Climate change impact assessments on the water resources of India under extensive human interventions

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Abstract Climate change is a major concern in the twenty-first century and its assessments are associated with multiple uncertainties, exacerbated and confounded in the regions where human interventions are prevalent. The present study explores the challenges for climate change impact assessment on the water resources of India, one of the world's largest human-modified systems. The extensive human interventions in the Energy–Land–Water–Climate (ELWC) nexus significantly impact the water resources of the country. The direct human interventions in the landscape may surpass/amplify/mask the impacts of climate change and in the process also affect climate change itself. Uncertainties in climate and resource assessments add to the challenge. Formulating coherent resource and climate change policies in India would therefore require an integrated approach that would assess the multiple interlinkages in the ELWC nexus and distinguish the impacts of global climate change from that of regional human interventions. Concerted research efforts are also needed to incorporate the prominent linkages in the ELWC nexus in climate/earth system modelling.

Keywords Climate change · Water resources · Human interventions · Impact assessment · Uncertainties · ELWC nexus

INTRODUCTION

Climate change, identified as one of the major global challenges in the twenty-first century, affects both natural and

human systems by increasing their vulnerability at various scales and with varying intensity (Stocker et al. 2013; Hansen and Cramer 2015). The warming climate has pervasive influence on the hydrologic cycle and hence on the water resources (Huntington 2006; Oki and Kanae 2006). Though water has been recognised as part of complex, dynamic and interdependent Energy–Land–Water–Climate (ELWC) nexus (Howells et al. 2013; Kraucunas et al. 2014), often the inter-sectoral responses to climate variability/change are not duly acknowledged in most global/regional-scale impact assessments (Arnell and Gosling 2013; Hagemann et al. 2013; Schellnhuber et al. 2014; Schewe et al. 2014). Human interventions in the ELWC nexus have had significant impacts on many of the earth's ecosystems including its land and water resources (Vitousek et al. 1997; Döll and Bunn 2014). These have been recognised to have every potential to outweigh the impacts of the projected climate change at least to the middle of twenty-first century in regions with high resource consumption such as the western United States and parts of Asia including India (Vörösmarty et al. 2000; Grafton et al. 2013; Haddeland et al. 2014). This calls for distinguishing and quantifying the impacts of both direct human interventions and that of climate change on the water resources of these regions (Destouni et al. 2013). There are concerted efforts to understand the ELWC linkages and impacts under a warming climate in the United States (Kraucunas et al. 2014), but in India such an assessment seems to be a major challenge due to multiple constraints. This study explores the challenges for an integrated inter-sectoral impact assessment on water resources of India as a first step towards distinguishing, quantifying and attributing the impacts of global climate change and human interventions in the ELWC nexus.

The Indian water sector is facing multiple challenges from a growing population, rapid urbanisation, changing

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agriculture and livelihoods, growing industries and power needs, privatisation and inter-state issues leading to overextraction and degradation of the existing resource base (Mall et al. 2006; Glazer and Likens 2012). In fact, India has the largest water footprint ($987 \text{ km}^3 \text{ year}^{-1}$) in the world even with considerable underestimation of the agricultural water use (Hoekstra and Chapagain 2007). These challenges have resulted in a wide range of micro- and macro-level conflicts across the country on issues of water allocation, equity and quality, displacement, resource degradation, inter-state and inter-basin water transfers and privatisation (Vaidyanathan 1999; Joy et al. 2008). Climate change exerts additional constraints to the extent that India is projected to fall under high water stress in the near future especially along the east coast, in the west and peninsular India (Vörösmarty et al. 2000; Arnell 2004). The international commitments of India to combat climate change impacts may also create additional pressures on the existing resource use pattern (IINCD 2015; UNFCCC 2015). India is trying to address the diverse facets of its resource consumption and their impacts on carbon emissions through multiple policy initiatives in the areas of energy, land use, agriculture, water, transportation and waste management (IINCD 2015). An integrated assessment that incorporates the inter-sectoral resource dependencies would be helpful to avoid exclusive/conflicting sectoral policies and their implementation.

