment in large-scale 'dam and transfer' schemes, diverting water from areas of perceived excess towards urban economies and intensive irrigation centres of high demand. India's National Informatics Centre (2017) lists 4,877 completed 'large dams' (as defined by the International Commission on Large Dams, ICOLD) with a further 313 large dams under construction across the country, impounding virtually all large rivers systems. The needs of people and ecosystems in donor catchments are poorly reflected in management decisions, though ramifications of physical impoundments, redirection of flows and changes in catchment ecosystem services may be profound (World Commission on Dams, 2000). Severe problems stemming from over-exploitation of groundwater have long been recognised, including depletion of water tables, saltwater encroachment, drying of aquifers, groundwater pollution, and soil waterlogging and salinisation (Singh and Singh, 2002) and local risk of subsidence (Rodriguez and Lira, 2008). Nevertheless, India's policy environment still favours energised tube well abstraction of receding and increasingly geologically contaminated groundwater to promote short-term agricultural profitability (FAO, 2011). This is leading to abandonment of centuries-long, geographically and culturally sensitive practices and loss of associated traditional wisdom balancing water access with recharge from episodic monsoon rainfall (Das, 2015; Raju, 2015).

This paper addresses vulnerabilities created by fragmented policy measures between rural development, urban and irrigation water supply, and downstream consequences for people and wildlife. Water vulnerability is a multi-factorial issue, comprising water scarcity, generally assessed on a volumetric basis, and water stress which includes factors such as water quality, accessibility and the commonly underestimated influence of governance arrangements and other social factors (Plummer *et al*., 2012). Water vulnerability is therefore a dynamic concept integrating geographical and climatic factors with demand, infrastructural conditions and prevailing institutional arrangements, economic policy, planning and management approaches (FAO, 2012). Essentially, the concept of water vulnerability is interpreted in this paper as relating to risks arising from availability of water of adequate quality and quantity to secure the wellbeing of humans and ecosystems.

This study focuses on the Banas catchment in Rajasthan state, India. The question addressed by this paper is how restoration of the Banas water system can be achieved at catchment scale, seeking mutual benefits for rural, urban, irrigation and wildlife co-dependents. This is addressed by the objectives of: characterising trends in the Banas catchment; identifying vulnerabilities for co-dependents; proposing systemic solutions to reverse degradation of the catchment socio-ecological system (SES); and identifying research and development priorities to achieve linked urban and rural livelihood and ecosystem security. These objectives are addressed by targeted visits, including empirical observations and semi-structured interviews at sites in upper, middle and lower river reaches, literature review, and identification and testing of proposed solutions within the cross-sectoral co-author community. Although the case study is geographically specific, underlying principles are of generic geographical relevance across water-stressed areas of the world.

2. Methods

Evidence-gathering for this study took the form of literature review and site visits to the upper, middle and lower Banas catchment including semi-structured interviews with key stakeholders active.

2.1 Literature review

Literature review took account of a diversity of peer-reviewed sources but also, by necessity, of technical reports (particularly by Government institutions in Rajasthan and at national level in India) and relevant media sources to assemble evidence where peer-reviewed literature was lacking. This diversity of published sources was used to characterise and document transitions in infrastructure development in the catchment. Learning from ecosystem-based catchment restoration solutions implemented elsewhere in Rajasthan was included in the review.

2.2 Site visits and semi-structured interviews

Site visits were conducted in three distinct zones of the Banas catchment: the headwater locations; the Bisalpur Dam mid-way down the river system; and Amblidha where the Banas transects the Ranthambhore Tiger Reserve. At these different locations, some interviews were prearranged whilst others were opportunistic. Interviewees included a range of Forest Officers in the upper and lower catchments, village gatherings, the Junior Site Engineer at the Bisalpur Dam, local people operating water infrastructure, and staff of NGOs. Given the heterogeneity of sites and the wide diversity of geographical and cultural perspectives of interviewees, it was neither feasible nor useful to undertake a uniform structured interview. Interviews were therefore of necessity semi-structured, building around how the five dimensions of the STEEP framework (social, technological, environmental, economic and political) manifested in the local setting. Observations and interviews at all field sites were recorded in writing at the time of the visit. Prompting questions from interviewers were structured around social arrangements, technology choice, environmental context including flows of ecosystem services, economic aspects, and political context (multi-scale governance, not just the formal policy environment). In order not to restrict the flow of information, interviewees were allowed to expand freely on answers to prompts, with key points of their feedback recorded for later dissociation around STEEP elements. Once all aspects of the STEEP framework were exhausted in conversations, interviews were concluded with thanks and a request to use this information for research purposes.

A two-day visit in June 2017 was undertaken in vicinity of the headwaters of the Banas system. This visit included the source of the South Banas (also known as the Katar) which rises in the grounds of a temple at Berokamath. The source of the North Banas (also known as the Gomti or Gomati) at Sevantri as also visited. Various river sites, including the first major impoundment of the South Banas at Bagara Dam, were also part of this visit. Invited meetings also took place with five local men from Bawara village situated on the banks of the South Banas upstream of the Bagara Dam, and a village community meeting at Kesar village in hill country between the sources of the two Banas headwaters. Opportunist discussions also occurred with people at small impoundments or operating water infrastructure at sites on the North Banas River.

A site visit was undertaken to the Bisalpur Dam in April 2017. This entailed observations of the dam infrastructure and locality, and in particular a semi-structured interview with Dharmendra Kaushik, Junior Site Engineer, who had been involved in the planning and building phase of the Bisalpur Dam between 1987 and commissioning in 2002 and had subsequently continuously held the role of Junior Site Engineer.

Visits to the lower Banas in Amblidha where it transects the Ranthambhore Tiger Reserve are documented in Everard *et al*. (2017). Visits by the senior author took place in April 2016 and April 2017, with other co-authors (in particular Khandal and Sahu) visiting and working in communities and habitat throughout the lower river reach on a routine basis.

Additional information is provided from the literature, and also the direct working experiences in the Banas of Forest Department and NGO co-authors. The spectrum of expert and interviewee input is listed in Table A1 in the Annex. It is recognised that this is a sparse sampling regime enforced by time and budgetary limitations relative to the size and heterogeneity of the catchment. However, attention has been paid to trends in water use and resources at key upstream, mid-river/dam and downstream locations to build an overview.

3. Results and Discussion

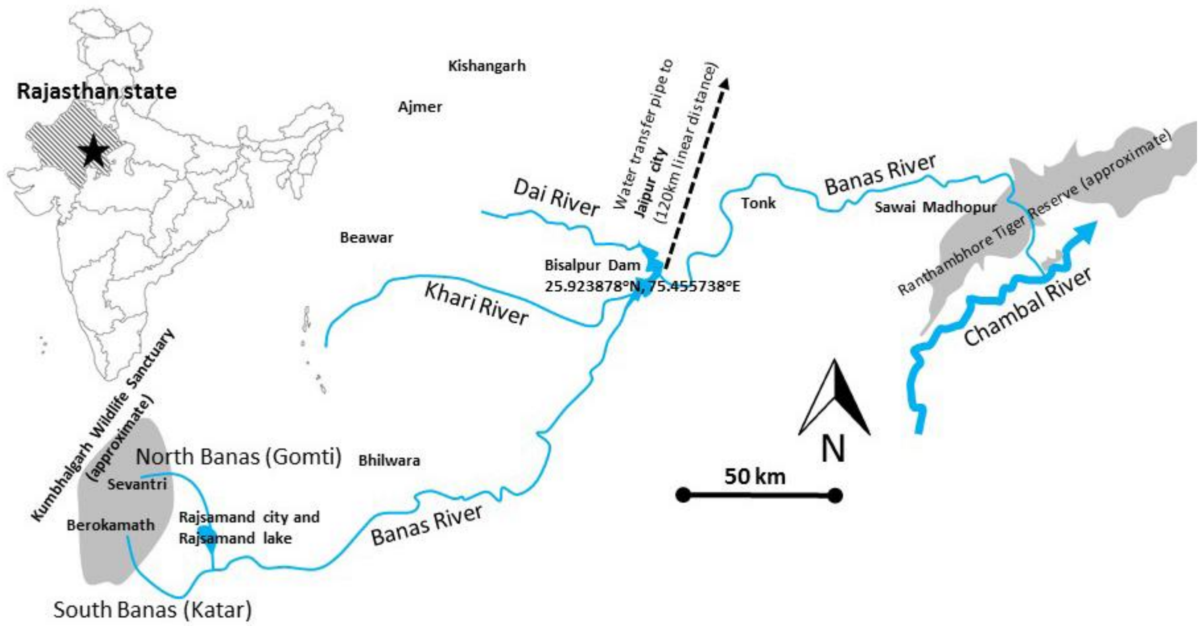
This Results and Discussion section draws on the evidence-gathering methods to characterise the Banas River and associated uses, including the Bisalpur Dam, then turning to explore socio-economic and ecological vulnerabilities across the Banas-Bisalpur nexus. Initiatives that have been successful in recharging shallow groundwater and catchments elsewhere in Rajasthan are also reviewed. This provides information supporting the consideration of options for a more systemic approach to catchment management.

3.1 Physical characteristics of the Banas catchment

The Banas is the only river with its entire course in the state of Rajasthan. The two headwaters of the main stem of the Banas River rise in the Kumbhalgarh Wildlife Sanctuary in the Khamnor Hills. The South Banas (Katar) rises at Berokamath in the hilly District of Udaipur. The North Banas rises at Sevantri in the relatively dry (average 556.1mm per annum rainfall, Table 1) District of Rajsamand District but which, in the vicinity of the headwaters and upper river, shares more of the hilly topography of the relatively moister Udaipur District (632.7mm per annum rainfall, Table 1). These two principal headwaters join approximately 10km to the east of the town of Rajsamand, the combined Banas subsequently flowing through Bhilwara, Tonk and Sawai Madhopur Districts before combining with the Chambal River which forms the border with Madhya Pradesh state near the village of Rameshwar in Sawai Madhopur District (Bhatt, 2005). In total, the Banas River is 512 km in length, with a catchment area of 45,833 km^2 (Department of Water Resources, 2000; Upadhyay and Rai, 2013). 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). There is a pronounced seasonal flow regime in the river system responding to episodic monsoon rainfall that typically peaks in July and August.

