Everard, M, Ahmed, S, Gagnon, AS, Kumar, P, Thomas, T, Sinha, S, Dixon, H and Sarkar, S

Can nature-based solutions contribute to water security in Bhopal?

Can nature-based solutions contribute to water security in Bhopal?

Dr Mark Everard, University of the West of England (UWE), Coldharbour Lane, Frenchay Campus, Bristol BS16 1QY, UK. (E: mark.everard@uwe.ac.uk, M: +44-(0)-7747-120019). Corresponding author

Prof. Shakeel Ahmed, Department of Geography, Faculty of Natural Sciences, Jamia Millai Islamia, New Delhi-110025, India. (E: shakeelifcgr@gmail.com; M: +91-9849919496).

Dr Alexandre S. Gagnon, School of Biological and Environmental Sciences, Liverpool John Moores University, Liverpool L3 3AF, UK. (E: A.Gagnon@ljmu.ac.uk; M: +44-7871-088198)

Dr Pankaj Kumar, Department of Earth and Environmental Sciences, Indian Institute of Science Education and Research Bhopal, By-Pass Road, Bhauri, Bhopal – 462066, M.P., India. (E: kumarp@iiserb.ac.in; M: +91-7974975701).

Dr T. Thomas, National Institute of Hydrology, Central India Hydrology Regional Centre, Bhopal, M.P., India. (E: thomas_nih@yahoo.com; M: +91-9893686808.

Dr Sumit Sinha, Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK. (E: Sumit.Sinha@jbarisk.com; M: +44-7715-302376).

Prof. Harry Dixon, Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Wallingford, OX10 8BB, UK. (E: harr@ceh.ac.uk; T: +44-1491-692254)

Dr Sunita Sarkar, Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Wallingford, OX10 8BB, UK. (E: sunsar@ceh.ac.uk; T: +44-1491-692254)

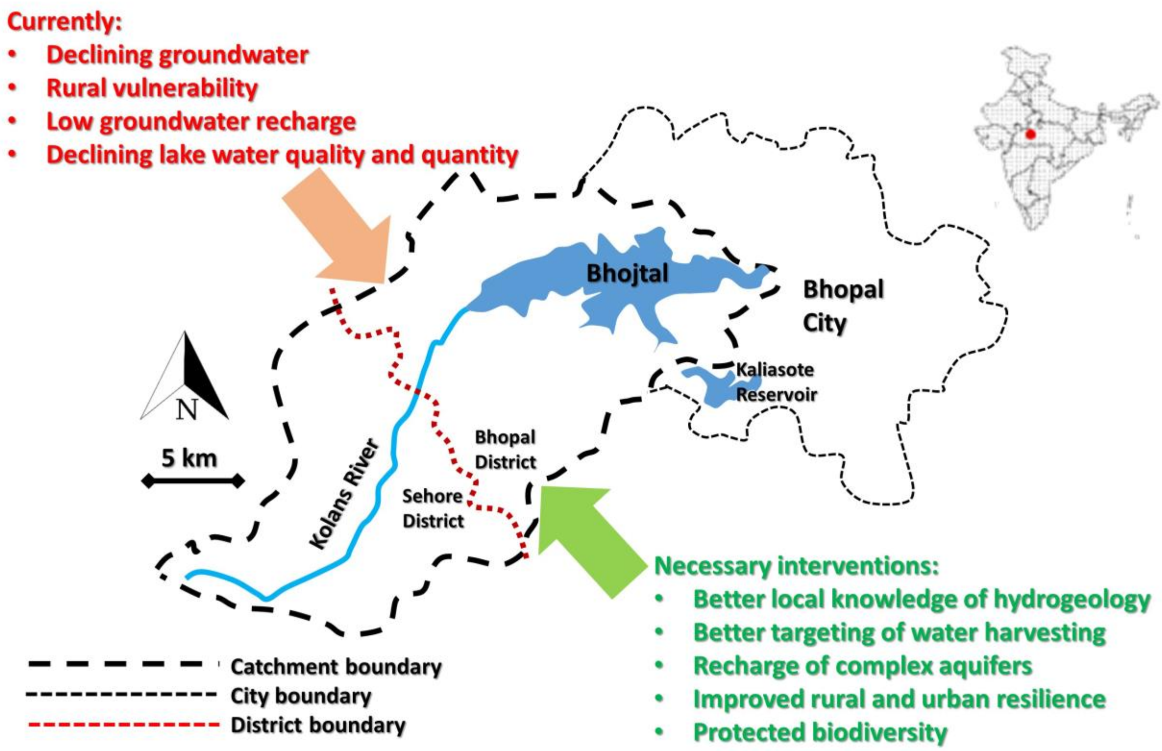
Abstract

Bhojtal, a large man-made lake bordering the city of Bhopal (Madhya Pradesh state, central India), is important for the city's water supply, connoted the lifeline of the city. Despite the dry though not arid and markedly seasonal climate, soil impermeability hampers infiltration into the complex geology underlying the Bhojtal catchment. Rural communities in the catchment are nonetheless high dependent on underlying aquifers. This paper develops baseline understanding of trends in the ecology, water quality and uses of Bhojtal, discussing their implications for the long-term wellbeing of the Bhopal city region. It highlights increasing dependency on water diverted from out-of-catchment sources, and also abstraction across the Bhojtal catchment in excess of replenishment that is depressing groundwater and contributing to reported declining lake level and water quality. Despite some nature-based management initiatives, evidence suggests little progress in haltering on-going groundwater depression and declines in lake water level and quality. Significant declines in ecosystem services produced by Bhojtal are likely without intervention, a major concern given the high dependency of people in the Bhopal region on Bhojtal for their water supply and socio-economic and cultural wellbeing. Over-reliance on appropriation of water from increasingly remote sources is currently compensating for lack of attention to measures protecting or regenerating local resources that may provide greater resilience and regional self-sufficiency. Improved knowledge of catchment hydrogeology on a highly localised scale could improve the targeting and efficiency of water harvesting and other management interventions in the Bhojtal catchment, and their appropriate hybridisation with engineered solutions, protecting the catchment from unintended impacts of water

extraction or increasing its carrying capacity, and also providing resilience to rising population and climate change. Ecosystem service assessment provides useful insights into the breadth of benefits of improved management of Bhojtal and its catchment.

Graphical abstract

NBS in Bhopal GRAPHIC (ME 2020-02-28)



Research highlights

- Bhojtal contributes significantly to Bhopal's water supply, but is degrading
- Despite adequate rainfall, soil impermeability and complex geology hamper recharge
- Increasing abstraction across the Bhojtal catchment is depressing groundwater
- Declines in ecosystem services are likely without appropriate interventions
- Localised knowledge of hydrogeology can optimise catchment management interventions

Key words

catchment management; hydrogeology; water resources; ecosystem services; groundwater recharge; RAWES

1. Introduction

Water has been a constant limiting factor for the development of India's booming population – 33 million at Independence in 1947, 1.37 billion in 2019 (a 42-fold increase), and is still rising at 1.08% per annum (worldometers.info, 2019) – and will remain so as part of the water-food-energy nexus subject to population, globalisation, urbanisation and climate change trends. The vitality of pressurised aquatic resources, both on the surface and underground, need to be increasingly safeguarded through positive management as a primary resource supporting continuing human wellbeing.

Madhya Pradesh state in central India is generally dry though not arid; mean annual rainfall varies from 650 to 1400 mm across the state with 1260 mm for Bhopal (CGWB, 2016). Centres of dense population and other demands place significant pressures on locally available surface and groundwater resources across the state. Bhopal, the state capital, is known as the 'City of Lakes' owing to the multitude of natural and man-made lakes in the vicinity. 14 lakes in the city act as water recharge units and, in conjunction with perennial river systems, formerly dense forest cover and low relief, have created a unique urban microclimate (Burvey *et al*., 2017). However, rapid urban expansion is eroding ecosystems surrounding the city. The vegetative cover of Bhopal declined from 92% in 1977 to 21% in 2014, with further predicted declines to 11% by 2018 and 4% by 2030 (Bharath Aithal, 2016). The Kerwa Forest Area (KFA) located at 10 km from Bhopal faces severe anthropogenic pressure compromising its critical roles as a carbon sink and source of water and other contributions to environmental quality for the residents of Bhopal city (Dwivedi *et al*., 2009).

Bhojtal, formerly known as Upper Lake or *Bada Talab* (‘Big Pond’), is the largest local lake, abutting Bhopal city. Local folklore attributes the lake’s construction to Paramara Raja Bhoj, king of Malwa from 1005 to 1055, when establishing the city of Bhojpal to secure the eastern frontier of the kingdom. Bhojpal, named after the king, was subsequently renamed Bhopal. The name of the lake was changed from Upper Lake to Bhojtal in 2011 to honour its creator. Bhojtal was formed by constructing an earthen dam across the Kolans River, which rises approximately 16 km from the head of Bhojtal (Figure 1). The earthen dam retaining Bhojtal was replaced in 1965 by an 11-gate dam, known as Bhadbhada, situated at the southeast corner of Bhojtal where it controls the outflow from Bhojtal into the Kaliasote River. Bhadbhada also forms the western edge of the city of Bhopal (comprising both Old Bhopal and New Bhopal). Van Vihar National Park borders Bhojtal to the South. Scattered human settlements and resorts occur in the eastern and northern shores, and agricultural fields lie to the West.