The present study critically reviews the impact assessments of climate variability and change on the water resources of India against the backdrop of the prevailing historic and future water resource potential, availability and use and its plausible changes as a part of ELWC system. The study specifically looks into: (i) the current water resource availability, use and uncertainties in its assessments in India, (ii) the uncertainties in the observed and projected climate change assessments in the country, (iii) the interlinkages in the ELWC nexus due to human interventions and its impacts on fresh water resources and (iv) the challenges in assessing the impacts of climate change on water resources under prevailing and increasing resource consumption.

The paper is organised in the following manner: “[Data and methodology](#)” section provides the data and methods employed in the present work. “[Water resources of India and uncertainties in assessment](#)” section details the current assessments of the water resources potential in India and uncertainties involved and “[Uncertainties in climate change assessments](#)” section provides a critical evaluation of the assessments of the observed and projected climate change. “[Energy–Land–Water–Climate nexus in India](#)” section discusses the ELWC nexus, its prominent interlinkages and the impacts of human interventions in the nexus on the water resources of the country. The sixth

section addresses the challenges and pathways in assessing the impacts of climate change on the water resources of India as part of the ELWC nexus followed by the concluding remarks.

DATA AND METHODOLOGY

The present study relies on both published literature and various fine resolution datasets to analyse the challenges in assessing the impacts of climate change on the water resources of India. The current groundwater (CGWB 2014) and surface water (CWC 1993, 2015) assessments are examined to identify the uncertainties in water resource assessments. A critical review is then carried out to assess the uncertainties in the observed and projected climate change impacts on the water resources of India. The interlinkages in the ELWC nexus are explored and the impacts of human interventions in the nexus which affect the water resources are analysed further.

The study uses the recent available fine resolution datasets on land, water, energy and climate which include: (i) 1 km SRTM DEM on topography (Jarvis et al. 2008), (ii) the distribution of major water infrastructure derived from 30 m SRTM Water Body Database (SWBD 2005), (iii) gridded precipitation data at 0.25° resolution from India Meteorological Department (IMD), (iv) cropped area, total and source-wise irrigated area at 1 km resolution (Siebert et al. 2013), (v) Runoff data from Global Runoff Data Centre and Central Water Commission (CWC), (vi) surface and sub-surface water quality data from the published reports of Central Water Commission (CWC) and Central Ground Water Board (CGWB) of India (CGWB 2010; CWC 2011) and (vii) source-wise power generation and sectoral power consumption data from the Central Electricity Authority (CEA) (2015).

WATER RESOURCES OF INDIA AND UNCERTAINTIES IN ASSESSMENT

India, situated north of the equator in South Asia, is the seventh largest in area and the second most populous country in the world. It is rich in its water resources which are highly modulated by its topographical, hydrogeological and climatic characteristics. The country has diverse topographic features, e.g. high mountains, hot deserts, high plateaus and extensive plains traversed by large rivers (Fig. 1). These topographical features have a very strong influence on regulating the regional climate and also affect surface water retention and runoff rates, dictate the direction of groundwater flow and influence groundwater recharge and discharge.

Fig. 1 Physical map of India with major mountains, plateaus and coastal plains (Data Source SRTM DEM 1 km resolution, Jarvis et al. (2008), Map projection: WGS 84 UTM Zone 43N)

The Indian subcontinent lies in the South Asian monsoon tract with wet summers and dry winters. The annual average precipitation is estimated as 1100 mm, about 75 % of which is contributed by the Indian Summer Monsoon Rainfall (ISMR) during June–September (See Supplementary Fig. S1). Out of the total estimated annual precipitation of 4000 km³, total fresh water availability is estimated to be 1869 km³, in which the utilisable yield is assessed as 1123 km³ due to physiographical, social, legal and technological constraints. Out of this, surface water contributes 690 km³ and replenishable groundwater contributes 433 km³ annually (CWC 2015). Two-thirds of the available surface water and half of the groundwater potential are confined to three major river basins of Ganga,

Brahmaputra and Godavari (see Supplementary Table S1) (CWC 2015).