The Banas River comprises ten major sub-catchments including the river’s main stem (Department of Water Resources, 2014): the Berach and Menali on the right bank, and the Kothari, Khari, Dai, Dheel, Sohadara, Morel and Kalisil on the left bank (Singh *et al*., 2007). Three principal tributaries comprise the upper river system upstream of the Bisalpur Dam: the Khari; the Dai; and the Banas which is the largest reaching a width of 900m above the Dam and that is itself broken into North and South forks in its headwaters. There are impoundments of varying sizes, mainly small, upstream on many of the smaller tributaries of the Banas, Khari and Dai. (See Figure 1.)

Figure 1: Location map of the Banas catchment, Bisalpur Dam and key cities, towns and other landmarks



3.2 Water availability and quality in the Banas catchment

The episodic nature of monsoon rains and the generally hot climate combine to result in groundwater supporting over 85% of India's rural domestic water requirements, 50% of urban and industrial water needs, and nearly 55% of irrigation demand (Government of India, 2007). 88% of India's extractions of groundwater are used for irrigation with 137% withdrawal of available groundwater (Central Ground Water Board, 2014). There has been a pronounced trend towards using deeper groundwater, accessed by mechanised pumping from tube wells. Between 1960-61 and 2010-11, the main sources of irrigation across India changed radically with an exponential rise from 0 to nearly 30 million hectares irrigated with water extracted from tube wells, twice as much as from any other source (Ministry of Agriculture, 2014). Increasing groundwater exploitation has been amplified by excessive and wasteful water usage due to low power tariffs, collectively contributing to a sharp fall in water tables (Planning Commission, 2007).

Rajasthan is India's second largest state with nearly 5% of the country's total population (^{c}69 million), but with only 1% of its water resources (Government of Rajasthan, 2010). The arid/semi-arid climate of Rajasthan and its paucity of surface water resources results in a high dependency on groundwater for irrigation and drinking water, exacerbating its depletion and risks associated with lack of alternative sources (Directorate of Economics and Statistics, 2011). More than 80% of water supply schemes in Rajasthan State depend on groundwater exploited via tube wells, open wells and hand pumps (Jain and Singh, 2014). Analysis of trends in water levels in wells in Rajasthan during pre-monsoon (May) and post-monsoon (November) periods between 1989 to 2014, also in relation to withdrawal rates from groundwater and water levels predicted from rainfall, reveal declining groundwater levels in both hard rock areas and tapping alluvial aquifers related to increasing groundwater draft (Central Ground Water Board, 2016a). In the pre-monsoon 2016 period, over 37% of Rajasthan's wells were accessing water 20-40 metres below ground level, with 19.09% reaching more than 40 metres (Central Ground Water Board, 2016b).

Exposure to geologically enriched water is exacerbated in regions of groundwater depletion, as deeper resources with longer residence times are extracted. In regions such as Rajasthan where the rate of groundwater extraction exceeds that of its renewal, geological contamination is an increasing problem (particularly salinity in western Rajasthan and fluoride in the southern part) as well as declining water yields and increasing pumping costs arising from competitive deepening of wells (Shah *et al*., 2001). 218 (90%) of the 243 blocks (administrative units within Districts) comprising the state of Rajasthan are declared 'dark zones', signifying groundwater depletion or degraded chemical quality particularly due to excessive fluoride, nitrate, chloride and total dissolved solids concentrations (Jain and Singh, 2014). Geological contamination of groundwater, particularly by fluoride, is an increasing issue with serious public health implications in Rajasthan (Brindha and Elango, 2011). Well depth and anion data for Districts of Rajasthan traversed by the Banas (Central Ground Water Board, 2016a) are reproduced in Table 1. The World Health Organization (2010) recognises excess fluoride as a major global public health concern stimulating tooth enamel and skeletal fluorosis following prolonged exposure to high concentrations, with an elevated risk of skeletal effects at fluoride intake rise above 6 mg/day, though fluoride can also be a cellular poison and can form hydrofluoric acid in the gut. The primary ingestion pathway is consumption of groundwater originating in regions with an abundance of the minerals fluorspar, fluorapatite and cryolite (IPCS, 2002) or crops taking up fluoride from high-fluoride irrigation water. Agrawal *et al*. (1997) recognise high fluoride concentrations in groundwater resources as one of the most important health-related geo-environmental issues in India, and in particular Rajasthan where high fluoride groundwater is distributed in all 31 of its Districts with three million (in 1997) people consuming water with excess fluoride. Dental and skeletal fluorosis associated with consumption of contaminated groundwater is a pervasive problem as a well as a locally acute issue in Rajasthan (Meena *et al*., 2011).

Table 1: Rainfall, well depth and anion data for selected Districts of Rajasthan (Central Ground Water Board, 2016a)

District	Annual average rainfall (1901-1970) in mm	Premonsoon well depth in metres below ground level), May 2014	Sites exceeding permissible limit (2014-15)		
			Fluoride (1.5 mg l^{-1})	Nitrate (45 mg l^{-1})	Chloride (1,000 mg l^{-1})
Udaipur	632.7	2.25 to 22.85	15% (4/27)	37% (10/27)	0% (0/27)
Rajsamand	556.1	4.53 to 21.19	23% (3/13)	77% (10/13)	0% (0/13)
Bhilwara	603.3	3.4 to 21.1	52% (13/25)	44% (11/25)	12% (3/25)
Tonk	598.2	2.05 to 31.45	35% (6/17)	53% (9/17)	18% (3/17)
Sawai Madhopur	655.8	2.75 to 12.75	30% (6/20)	50% (10/20)	0% (0/20)
Rajasthan state	549.1	0.02 to 112.85	28% (154/561)	43% (240/561)	11% (59/561)

Data to substantiate reported trends in abandonment of traditional water recharge practices are elusive, though a growing literature asserts that their restoration could be significant in rebalancing water resource recharge with demands on receding groundwater (for example Shah and Raju, 2002; Pandey *et al*., 2003; Rathore, 2005; Narain *et al*., 2005; Everard, 2015). Increasing numbers of tube wells suggest a proportionate decline in traditional water management techniques, though the lack of licencing of mechanised extraction provides no authoritative record of how many pumps are in operation or the depth at which they are extracting water. One unsubstantiated estimate by the Junior Site Engineer at Bisalpur Dam was that only 1-2% of villages in the catchment upstream of the dam retain traditional rainwater harvesting infrastructure, with most now reverting to energised tube well abstraction of groundwater without any contribution to its recharge (Dharmendra Kaushik, Personal Communication). A Central Ground Water Board (2013a) assessment of Rajsamand District, where much of the main stem of the upper Banas rises and flows and which hosts 1,037 villages, recorded an overall 126.73% over-development of groundwater exploitation leading to declining and frequently critical levels with diverse forms of wells from 8-203 m depth accessing water with an electrical conductivity 300 to 3,440 µS cm^{-1} (at 25°C). The main stem of the Banas flows next through Bhilwara District, hosting 1,834 villages experiencing a 135.55% (over)exploitation of groundwater with high salinity (35-2453 mg Cl l^{-1}), fluoride (0.24 -7.24 mg F l^{-1}) and nitrate (5.2-749 mg NO_3 l^{-1}) contents and an overall scarcity of water (Central Ground Water Board, 2013b). There are no Environmental-flow (E-flow) requirements in place in the upper Banas River (Gupta *et al*., 2014).

The implications for groundwater storage of increasing groundwater withdrawals through rapid proliferation of tube wells in India has not been well studied, though negative trends have been observed in West Bengal (Chinnasamy and Agoramoorthy, 2016). Simplistic assumptions about recharge versus use also tend to overlook the complexities of groundwater system dynamics at regional and district levels, most monitoring by India's Central Ground Water Board relating to shallow, unconfined aquifers with only 5% of Rajasthan's monitoring wells reaching the deep, confined aquifers that are tapped by many irrigation wells (Chinnasamy *et al*., 2015). The dynamics, recharge rates and potentially substantial residence times of these deep aquifers are barely understood, raising significant questions about the sustainability of their use for purposes other than as emergency reserves (Dragoni and Sukhija, 2008).

Declining levels and pervasive and rising geological contamination of water in wells, and the questionable quality and sustainability of increasingly exploited deeper, confined aquifers, suggest that a renewed focus on recharge and use of shallow, renewable unconfined aquifers presents a more precautionary and sustainable pathway of water resource development. Stewardship and sustainable exploitation of renewable elements of the water resource are the focus of traditional water stewardship techniques found across Rajasthan (Sharma and Everard, 2017). The need to reorient water resource development on a more sustainable path is made more urgent by Rajasthan's increasing human population, including disproportionately rapid growth in urban areas (Table 2). This may increase pressure for continued dispossession of water rights from rural people as a supply-side solution to support industrial and urban economic growth identified by Birkenholtz (2016). Birkenholtz (2012) reports that the Government of Rajasthan's Water Resources Department declared 27,000 anicuts in the Banas River basin upstream of Bisalpur Reservoir illegal in April 2010, arguing that they inhibited filling of the reservoir, demonstrating not merely rural-urban power asymmetries in water resource appropriation but also naivety about the role of water retention and infiltration in the upper catchment as a net contribution to catchment water storage and groundwater recharge.

Table 2: Population growth in Rajasthan and selected Districts (Directorate of Census Operations Rajasthan, 2011)

State or District	Total population growth, 2001-2011	Urban population growth, 2001-2011
Rajsamand	17.7%	42.8%
Bhilwara	19.2%	23.6%
Tonk	17.3%	25.5%
Sawai Madhopur	19.6%	25.3%
Rajasthan state	21%	29%

3.3 Water exploitation in the headwaters of the Banas

Evidence about water use and trends from villages in the Khamnor Hills, from which the two main headwaters of the Banas rise, was primarily derived from the visit in June 2017 and relevant literature. This included field observations from river sites including the source springs of both the North and South Banas as well as interviews with village groups, Forest Officers and opportunistic meetings from people at sites on both sub-catchments. Evidence from semi-structured interviews is collated using the STEEP framework in Table A2 of the Annex.