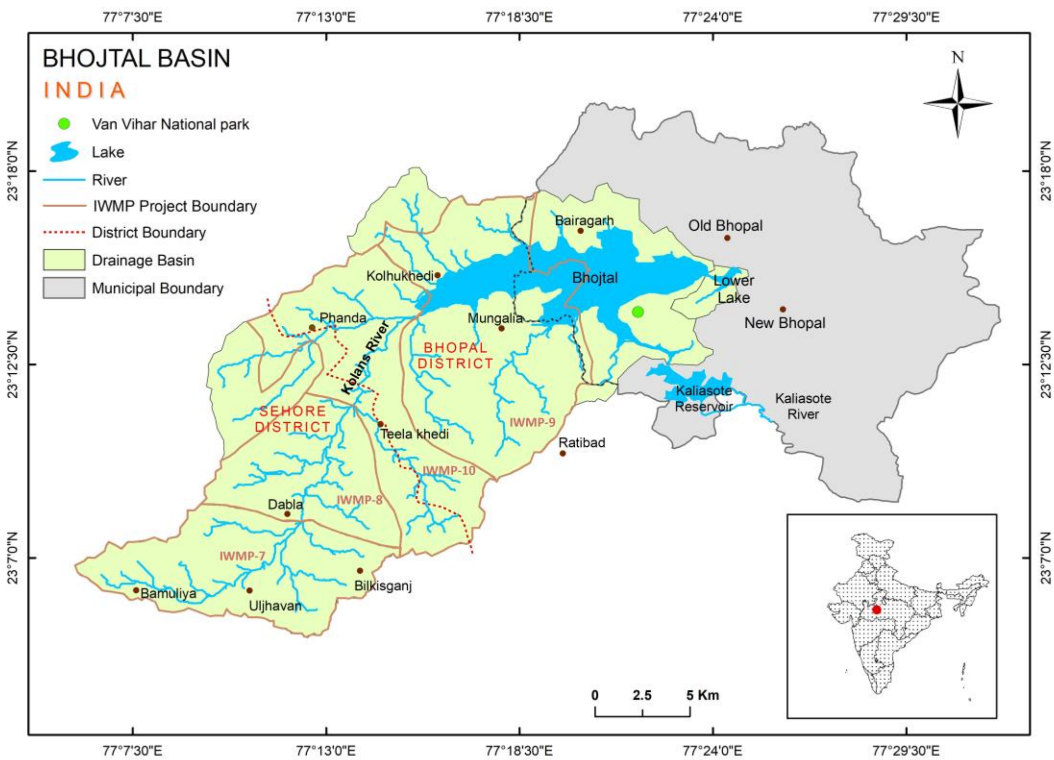


Figure 1: Map of Bhojtal catchment and associated cities and towns

A range of studies on the quality and uses of Bhiojtal and its catchment have been undertaken, and are integrated into the Results and Discussion sections of this paper. However, there appears to be only a single ecosystem service study of the Bhoj Wetland by Verma *et al*. (2001), a World Bank-sponsored valuation study as a basis for determining options for sustainable use. The Verma *et al*. (2011) study used market price, replacement cost and contingent valuation methods, to estimate the value of drinking and irrigation water supply and recreational activities, but also reporting increasing numbers of outbreaks of various waterborne diseases in Bhopal city. It was concluded that deteriorating water quality and societal benefits and values are likely to decline if water quality and availability continue to deteriorate.

This study includes assessment of both current ecosystem service provision by the lake ecosystem, and also of an *ex ante* assessment of likely changes in services were current declines in lake quality to occur.

This research collates knowledge from the literature on the quality and quantity of water in Bhojtal, trends in water resource use, the dynamics and contributions of the lake catchment area, and implications for the long-term wellbeing of the socio-ecological dependencies of the Bhopal city region. Informed by structured literature reviews, field visits and local knowledge, current delivery and potential future enhancement of a catchment-based approach to address rural needs are assessed. These findings inform recommendations for future management, greater resilience in the face of climate change, and further research needs.

2. Methods

Three methods were deployed to gather information about the state and prognosis of Bhojtal and its catchment, its contributions to the wellbeing of local people, and potential changes in management focus.

2.1 Structured literature searches

Structured literature searches (summarised in Supplementary Material) were undertaken to obtain material relevant to understanding the history, condition, uses and current trends in Bhojtal. Catchment characteristics and water resource exploitation by the Bhopal city region were addressed, along with lake level, hydrology and hydrogeology, and several specific ecosystem services. Given a paucity of peer-reviewed material, technical reports and informal media are also reviewed.

2.2 Site visits

The research team made a site visit on 25th February 2019 to the IWMP7 sub-catchment of the upper Kolans River in Sehore District, Phandra Block, where watershed regeneration is being undertaken in a catchment area of 9,700 ha. This is part of an initiative promoted by Madhya Pradesh state government which, in 2008, merged a range of individual watershed development programmes into a single comprehensive Integrated Watershed Management Programme (IWMP) (PRD, Undated). The IWMP is broken into a range of units in which interventions are targeted to enhance land and water resources, including a range of water management solutions as well as diversification of farming. IWMP7 and IWMP8 span much of the upper Bhojtal catchment (Figure 1). The management of IWMP7 was taken on from 2013 by ITC Ltd, an Indian multinational conglomerate company, through its Corporate Social Responsibility (CSR) programme, as described in the company's CSR portal[1].

ITC staff, local farmers and the Sarpanch (headman) of the Gram Panchayat (village council) were interviewed during the 25th February 2019 visit to IWMP7. Local academic partners secured consent to use anonymised responses for

[1] https://www.itcportal.com/about-itc/policies/corporate-social-responsibility-policy.aspx, accessed 28th February 2020.

research purposes prior to the interviews and meetings.

A further site visit on 1st March 2019 surveyed the downstream end of Bhojtal, including the lake margin of Bhopal city and the wastewater treatment lagoons located to the south of the lake. Further details concerning site visits, expert presentations and interviews/interviewees are described in Supplementary Material.

2.3 Ecosystem service assessment of Bhojtal

Ecosystem service production at Bhojtal was assessed using the Rapid Assessment of Wetland Ecosystem Services (RAWES) approach. RAWES was adopted under Ramsar Resolution XII.17 (Ramsar Convention, 2018; RRC-EA, In press) as a rapid and cost-effective method for the systematic assessment of ecosystem services provided by wetlands, recognising the time and resource limitations faced by operational staff. A systemic approach is essential for expressing the overall condition of a wetland in a manner that informs ecosystem management (Stein *et al*., 2009), highlighting the operational need for a genuinely rapid assessment (Fennessy *et al*., 2007; Kotze *et al*., 2012). RAWES provides a simple, user-friendly approach, supporting systemic assessment of the full range of wetland ecosystem services, requiring only two appropriately trained people to undertake no more than half a day in the field and another half-day of preparation and analysis to perform the assessment (McInnes and Everard, 2017). RAWES addresses the four ecosystem service categories (provisioning, regulatory, cultural and supporting) defined by the Millennium Ecosystem Assessment (2005). Despite their redefinition as functions in some subsequent reclassifications (for example TEEB, 2010; Braat and de Groot, 2012) to avoid 'double-counting' benefits, supporting services were explicitly retained recognising the necessity of integrating their vital underpinning roles into decision-making to avert undermining the functioning and resilience of ecosystems. RAWES can be used across a range of scales from whole-wetland (as applied in this study) to localised zones of large and complex wetlands. An explicit aspect of RAWES is integration of diverse types of knowledge (quantitative, published but also reported and observational) to develop a systemic picture, as focusing only on subjects for which data and peer-reviewed evidence is available is generally to favour 'business as usual' management and exploitation that overlooks and risks the continued marginalisation of ecosystem services for which evidence is sparse or lacking.

Assessors in this study consequently interacted with a range of experts, local stakeholders and community groups, government officials, NGOs and other interested parties (see Supplementary material), as well as drawing from field observations and the structured literature review to complete RAWES assessments. Comparative RAWES assessments were made: (1) current production of ecosystem services; and (2) consensual consideration amongst the author team concerning likely changes in future ecosystem service production if the condition of Bhojtal continues to deteriorate in the absence of restorative interventions.

3. Results

3.1 Characteristics and trends in Bhojtal

Bhojtal has a maximum surface area of 31 km^2 with storage capacity of 117.07 million m^3, with a 'full tank level' of 508.65 metres above sea level (MASL) and a 'dead storage level' (the level at which water cannot be drained by gravity through its outlet) of 503.53 MASL (Kumar and Chaudhary, 2013). Bhojtal is fed by a predominantly rural catchment of 305 or 361 km^2 (varying by author descriptions) – 80% agricultural, 5% forest and the remainder is urban though increasing in proportion (Dwivedi and Choubey, 2008; Dwivedi *et al*., 2017) – spanning 84 villages across Sehore and Bhopal Districts (ITC, Undated a; WWF, 2006; ILEC, undated).

Many lotic and lentic water bodies in Madhya Pradesh have become depleted and degraded due to improper management, excessive exploitation, falling groundwater levels, siltation and pollution, compromising water quality and availability for thousands of villages in the state (Sachdev, 2008; Pani *et al*., 2014). However, the structured literature surveys (see Supplementary Material) returned no scientifically documented evidence of declining water level or other hydrological change in Bhojtal. Despite the Madhya Pradesh Climate Change Knowledge Portal (2019a and 2019b) reports no significant observed trends in maximum or minimum temperatures or in rainfall in Madhya Pradesh from 1984 to 2013, interviewees during site visits reported that the lake level has declined most noticeably during the summer season (March to June). News media endorse interviewee perceptions of declining lake level (e.g. Times of India, 2017), lake level in June 2019 reported as reaching 'dead storage level' after lower than average monsoon rainfall in 2018, followed by a summer with very high temperatures that increased the already substantial evaporation rate of approximately 1.27 mm from Bhojtal on a typical summer day, enabling people to walk on the bed of the lake to access an island dargah (shrine) on foot (ANI, 2019). CSE (2017) reports that rapid urbanisation and encroachment have reduced the effective catchment area of both Bhojtal and the Lower Lake. There has also been a reduction in lake water storage capacity, owning to the estimated sediment yield entering Bhojtal of 1.40 Mm^3 yr^{-1} (Upadhyay *et al*. 2012a), for which the authors advocate taking measures to reduce soil erosion from the catchment.