There are multiple uncertainties in the assessment of water resources in the country. The water resources assessment in India is primarily based on the average amount of precipitation received. The estimation of the mean annual precipitation itself shows high variability across different datasets (Prakash et al. 2014). There is also high spatial inter- and intra-annual variability in precipitation which significantly affects both regional and seasonal surface and groundwater availability across the country. The regional assessments of surface and groundwater are carried out independently by the central agencies of CWC and CGWB, respectively and there are scale

mismatches in the basic units of assessment (CGWB 2014; CWC 2015). The surface water assessments are carried out at the river basin level whereas the primary groundwater assessments are conducted at the taluk/block level. The surface water assessments in India are carried out for 20 river basins, 10 of which are aggregations of multiple basins. For example, the entire west coast of India with 114 medium and small river basins and 238 independent coastal watersheds is aggregated into two basin units in the CWC assessment (CWC 1993, 2015; Sreeja et al. 2016). The taluk/block-level groundwater assessments are also aggregated into these 20 river basin regions (CWC 2015). Even if aggregation of groundwater blocks is achieved at the river basin level, there is physical-scale mismatch between surface and groundwater boundaries especially in regions with transboundary aquifer systems (Jarvis 2006; CGWB 2014). India has extensive alluvial, soft rock and coastal regions where transboundary aquifer systems predominate and therefore the boundary-related uncertainties can be substantial. Aggregation of administrative blocks into basins also brings in the additional scale problems of administrative and basin boundary mismatches (Sreeja et al. 2012). Hence, the total water availability assessed in any river basin is subject to these scale-dependent uncertainties. These errors in the quantification of the existing resource base add to the uncertainties in distinguishing the climate change-induced impacts on water resources.

Uncertainties also exist due to the lack of detailed sectoral assessment of agricultural, industrial and domestic water uses and the recent shifts in the sectoral water consumptions in the country. For instance, water has been allocated to Concentrated Solar Power (CSP) plants in Rajasthan from the agricultural water apportionments in the Indira Gandhi Canal (Bhushan et al. 2015a). Such unplanned reallocations can be observed across the country for satisfying the rising demands for water in the power, industry and domestic sectors (Joy et al. 2008; Shah and Kumar 2008). The increasing water scarcity and the piecemeal and sectoral approach to water legislation have exacerbated inter-sectoral allocation issues and increased conflicts between different users (Cullet et al. 2015). These reallocations and ensuing conflicts take place both formally and informally. For instance, the city of Chennai in Tamil Nadu is able to obtain water from the Krishna river for drinking water needs through a formal allocation in the Krishna tribunal award even when the Tamil Nadu state does not have any riparian rights in the basin (Shiva et al. 1991; Molle and Berkoff 2006). On the other hand, informal and unregulated market transactions from agricultural to urban use have been observed in some cities of India where former irrigation wells are now used for drinking water supply through tankers (Molle and Berkoff 2006).

The current surface and groundwater resource assessments (CWC 1993, 2015; CGWB 2014) are mostly empirical in nature and do not depict the variations in regional and seasonal water availability and use. Inter-annual variability in precipitation also exerts additional uncertainty in water availability. The current assessments do not provide the extent of spatio-temporal changes in surface and groundwater resources brought about by these natural variabilities in the climate. The insufficiencies in the present water resource assessments and datasets in terms of the incorporation of regional and seasonal heterogeneities, natural variability and changing water use pattern along with aggregation of assessment units and scale/boundary mismatches pose difficulties in distinguishing the impacts of climate change on the water resources. This is a major hindrance to climate change impact assessments and adaptation/mitigation measures at meaningful scales. On the other hand, climate change assessments are riddled with their own uncertainties that are being explored in the following section.