On the basis of this evidence, water vulnerabilities in the upper Banas were observed to relate significantly to technological changes, particularly increasing use of mechanised pumps that are progressively displacing traditional water management systems such as harens, open wells and rehats (Figure 2). This trend appears to be in a positive feedback loop, with water levels in the formerly better watered Khamnor Hills now receding under intensive pumping and consequently becoming inaccessible by traditional means. This in turn makes maintenance of bullocks to power traditional technologies economically non-viable. Disconnection of extraction rates from natural renewal rates also appears to be creating vulnerabilities relating to water quality, a trend that is recognised at village scale but for which no solutions are in place due at least in part to a lack of alternative water sources. There is also a concern that traditional knowledge relating to locally attuned water management is being lost. Rising populations and the economic non-viability of declining farm sizes compound these problems, with rural communities dependent on other income – principally local labour and emigration of younger men to cities – to supplement subsistence needs. The long-term prognosis arising from increasingly mechanically intensive water extraction practices, compounded by the demands of increasing resort developments supporting a tourism industry that does not operate in sympathy with village-scale water governance, are serious for the viability of local communities for whom water rather than land area is a limiting factor for food production. Many of these problems are not soluble by village-level governance alone. However, there is at present a lack of catchment-scale planning.

Figure 2: A rehat, or Persian wheel, in operation, a central wheel driven by bullocks to turn a chain of pots drawing water up from ann adjacent open well (June 2017, image © Dr Mark Everard) – Low resolution version of image Fig 6 – Rehat in operation.JPG inserted to aid reviewers

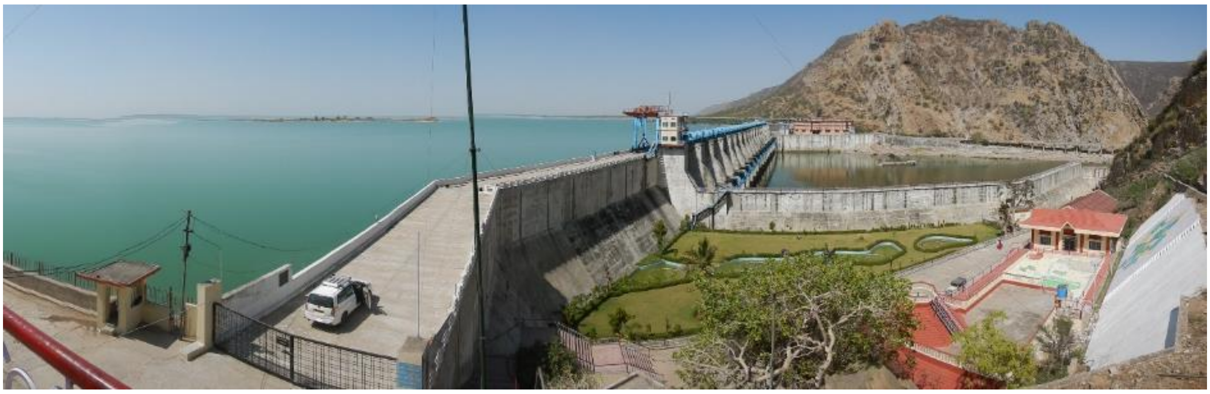
3.4 Water management and diversion at the Bisalpur Dam

Construction of the Bisalpur Dam-reservoir complex (25.924790^{o}N, 75.456060^{o}E, altitude 831 m asl) was completed between 1995 and 1999 as a project of the Government of Rajasthan, located at a rock gorge 255 km river distance downstream from the head of the Banas River immediately downstream of the confluence of the Khari and Dai river systems, for the purpose of providing drinking water, irrigation of a command area of 81,800 hectares and fishery co-benefits (Government of India, 2013; Government of Rajasthan, 2014). The Bisalpur Dam had a height of 39.5 m above deepest foundation, 574 m total dam length, with an effective storage capacity of over 1.1 km^3 (National Informatics Centre, 2017). The Bisalpur Dam qualifies as a ‘large dam’ under ICOLD criteria (above 15 metres in height from the lowest point of foundation to top of dam and retaining a reservoir of more than 1 million m^3) warranting inclusion on the World Register of Dams (ICOLD, 2017). The Bisalpur Dam has 18 spillways to release water during high monsoon flows (Figure 3).

Prior to dam construction, local communities drew water from approximately 60 tube wells. Dam construction and filling submerged and displaced significant numbers of villages and inhabitants, resulting in substantial protests against perceived unjust provisions under the state government’s rehabilitation and resettlement policy

(Agarwal *et al*., 1999), culminating in many displaced people becoming landless and/or homeless (Mathur, 2013).

Figure 3: The Bisalpur Dam (April 2017, image © Dr Mark Everard) – Low resolution version of image Fig 2 – Bisalpur Dam.JPG inserted to aid reviewers



The Bisalpur Dam has since been substantially increased in height and capacity over two phases. The primary purpose of these redevelopments was to provide drinking water for the city of Jaipur some 120 km to the north (Central Water Commission, undated). Jaipur City and its environs had exhausted viable local potable water supplies, firstly from overexploitation of its local groundwater sources and subsequently of the resources of the Ramgarh Reservoir (see Box 1).

Box 1: Water supply to Jaipur City, Rajasthan state, India

Jaipur, located in the semi-arid zone of the Indian state of Rajasthan, is India's 10th largest city with a population of over 3.1 million people and is expected to grow to 4.21 million by 2025 (UN Habitat, 2013). Water demands were initially served by local open wells, regenerated by capture of periodic monsoon rains. Development of the water supply system is now around 100 years old, with initial supply augmentation in 1918 via a series of 16 large-diameter open wells with limited piped water supply (Jain, undated).

The Ramgarh Reservoir had been constructed some 32 km to the north east of Jaipur by damming the Banganga River in 1897, with reservoir filling commencing in 1903 for local water supply and irrigation but also providing a valuable fishery (Sugunan, 1995).

In 1952, Jaipur City turned northwards to appropriate water from the Ramgarh Reservoir to complement its insufficient local resources, raising the Ramgarh Dam to increase the volume of Ramgarh Lake to provide 7.0 megalitres of water per day (MLD) to the city. Ramgarh Dam was raised once more in the late 1960s and again in 1982 to augment supply, at its peak area the lake spanning 15.5 km^2 in the wet season. However, encroachment by urban development around the lake has since resulted in cessation of free flows of water into the lake, which has now been dry since 2000 (Sunny, 2000). Aside from implications for Jaipur City, an important source of drinking water, irrigation and fish was lost, and the rights of local people dispossessed. Long before this formerly valued wildlife and amenity area dried completely, limitations on the availability of surface water were being realised. Tube well drilling was introduced in late 1960s, tapping into groundwater below and adjacent to Jaipur City.

As a larger and more reliable source, work began extending the Bisalpur Dam on the Banas River some 120km to the south of Jaipur in 2006, with water reaching Jaipur from the dam in 2009. Jaipur city is outside of the natural catchment of the Banas River, the flow and linked ecosystems of which are compromised by large-scale impoundment and water transfers. Design demand from the Bisalpur system has since been increased in stages, water transfer pumping stations transferring water to the south of Jaipur City. Canals transporting the water have high leakage and evaporation rates, causing further problems through wastage. Tanker transportation of water serves un-piped areas of Jaipur city throughout the year.

Jaipur's water supply is still augmented by pumping from tube wells, although groundwater in Jaipur City is overdrawn by a calculated 600% with no more land area available to enhance recharge to meet the demands of rapid continuing urbanisation. Groundwater under the city is not only retreating to around 400 feet (122 metres) but is increasingly contaminated from geological and anthropogenic sources (Yadav and Garg, 2011). Tatawat and Singh Chandal (2008) surveyed water from hand pumps around the city measuring conductivities from 345-2,550 $\mu S\ cm^{-1}$ (at 25°C) with a World Health Organization (2011) maximum limit of 1,400 $\mu S\ cm^{-1}$, total dissolved solids from 239.6-1,435 $mg\ l^{-1}$ (maximum limit 500 $mg\ l^{-1}$) and chloride from 32.49-624.81 $mg\ l^{-1}$ (against a recommended maximum of 250 mg/l but without formal health guideline). Fluoride is a major cause for concern, with 40% of groundwater samples from Jaipur exceeding a permissible limit of 1.5 $mg\ l^{-1}$ (Central Pollution Control Board, 2008; World Health Organization, 2011).

There is an increasing rate of tube well failures due to the declining water table. In addition to municipal wells, a large number of additional tube wells drilled by private owners exploit water indiscriminately, further depleting the water table and adversely affecting water quality. Jaipur is increasingly dependent upon the Bisalpur Dam, and so is vulnerable to the declining quantity and quality of water in the Banas-Bisalpur system (Dass *et al*., 2012).

The Bisalpur Dam had been providing water to the towns of Ajmer, Beawar and Kishangarh since 1994, but a major project of the Government of Rajasthan's Water Resources Department increased dam capacity to begin serving the City of Jaipur and en route villages from December 2008 (Government of Rajasthan, 2014). The Bisalpur-Jaipur Water Supply Project (BWSP) was instigated by the Government of Rajasthan in 2005 to deliver water from the existing Bisalpur Dam headworks to the south edge of Jaipur City. Phase I of the BWSP included provision for 360 MLD to Jaipur City and 40 MLD for rural areas, with Phase II increasing these volumes to 540MLD and 60MLD respectively, with potable water from Bisalpur Dam reaching Jaipur from March 2009 (RUIDP, 2017). Subsequent dam raising has not been without vigorous dispute, with 10 protesting farmers shot of which 5 were killed in

2005 as the dam was raised to achieve a storage of 38.7 tmcft (over 10^8 Ml) by 2007 (Bhaduri, 2015; Shiva, 2015).

There are further proposals to transfer an additional 300 mm^3 $year^{-1}$ of water from the Anas River in the Mahi Basin to the Berach River in the Banas Basin to augment the Bisalpur Dam (Department of Water Resources, 2014). There are also reports (with quotes from senior staff though at the time of writing no official announcements) of the Government of Rajasthan's Public Health Engineering Department (PHED) proposing a second phase of the Bisalpur project to be completed in 2019 increasing the allocation of water to Jaipur City from 600 to 930 MLD (Joseph, 2016).