Upadhyay *et al*. (2012b) observed hyper-eutrophic conditions throughout a prolonged study period on Bhojtal. Magarde *et al*. (2011) also observed elevated phosphate and nitrate concentrations and turbidity when spill channels were opened during and following the monsoon, attributed to the release of nutrients from the soil in the catchment, leading to profuse phytoplankton growth and particularly *Microcystis aeruginosa*). *M. aeruginosa*, a small unicellular cyanobacterium (blue-green algae) potentially forms algal blooms that may generate microcystin toxins constituting one of the most prevalent global causes of drinking water pollution (WHO, 1998). Cyanobacterial blooms can also compromise uses of the water, increasing water treatment costs and damaging both lake ecology and local tourism (Sömek *et al*., 2008). Microcystin and other algal toxins have also been linked to mortality and disease in a range of organisms, including humans (Zanchett and Oliveira-Filho, 2013). Cyanobacterial blooms therefore represent a potentially significant threat to water security. Higher values of BOD occurred when Bhojtal was stagnant due to scant rainfall, and when decomposition activities were enhanced as temperatures increased (Magarde *et al*., 2011). These trends agree with Talwar *et al*. (2013) who monitored a range of physico-chemical parameters in the lake water column, finding a general increasing trend in solute concentrations due to surface runoff entering the lake during the rainy season. All physico-chemical parameters except dissolved O_2, CO_2 and BOD in Bhojtal were found to be below the quality limits recommended in India for drinking water (Virha *et al*., 2011; BIS 2012). Nonetheless, Kumar and Chaudhary (2013) observed that dissolved O_2 concentration in Bhojtal increased while BOD, COD and other nutrient substances decreased considerably during the preceding decade as a result of implementing the 'Lake Bhopal Conservation and Management Plan' initiative in 1995 by the Government of Madhya Pradesh with funding from the Japan Bank of International Cooperation (JBIC). Khan and Ganaie (2014) observed high values of free CO_2 in Bhojtal, indicative of the higher trophic status of the lake, and elevated chloride values indicating that the lake waters are receiving sewage and other runoff materials from its catchment area. Heavy metal contamination caused by the religious practice of idol immersion in Bhojtal was reported by Vyas *et al*. (2007), though Virha *et al*. (2011) observed that only nickel and chromium exceeded BIS (2012) limits for drinking water, with copper, lead and mercury within safe limits.

3.2 Geology and hydrogeology of the Bhopal region and Bhojtal catchment

Large, permanent lakes are almost always discharge areas for regional groundwater systems (Freeze and Cherry, 1979). Given the monsoonal climate, ephemeral tributary rivers and complex groundwater of its catchment, aquifers may play a significant role in maintaining levels and quality in Bhojtal. Comprehensive understanding of the hydrogeology of the Bhojtal catchment is therefore essential to support management.

In west-central India, Deccan Trap basalts occur as alternate Vesicular Amygdaloidal Basalt (VAB) and Compact Basalt (CB) layers in a vertical pile of historic lava flows (Kulkarni *et al*., 2000). These stacked layers form a vertical sequence of step-like geomorphology ('trappean' morphology), Deolankar (1980) and Kulkarni *et al*. (2000) identifying three main accessible aquifer systems underlying the catchments of Maharashtra and west-central India. These lineaments (linear landscape features) are considered potential manifestations of subsurface faults and fractures and are found to be underlain by zones of localised weathering and increased permeability and porosity. Hence, the location of these lineaments is closely related to groundwater flows and yield.

Lineaments constitute the bulk of the Kolans catchment, with Deccan Trap basalts occupying 85% of Bhojtal catchment (ITC, Undated a). However, weathering of basalt rocks generates an overlying black cotton soil, a clay material with particle size less than 2 μm with swelling and shrinking characteristics responding to moisture content. This overlying material thus has low vertical permeability (Singh *et al*., 2018) and, as a result, run-off generation exceeds infiltration, with significant recharge possible only in shallow soil areas where structured clay/silts directly overlie weathered basalt surface aquifers (Hodnett and Bell, 1981). Hence, groundwater storage is limited in both Bhopal and Sehore districts but is still widely used where aquifers are accessible (ITC, Undated a).

An Aquifer Mapping Report for Phanda Block in Bhopal District conducted by the CGWB (CGWB, 2016) drew hydrogeological data from 10 exploratory wells up to 200 m deep in 2012-13, noting that the bedrock was exclusively basaltic and had three aquifers; this observation is consistent with the region's trappean morphology and identification of three main accessible aquifer systems underlying catchments in Maharashtra and west-central India (Deolankar, 1980; Kulkarni *et al*., 2000). ITC (Undated a) report a series of alternately exposed areas of VABs and CBs as the land slopes downwards along the Bhojtal catchment, with three operative groundwater systems in amygdaloidal basalt underlain by compact basalt, with the uppermost groundwater system having the best-developed network of openings with higher transmissivity and storage coefficient (ITC, Undated a). Although the three aquifers have been identified in formations with different hydrogeological characteristics and depth, they are unconfined in nature due to the presence of vertical fractures and fissures and are of varying storage capacity and specific yield. Beneath them is a confined aquifer in the underlying Bhander sandstone, which is tapped by deep bore wells, but which is unlikely to be recharged by infiltration within the catchment (ITC, Undated a).

Overall, CGWB (2016) considered that only 4.26% of the Kolans catchment above Bhojtal fell into a 'very high' groundwater potential class, with 29.29%, 45.79% and 20.64%, respectively, falling into 'high', 'moderate' and 'low' classes. Despite this, the CGWB (Undated) reports that the "*Govt. of Madhya Pradesh is utilising the NAQUIM report for construction of recharge shafts and percolation tanks in Kolans watershed of Phanda block of Bhopal district*".

Groundwater depletion as a consequence of increased abstraction was observed across the entire catchment area, reducing baseflow contributions to streams and directly to Bhojtal, with many dug wells running dry and resulting in farmers resorting to progressively deeper bore wells (ITC, Undated a). Across the Bhojtal catchment, ITC (Undated a) identified 5,825 functional and 11,622,343 dysfunctional tube wells, and 529 functional and 120 dysfunctional open wells. Electrical conductivity (EC), total dissolved solids (TDS) and salinity measured in dug wells and bore wells now exceeding permissible limits (ITC, Undated a). Currently, nearly all of the streams tend to flow only during and for a few days after the monsoon due to rapid water table depletion.

About 74% of irrigation in Sehore District is from groundwater and, although the level of irrigation is very low, groundwater development is substantial with areas of withdrawal exceeding recharge, leading to groundwater depletion. As of 31st March 2007, India's Central Ground Water Board (CGWB) monitored 29 dug wells of which four had piezometers in Bhopal District, and 12 in Sehore District (CGWB, 2013b). In 2012, the pre-monsoon depth to water level was 5.15-18.4 m in Bhopal District, rising to 1.24-11.61 m post-monsoon, with a 10-year (2003-2012) declining trend of 0.08-0.37 m yr^{-1} (pre-monsoon). In Sehore District, CGWB (2013a) reported pre-monsoon groundwater depths of 4.30-16.86 m with a 10-year (2003-2012) declining trend of 0.1-5.22 m yr^{-1}. Wells tapping upper aquifers apparently produce higher average yields than those tapping deeper layers (the hydrogeology of the catchment is described below).

Knowledge gaps about the hydrology and hydrogeology of the Bhojtal catchment is worrying given the focus of, and ongoing active interventions in, groundwater recharge under the IWMP programme. Further research is in hand under the Government of India's National Aquifer Mapping and Management Programme (NAQUIM[2]), a multidisciplinary programme combining geological, hydrogeological, geophysical, hydrological, and water quality data to characterise the quantity, quality and movement of groundwater in India's aquifers, addressing data gaps identified by the State Ground Water Department (CGWB, Undated). The CGWB, working with State Ground Water Departments, has already achieved extensive coverage across India (Balasubramanian, 2016). Owing to the geological complexities of the catchment, a detailed understanding of water flows in underground strata is essential to inform appropriate placement and types of water harvesting structures to alleviate pressures on groundwater resources.

3.3 Bhojtal catchment ecology

Management interventions in the Bhojtal catchment are intended to safeguard wildlife, as well as to promote lake recharge and rural livelihoods. Consequently, ITC (Undated b) undertook a biodiversity assessment of existing and potential native

[2] NAQUIM: http://cgwb.gov.in/AQM/NAQUIM.html.

plants and animals. This was a baseline assessment from which to understand the impact of development activities on local biodiversity, conducted between November 2017 and March 2018 in conjunction with local partner NGOs and 21 villages in the Kolans River catchment. Observed biodiversity included angiosperms (263 species), mammals (25 species), birds (73 species), reptiles (25 species) amphibians (8 species), butterflies (22 species) Odonata (15 species) and non-chordates (21 species). The absence of both local and migratory ducks during winter was taken as an indicator of the absence of fish, due to the drying of waterbodies. From this baseline assessment, a 26-point biodiversity conservation action plan was developed. However, there are currently no available reports to determine implementation of the plan and resultant biodiversity responses.