UNCERTAINTIES IN CLIMATE CHANGE ASSESSMENTS

Precipitation and temperature are the most important climate variables and runoff, evapotranspiration (ET) and soil moisture are the most important hydrologic variables which affect the water resources of any region. The variability and change of these principal hydro-climate parameters have been studied over the years using various datasets at multiple spatial and temporal resolutions. These datasets include individual gauge records, interpolated gridded products, satellite products, reanalysis data, outputs from General/Regional Circulation Models (GCMs/RCMs) and some proxy variables. They have been assimilated from various sources using different assimilation techniques and have different uncertainty levels. Uncertainties in climate change assessments arise out of the internal variability of the climate system which is prominent at smaller spatio-temporal scales and uncertainties from climate models and future scenarios which dominate at larger spatio-temporal scales (Hawkins and Sutton 2009). The studies that explore the observed and projected changes in the climate and its impacts on the water resources can be grouped into: (i) the assessment of the observed variability/changes in the climate and hydrologic variables and/or their interactions/distributions, (ii) projection of climate variables using GCMs/RCMs for various emission scenarios and (iii) projection of hydrologic variables using GCMs/RCMs outputs directly and by coupling GCMs/RCMs climate outputs with land surface models

(LSMs). A critical evaluation of some of the salient studies is undertaken as a part of this analysis.

For the Indian subcontinent, significant warming trends in the All India Mean Temperature (AMT; 0.5–0.7 °C for the last century) have been reported, although these trends are also highly heterogeneous in their seasonal and regional distributions (Kothawale and Rupa Kumar 2005; Solomon et al. 2007; Jain and Kumar 2012; Stocker et al. 2013; Jayaraman and Murari 2014). The minimum AMT (AMT-min) (0.12 °C 100 years⁻¹) and maximum AMT (AMT-max) (1.02 °C 100 years⁻¹) also show increasing trends for the last century (Kothawale and Rupa Kumar 2005). These temperature trends display a rapid acceleration post-1970s coinciding with the unprecedented increases in global emissions (Kothawale and Rupa Kumar 2005; Peters et al. 2013). The observed precipitation on the other hand, shows a decreasing trend post mid-twentieth century. Both Annual Mean Precipitation (AMP) and ISMR, which contribute a major share of AMP, are found to exhibit decreasing trends although these trends show high regional variations (Saha et al. 2014; Roxy et al. 2015). Changes are also observed in extreme precipitation in the subcontinent. Though a spatially aggregated extreme precipitation analysis shows an increasing trend post 1950, a fine resolution analysis at 1 degree reveals a spatially non-uniform trend (grid cells with increasing (40 %), decreasing (38 %) and no (22 %) trend). The regions with increased urbanisation post 1975 exhibit increasing trends in precipitation extremes which is reported to be an indication of the influence of regional factors (Ghosh et al. 2012; Vittal et al. 2013). The reduced thermal contrast between the land and the sea due to an increase in the Indian Ocean sea surface temperature is pointed out to result in declining trends in ISMR, contrary to earlier expectations of increased precipitation in the tropics following global warming (Roxy et al. 2015). It is also argued that the present declining trend in ISMR is part of its natural variability wherein declining trends coincide with the decreasing phase of the multi-decadal oscillation (Sinha et al. 2015). Similarly, even though a warming climate is expected to increase evaporation and ET, it is observed that the reduced soil moisture availability and influence of other climatic variables [wind, solar radiation, relative humidity (RH)] nullified the effects of temperature increases on ET and resulted in recent declines in evaporation/ET trends in various parts of the country (Jung et al. 2010; Jhajharia et al. 2012, 2014). Chattopadhyay and Hulme (1997) and Bandyopadhyay et al. (2009) reported that the reduction in wind speed and increase in RH and cloud cover resulted in the decrease of ET even under a warming climate. For tropical surface water balance, RH is found to be more critical than temperature (Chattopadhyay and Hulme 1997). The evaporation/ET trends also exhibit high spatial variability (Jung et al. 2010).

A significant increase in ET and concurrent decrease in observed runoff is reported from the Krishna river basin in peninsular India due to extensive flow regulation and increase in irrigation in the second half of twentieth century (Jaramillo and Destouni 2015). A higher reduction in total average annual runoff is attributed to human interventions (61 % of simulated runoff) in the basin rather than to climate variability (6–15 % of simulated runoff) during the period (Bouwer et al. 2006). Significant decline in annual runoff trends (40–50 %) is also observed in the Mahanadi river basin during 1926–1980 (Rao 1995) and in more recent years (Mujumdar and Ghosh 2008; Panda et al. 2013). An intensification in inter-annual variability of extreme streamflow and precipitation indices is also reported (Panda et al. 2013). Declining trends in observed streamflow despite insignificant changes in precipitation are also reported in other river basins such as Musi (Nune et al. 2014) and Gomti (Abeyasingha et al. 2015) which are mainly attributed to increased human interventions. There are limited studies on the impact of climate change on the observed runoff in the Indian river basins mainly due to lack of consistent and long-term data. The Global Runoff Data Centre (GRDC) provides monthly runoff data from 44 stations in India in which only a few have long-term data (GRDC 2015). CWC has 544 river discharge gauging stations most of which started operation after the 1980s, of which data from 336 stations are made available through a web portal (<http://india-wris.nrsc.gov.in/>). The runoff measured at most of these stations is highly modified due to large-scale river basin developments/withdrawals and therefore exerts additional uncertainties.