Under operational targets at the time of the site visit to the Bisalpur Dam in April 2017, the cities of Jaipur, Ajmer and Tonk receive significant water from the Bisalpur Dam headworks, with a further extensive area irrigated for agriculture in Tonk District via two canals on each bank of the river and substantial estimated annual evaporation from the Reservoir surface. Data in Table 3 is derived from an operational manual *Rajasthan Water Resources, Bisalpur Dam* published by the Department of Water Resources, Government of Rajasthan, shared during the site visit by the Junior Site Engineer but regrettably not published online. Though these values are not peer-reviewed, if treated cautiously they are at least indicative of the substantial quantities of water diverted or evaporated from the Bisalpur Reservoir that are lost to the Banas system.

Table 3: Approximate water diversion and loss from the Bisalpur Dam (Department of Water Resources operational manual: 'Rajasthan Water Resources, Bisalpur Dam')

Water diverted or lost	Reported tmcft annually	Recalculated values	
		Average Mld	%
To Jaipur city	11	853	34%
To Ajmer city	5	388	15%
To Tonk city	0.5	39	1.5%
To 88,000 ha land irrigated in Tonk District	8	620	25%
Loss through evaporation from reservoir surface	8	620	25%
Required releases to the downstream river	0	0	0%
TOTALS	32.5	2,520	100%

There are no planned releases to the Banas River downstream of the Dam, as the river has not been assigned an Environmental Flow requirement (Gupta *et al*., 2014), largely on the assumption the river is seasonal and dry outside of the monsoon season (Dharmendra Kaushik, Personal Communication). There is no hydroelectric generation at the Bisalpur Dam, the primary purpose of which is water storage and diversion for urban and irrigation uses. The Dam also lacks any form of fish passage. Migratory fish species, particularly mahseer (*Tor* spp.), have been long known from the Chambal River (TWFT, 1984; Desai, 2003) and the reach of the lower Banas running through the Ranthambhore Tiger Reserve (Everard *et al*., 2017) as well as sampled from Bagara Dam and an upstream section of the South Banas

(Katar) river Bawara village during the June 2017 site visit (Figure 4). The mahseer species *Tor tor* is known from the Chambal river and is of conservation concern (Pinder and Raghavan, 2013), classified as Near Threatened (NT) in the IUCN Red List (IUCN, 2017). However, mahseer are reported as absent from the Bisalpur Dam and adjacent river (Dharmendra Kaushik, Personal Communication). The Dam therefore appears to have eliminated mahseer, and by implication probably other riverine fishes, further skewing the distributional benefits and costs of management across the catchment. Annual dam management and maintenance of ₹900 crore is effectively recouped from the ₹1,000 crore gross charges for irrigation water, though individual charges to farmers per hectare per crop are affordable (Dharmendra Kaushik, Personal Communication); no mention was made in interviews or in the literature of charges levied on urban beneficiaries of water diverted from the Bisalpur Dam beyond transmission and distribution costs.

Figure 4: A mahseer, genus Tor*, sampled from the Bagara Dam (April 2017, image © Dr Mark Everard) – Low resolution version of image Fig 3 – Tor species from Bagara Dam.JPG inserted to aid reviewers*

Bisalpur Lake and the cities and irrigated land that its water serves are vulnerable to both declining quantity and quality of water. The Central Pollution Control Board (2015) has recognised the Banas River, including the vicinity of the Bisalpur Dam, as amongst the highest priority rivers for pollution control action largely on the basis of biochemical oxygen demand (BOD) in the range of 4.2-39.9 mg l^{-1}. Between 2002 and April 2017, the lake had only completely filled nine times and had completely dried out in 2006 prior to the July rains, during which time the needs of Jaipur were met from six tube wells tapping into groundwater 100 feet deep around the dam area (Dharmendra Kaushik, Personal Communication). Gupta *et al*. (2014) chart the declining trend of water inflow into the Bisalpur Reservoir by comparing theoretical yield based on rainfall data from 1981-2012 with actual inflow, noting a slight increase in rainfall yet a fall in actual inflow ascribed to upstream development including construction of extensive anicuts, population growth and inter-annual variations in rainfall contributing to both episodic and chronic shortages in water supplies and irrigation facilities. Gupta *et al*. (2014) conclude that the Bisalpur Dam operates substantially below its design dependability (defined in terms of how many times a dam fills completely or spills over relative to the expected probability), putting at significant risk the urban centres and irrigated command areas it supplies. Recognising that this trend of increasing rainfall yet decreasing filling of the Bisalpur Dam is similar to that which occurred at the Ramgarh Dam (see Box 1), formerly a principal source of water for Jaipur but now completely dry leading to development of the BWSP, Gupta *et al*. (2014) call for removal of anicuts and cessation of encroachment by construction and increased agriculture upstream to prevent the future drying of this "…*life line of Central Rajasthan*".

Increasing dependence of Jaipur and other cities on the waters of the Bisalpur Dam, originally built for local drinking water and irrigation purpose, therefore perpetuates a this pattern of urban appropriation and rural dispossession observed in Jaipur's history of water management and more widely across the developing world. The observed declining flows and quality of water entering the Bisalpur Reservoir, and observations that the dam operates substantially below its design dependability, puts at significant risk the urban centres and irrigated command areas that the Banas-Bisalpur scheme supplies. It also raises additional civil vulnerabilities, with a history of protest by affected local people dispossessed and disadvantaged by perceived political asymmetries favouring remote urban and industrial economic activities. Further vulnerabilities arise from the substantial amount of water (25%) lost to the system through evaporation from the reservoir surface, a vulnerability potentially averted if more water could be stored as an underground resource across the catchment rather than accumulating the surface behind the dam.

3.5 The Banas catchment below the Bisalpur Dam

Downstream of the Bisalpur Dam, the river is starved of flows beyond those limited periods when the dam overtops (noting that the dam only filled completely nine times between 2002 and 2017), reportedly as the lower river is assumed to be seasonal. Historic and observational evidence highlights that the river was formerly a significant source of year-round water, and that many stretches still hold perennial water. Above-ground and underground flows in the Banas River were the primary source of water to the city of Sawai Madhopur until the 1980s (Y K Sahu, Field Director, Ranthambhore Tiger Reserve, Personal Communication). 8.0 MLD of water is now supplied to Sawai Madhopur from surface and groundwater supply sources including 78 tube wells and 10 open wells adjacent to the city, though with some water still lifted from an open well connected to an intake constructed on the banks of Banas River (Local Self Government Department, 2008). Photographic evidence of permanent water in the lower Banas River taken in notably dry periods (Figures 5 and 6) further endorses that the lower Banas can not be assumed to be a naturally dry river outside of monsoon season. Low flows in the downstream section of the Banas outside of the monsoon season are further compounded today by largely illegal and extensive sand and gravel mining destroying the structure of the exposed river bed, further suppressing the groundwater table (ISET and CEDSJ, 2011) and impacting on the availability of fish spawning and other habitat. These water losses starve the river of dry weather flows outside of the monsoon season. This has potentially significant ramifications for riparian communities and their livelihoods.

Figure 5: Large pool on the Banas River running through the Ranthambhore Tiger Reserve during a severe drought including two 'missed' monsoons (April 2016, image © Dr Mark Everard) – Low resolution version of image Fig 4 - Banas at Amblidha.JPG inserted to aid reviewers

Figure 6: The lower Banas River viewed downstream from National Highway 1, 20km north of Sawai Madhopur, carrying substantial water in summer, the driest time of year, in a notably dry year (April 2017, image © Dr Mark Everard) – Low resolution version of image Fig 5 - Banas from NH1 20km north of Sawai Madhopur.JPG inserted to aid reviewers

Everard *et al*. (2017) record the concerns of village people from the of Amlidha region buffer zone of the Ranthambhore Tiger Reserve about livelihood implications arising from diminishing flows in the Banas River. These people now mostly obtain water for domestic use from pumped tube wells close to villages, with some water also pumped from the Banas River and transported in small quantities by women or in larger quantities by vehicles. Secondary impacts include the exploitation of other alternative resources such as tube wells situated around Sawai Madhopur, potentially negatively impacting wider ecosystems and human opportunities. River drying due to diversion of flows therefore has long spatial-range impacts on people. It also has potentially significant impacts on wildlife, both terrestrial and aquatic, with declining flows from the Banas now limiting water availability in Ranthambhore Tiger Reserve and well as reaching the Chambal National Gharial Sanctuary downstream of the confluence of the Banas. Pressures can arise directly from declining water availability, but also as secondary impacts through degradation of complex riparian habitat at Ranthambhore (Forest Department, 1990) and in contributing to potential wildlife-human conflicts (Everard *et al*., 2017).

Locally, the The Banas River is referred to as *Van Ki Asha* ('Hope of forest') for its important role in bringing water across the state as well as the "…*lifeline of central Rajasthan*" yet, given the depleting state of the river and almost complete diversion of its waters in the middle of its course, that service is now almost completely compromised. Current alternative surface reservoir and groundwater development closer to the city of Sawai Madhopur therefore places greater pressure on local resources. Declining river flows also compromise the capacities of downstream communities to meet their needs, reduce water flows through and into globally significant tiger and gharial reserves, and may contribute to increasing wildlife-human conflict for limited resources. These downstream vulnerabilities are compounded by climate change and also by extensive sand mining in the bed of the Banas River that further depresses the water table (ISET and CEDSJ, 2011).

3.6 The potential role of water harvesting in catchment restoration

India has a long history of localised innovations intercepting monsoon run-off to recharge groundwater, where water is protected from high evaporative rates and accessible throughout the year (Pandey *et al*., 2003). There is a growing literature asserting that traditional knowledge, currently being lost through village abandonment and conversion to mechanised techniques, can play significant roles in rebalancing water resource recharge with demands on receding groundwater if appropriately supported by reformed policies and investment (for example Shah and Raju, 2002; Pandey *et al*., 2003; Rathore, 2005; Narain *et al*., 2005; Everard, 2015).