3.4 Water resource exploitation by the Bhopal city region

Bhojtal is regarded as the lifeline of Bhopal, as it serves the domestic water needs of roughly 40% of the population of Bhopal and its environs (Chaudhary and Uddin, 2015). In 2001, 28 million gallons per day of water was drawn from Bhojtal to provide for the needs of Bhopal (Verma, 2001). Until 1947, the water abstracted from the lake for public supply was untreated, though has subsequently received treatment (Verma, 2001). Based on analyses of multiple chemical parameters from lake water samples, Chaudhary and Uddin (2015) confirmed that the water abstracted from Bhojtal requires appropriate water treatment measures prior to use for drinking. Safeguarding freshwater resources is of critical importance as some groundwater resources are still contaminated in the aftermath of the December 1984 explosion at the Union Carbide India Limited (UCIL) pesticide plant in Bhopal, still considered the world's worst industrial accident, with chloroform, carbon tetrachloride and other organochlorine pollutants substantially exceeding WHO guidelines (Häberli and Toogood, 2009).

In 2017, the demand for water for the city of Bhopal stood at 321 million litres per day (MLD), with a projected demand of 543 MLD by 2033 as the city population is expected to increase to about 3.5 million (Burvey *et al*., 2017). The current amount of water supplied by the BMC should be sufficient for the entire city. However, due to unequal distribution, about 40% of the population depends on groundwater from private boreholes, especially amongst peri-urban communities (Burvey *et al*., 2017). Wadwekar and Pandey (2018) estimated a deficit of 11 million litres of water per year, representing approximately 15% of demand. (Based on city demands presented by Burvey *et al*., 2017, 11 million litres per year would represent a far smaller proportion.) These communities, along with those supplied by tankers, face the worst of the water shortages that affect Bhopal during summers (Burvey *et al*., 2017), particularly over the months from April to June, with delays in the monsoon worsening the situation. Consequently, lack of consideration and proportionate measures to recharge the area's water table level while extracting groundwater constitute key drivers of scarcity.

Urban boreholes require consents, though there are many illegal pumps (Burvey *et al*., 2017). Rural boreholes remain uncontrolled, consistent with the observation by Wadwekar and Pandey (2018) that groundwater development in the country is currently mostly unregulated. Across India, groundwater levels in about 54% of wells are decreasing, with 16% decreasing by more than one metre per year (Burvey *et al*., 2017). Significant and ongoing declines in groundwater levels in Bhopal District are attributed by CGWB (2013b) to overexploitation of groundwater. Wadwekar and Pandey (2018) recommend spatial planning interventions and related policy measures to regenerate groundwater resources around Bhopal through rain water harvesting.

Bhopal, like many Indian cities, is growing at an unprecedented rate and is exploiting water resources more quickly than they are regenerated, leading planners to reach out beyond the city for new supplies (Wadwekar and Pandey, 2018). The Bhopal Municipal Corporation (BMC) has dealt with the increased demand for water by diversifying sources to include local reservoirs (mainly Bhojtal), groundwater and more distant resources (Burvey *et al*., 2017) including water transfers from three other sources outside of the catchment that now serve the city. Development of Kaliasote Reservoir, located 42 km to the south-southwest of the city (Figure 1), took place in 1989. The reservoir was formed by the construction of a dam on the Kolar River, which drains southwards into the Narmada River system (Rainwaterharvesting.org, undated). Water is also drawn from the Kerwa Reservoir situated approximately 11 km to the south west of the city outside the Bhojtal catchment. Furthermore, direct abstraction and water transfer from the Narmada River now accounts for 39% of the city water supply (Burvey *et al*., 2017). Further minor sources of domestic water that supplement water supply to Bhopal city include water captured through roof water harvesting, a practice made mandatory in 2009 by the BMC. BMC takes a refundable security deposit of 5,000 Indian Rupees from those seeking to build new property to ensure the implementation of a rainwater harvesting system on or in all new buildings with a rooftop area exceeding 1,000 ft^2 (Ganguly, 2014). In 2012, rainwater harvesting became compulsory for new houses below 1,000 ft^2, with increased deposits to ensure that schemes are implemented. However, much more needs to be done to create mass awareness to encourage rooftop rainwater harvesting in all government and private buildings (Ganguly, 2014).

3.5 Management of water services to the Bhopal region

Bhopal was selected in 2015 as one of the first 20 Indian cities under the Prime Minister's flagship Smart Cities Mission (Ministry of Housing and Urban Affairs, undated). The inclusion of water services into this definition of 'smart' is unspecified, and so water is not routinely considered within Smart City plans across India.

Late-colonial and post-independence (1947) India embarked on a technocentric approach to water management, with widespread abandonment of its long tradition of community-based water harvesting. Over-reliance on technically efficient, extraction- and transfer-based solutions is one of the drivers of a tendency to search increasingly remotely for perceived surplus water resources, appropriating and often ultimately depleting them. Water resources in donor catchments can in turn become depleted, degrading ecosystems and marginalising local communities dependent on these resources, with potential to foment civil unrest (Birkenholtz, 2016) and increasingly raising questions about distributional equity (Routledge, 2003). Inter-state conflicts with diverse water uses, including for hydropower, are also increasingly likely (Kumar, 2014). This situation has been described in the context of the Banas catchment in Rajasthan state (Everard *et al*., 2018). Barraqué *et al*. (2008, p.1156) recognised this tendency as a “civil engineering paradigm” in which a narrowly engineering-based approach to addressing the water demands of growing cities drives and repeats a cycle of “taking more from further”. The ever more distant appropriation of water by Bhopal city replicates this “civil engineering paradigm” model. This approach, when compounded by population growth, urbanisation and climate change, is compromising the quality, quantity and equitable distribution of water supply (Sinha *et al*., 2013; Everard, 2015).

Countervailing this trend has been increasing recognition that catchments serving India’s cities were not only foundational to former flourishing settlements, but are a crucial resource for future sustainability (Everard, 2019). Nature-based water management is now consequently increasingly recognised as a significant contributor to water stewardship, potentially informing ‘smart(er)’ water management regimes as an essential component of the Smart Cities initiative (Drew, 2019). However, sustainable solutions lie not solely in either engineering or nature-based solutions (NBSs), but in their context-specific hybridisation supporting local, rural needs whilst replenishing ecosystems from which large-scale water resources are withdrawn (UN Water, 2018; Everard, 2019).

3.6 Other uses of Bhojtal

Additional uses of Bhojtal include tourism, recreation, navigation, and subsistence and commercial fisheries, supporting the livelihoods of many families (Verma, 2001). Bhojtal has matured over its millennium of existence to support a diverse flora and fauna (WWF, 2006). The adjacent Chhota Talaab (‘small lake’ or ‘lower lake’ as depicted in Figure 1) is also a man-made lake constructed approximately 200 years ago, largely fed by leakage from Bhojtal, and is surrounded by the city of Bhopal. Bhojtal and Chhota Talaab collectively constitute the Bhoj Wetland, rich in biodiversity including 180 migratory and local avian species, and designated as a Ramsar Site in August 2002 (Ramsar Convention, 2012). The Bhoj Wetland is the only Ramsar site in Madhya Pradesh.

3.7 Management of Bhojtal and its catchment

Formerly, wastewater was discharged directly into Bhojtal. Since the middle 2010s, approximately 95% of wastewater from the city is captured and diverted to a sewage treatment system comprising a cascade of open lagoons located to the South of the city. In that system, wastewater is subject to regular BOD/COD analysis but without chemical inputs, with the treated effluent diverted away from the lake into the Kaliasote River. Some treated wastewater is retained for watering urban public gardens and roadside trees. However, illegal wastewater discharges into the lake are common. Ayub (2019) refers to an unpublished report produced by the Centre for Environmental Planning and Technology (CEPT) at Ahmedabad University that found that around 7,500 m^3 of ‘unchecked sewage’ is still directly discharged into Bhojtal every day, including from commercial areas and other developments, with additional significant inputs from agriculture and motor boating. A hospital on the northeast lakeshore was observed (during field visit in February 2019) to have its own sewage treatment plant discharging directly into the lake, and Burvey *et al*.

(2017) report that sewage problems in residential areas along Bhojtal and Chhota Talaab are not being addressed properly.

The ‘Lake Bhopal Conservation and Management Plan’, described above, entailed seven elements: desilting and dredging; deepening and widening of spill channel; prevention of pollution (sewerage scheme); management of shoreline and fringe area; improvement and management of water quality; consulting services; and additional works (JICA, 2007). Although much of this programme addresses issues in and peripheral to the lake rather than extensive catchment-based interventions, ‘catchment area treatment’ included afforestation with 1.7 million trees over 962 ha and creation of buffer zones around the lake. Establishment of appropriate institutional arrangements for post-project follow-up was recognised as essential for the sustainability of the whole programme.

Subsequent to the above programme, Bhoj Wetland (Bhojtal and Chhota Talaab collectively) has benefited from an integrated, multi-disciplinary conservation and management project with further financial assistance from JBIC (Sachdev, 2008). Verma (2001) lists 15 sub-project interventions under the JBIC-supported Bhoj Wetland restoration programme (reproduced in the Supplementary Material), including new sewage treatment lagoons (visited by the research team in March 2019), and effluent diversion to the South of the city. Evidence of water quality and level in Bhojtal indicates little progress in halting on-going declines.