The future projection of climate variables is achieved through the simulations from GCMs and RCMs for different future radiative forcing scenarios (viz. Representative Concentration Pathways—RCPs). Global- and regional-scale studies using the GCM/RCM output of the Coupled Model Inter-comparison Project phase 3 and 5 (CMIP3 and CMIP5) for various future emission scenarios report an increasing trend in AMT, AMTmax and AMTmin for the Indian subcontinent for the twenty-first century (Chaturvedi et al. 2012; Deser et al. 2012; Stocker et al. 2013). It is further reported that when global AMT reaches 2 °C above pre-industrial level, most of the Indian land mass would experience a higher increase of 2.5–2.75 °C at an earlier time period of 2030–2040 (Joshi et al. 2011).

There is no consensus among studies on the impact of global warming on the evolution of future monsoon and precipitation pattern over India from both CMIP3 and CMIP5 GCMs (Solomon et al. 2007; GoI 2010a; Krishna Kumar et al. 2011; Stocker et al. 2013). Only a few locations in India show high confidence in the sign of change even under RCP8.5 (Stocker et al. 2013). Multi-model CMIP5 GCM simulations for RCP4.5 show

significant enhancement of global monsoon activity including the Indian monsoons and a westward expansion of the monsoon domain over Asia (Hsu et al. 2013; Lee and Wang 2014). The precipitation projections are found to be less reliable than temperature projections and model agreement and robustness increase from near to long term and from lower to higher emission scenarios (Chaturvedi et al. 2012). It is also reported that for the long term, there are consistent increasing trends in the frequency of extreme events. The spatial changes in future rainfall are also observed to be divergent with wet areas becoming wetter and dry areas becoming drier (Salvi et al. 2013). Both CMIP3 and CMIP5 GCMs, at their original scales, fail to model this spatial variability in ISMR and show uniform increasing trends across the domain (Shashikanth et al. 2014a, b). GCMs and RCMs therefore possess limited skill and have high bias while projecting fine-scale variables such as precipitation. The extent, intensity and direction of changes projected by various GCMs also differ according to the model structure and parametrisations. Moreover, most of the CMIP5 GCMs even fail to capture the decreasing trend in observed ISMR (Saha et al. 2014). For the Indian monsoon, most of the GCMs show uniform wet bias and even multi-model ensemble assessments have limited skill to address model uncertainties (Saha et al. 2014). The wet bias, high internal variability and failure of GCMs to capture decreasing trend in observed ISMR make most of these projections highly unreliable.

The future runoff and evaporation/ET are assessed directly from GCM/RCM simulations and through coupling GCM/RCM climate projections with Land surface (Hydrological) models (LSMs). Multi-model projections for the end of the twenty-first century using runoff outputs from 11 CMIP5 GCMs show increase in flood frequency (under RCP8.5) and increase in mean, high and low streamflows (under both RCP8.5 and 4.5) in most parts of the Indian subcontinent (Hirabayashi et al. 2013; Koirala et al. 2014). CMIP3 GCMs also project an increase in future runoff and evaporation under the A1B scenario for India (Nohara et al. 2006). Large-scale uncertainties are reported in basin-scale water fluxes from CMIP5 GCMs (Bring et al. 2015). The simulation of freshwater fluxes vary widely among models and even the multi-model mean deviates significantly from the observations. There is also high spatial variability in runoff projections; the cold and tropical regions are reported to overestimate while temperate regions underestimate the basin-scale water fluxes (Siam et al. 2013; Bring et al. 2015). The uncertainties associated with the projections of climate variables from GCMs exert high uncertainties in future runoff and evaporation estimates (Immerzeel et al. 2013; Törnqvist et al. 2014). CMIP5 GCMs overestimate the increase in evaporation with increase in temperature in the tropics where