Watershed management programmes promoting the distributed restoration of small-scale water harvesting have resulted in significant impacts on catchment hydrology and downstream water availability in Andhra Pradesh and other parts of India (FAO, 2012). Significant groundwater rises are reported where community-based participatory methods have been developed at benchmark sites in several Indian states/provinces amongst a wide range of experimental watersheds across Asia (Wani *et al*., 2003, 2005, 2006 and 2009). There are commonalities between the diverse traditional methods to accelerate the natural recharge of soil moisture and groundwater in India with those observed across Africa, Asia, the Americas and the wider drier tropical world (Pearce, 2004; Everard, 2013, Mati, 2007).

Successes brokered by the NGO Tarun Bharat Sangh, largely across Alwar District of Rajasthan since the mid-1980s working with communities to reinstate or innovate traditional water-harvesting structures (WHSs) and associated local governance mechanisms, have driven substantial socio-economic and ecological regeneration at village scale. These successes have subsequently been elevated in scale by formation of *Pad Yatra* (catchment-scale 'water parliaments') to foster collaboration, resulting in regeneration of whole catchment systems including reappearance of perennial water bodies after decades of channels drying outside of the monsoon season (reviewed by Kumar and Kandpal, 2003; Sinha *et al*., 2013; Everard, 2015). Regeneration of catchments has brought ecological and socio-economic uplift, but also restored ecosystems of medicinal, spiritual and other cultural values (Everard, 2016), as well as resilience for wildlife and livelihoods (Torri, 2009). These trends are confirmed by remote sensing, within the spatial and spectral limitations of time series datasets (Davies *et al*., 2016).

This evidence supports the view that beneficial outcomes for the socio-ecological system of the Banas river could arise from a concerted and targeted programme of catchment regeneration, founded on management regimes favouring recharge of resources from monsoon run-off that has been a key feature of water management throughout Rajasthan prior to mechanisation. It is not merely the local people, who are its primary actors, who would benefit from greater water security. If integrated across sub-catchments, regeneration of hydrology across the basin may play a role in more secure water access and ecosystem vitality, also reducing geological contamination from deep groundwater. This type of connected, ecosystems-based approach to water resource restoration could result in win-win-win outcomes for these three linked upstream, dam-dependent and downstream components of the river system. If a comprehensive programme can be implemented, working from the upper reaches of the Banas system, these benefits can then potentially cascade down to the Bisalpur Reservoir, and hence play a strategic role in safeguarding the quality and quantity of water available for urban and agricultural exploitation as well as providing headroom for releases to the lower river as relief for affected ecosystems and communities. None of these potential benefits are thus far quantified in the Banas, though evidence from catchment regeneration in Alwar District suggests a high likelihood of success if this integrated approach can be scaled up and connected between villages along river systems.

3.7 Opportunities to improve the sustainability of the Banas system

Reappraising the Banas-Bisalpur complex in a joined-up way, with management framed by ecosystem processes rather than immediate utility, thereby raises options for reversing the cycle of degradation currently gripping the Banas-Bisalpur system and its beneficiaries. The STEEP framework (social, technological, environmental, economic and political) has already been used to organise feedback from semi-structured interviews. STEEP has previously been applied to addressing sustainability goals (Steward and Kuska, 2011), including as a systems model addressing technology choices and governance systems in the management of water, ecosystem service flows and dependent development issues in South Africa

(Everard, 2013), Europe (Everard *et al*., 2012) and India (Everard, 2015). STEEP is used here to explore opportunities to improve the sustainability of the Banas system, addressing the significant, linked vulnerabilities identified for its rural, urban, agricultural and wildlife dependents.

From the social perspective, the demands that people place on water resources in the river ultimately depresses groundwater levels and associated livelihood opportunities, as water is the primary limiting factor of food production. Traditional knowledge is being lost as younger people abandon village life for improved economic opportunity in cities, promoting greater reliance on mechanised water extraction techniques that may ultimately limit future livelihood opportunities. Across the Banas catchment as a whole, there is also a repeating pattern of resource dispossession as the needs of remote urban people are served in preference to those in the lower catchment by diversion of substantial volumes of water from the Bisalpur Dam. Overall, modern, technocentric and water-hungry lifestyles are supplanting traditional livelihoods generally evolved in balance with the capacities and vagaries of localised climate, culture and water systems.

Technologically, the proliferation of mechanised water extraction and diversion technologies has already been described as driving a positive feedback loop, in which mechanised pumping techniques become necessary to access receding groundwater levels depressed by high extraction rates. Traditional water extraction practices such as open wells and rehats, still widespread but in decline around the upper catchment, automatically limited extraction rates to the replenishment of open wells from shallow groundwater. By contrast, electric or diesel pumps attached to tube wells have no such limits and also withdraw water from deeper underground, including tapping into deeper and potentially confined aquifers which tend to be more geologically contaminated and may not be renewable. Large-scale water diversions out of the Banas catchment from the Bisalpur Dam without regard for the needs of people and ecosystems in the lower catchment also reflect a blinkered technological approach.

Environmental processes recharging shallow, unconfined groundwater and surface waters are consequently being overridden. There was no evidence that the dynamics of deeper aquifers, and their connections with shallower, unconfined groundwater, are understood. Current vulnerabilities across the whole Banas-Bisalpur socio-ecological system stemming from declining water quantity and quality could, however, be addressed by a renewed focus on processes regenerating water resources and the limitation of extraction to rates commensurate with replenishment of shallow groundwater. In the case of the Kesar village meeting, opportunities were identified with the community for adoption of water-efficient irrigation as well as opportunities for recharging the shallow groundwater, which may save significant volumes of water relieving some impending pressures. The World Health Organization (2011) recognises well-designed and managed rainwater harvesting at both household and larger community scales as providing an important source of drinking water with very low health risk, which can also be blended with water from other sources to reduce the levels of contaminants of health concern including fluoride. A range of NGOs is working with communities to recognise, restore or innovate water harvesting practices to improve livelihood security, which have in several cases cumulatively had the effect of regenerating catchment hydrology, ecosystems and livelihoods. A range of water-wise solutions from Rajasthan, including water recharge, access and efficient usage, are documented by Sharma and Everard (2017) including description of their purposes, geographical suitability, and construction and maintenance requirements.

The economics of water management in the Banas are currently short-term and utilitarian. This includes investment in increasingly efficient extraction technologies that, though yielding immediate returns through irrigation, appear to be depleting the quantity and quality of accessible water and may in the longer term result in village livelihoods becoming non-viable. Perhaps the more pressing utilitarian issue is the resource dispossession from the Banas catchment and its predominantly rural dependents to serve the demands of remote urban and industrial economies, a form of economic hegemony replicated frequently in the developing world. Both mechanical extraction and diversion are progressively depleting water, the core resource of the Banas system and its dependent human population and wildlife on the current trajectory of declining flows and water quality. On the basis that this appropriation strategy without regard for resource regeneration replicates former exploitation patterns that have ultimately depleted water resources, it may also ultimately limit economic opportunity in urban areas to which water is now diverted. A wise investment for the longer term would be on resource recharge for the security of the whole connected socio-ecological system.

Overall, governance of water resources in the Banas is highly fragmented. There is no watershed-level planning. Water exploitation is instead driven by local and immediate demand. The lack of clear overview and potential regulation of what is happening to the catchment water system is not helped by the lack of requirements for licences to sink tube wells, except in 'dark zones' designated where groundwater is significantly overexploited (Press Information Bureau, 2013). Reform of water management based on an overview of the catchment, incentivising resource recharge and balancing extraction with replenishment, presents a major stepping stone towards sustainable development. India already has de facto commitments to taking this systemic approach to water planning based on ecosystem processes as a contracting party under the Convention on Biological Diversity (Convention on Biological Diversity, undated) and the Ramsar Convention, and its aspirations to adopt an integrated water resource management (IWRM) approach.

The need for a systemic approach to the Banas-Bisalpur nexus reflecting the value of protecting or enhancing regenerative ecosystem processes is far more than a matter of altruistic concern. It is the means by which the currently degrading socio-ecological cycle, including repetition of Jaipur City's historic pattern of depletion of its local resources and the Ramgarh Dam, can be effectively reversed. Placing the regeneration of underpinning hydrological processes at the heart of future strategies is fundamental for a more sustainable approach to resource exploitation and conservation. It changes the emphasis from exploitation of resources in the immediate term using the most efficient technological means, towards an emphasis on the ecosystem processes constituting the primary natural infrastructure upon which extractive uses depend. This can result in potential win-win-win outcomes for the whole socio-ecological system in the upstream sector, the Bisalpur Dam and beneficiaries of its diverted water, and downstream reaches. Importantly, taking account of the upstream-to-downstream cascade of hydrological, chemical and ecosystem service flows, self-beneficial ecosystem-based interventions need to start at the top of the catchment.

3.8 Power asymmetries

A frequent observation through this Results and Discussion section has been instances of urban economies dispossessing water management schemes (the Ramgarh Dam and the Bisalpur Dam) and water rights of rural communities, with the needs of wildlife and communities largely excluded from decision-making and consequently dependent upon residual natural resources. This general trend of power asymmetries leading to skewed outcomes favouring the already most privileged is observed more widely in water management practices (World Commission on Dams, 2000; Everard, 2013; Birkenholtz, 2016). Further power asymmetries arise where local people have access to mechanised tube wells, enabling them to competitively pump water thereby not merely degrading and depressing groundwater levels but also breaking down the bonds of community participation in water management even to the extent of threatening the viability of food production and other livelihood needs in the longer-term future. The shift in perception of water from community resource towards utilitarian and economic commodity further drives incentives for mechanically efficient extraction, rather than seeking to balance exploitation with recharge rates. The net effect is one of declining community stewardship of resource quality and quantity, favouring competitive exploitation and a void of governance relating to resource sustainability and equity at catchment scale.

Further asymmetries in distribution of benefits and costs of water management arise from disruption of the longitudinal continuity of the river by the impassable barrier of the Bisalpur Dam, reducing flows of water and fragmenting wildlife. Mahseer fishes (genus *Tor*) sampled from the upper South Banas, possibly from a relic population stranded by downstream disconnection, and reported from the lower river provide evidence of these generally migratory fishes having formerly occupied more of the river. This is indicative of prospects for other wildlife and the flows of ecosystem services to which it contributes. Risks stemming from these asymmetric water vulnerability and resource access include biophysical wellbeing including food security and human health, the viability of community economic activities, and of the ecosystems they depend on, as well as the potential for civil disruption.