The Government of Madhya Pradesh has set a target to construct ponds in

100,000 fields to address growing water security threats (Sachdev, 2008) as part of its 'Water Worship and Stop Water Campaign', under the Rajiv Gandhi Watershed Management Mission (RGWMM) initiated in the State in 1994. RGWMM aims to improve land and water resources in environmentally degraded villages (NRCDDP, Undated). In Madhya Pradesh, ownership of ponds over 10 ha in area has been transferred to Gram Panchayats (local, community-based governance institutions recognised by the state), with additional rights to access other, smaller ponds under the Tribal Rights Act (The Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006).

In IWMP7 of the Bhojtal catchment area, ITC (Undated a) proposed a number of intervention measures. These included: soil and water conservation measures using vegetative and engineering structures particularly at upper ridges of watersheds; construction of small check dams or percolation tanks for recharge purposes in areas marked for 'drainage line recharge measures'; restriction of excessive use of bore wells, particularly with those with higher pump capacities; and installation of recharge measures on mapped recharge areas. Excavation of 'sunken ponds' to promote deep infiltration was also considered, but construction of these ponds was dismissed as it was thought that they might interfere with surface water and groundwater in the catchment.

During the visit to IWMP7 on 25th February, the research team observed a number of management interventions implemented by ITC in collaboration with farmers, the Sarpanch (head of the Panchayat) and other local community representatives. The IWMP7 region is exclusively rural, with farmers taking a wheat crop in the khariff season (post-monsoon: September to December) but with no cropping possible due to water shortages in the rabi season (summer dry period: typically from February to April: NFSM, 2018). Since the ITC company took over management of IWMP7 in 2013, a range of water harvesting structures have been installed in 16 villages. Precise targeting and clear rationales for selection of water management interventions are of great importance here as only 4.26% of the Kolans catchment was considered to fall into a 'very high' Groundwater Potential Class (CGWB, 2016). Optimally, interventions should be designed and managed to achieve co-benefits simultaneous for both local communities and overall catchment hydrology. The selection of water management measures is based on a 'treatment map' reproduced in the ITC (Undated a) hydrogeological report, identifying areas suitable for four types of 'treatment': drainage and recharge measures (mainly in upper tributaries); farm ponds; recharge measures; and soil and water conservation measures.

ITC staff reported that the company had implemented 216 water management structures in IWMP7, including stop dams, check dams, gully plugs, farm ponds and field bunds. Land of greater than 25° slope was recognised as unsuitable for cultivation, though on nullah (drainage lines) some loose boulder check dams and gabions were constructed to intercept water. In areas of low slope, field bunds are commonly dug along contours to retain water and soil, with farm ponds and field bunds commonly installed in flatter land. Farmers can pump water from farm ponds, which fill during the monsoon season, and can typically irrigate one hectare of land twice, or two hectares once. Farmers with ponds on their land have exclusive use of the stored water. As this is a region with high evapotranspiration rates, the farm ponds are deep with a small surface area. They are intended to store water in addition to recharge groundwater, with material extracted when desilting the ponds used to build field bunds. Given the impermeable nature of the black soils and underlying basaltic rock, it is assumed that these ponds make no contribution to regenerating flows of water downstream to Bhojtal, but only serve a primary purpose of storing water for use by farmers. However, ITC (Undated a) recognised that farm ponds dug sufficiently deep to penetrate the regolith could potentially facilitate infiltration and aquifer recharge, though none were observed during the site visit.

The biggest problem reported by ITC associated with implementation of catchment restoration was community participation in schemes, particularly in those elements directed at supporting biodiversity, as well as adoption of less water-intense cropping. To help increase community participation, ITC has established water user groups (WUGs) that, along with village development committees, participate in decision-making and design, then taking on management of the water harvesting structures. *Chauppal* ('meeting places') have also been established to promote direct marketing by farmers, contributing to improved incomes.

The IWMP7 programme reportedly monitors sediment runoff in the lower catchment, with the aim of reducing the 13g l^{-1} sediment input to Bhojtal measured at the outset of IWMP interventions (personal communication, ITC). Groundwater levels are also reportedly monitored in some of the approximately 170 open wells in the programme area, though many open wells are lined and so effectively act as sumps from which water pumped from aquifers is then available to the community. Well inventory data is reportedly collected in the lower part of the IWMP7 sub-catchment, where each village has around 10 open wells from which local people collect and submit data seasonally. ITC collaborates with CGWB in the interpretation of groundwater data, though the CGWB has only two monitoring wells across IWMP7 and the downstream IWMP8 sub-catchment. The degree to which surface variations are monitored in the catchment is unknown. ITC Ltd interviewees reported that, to date, as a result of these catchment management actions, groundwater is rising, with modelling indicating positive impacts on recharge of Bhojtal. However, as the research team was not granted access to the supporting dataset, these assertions could not be tested.

3.8 Ecosystem service assessment and projection for Bhojtal

The RAWES-based assessments of Bhojtal integration a diversity and informal types of knowledge, recorded in detail in the Supplementary Material, are summarised in Table 2. This assessment addressed current ecosystem service provision, and also trends in ecosystem service flows were declining trends to continue without proactive restorative interventions.

Table 2: RAWES assessments of ecosystem services provided by Bhojtal, with likely trends assessed if lake deterioration is not addressed

Ecosystem service category	• **Significance and scale of service provision by Bhojtal** ○ **Trend without intervention**
Provisioning services	• Fresh water and food production were assessed as significantly positive, both delivering predominantly local benefits ○ However, both fresh water and food production are likely to decline with deteriorating lake condition
Regulating services	• Regulation of local climate, hydrology and pollination (all with local and catchment-scale benefits) as well as global climate regulation (global impact) were considered significantly positive ○ These regulating outcomes are unlikely to be affected by deteriorating lake condition • Regulation of air quality and natural hazards were considered to be positive and to deliver local benefits ○ These regulating outcomes are also unlikely to be affected by deteriorating lake condition • Water purification and waste treatment were considered positive and of local benefit ○ There is a high likelihood of these regulating outcomes are to be affected by continuing declines in lake condition
Cultural services	• Cultural heritage services were considered significantly positive

	and expressed at all scales from the local to the global
	  ○ Cultural heritage is unlikely to be affected by deteriorating lake condition unless gross pollution ensues
	• Recreation, tourism and aesthetic value were considered significantly positive and of benefit at local, catchment and national scale
	  ○ These beneficial services are likely to be negatively affected by deteriorating lake condition
	• Spiritual and religious values and social relations were considered to be significantly beneficial at local and catchment scales
	  ○ These beneficial services are likely to be negatively affected by deteriorating lake condition
	• Inspiration of art, folklore, architecture, etc. were considered to be beneficial at local and catchment scales
	  ○ These beneficial services are likely to be negatively affected by deteriorating lake condition
	• Educational and research benefits were considered positive and expressed at all scales from the local to the global
	  ○ These beneficial services are likely to be negatively affected by deteriorating lake condition

Supporting services	• Soil formation was considered significantly positive and of benefit at local scale ○ Soil formation is unlikely to be negatively affected by deteriorating lake condition, though there may be

	escalating concerns about contamination
	• Primary production, and associated photosynthetic oxygen generation, were considered significantly positive and of benefit at local and catchment scales
	  ○ Primary production and photosynthetic oxygen production are unlikely to be affected overall by deteriorating lake condition, though species composition achieving is expected to change
	• Nutrient cycling was considered positive and of benefit at catchment scale
	  ○ Nutrient cycling is unlikely to be affected by deteriorating lake condition, though species composition achieving it is expected to change
	• Water recycling was considered to be positive and expressed at local scale
	  ○ Water recycling is unlikely to be affected by deteriorating lake condition, unless the density of moisture-capturing peripheral vegetation declines significantly
	• Provision of habitat was considered significantly positive and of benefit at all scales from the local to the global
	  ○ There is a high likelihood of the provision of habitat service declining in value with deteriorating lake condition, leading to potentially significant shifts in species composition

4. Discussion

Bhopal city was formerly substantially reliant on Bhojtal for its water needs, resources feeding the lake also serving communities within the Kolans catchment. Urban encroachment, siltation and other forms of pollution now compromise the quality and quantity of lake water, and lake level appears from corroborating anecdotal sources to be declining. Pollution control and improved catchment management are priorities to safeguard this vital water source, and also to avert risks from secondary problems particularly including cyanobacterial blooms. The layered underlying geology and low permeability of overlying black cotton soils across the Bhojtal catchment is complex, and the potential and rate of recharge of the three accessible aquifer systems exploited is far from well understood. With only 4.26% of the Kolans catchment above Bhojtal falling into a 'very high' groundwater potential class, and sequential groundwater depletion occurring over longer timescales across the catchment, lack of knowledge about wider catchment hydrogeology brings into question the efficacy of ongoing recharge initiatives. The impact of these initiatives on catchment biodiversity also remains unknown. Ongoing declines represent a threat for communities in the catchment reliant on groundwater and for recharge of Bhojtal, the capacity and quality of which is further threatened by siltation from catchment land uses.