increasing near surface relative humidity and decreasing wind speed offsets the evaporation increases (Láiné et al. 2014). The model uncertainties in LSMs compared to GCMs for future runoff projections are highly contradictory. Prudhomme et al. (2014) report higher uncertainties in LSMs than in GCMs at the global scale while Gosling et al. (2011) and Raje and Krishnan (2012) report the contrary at a regional scale. Even after downscaling, the uncertainties in GCMs are reported to outweigh the uncertainties in LSMs (Raje and Krishnan 2012). Hence, projected runoff and ET estimates are to be dealt with extreme caution. The failure of most of the GCMs to capture the observed ISMR trend makes future runoff/ET projections also highly undependable. The impacts of projected climate changes on the Indian water resources are therefore riddled with high uncertainties.

On the other hand, direct human interventions in the resource base affects water fluxes (Gordon et al. 2005; Destouni et al. 2013) and thereby the regional climate (Destouni et al. 2010). Irrigation plays a significant role in modulating water fluxes and regional climate in many parts of the world including India (Jarsjö et al. 2012; Asokan and Destouni 2014). Land use changes such as deforestation and urbanisation, water storage and withdrawals for power generation, industry and resource extractions also significantly affect the water resources in multiple ways. In the last century, climate-induced changes in water flux are often overshadowed by landscape changes in many parts of the world (Jaramillo and Destouni 2014).

It is evident from the above discussions that apart from the data uncertainties and uncertainties in the observed and projected climate variables, human interventions on the resources have significant potential to surpass/amplify/mask the impacts of climate change. Hence there is a need to examine these prominent interventions and linkages in the resource sectors of energy, land and water and their interlinkages to climate to assess and distinguish the impacts of global climate change on the water resources of the country.

ENERGY–LAND–WATER–CLIMATE NEXUS IN INDIA

The ELWC nexus is the multitude of dynamic linkages that exist between the resources of energy, land and water in a region and its relations to the regional/global climate system. These linkages are the result of the functional and human-induced interdependencies among the resource sectors and the climate. This is particularly relevant in the regions of high resource consumption (see Supplementary material and Fig. S6 for more on ELWC linkages) (Hoff 2011; Skaggs et al. 2012; Howells et al. 2013; Kraucunas

et al. 2014). Here, we examine the ELWC nexus in the context of India to explore the challenges in assessing the observed and projected impacts of climate change on water resources under extensive human interventions.

Interventions in energy–land–water sectors

The development of the energy, land and water sectors has been historically driven by demand-oriented exclusive sectoral policies in India and these have undergone accelerated changes post 1970s (see Supplementary Figs. S2, S3–S5). The current state of development of the resources of energy, land and water in India is discussed prior to an exploration of the linkages between various components in the ELWC nexus that impact water resources.

India is the third largest energy consumer with 6 % of global energy consumption by about 18 % of the world population (IEA 2015b). Petroleum products (45 %), coal and lignite (33 %), electricity/power (16 %) and natural gas (5 %) are the major commercial sources of energy in India, without accounting for non-commercial biomass sources. The industrial (45 %), transportation (22 %), residential (12 %) and agricultural (6 %) sectors are the major consumers (see Supplementary Table S2) (TERI 2015). India is the third largest power producer in the world with a generation capacity of 272 GW, mainly from coal-based thermal (61 %) and hydro (15 %) power plants. Industrial (42 %), domestic (24 %) and agricultural (18 %) sectors are the major consumers of electricity (CEA 2015) (see Supplementary Table S3). There is an exponential growth in power generation and consumption after 1980s along with the rise of the domestic sector as the second largest consumer coinciding with the rapid urbanisation trends in India (see Supplementary Fig. S4). The domestic sector is becoming the most prominent consumer in several states even while about 20 % of the population still have no access to electricity (IEA 2015a).