Viewed on a systemic basis, an ecosystem-based approach to water resource management across the Banas system is as advantageous for more powerful urban beneficiaries as it is to rural communities whose livelihoods would be secured by refocusing on local-scale recharge of water resources. Without such an eco-centric and ‘bottom up’ strategy, increasing water vulnerability for all linked constituencies benefitting from the resources of the Banas system is the only likely outcomes.

3.9 Policy fit and practical implementation

Global society is emerging from a model of management for narrowly framed problems and solutions, largely blind to wider ramifications, into a paradigm of systemic awareness informed by interconnections between ecosystem services and their associated beneficiaries (Everard, 2017). Legacy water resource exploitation policies and practices founded on technical extraction efficiency, without regard for balancing resource regeneration rates and their broader and longer-term socio-ecological consequences, are evident across India over recent times for example in the form of stimuli for improving agricultural profitability in the short term though ironically threatening food security in the long term (Zaveri *et al*., 2016).

In Rajasthan, there is growing recognition that recent historic over-emphasis on water exploitation without balancing recharge needs to be redressed. *Jal Swavlamban Abhiyan* ('water self-reliance mission') is a significant Rajasthan Government strategy implemented from early 2016 that emphasises and invests in decentralised water management for self-sufficiency (The Hindu, 2015). At the launch of the second phase, Rajasthan's Chief Minister, Vasundhara Raje, said that the first phase of *Mukhyamantri Jal Swavlamban Abhiyan* (MJSA) benefitted 42 lakh (4.2 million) people and 45 lakh (4.5 million) livestock and brought 25 blocks across Rajasthan into a 'safe' water security condition, with the second phase intended to cover 4,200 villages and 66 townships (Times of India, 2016). These figures are not substantiated, and superficially appear optimistic (heavy rains in August 2016 broke a two-year severe drought possibly skewing perceived outcomes) but indicate clear political intent to restore or promote groundwater recharge practices. This intent is being echoed in other water-limited Indian states, for example in Gujarat (Shah, 2014). Catchment regeneration also contributes to the UN Sustainable Development Goals (SDGs: United Nations, 2015), particularly 6 of the 8 targets under SDG6 (clean water and sanitation). Common understanding and consensus is now required across government departments, NGOs, village and local communities and other interests to convert far-sighted political intent into practical policies and effective tools to promote practical outcomes.

The Banas system presents a focused case study of both problems created by fragmented exploitation and the potential for systemic solutions. In particular, the direct linkage between declining water levels and quality from the headwaters ramify not merely as vulnerabilities for local people but also downstream to diverse beneficiaries throughout the catchment. From an economic perspective, the most substantial values are associated with urban beneficiaries of water diverted from the Bisalpur Dam, dispossessing the perceived lower priorities of local people, irrigation and wildlife in the lower river. Costs associated with vulnerabilities to these economically privileged constituencies are substantial, and will escalate dramatically on current trends if overexploitation of the Banas follows the same trajectory as the now depleted Ramgarh Dam and local groundwater resources around Jaipur. Construction, upgrades to, and ongoing maintenance and operation of the Bisalpur Dam already entail significant investment, apparently with most maintenance costs paid by irrigation beneficiaries rather than the urban users of most of the water. Further, presumably substantial, costs will also be associated with reported proposals to transfer additional water from the Anas River that, in essence, replicates former failed or failing models of resource appropriation and dispossession for assumed water security.

A systemic perspective recognises that recharge and stewardship of the resource, a central feature of traditional geographically adapted water management innovations, is at least as important as water abstraction technologies. Recent Indian policy has overlooked this important element of the system. Rural areas of the Banas present an underexploited opportunity for promoting uptake of water-harvesting structures (WHSs) for the benefit of the wider catchment and its dependents as "…*the status of villages in the catchment is very poor because of no involvement of government and* *non-government organizations*…" (Upadhyay and Rai, 2013, p.91). Where a variety of WHSs have been installed, they have helped regenerate vegetation and also given villagers resilience against drought as compared to parts of the Banas catchment where these structures are absent (Upadhyay and Rai, 2013). Successes in Alwar District of Rajasthan illustrate the potential for self-beneficial but also integrated restoration of water harvesting to regenerate the socio-ecological system of whole small catchments. Although villagers in the Banas system were found to know the importance of water conservation, there is currently a lack of formal and informal institutions offering training for further improvement of soil and water conservation techniques (Upadhyay and Rai, 2013). Replication of successful regeneration schemes with appropriate geographical and cultural adaptations in the Banas catchment, particularly focused initially in the upper river enabling benefits to cascade downstream, appears to present a significant opportunity to contribute to increased resilience for all of the river system's rural, urban, irrigation and wildlife beneficiaries.

Assigning some form of economic value to water resources and ecosystem services represents a powerful tool to embed their conservation into the policy environment (Daily *et al*., 2009). Payments for ecosystem services (PES) is an established and now globally widespread model for bringing the values of often formerly overlooked ecosystem services into mutually beneficial markets (OECD, 2010). PES solutions have proven effective for protecting water quantity and quality for downstream uses. UK, US and French examples cited previously constitute a small subset of higher-profile examples of operational water-related PES schemes globally (Everard, 2013; Schomers and Matzdorf, 2013). PES therefore represents one of many potential tools that can make use of existing investments to provide an economically efficient means to improve water security simultaneously in the upper Banas catchment, for users of water impounded by the Bisalpur Dam, and for communities and ecosystems downstream of the Dam. A proportion of the substantial planning, development and ongoing expenses incurred by beneficiaries of technological solutions at the Bisalpur Dam, including fair payments by beneficiaries who currently do not pay, could be diverted under formal PES arrangements to promote recharge and efficient use practices in communities in the upper catchment ('providers' in PES terms but also net beneficiaries of water-wise solutions) for the benefit of enhanced water security. Enhanced payback could result through improved security of water quantity and quality in the system as a whole, and reduced likelihood of civil disruption and costs averted from further water appropriation schemes. Furthermore, if these water resource investments were integrated with existing rural development, public health and other budgets, a highly efficient mechanism to deliver multiple, simultaneous socio-ecological system benefits could ensue both locally and at catchment scale from strategic, multi-beneficial interventions in the spirit of 'systemic solutions' (*sensu* Everard and McInnes, 2013). PES is not the only feasible economic instrument to generate investment in 'bottom-up' recharge of the Banas system, for example with instruments such as 'green bonds' – be they sovereign or private – playing roles in ecosystem and community regeneration elsewhere across the world (Hall *et al*., 2017)

Implementation of a wide-scale programme of water resource regeneration and efficient use for self-beneficial purposes, with the potential for cumulative impact on restoring shallow groundwater and surface flows in the river system, may most effectively be delivered by the existing network of community-facing NGOs already active across Rajasthan, ideally in a targeted pilot sub-catchment to demonstrate efficacy as a stepping stone towards upscaling the approach. Many effective and proven techniques are known, and documentation (such as Sharma and Everard, 2017) exists to expedite the uptake of locally appropriate solutions attuned to local geography, needs and culture.

It is recognised that there are many knowledge gaps to be filled in progressing this shift in policy and practical implementation, hence the precautionary language of the previous paragraphs. However, this is best approached as a matter of 'action research': taking an adaptive, learning approach based on practical action to reverse the degrading condition of water systems and dependent ecosystems and livelihoods. There is certainly an urgency to reversing the current degrading cycle if the integrated rural, urban, irrigated and wildlife elements of the Banas-Bisalpur complex are to remain viable in the longer term.

3.10 Research and development needs

The preceding discussion of vulnerabilities, potential solutions, and policy and implementation options are supported in principle by available evidence. However, they lack quantification in this specific context. It is necessary to quantify likely outcomes to identify and justify options for reform of policies and management practices and redirection of associated investment. Furthermore, although the multiple authorship of this paper represents an initial consortium of common interest sharing ideas to shift the management paradigm for net increased socio-ecological security and opportunity, further common understanding and consensus is required across all relevant government departments and other interested institutions (particularly municipality, community leaders, and government Irrigation and Water Services Departments). It will also be important to engage local community representatives to build on local needs and traditional knowledge, to test proposals in a local context, and to assure their legitimacy. Key research questions highlighted by the above discussion include:

- How does the catchment function naturally? A comprehensive catchment GIS that, importantly, includes the dynamics and interactions of different strata of the groundwater system, built from new data and relevant existing datasets (such as water flows, quality flow, climate, land cover, abandonment of WHSs, remote sensing and other relevant metrics) would enable analysis of longer-term trends in the catchment, and between sub-catchments, and also serve as a model for scenario-testing.
- What water management options – traditional, engineered, novel or combinations – can balance recharge of ground and surface waters with their use to support sustainable livelihoods in the diverse villages and towns of the catchment, taking account of geological and cultural differences and interdependencies?
- What is the most effective mechanism to promote sustainable water management practices across the catchment, or a pilot sub-catchment, mediating high-level aspirations for water self-sufficiency with operational acceptance and implementation? This research question is optimally addressed through action research in partnership with government bodies, local delivery

NGOs, and academic and citizen monitoring of outcomes for water quantity and quality in pilot sub-catchment(s).

- What are the costs and benefits of an ecosystem-centred approach as compared to the current narrowly technocentric development model? In broad terms, this research will underpin assessment of the potential for a PES scheme to promote management options likely to optimise multi-beneficial outcomes. Distributional equity issues relating to historic and potential future schemes should be taken into account.
- What governance arrangements, including reform of policies and refocusing of different strands of municipal and public funds, can most effectively bring about this shift in paradigm? This research strand would be enacted in direct collaboration with government partners tasked with leading *Jal Swavlamban*, addressing the SDGs, and other programmes relevant to water security.
- Is an Environmental Flow standard necessary for the lower Banas River, and if so what is the most socially and ecologically beneficial regime for releases from the Bisalpur Dam? This will be informed by historic records (e.g. former extraction of water from the lower river to supply Sawai Madhopur), modelling of an un-impounded river, consideration of the needs of downstream ecosystems and communities, and also consideration of the benefits likely to accrue from establishing Environmental Flows and installing a fish pass in the Dam.
- How is an integrated programme best targeted to ensure maximum benefits for all integrated rural, urban, irrigation and wildlife beneficiaries of catchment processes, noting that hydrological functions run from upstream to downstream? This research stage is about an optimal approach to up-scaling a catchment regeneration programme, potentially with detailed design of a pilot sub-catchment scheme but including lessons for wider uptake in Rajasthan and beyond.