Water resources are also withdrawn from urban boreholes that, though requiring consents, appear to include many illegal pumps, whilst rural boreholes remain unregulated. Uncontrolled extraction from aquifers not only threatens the viability and sustainable management of groundwater and lake recharge, but may expose some borehole users to historic organochlorine contamination residual from the 1984 Union Carbine explosion. Increasing appropriation of water now occurs from sources beyond Kolans/Kailisote catchment, particularly from the Narmada drainage basin from which direct abstraction and transfer now accounts for 39% of Bhopal's water supply. This follows the "civil engineering paradigm" (*sensu* Barraqué *et al*., 2008), a narrowly engineering-based approach to addressing the water demands of growing cities driving and repeating a cycle of "taking more from further". This flawed paradigm assumes that there will always be 'surplus' water available from increasingly remote sources and that its withdrawal, generally without recompense from the beneficiaries of water transfers, will not compromise the needs of communities and ecosystems in donor catchments. These assumptions are not only increasingly contested, but can be sources of conflict (Birkenholtz, 2016). They also overlook energy and other inputs to the process, potential supply vulnerability, and represent a technocentric solution that overlooks alternative means of water supply including ensuring or regenerating the sustainability of local sources (World Commission on Dams, 2000; Everard, 2013).

Nature-based water management solutions, many of which historically sustained India's water needs, are becoming increasingly recognised as significant contributors to sustainable stewardship of water resources. Localised demands from contemporary high population levels and urbanisation require intensive, engineered solutions, though nature-based solutions (NBSs) appropriately hybridised with engineered infrastructure at catchment scale can serve rural needs whilst simultaneously replenishing resources extracted by engineered infrastructure to serve concentrated demands in complex, mixed catchments (UN Water, 2018; Everard, 2019). Rainwater harvesting and other NBSs are an important part of this mixed approach, also simultaneously tackling siltation as recommended by Wadwekar and Pandey (2018), though 'engineered' versus 'nature-based' solutions is a false dichotomy as, in practice, engineered solutions are often closely reliant on upstream ecosystem processes such as flow buffering, erosion regulation and physicochemical purification (Everard, 2019). Consequently, the term 'green infrastructure' often also encapsulates what might otherwise be considered a hybrid approach (Kabisch, 2017). Determination of an appropriate mix of NBS and 'grey' solutions remains unclear due to a lack of tools, technical guidelines and approaches (UN Water, 2018). Everard (2019) recognised the lack of a shared conceptual model of the systemic impacts of all technology choices on catchment dynamics, offering an ecosystem service-based approach to recognise strengths and externalities of each approach and hence the appropriate hybridisation to optimise catchment functioning. Hybridised solutions encompassing both NBSs and 'grey' (heavy engineering) infrastructure are likely to constitute the most sustainable water management strategy to protect the quality and availability of water in Bhojtal and its catchment. Measures to improve the quantity and quality of inflows to Bhojtal through the IWMP programme, as well as Government of Madhya Pradesh targets to construct ponds to address growing water security threats, are largely based NBS approaches, and so have the potential to increase the sustainable management of water resources. However, current lack of knowledge about the hydrogeology of the Bhojtal catchment and of recharge points and recharge rates inevitably hampers optimal targeting, identification of locally effective solutions and hence likely programme efficacy. Unless water harvesting and management structures are directly geared to local hydrogeology and societal needs on a highly localised scale, it is unlikely that co-beneficial outcomes will arise for local communities and the recharge and biodiversity of catchments (Sharma *et al*., 2018). In fact, water harvesting structures that are not exactly aligned with subsurface faults may have the perverse effect of inhibiting the flow of water into the lake, failing to reverse the declining trends in the lake water quality and quantity. Conversely, if located and optimised on the basis of localised scientific knowledge of geological structure, the same number or fewer water-harvesting structures could make substantial positive contributions to water resource enhancement, representing efficient utilisation of limited funds. Lack of monitoring of ecological, hydrological and water quality outcomes, both in the catchment and in the lake, currently provides no assurance of the effectiveness of installed measures, though groundwater trends suggest that recharge is not keeping pace with resource exploitation. This highlights a further research need: characterisation of the strengths and externalities of current and proposed water management solutions, and identification of hybridised approaches that can mitigate unintended or overlooked negative impacts on catchment carrying capacity. In Bhopal city itself, additional solutions such as roof top water harvesting as well as addressing demand management can also reduce overall demands on catchment and lake resources.

Safeguarding or regenerating local resources through NBSs and other means can contribute to reducing reliance on appropriation of often contested remote resources, countering presumptions in favour of the flawed ‘civil engineering paradigm’ and representing important components of sustainable water management (Everard, 2019). Local catchment and groundwater restoration can also serve to safeguard or regenerate ecology and the diversity of services through which ecosystems support local and wider needs. Integration of the concept of hybridising nature-based with engineered solutions to regenerate catchment carrying capacity and regional self-sufficiency into definitions of ‘Smart Cities’ can make a significant contribution to water security, countering narrowly technocentric presumptions blind to their externalities. Research necessary to inform recharge programmes that can contribute to sustainable, hybridised solutions include greater detail on catchment geology and hydrogeology, specifically including recharge points and rates, identification of contextually effective recharge interventions delivering both local and catchment-scale benefits, engagement of local communities to better understand and collaborate in identified solutions, the compound impact of small-scale water management interventions, and post-installation monitoring to inform adaptive management strategies.

Ecosystem service assessment using the RAWES approach revealed the importance of fresh water and food production provisioning services but also their vulnerability to deteriorating lake and catchment condition. Local and global climate, air quality, natural hazard, hydrological and pollination regulating services were also deemed important though less vulnerable to declining lake and catchment quality, though the important regulating services of water purification and waste treatment are highly likely to be compromised if lake condition continues to decline. A broad range of cultural services provided by the lake and catchment ecosystem was also considered positive and significant, serving beneficiaries across a range of spatial scales, but were also all considered vulnerable if lake condition continues to deteriorate. Supporting services provide important foundations for continued flows of other, more directly consumed ecosystem services, and are also vulnerable to unaddressed declines in lake and catchment condition. Degradation of this linked suite of ecosystem services, if measures to reverse observed declining lake and catchment condition are not implemented, would cumulatively be harmful to the wellbeing of the Bhopal city and wider regions and, at least for some services such as tourism and climate regulation, broader geographic scales. Conversely, investment in catchment restoration could not only contribute to water security but also rebuild the foundational ecosystems and its multiple beneficial services, yielding many linked co-benefits including resilience against climate instability and other demographic trends. Overall, RAWES assessments, based on a semi-quantitative approach collating different types of knowledge to make a fully systemic assessment, indicate that significant declines in ecosystem service value are likely without positive intervention. This finding is in general agreement with a valuation study of the Bhoj Wetland undertaken by Verma *et al*. (2001), as a basis for determining options for sustainable use, that broadly concluded that declining trends in quality and availability are likely to reduce the net value of the Bhoj wetland to society in unabated, albeit that the Verma *et al*. (2001) study addressed a smaller subset of ecosystem services.

Identification of locally appropriate and effective solutions necessitates context-specific hybridisation of engineering with nature-based approaches, nuanced to the details of local geology, geography and societal needs such that rural needs are supported without compromising the replenishment of water resources at larger landscape scales (Everard, 2019). Achieving this goal requires integrated and open management arrangements, such that local solutions delegated to institutions (CSR wings of companies such as ITC Ltd, local NGOs, communities, etc.) are transparently allied to robust scientific assessment of local geography and community-defined needs. This is essential as a solution that works well in one situation may not only be wholly ineffective in a different situation but, as a worst case, may be positively damaging for example by reducing groundwater recharge by withholding water in areas where it is unable to percolate into aquifers. At present, management interventions are undertaken in good faith. However, detailed assessment of outcomes informing an adaptive approach is necessary to improve benefit realisation from what is essentially a 'live experiment'. Monitoring of outcomes from catchment intervention programmes is therefore critical, to generate understanding of their outcomes for local communities and overall catchment hydrology, including at catchment outflows as well as lake levels, ecology and water quality, to then inform adaptive management of the Bhojtal catchment. At present, the research team welcomes the zonation approach being undertaken in the IWMP zones upstream of Bhojtal, highlighting potential technical solutions based on an overview of catchment hydrogeology. However, the extent to which physical solutions are precisely aligned with the fine, granular scale of the complex underlying geology of the Bhojtal catchment is impossible to determine based on current documentation. Furthermore, actual outcomes cannot at this point be confidently assessed for lake recharge, for the benefit of local communities and for biodiversity.

Greater investment in catchment resilience can also take better account of climate change, which is highly likely to increase uncertainties in the timing and extent of rainfall and the temperature profile with associated implications for evaporation, heat stress and water demand (Molina-Navarro *et al*., 2018). Adaptation measures need to be explored, including preparation for more weather extremes.

Bhojtal, and security of water and additional ecosystem service supply to the Bhopal city region and across wider geographical scales, is the focal case study within this paper. However, principles deduced are relevant and transferrable to regions facing similar trends in resource decline, climate and other vulnerabilities, and changing demographics.

Acknowledgements

This paper was made possible by funding from the India-UK Water Centre (IUKWC), which brought scientists and community members together in the Bhopal region of Madhya Pradesh from 24th February to 2nd March 2019. The Natural Environment Research Council (NERC) in the UK and the Ministry of Earth sciences (MOES) in India provides funding for the IUKWC. The authors are grateful to Giriraj Shah, ITC Ltd, for help accessing the unpublished ITC Hydrogeological appraisal and

biodiversity assessment for the Bhojtal catchment.

References

ANI. (2019). Bada Talab in Bhopal reaches dead storage level. *Asian News International* (ANI), 6th June 2019. [Online]. (https://www.aninews.in/news/national/general-news/bada-talab-in-bhopal-reaches-dead-storage-level20190606234640/.)