Out of the total land area reported under utilisation (306 Mha) in the country, 46 % is agricultural net sown area (140 Mha) and 8 % is agricultural fallow lands (26 Mha) followed by 23 % under forests (70 Mha) and waste lands (70 Mha) each (GoI 2014). The land is also a source of metallic and non-metallic minerals extracted through 3978 mines extending over 4980 km² located within these land use categories (GoI 2015). Besides, a significant amount of land area is used for transportation and power transmission networks, industrial and power projects and human settlements. A major part of the agricultural land is under intensive cultivation with a high cropping intensity of 139 % (GoI 2014) (Fig. 2a). Even though rainfed cultivation is still predominant, 43 % of the net sown area is under irrigated agriculture (Fig. 3a, b).

Post independence, India had prioritised large infrastructure developments in the water sector so that the country now ranks fourth in the number of large dams (WCD 2000) and has one of the world's highest volumes of stored water (Shiklomanov and Rodda 2004). At present, India has 4857 completed large dams with a total storage capacity of 253 km³ (CWC 2015) which differs considerably from the Global Reservoir and Dam (Grand) database estimate of 320 dams (Lehner et al. 2011). Apart from these large reservoirs, India still has a large number of minor irrigation structures such as lakes, tanks and ponds managed either by the provincial governments, communities or individuals. The total number of tanks is estimated to be 556 000 of which 471 000 are in use (MoWR 2013) (Fig. 2b). India has made an investment of 5143 billion rupees in irrigation and flood control structures upto the XI Plan (2007–2012) (GoI 2013). The investment in major and medium structures amounts to 68 % of this total outlay, minor irrigation and command area development takes up 22 % and the remaining 10 % went into flood control structures. It is estimated that there are about 25.5 million pumps, pumping out about 230 km³ of groundwater annually (Garduño et al. 2011). The investments in groundwater development are mostly by individual farmers/industries supported by subsidised power tariffs by the state. There is also high spatial and seasonal variability in the use of ground and surface water across India (Fig. 3c, d).

Linkages to water resources in the ELWC nexus

Water is the critical resource central to all development activities including agriculture, livestock, industry and power generation (Mall et al. 2006). The multiple and reciprocal linkages of water to other nexus components of energy, land and climate due to the prevalent human interventions are explored here (Fig. 4). Depending upon the type and technology used, water requirements for power generation vary widely. The thermal power industry in India is estimated to withdraw 40 km³ of water annually (IEA 2012). It has been noted that Indian coal plants with cooling towers consume twice as much water (4 m³ MWh^{−1} on an average) as their global counterparts (Bhushan et al. 2015b). The 135 MT of coal beneficiation capacity consumes 27–35 Mm³ of clean water per annum. Apart from the direct use of water, the coal washeries discharge effluents into the river system forming a major source of heavy metal pollution. For instance, the river Damodar has 14 coal washeries in a stretch of 38 km discharging 300–500 m³ day^{−1} of effluents into the river (Ghose 2001; Sundararajan and Mohan 2011). Most of these plants are located in areas with severe water scarcity

Fig. 2 **a** Cultivated area (as a percentage) at 1 km resolution as per Global Consensus Landcover map. **b** Surface water bodies and major tanks in India (Data Source **a**Tuanmu and Jetz (2014), **b** SWBD (2005), Map projection: WGS 84 UTM Zone 43N)

that has triggered conflicts and temporary plant shutdowns due to water shortage (Bhushan et al. 2015b). In addition to the existing 581 coal mines in India spread over about 2100 km² of land area (including 550 km² of forests), 119 coal mining projects have been sanctioned recently which would result in a loss of an additional 315 km² of forestland. Water consumption by the thermal plants is highly subsidised and is expected to increase by more than 80 % by 2020s which can exert additional strain on local water and land resources and conflicts among other competitive users (Bhushan et al. 2015b). The evaporation loss from the water storage in the thermal plants is reported to be very high as in the case of Barsingsar Thermal Power Station in Rajasthan where 30 % of the water stored is lost through evaporation (Bhushan et al. 2015b) affecting the regional water vapour flux and the climate.