3.11 Implementation in other water-stressed regions

Many regions of the developing world are subject to similar issues water vulnerability, driven by rising populations, a changing climate, and technological and economic/policy focus of water extraction without balancing recharge (UNESCO, 2006). Many of the attributes of this locally focused research have wider generic applicability across India, as well as tropical Africa elsewhere in Asia and the central and southern Americas. The growing global population and supporting natural resources base makes this challenge as germane to many regions currently considered more water-secure (Vörösmarty *et al*., 2000).

The underlying principle of refocusing on ecosystem processes and enhanced resource recharge to rebuild primary natural capital securing socio-ecological systems is as relevant in these other environments (Millennium Ecosystem Assessment, 2005). However, they need to be attuned to local geography and culture, much as the heterogeneous schemes observed across the Indian state of Rajasthan are themselves diverse and locally adapted. STEEP represents a systemic framework helpful for consideration of how local adaptation can be achieved, accounting for tightly interconnected social contexts and needs, appropriate technologies, environmental conditions both regionally and locally, economic needs and incentives, and the wider formal and informal policy environment including opportunities and areas for reform.

4. Conclusions

The Banas catchment is in a cycle of linked ecosystem and socio-economic degradation as a result of intensifying water exploitation practices that are out of balance with natural or enhanced water resource regeneration. Communities in the upper river, the many millions of people now almost wholly reliant on piped supplies from the Bisalpur Dam, downstream communities, and the ecology of the river and the many beneficial ecosystem services it provides are all subject to increasing vulnerabilities. Perpetuating a serially failing technocentric resource appropriation model will not result in sustainability.

Rebalancing resource recharge with exploitation across the Banas-Bisalpur nexus could yield multiple co-benefits for all affected communities and ecosystems. Regeneration of the socio-ecological vitality of Rajasthani river systems has been demonstrated in Alwar District and elsewhere across India and the arid developing world, and could be achieved in the Banas catchment were resources and capacity-building available to promote a concerted and targeted programme of rehabilitation or innovation of traditional water management practices.

A paradigm shift towards an ecosystem-based approach has associated costs, but the benefits are substantial and particularly when risk of failure of water supply to a major city are taken into account. There is also significant potential for overall cost efficiencies when benefits to all linked rural, urban, irrigation and wildlife constituencies are considered, together with the potential for pooling diverse, currently fragmented rural development, water resource, wildlife and other budgets into strategic water resource interventions yielding multi-beneficial outcomes.

There is political recognition, significantly through the Rajasthan's *Jal Swavlamban Abhiyan* programme, of the need to rebalance water management towards recharge rather than solely efficient engineered extraction of declining and increasingly contaminated resources. Rajasthan also has an active network of well-established, community-facing NGOs that could serve as extension workers and locally trusted brokers to work with distributed rural communities towards local and catchment-scale socio-ecological regeneration.

Research needs are identified to underpin robust policy, practice and redirection of investment. Although quantification of details is necessary, the basic principle of refocusing effort on recharge as a more sustainable and approach to water security is established.

Achievement of water security is a growing challenge across the developing world, and also increasingly in the already developed world. Basic principles of ensuring that resource exploitation is balanced with recharge remain important, including technology choice and appropriateness to geographical and cultural contexts and how this is shaped by economic and policy environments.

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Annex: Raw source of information used in this paper

Table A1: Key experts and interviewees and their interests

Informant and role • **Perspective**
Academic sector
University of the West of England (author team) • Expertise in ecosystem services and sustainable water management, particularly community-based water management and their integration with engineered systems
JK Lakshmipat University, Jaipur (author team) • Expertise in sustainable water management, and water quality/chemistry
IIT Delhi (author team) • Expertise and interest in community development
Government sector
Dharmendra Kaushik (dharmendrakaushik1964@gmail.com), Junior Site Engineer, Bisalpur Dam (interviewee) • Involved in the building phase of the Bisalpur Dam between 1987 and commission in 2002, and continuously held the role of Junior Site Engineer of the Bisalpur Dam from 2002 to the time of interview (April 2017)
Forest Department, Ranthambhore Tiger Reserve (author team) • Concerned with wildlife conservation and interested in ecosystem service delivery to local communities including averting and redressing wildlife-human conflict, focused on the downstream sector of Ranthambhore Tiger Reserve
Forest Department, Upper Banas (author team and also other Forest Officers coordinating the visit) • Concerned with wildlife conservation and interested in ecosystem service delivery to local communities, focused on the Banas catchment headwater area including Kumbhalgarh Wildlife Reserve
NGO sector
Wells for India (author team) • Promotes community-based collaboration on water harvesting, water management and sanitation solutions
Tiger Watch (author team) • Focused on tiger conservation, nationally but with a particular focus on the Ranthambhore Tiger Reserve, concerned with wildlife conservation also with interests in the National Gharial Sanctuary. Interested also in ecosystem service delivery from the Reserve, and averting and redressing wildlife-human conflict
Wetlands International (author team) • A broad remit of wetland and aquatic ecosystem conservation interests for inherent and societal benefits
Mahseer Trust (author team) • Focused on the conservation of mahseer (fishes) and the rivers that support populations for their many societal values, from subsistence and recreational to spiritual and associated ecosystem services
WWF-India (author team)

• A broad remit of wildlife conservation interests for inherent and societal benefits
Local communities
• Village meeting in Kesar • Meeting with male elders in Bagara village • Meeting at Sevantri and guidance to sites in the Gomti • Meetings with villagers in Amlidha • Opportunist conversations with rural inhabitants and water users in both the upper Banas and Amlidha

Table A2: Evidence on water use and trends from the upper Banas stratified by STEEP criteria

Key points from interview with officer in charge of the Bagara Dam on the South Banas River (2nd June 2017). • Social factors: The Bagara Dam was constructed by the Forest Department to provide drinking water for 224 villages downstream. • Technological factors: The Bagara Dam is the first impoundment from source of the South Banas, constructed at 660m above sea level with a height of 32 feet (nearly 10 metres) to crest. • Environmental factors: In the hilly country of the upper Banas (both South and North), the water table is generally high and the quality of the water is generally good due to natural water capture by the vegetated hills. Many traditional WHSs are still operated in the upper Banas system. However, water availability for villages declines as the South Banas flows downstream into flatter lands, with receding water levels and declining quality. Udaipur District has no dark zones as it is in hilly with good vegetation and water capture, but the downstream Districts of Rajsamand and Bhilwara have many dark zones Of the 243 Blocks (a ‘Community development block’ is the administrative sub-division below the tehsil, or sub-District) within a state) comprising the state of Rajasthan, 197 (81%) are over-exploited. Mahseer and a range of other cyprinid fishes are present in the Bagara Reservoir, and were sampled for taxonomic analysis during the visit to dam. • Economic factors: A licenced fishery is based on the shore of the Bagara Reservoir. • Political factors: Dams/anicuts are built by the Forest Department or by the Soil Conservation Department, depending on whose land they lie, with the exception of large dams that are built by the Water Resources Department. Water exploitation is by local demand, not watershed planning. No licences are required to sink tube wells, except in ‘dark zones’ (areas of depleted or contaminated groundwater).
Collated points from semi-structured interview (2nd June 2017) with five men from Bawara Village, Udaipur District, situated on the banks of the South Banas river

upstream of the Bagara Dam, invited to share their views at the nearby Forest Department nursery.

- Social factors: Bawara Village is small, comprising scattered households across the river valley. There is little population growth, but a principal problem is the decreasing size of individual landholdings as inheritance passes to multiple children. Some better-off families have their own wells. There are also some wells open to the community. However, most water supply derives from small shared wells typically serving 8-10 families.
- Technological factors: There is a high continuing reliance on traditional water methods of water access, with tube wells rare. Water from many wells is accessed by rehats (Persian wheels in which animal power drives a chain of buckets lifting water from an open well) mostly driven by bullock power, though bullock numbers are reducing with increasing mechanised (electric and diesel) pumping from open wells and river beds. Bullocks would no longer be maintained if rehats fell into decline. There is also increasing use of tractors, displacing the need for animal power. Irrigation of winter crops also makes use of haren (gravity-based systems in which water intercepted and diverted by check dams is diverted via channels to irrigate fields over distances of up to 10km). There are concerns that the more rapid rates of water extraction through mechanised pumping are exceeding resource renewal rates, leading to declines in water levels in wells and the river rendering traditional access methods ineffective.
- Environmental factors: Water is perceived as of good quality. Water is not yet limiting, proximity to the river contributing to a high water table. However, though declines in levels due to mechanised pumping are recognised. The natural resources of the landscape still sustain people's needs including the recycling of organic fertilisers and harvesting of wild food (including fruits such as custard apples), dead wood, and leaves for feeding livestock. Though the diet is predominantly vegetarian, some people eat small fish from the river. Sampling during the visit resulted in capture of mahseer (a fin clip was taken for DNA analysis) and other small unidentified cyprinid species.
- Economic factors: The non-viability of increasingly small land-holdings is a significant economic concern, with significant outmigration of younger men into cities as landholdings are often insufficient even for subsistence agriculture. Older men and others remaining in the village have to supplement their incomes from local labour (such as construction and road repairs).
- Political (governance) factors: Most decision-making in the village, including that germane to water management, still relies on traditional local governance structures such as *Gram sabha* though wealthier families can act autonomously, for example in the construction of their own wells.

Collated points from semi-structured interview (2nd June 2017) in Kesar Village, situated in hilly Khamnor Hills terrain between the headwaters of the South and North Banas, to which all villagers were invited. (A constantly shifting number of people, estimated as fluctuating between 25 and 50, attended with men only speaking.)