Ayub, J. (2019). Madhya Pradesh: Sewage seeps into Upper Lake. *Times of India, Bhopal*, 28th August 2019. [Online]. (https://timesofindia.indiatimes.com/city/bhopal/sewage-seeps-into-upper-lake/articleshow/70865978.cms, accessed 17th September 2019.)

Balasubramanian, A. (2016). Aquifer Mapping Programme of India. Presentation at the conference Training to Hydrogeologists of Karnataka, held at the Administrative Training Institute (ATI), Mysore, October 2016. DOI: https://doi.org/10.13140/RG.2.2.11612.59524.

Barraqué, B., Formiga Johnsson, R.M. and Nogueira de Paiva Britto, A.L. (2008). The development of water services and their interaction with water resources in European and Brazilian cities. *Hydrology and Earth System Science*, 12, pp.1153–1164.

Bharath Aithal, T.R.V.S. (2016). Agent based modelling urban dynamics of Bhopal, India. *Journal of Settlements and Spatial Planning*, pp.1-14.

Birkenholtz, T. (2016). Dispossessing irrigators: Water grabbing, supply-side growth and farmer resistance in India. *Geoforum*, 69, pp.94–105.

BIS. (2012). *Indian Standard, Drinking Water — Specification (Second Revision), ICS 13.060.20 – IS 10500 : 2012*. Bureau of Indian Standards, New Delhi. (http://cgwb.gov.in/Documents/WQ-standards.pdf, accessed 29th February 2020.)

Braat, L.C. and de Groot, R. (2012). The ecosystem services agenda: bridging the worlds of natural science and economics, conservation and development, and public and private policy. *Ecosystem Services*, 1, pp.4-15. DOI: doi.org/10.1016/j.ecoser.2012.07.011.

Burvey, M., Mani, N., Singh, D., Katyal, S., Singh, B.K., Pandey, K. and Singh, V. (2017). *Children Focused City Resilience Strategic Directions for Bhopal*. Gorakhpur Environmental Action Group, supported by United Nations Children's Fund, New Delhi, India.

CGWB. (2013a). *District ground water Information booklet: Sehore District, Madhya Pradesh*. Ministry of Water Resources, Central Ground Water Board North Central Region, BHOPAL 2013. (http://cgwb.gov.in/District_Profile/MP/Sehore.pdf, accessed

31st July 2019.)

CGWB. (2013b). *District ground water Information booklet: Bhopal District, Madhya Pradesh*. Ministry of Water Resources, Central Ground Water Board North Central Region, BHOPAL 2013. (http://cgwb.gov.in/District_Profile/MP/Bhopal.pdf, accessed 28th February 2020.)

CGWB. (2016). *Aquifer Mapping Report for Phanda Block, Bhopal District, Madhya Pradesh*. Central Ground Water Board, Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India. (http://cgwb.gov.in/AQM/NAQUIM_REPORT/MP/PhandaBlockBhopal.pdf, accessed 17th September 2019.)

CGWB. (Undated). *NAQUIM Success Story*. Aquifer Information and Management System, Central Ground Water Board, Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India. [Online.] (http://aims-cgwb.org/naquim-success-story.php, accessed 17th September 2019.)

Chaudhary, M.P. and Uddin, S. (2015). Physico-chemical analysis in winter season of Bhojtal water in Bhopal region of Madhya Pradesh, India. *International Journal of Mathematical Archive*, 6(4). [Online]. (http://www.ijma.info/index.php/ijma/article/view/3531, accessed 17th September 2019.)

CSE. (2017). *Churning Still Water: A briefing paper on the state of urban water bodies, conservation and management in India*. Centre for Science and Environment (CSE), New Delhi. [Online]. (https://www.cseindia.org/churning-still-water---briefing-paper-on-urban-waterbodies-3753, accessed 17th September 2019.)

Deolankar, S. (1980). The Deccan Basalts of Maharashtra, India – Their potential as aquifers. *Ground Water*, 18, pp.434–437.

Drew, G. (2019). Political Ecologies of Water Capture in an Indian 'Smart City'. *Ethnos* [Published online 13th February 2019]. DOI: https://doi.org/10.1080/00141844.2018.1541918.

Dwivedi, P., Mishra, A., Karwariya, S., Goyal, S. and Thomas, T. (2017). SCS-CN Method for Surface Runoff Calculation of Agricultural Watershed Area of Bhojtal. *Suresh Gyan Vihar University Journal of Climate Change and Water*, 4, pp.9-12.

Dwivedi, P., Rathore, C.S. and Dubey, Y. (2009). Ecological benefits of urban forestry: The case of Kerwa Forest Area (KFA), Bhopal, India. *Applied Geography*, 29(2), pp.194-200. DOI: https://doi.org/10.1016/j.apgeog.2008.08.008.

Dwivedi, V.K. and Choubey, V.K. (2008). Hydrodynamics of the Upper Bhopal

Lake, M.P., India. In: Sengupta, M. and Dalwani, R. (eds.), *Proceedings of Taal 2007: the 12th World Lake Conference*. pp.2110-2125.

Everard, M. (2013). *The Hydropolitics of Dams: Engineering or Ecosystems?* Zed Books, London.

Everard, M. (2015) Community-based groundwater and ecosystem restoration in semi-arid north Rajasthan (1): Socio-economic progress and lessons for groundwater-dependent areas. *Ecosystem Services*, 16, pp.125-135.

Everard, M. (2019). A socio-ecological framework supporting catchment-scale water resource stewardship. *Environmental Science and Policy*, 91, pp.50-59. https://doi.org/10.1016/j.envsci.2018.10.017.

Everard, M., Sharma, O.P., Vishwakarma, V.K., Khandal, D., Sahu, Y.K., Bhatnagar, R., Singh, J., Kumar, R., Nawab, A., Kumar, A., Kumar, V., Kashyap, A., Pandey, D.N. and Pinder, A. (2018). 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. *Science of the Total Environment*, 612, pp.1249-1265.

Fennessy, M.S., Jacobs, A.D. and Kentula, M.E. (2007). An evaluation of rapid methods for assessing the ecological condition of wetlands. *Wetlands*, 27(3), pp.543-560.

Freeze, A. and Cherry, J. (1979). *Groundwater*. Prentice Hall, 604pp.

Ganguly, R. (2014). Mandatory on paper, rainwater harvesting given a miss in Bhopal. *The Times of India*, 22nd March 2014. (https://timesofindia.indiatimes.com/city/bhopal/Mandatory-on-paper-rainwater-harvesting-given-a-miss-in-Bhopal/articleshow/32472702.cms, accessed 17th September 2019.)

Häberli, H. and Toogood, C. (2009). *Analysis of chemical contaminants in groundwater and assessment of the qualitative and quantitative drinking water supply situation in the communities surrounding Union Carbide India Ltd. (UCIL) plant site in Bhopal*. The Bhopal Medical Appeal, Bhopal. (https://www.bhopal.org/wp-content/uploads/2016/06/BMA-Sambhavna-Bhopal-Water-Report.pdf, accessed 29 8th February 2020.)

Hodnett, M.G. and Bell, J.P. (1981). *Soil physical processes of groundwater recharge through Indian black cotton soils*. Institute of Hydrology, Wallingford. (http://eprints.icrisat.ac.in/8702/1/RP-01601.pdf, accessed 29th February 2020.)

ILEC. (Undated). *World Lake Database: Bhojtal*. International Lake Environment Committee (ILEC). (http://wldb.ilec.or.jp/Details/Lake/ASI-205, accessed 17th September 2019.)

ITC. (Undated a). *Hydrogeological appraisal in the catchment area of Upper Bhopal Lake in Sehore and Bhopal Districts of Madhya Pradesh*. Unpublished report supporting management interventions in IWMP7. ITC Limited, Kolkata.

ITC. (Undated b). *Biodiversity assessment of the existing and proposed native species of plants and animals including baseline data collection for biodiversity conservation action plan in the project villages at Sehore Block of Sehore District, Madhya Pradesh*. Unpublished report supporting management interventions in IWMP7. ITC Limited, Kolkata.

JICA. (2007). *Lake Bhopal Conservation and Management Project*. Japan International Cooperation Agency (JICA), Tokyo. (https://www.jica.go.jp/english/our_work/evaluation/oda_loan/post/2007/pdf/project32_full.pdf, accessed 17th September 2019.)

Kabisch, N. (2017). *Nature-Based Solutions to Climate Change Adaptation in Urban Areas Linkages between Science, Policy and Practice*. Springer, London.

Khan, M.U.Z. and Ganaie, I.M. (2014). Assessment of Physico- Chemical Parameters of Upper Lake Bhopal M.P. *International Journal of Engineering Research and General Science*, 2(4), p.354. www.ijergs.org

Kotze, D.C., Ellery, W.N., Macfarlane, D.M. and Jewitt, G.P.W. (2012). A rapid assessment method for coupling anthropogenic stressors and wetland ecological condition. *Ecological Indicators*, 13(1), pp.284-293.

Kulkarni, H., Deolankar, S.B., Lalwani, A., Joseph, B. and Pawar, S. (2000). Hydrogeological framework of the Deccan basalt groundwater systems, west-central India. *Hydrogeology Journal*, 8(4), pp.368-378. DOI: 10.1007/s100400000079.

Kumar, A. and Chaudhary, O. (2013). Conservation Plan of Upper Lake, Bhopal: Water-Quality Centric Case Study. *International Journal of Emerging Technology and Advanced Engineering*, 3(1), p.574. (www.ijetae.com: ISSN 2250-2459.)