- Social factors: Kesar Village comprises approximately 500 households. The village has almost doubled in population over the past 30-40 years. About 50 open wells serve the needs of the village. The younger men from virtually all households work away in cities. The erosion of traditional water management skills, and the physical strength necessary to operate them, is being lost.

- Technological factors: The water table in this hill country is relatively high, and water from many of the approximately 50 open wells in the village is still commonly accessed using rehats (Persian wheels). However, there has been a significant trend towards motorised pumping and the progressive abandonment of traditional methods: whereas there were 40-50 rehats operational in the village only five years previously accessing water from a depth of about 20 feet (6 metres), at the time of the meeting only 10 rehats remained operational. There is increasing reliance on tube wells, mainly using electric pumps despite the erratic electricity supply, which access groundwater as deep as 200-400 feet (61-122 metres). Declining groundwater levels mean that restoring rehats would not serve people's needs as they can not access deepening groundwater. Opportunities were identified in the meeting for adoption of water-efficient irrigation as well as opportunities for recharging the shallow groundwater, which may save significant volumes of water relieving some impending pressures. However, on current trends, the prognosis of water scarcity over coming decades is that villages such as Kesar may be increasingly abandoned due to insufficient water.

- Environmental factors: The declining water table from its recent high level is a significant cause for concern. So too is the quality of water abstracted from deep groundwater by tube well. The Panchayat (traditional village governance institution) organised water testing, which revealed high fluoride levels. Villagers complained of chronically aching knees and legs, recognising that this was likely a result of fluorosis through increasing use of fluoride-rich water. Though unhappy about this situation, the convenience of accessing water by turning a switch rather than driving bullocks to operate a rehat overrode concerns about long-term health risks. Also, traditional wells and extraction methods become increasingly less viable as groundwater recedes. Access to quantities of water was an over-riding priority as it is water, not land area that limits food production in Kesar. There is also declining reliance on naturally harvested medicinal plants, with increasing use of western pharmaceuticals. There are also occasional conflicts with panther (leopard: *Panthera pardus*) predation of stock and herbivores eating crops.

- Economic factors: there was a polarisation of opinion about the extent of food sufficiency in the village, some growing enough for their own consumption but other villagers pointing out a high dependence on a government ration shop selling wheat imported from outside of the region. To afford sufficient food, many families in Kesar Village depended on income from local labour and money sent back by emigres working away in cities (predominantly in Bombay). Villagers also noted that keeping bullocks is expensive (around ₹200 per day) so declining agricultural benefits from farming smaller fields was leading to reductions in stock numbers, further driving the trend towards abandoning rehats in favour of mechanised pumps.

- Political (governance) factors: Village governance matters are mainly addressed through the Panchayat. Issues of concern include declining water levels, decreasing water quality with associated health risks and food insufficiency also linked to water access. A positive feedback was noted, mechanised technology depressing well water levels such that rehats become ineffective and bullocks unaffordable, driving increasing need for deeper mechanised wells. There were no current answers to address this worrying trend and is prognosis.

Collated points from semi-structured interview (2nd June 2017) in Sevantri Village, from which the North Banas river rises at an impoundment that is also the site of Sevantri Temple, and other sites down to anicuts approximately 10km downstream from the source. The discussions were predominantly with the proprietor of a hotel at Sevantri accompanying the survey team on its tour of these Gomti river sites, but also with other local people encountered at visited sites on an *ad hoc* basis.

- Social factors: The source of the river is of spiritual importance to the people of Sevantri and its environs. Water is also drawn from the impoundment to meet people's needs. People value anicuts constructed on the Gomti for watering their stock animals.
- Technological factors: The barrage at Sevantri is an engineered structure retaining water for multiple uses. Series of anicuts also retain open water bodies along the upper river.
- Environmental factors: a diversity of biodiversity was observed using the impoundment at Sevantri (fish, reptiles including snakes and terrapins, birds), with diverse aquatic vegetation and fish observed in several downstream anicuts.
- Economic factors: Sevantri itself is a place of pilgrimage, the small hotel demonstrating an aspect of its economic value. Most livelihoods in the upper North Banas are agricultural.
- Political (governance) factors: The religious significance of the impoundment at Sevantri, which is the site of a temple and a place of religious ceremonies, imposes local control of contamination of the water or harm to its biota. Otherwise, the sparse population of people is free to make use of the ecosystem services of the upper river with little or no evident regulated restrictions.

Collated additional points observed by visits to a range of river sites in the upper Banas, and in discussion with a range of Forest Department officers interviewed opportunistically on our tour.

- Social factors: There are no large towns in the Khamnor Hills around the headwaters of the Banas River, the population scattered across the hilly terrain in small villages. The Kumbhalgarh Fort though is a significant tourist attraction, with many resorts being built relatively recently to accommodate the demands of richer tourists and assumed to ump significant volumes of groundwater without licence to maintain green lawns, swimming pools and other tourist luxuries in a semi-arid landscape.
- Technological factors: Many traditional water harvesting and access technologies were observed and reported as in place in the hilly region of the upper Banas. The first major impoundment on the South Banas is the Bagara Dam, noted separately. Proliferation of tube wells is increasing, both for farm use and to support the heavy demands of resorts.
- Environmental factors: The water table and water quality are generally high in the Khamnor Hills due to the hill country intercepting monsoon rains. However, declines in groundwater level are noted with the pervasion of mechanised pumping. Water availability declines as the Banas runs from the hills onto flatter lands: Udaipur District has no Dark Zones (areas where the quantity and/or quality of groundwater is poor) as it is hilly with good vegetation, but the downstream Districts of Rajsamand and Bhilwara are problematic.
- Economic factors: The economy of the region is split between subsistence and cash crop farming, but is substantially subsidised by income from young men working away in cities, local labour and a booming tourist economy.
- Political (governance) factors: Overall governance of water resources in the Banas is highly fragmented. There is no watershed planning. Water exploitation is instead driven by local demand. Dams/anicuts are built by either the Forest Department or the Soil Conservation Department, depending on whose land they are on, with the exception of large dams that are built by the Water Resources Department. No licences are required to sink tube wells, except in ‘dark zones’. Tube wells are proliferating for local and resort uses. Lack of planning based on an overview of the catchment, incentivising resource recharge and balancing extraction with replenishment, presents a major obstacle to sustainable development.

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Figure
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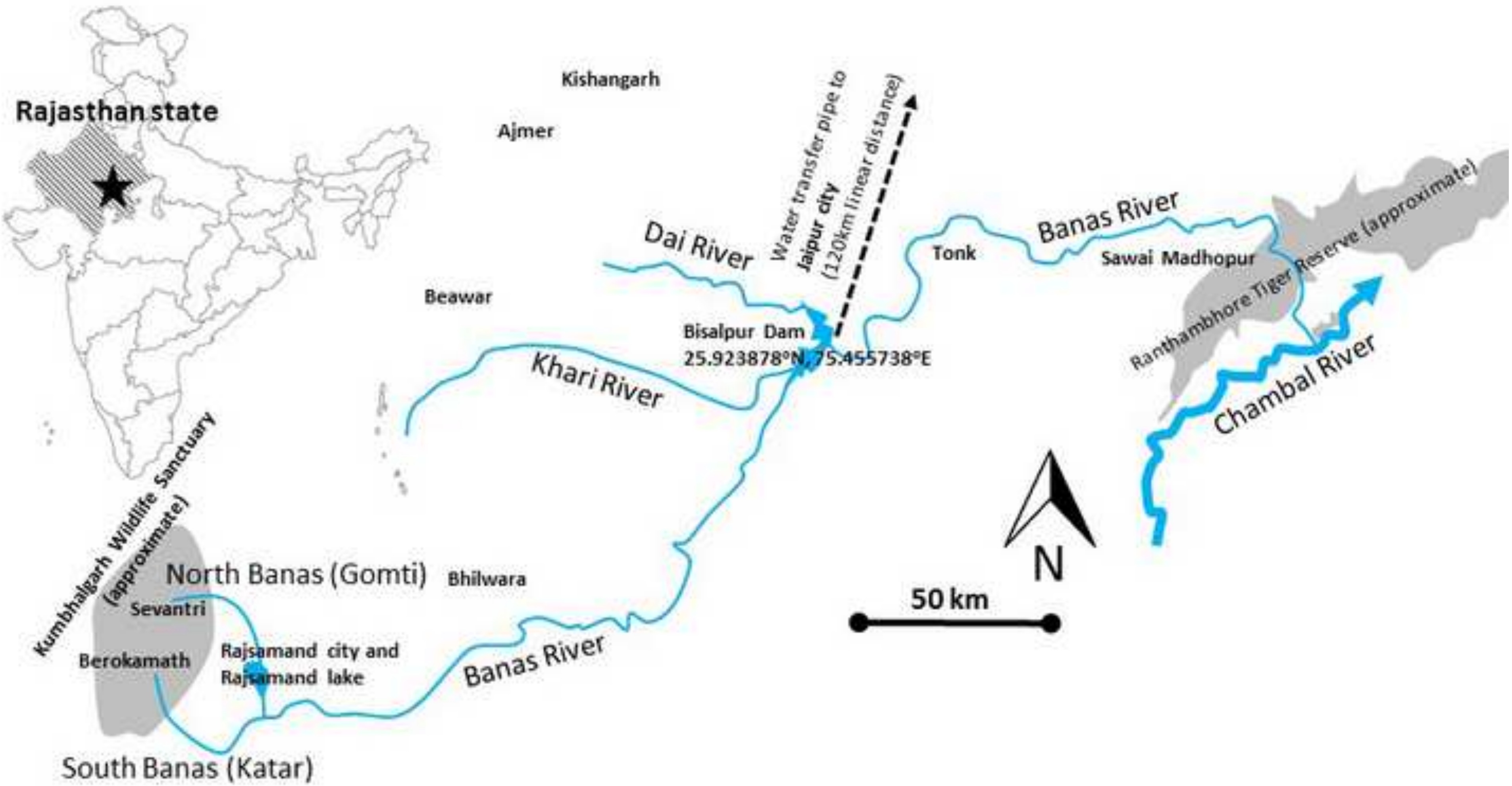

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