Kumar, M.D. (2014). Chapter 14: The hydro-institutional challenge of managing water economies of federal rivers: a case study of Narmada River Basin, India. In: Garrick, D.E., Anderson, G.R.M., Connell, D. and Pittock, J. (eds.) *Federal Rivers: Managing Water in Multi-Layered Political Systems*. IWA Publishers.

Madhya Pradesh Climate Change Knowledge portal. (2019a). *Madhya Pradesh Temperature Data Visualization: Yearly Trend of Observed Temperature in MP*. Madhya Pradesh Climate Change Knowledge portal. [Online]. (http://www.climatechange.mp.gov.in/en/temprature-dashboard, accessed 17th September 2019.)

Madhya Pradesh Climate Change Knowledge portal. (2019b). *Madhya Pradesh Temperature Data Visualization: Trends of Rainfall Change in Madhya Pradesh*. Madhya Pradesh Climate Change Knowledge portal. [Online].

(http://www.climatechange.mp.gov.in/en/temprature-dashboard, accessed 17th September 2019.)

Magarde, V., Iqbal, S.A., Iqbal, N. and Zaafarany, I. (2011). Limnological Studies of Upper Lake of Bhopal (India). *Oriental Journal of Chemistry*, 27(2), pp.703-711.

McInnes, R.J. and Everard, M. (2017). Rapid Assessment of Wetland Ecosystem Services (RAWES): An example from Colombo, Sri Lanka. *Ecosystem Services*, 25, pp.89-105.

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: synthesis*. Island Press, Washington DC

Ministry of Housing and Urban Affairs. (Undated). *Smart Cities Mission*. Ministry of Housing and Urban Affairs, Government of India. (http://smartcities.gov.in/content/, accessed 17th September 2019.)

Mitra, A. (2017). *Peri-urbanity and the Smart City: Case Studies of Bhopal and Visakhapatnam, India*. Gorakhpur Environmental Action Group, Gorakhpur, Uttar Pradesh, India.

Molina-Navarro, E., Andersen, H.E., Nielsen, A., Thodsen, H. and Trolle, D. (2018). Quantifying the combined effects of land use and climate changes on stream flow and nutrient loads: A modelling approach in the Odense Fjord catchment (Denmark). *Science of the Total Environment*, 621, pp.253-264.

NFSM. (2018). Crop calendar of NFSM crops. National Food Security Mission (NFSM), Government of India. (https://nfsm.gov.in/nfmis/rpt/calenderreport.aspx, accessed 17th September 2019.)

NRCDDP. (Undated). *Integrated Watershed Development Rajiv Gandhi Watershed Management Mission, Madhya Pradesh*. National Resource Cell for Decentralised District Planning (NRCDDP). (http://www.nrcddp.org/resources_data/Res100028.pdf, accessed 17th September 2019.)

Pani, S., Dubey, A. and Khan, M.R. (2014). Decadal Variation in Microflora and Fauna in 10 Water Bodies of Bhopal, Madhya Pradesh. *Current World Environment*, 9(1). DOI: http://dx.doi.org/10.12944/CWE.9.1.20.

PRD. (Undated). *Welcome to Rajeev Gandhi Mission for Watershed Management*. Panchayat & Rural Development Department, Government of Madhya Pradesh. (http://prd.mp.gov.in/RGWM/Default.aspx, accessed 17th September 2019.)

Rainwaterharvesting.org. (Undated). *Bhopal Municipality takes rainwater harvesting seriously*. (http://www.rainwaterharvesting.org/newsletter/bhopal_municipality.html, accessed 17th September 2019.)

Ramsar Convention. (2012). *The Annotated Ramsar List: India*. The Ramsar

Convention on Wetlands, Gland. (http://archive.ramsar.org/cda/en/ramsar-documents-list-anno-india/main/ramsar/1-31-218%5E16561_4000_0__, accessed 17th September 2019.)

Ramsar Convention. (2018). *Resolution XIII.17: Rapidly assessing wetland ecosystem services*. 13th Meeting of the Conference of the Contracting Parties to the Ramsar Convention on Wetlands. https://www.ramsar.org/about/cop13-resolutions.

Routledge, P. (2003). Voices of the dammed: discursive resistance amidst erasure in the Narmada Valley, India. *Political Geography*, 22(3), pp.243-270. DOI: https://doi.org/10.1016/S0962-6298(02)00095-1.

RRC-EA. (In press). *Rapid assessment of ecosystem services: a practitioner's guide*. Ramsar Regional Centre – East Asia, Suncheon. Web link when uploaded

Sachdev, S. (2008). Case study of Madhya Pradesh on conservation of water resources. In: Sengupta, M. and Dalwani, R. (eds.) *Proceedings of Taal 2007: the 12th World Lake Conference*. pp.1430-1441.

Sharma, O.P., Everard, M. and Pandey, D.N. (2018). *Wise Water Solutions in Rajasthan*. WaterHarvest/Water Wise Foundation, Udaipur, India.

Singh, T., Mahalaha, R., Sen, R. and Khan, S. (2018). Modification of geotechnical properties of black cotton soil through inorganic chemicals. *International Journal of Civil Engineering and Technology (IJCIET)*, 9(3), pp.633–639.

Sinha, J., Sinha, M.K. and Adapa, U.R. (2013). *Flow – River Rejuvenation in India: Impact of Tarun Bharat Sangh's Work*. SIDA Decentralised Evaluation 2013:28. Swedish International Development Cooperation Agency, Stockholm.

Sömek, H., Ustaoğlu, M.R. and Yağci, M. (2008). A Case Report: Algal Bloom of Microcystis aeruginosa in a Drinking-Water Body, Eğirdir Lake, Turkey. *Turkish Journal of Fisheries and Aquatic Sciences*, 8, pp.177-179.

Stein, E.D., Brinson, M., Rains, M.C., Kleindl, W. and Hauer, F.R. (2009). Wetland assessment debate: wetland assessment alphabet soup: how to choose (or not choose) the right assessment method. *The Society of Wetland Scientists Bulletin*, 26(4), pp.20-24.

Talwar, R., Bajpai, A. and Malik, S. (2013). Study of seasonal variations in upper lake, Bhopal with special reference to impact of monsoon season. *International Journal of Environmental Sciences*, 4(3), pp.240-249.

TEEB. (2010). *The Economics of Ecosystem and Biodiversity (TEEB): ecological and economic foundations*. Earthscan, London

Times of India (2017). Bhopal: Water level drops in Upper Lake, Kolar dam. *Times of India, Bhopal section*, 19th April 2017. (https://timesofindia.indiatimes.com/city/bhopal/bhopal-water-level-drops-in-upper-lake-kolar-dam/articleshow/58249678.cms, accessed 17th September 2019.)

UN Water. (2018). *World Water Development Report: Nature-based Solutions for Water*. UN-Water. (https://www.unwater.org/publications/world-water-development-report-2018/, accessed 28th February 2020.)

Upadhyay, R., Pandey, K. A., Upadhyay, S. K. and Bajpai, A. (2012a). Annual sedimentation yield and sediment characteristics of Upper Lake, Bhopal, India. *Research Journal of Chemical Sciences*, 2(2), pp.65-74.

Upadhyay, R., Pandey, K.A., Upadhyay, S.K., Bassin, J.K. and Misra, S.M. (2012b). Limnochemistry and nutrient dynamics in Upper Lake, Bhopal, India. *Environmental Monitoring and Assessment*, 184(11), pp.7065–7077.

Verma, M. (2001). *Economic valuation of Bhoj wetlands for sustainable use*. Report for World Bank assistance to government of India, Indian Institute of Forest Management (IIFM), Bhopal, India. (http://iifm.ac.in/wp-content/uploads/bhojwetlands2001.pdf, accessed 17th September 2019.)

Virha, R., Biswas, A.K., Kakaria, V.K., Qureshi, T.A., Borana, K. and < Malik, N.

(2011). Seasonal Variation in Physicochemical Parameters and Heavy Metals in Water of Upper Lake of Bhopal. *Bulletin of Environmental Contamination and Toxicology*, 86(2), pp.168–174.

Vyas, A., Bajpai, A., Verma, N. and Dixit, S. (2007). Heavy metal contamination cause of idol immersion activities in urban lake Bhopal, India. *Journal of Applied Science and Environmental Management*, 11(4), pp.37-39.

Wadwekar, M. and Pandey, R. (2018). Assessing Ground Water Recharge Potential through Rain Water Harvesting in Urban Environment – A Case of Bhopal City. SSRN Electronic Journal. [Online]. DOI: 10.2139/ssrn.3269196.

WHO. (1998). *Guidelines for drinking-water quality, 2nd ed. Addendum to Vol. 2. Health criteria and other supporting information*. World Health Organization, Geneva, 1998.

World Commission on Dams. (2000). *Dams and Development: A New Framework for Better Decision-making*. Earthscan, London.

worldometers.info. (2020). India Population (LIVE). [Online]. (https://www.worldometers.info/world-population/india-population/, accessed 28th February 2020.)

WWF. (2006). *Bhoj Wetland*. Worldwide Fund for Nature.

(https://web.archive.org/web/20070303162320/http://www.wwfindia.org/about_wwf/what_we_do/freshwater_wetlands/our_work/ramsar_sites/bhoj_wetland_.cfm, accessed 17th September 2019.)

Zanchett, G. and Oliveira-Filho, E.C. (2013). Cyanobacteria and Cyanotoxins: From Impacts on Aquatic Ecosystems and Human Health to Anticarcinogenic Effects. *Toxins*, 5(10), pp.18