Water resources are also affected by hydroelectric projects through altered streamflow patterns, submergence and fragmentation of the catchments. The total area submerged by 4039 of 4857 large dams in India is estimated to be 50 000 km², about half of which is used for hydropower generation (CWC 2012). The energy sector accounts for 57.8 % of India's GHG emissions mainly through fossil fuel combustion for electricity generation (37.8 %) (GoI 2010b) without accounting the considerable GHG emissions from reservoirs. In fact, India's large dams contribute atleast 28 % of the total global reservoir methane emissions

and are responsible for one fifth of the country's GHG emissions (Lima et al. 2008). Reservoirs are also the largest contributors to the increased global ET (Sterling et al. 2013; Jaramillo and Destouni 2015). For instance, considerable increases in ET have been reported from the Krishna and Godavari basins in India due to extensive reservoir creation and increase in irrigated agriculture (Jaramillo and Destouni 2015).

On the other hand, climate variability and change pose additional stresses. Globally, large reductions in usable capacities of hydro (61–74 %) and thermal (81–86 %) power plants are projected due to climate change impact on water resources for 2050s (van Vliet et al. 2016). However, an increase in usable capacities of both hydro and thermal power plants is reported for the Indian region (van Vliet et al. 2016) which could be a reflection of the wet bias in the future projections as discussed in “Uncertainties in climate change assessments” section. India's commitment towards climate change mitigation through 33–35 % reduction in CO₂ intensity by 2030s and increasing renewables in the energy mix for a low-carbon transition also comes with considerable water and land costs (Hoff 2011; UNFCCC 2015). The proposed 292 hydropower projects, mostly in the Indian Himalayas, to double India's existing hydroelectric capacity by 2020s would submerge an additional 4000 km² of land including 541 km² forests (Pandit and Grumbine 2012). The CSP plants in Rajasthan

Fig. 3 **a** The area equipped for irrigation as a percentage of each of the 5 arc-minute resolution grid cells, **b** the actual area irrigated as a percentage of area equipped for irrigation, **c** percentage of area equipped for irrigation by surface water and **d** percentage of area equipped for irrigation by groundwater as of 2005 (Data source Siebert et al. (2013), Map projection: WGS 84 UTM Zone 43N)

have been allocated $8\text{--}13 \text{ m}^3 \text{ MWh}^{-1}$ of water which is about 4 times the international standards and 3 times more water than required for conventional coal-based power plants (Bhushan et al. 2015a). The biofuel substitution targets of 20 % by 2020s is projected to involve at least 0.5

million km^2 of land area that can substantially increase competition for water and land resources and increase the GHG emissions from land conversions for biofuel crops (Ravindranath et al. 2011; Purohit and Fischer 2014). Despite the increasing scarcity and conflicts over these

Fig. 4 Energy–Land–Water–Climate nexus in India. The prominent interlinkages involving water in the nexus are also provided as coloured arrows and text. The resource availability and consumption estimates shown in the figure are indicative only because of multiple uncertainties in their assessments (see Supplementary material and Fig. S6 for more details)

resources, the country has not yet developed any benchmark for water and land requirement in any of the renewable energy options, even when the renewable energy target is set at 175 GW by 2020s (Khare et al. 2013; Bhushan et al. 2015a). The energy sector is becoming thirstier and increasing water-energy risk necessitates the inclusion of water and land costs before translating them as a part of climate change policies.

India is the largest agricultural resource user in the world in terms of arable and irrigated land area and groundwater consumption (FAO 2015). Agriculture, the livelihood mainstay (60 %) and the major landuse (42 %) in the country, consumes the largest share of water (80 %) and considerable amount of energy creating multiple nexus linkages. The surface water irrigation from large dams and minor irrigation amounts to a net area of 16 Mha and 2 Mha, respectively (MoWR 2013; CWC 2015). Despite the heavy development of surface water sources, the dominance of surface water irrigated area is at present limited to the paddy-growing tracts of Jharkhand and Orissa states, Indira Gandhi canal command of north western Rajasthan and the Cauvery delta in Tamil Nadu (Fig. 3c). A major share (62 %) of the net irrigated area in India is still found to be dependent on groundwater resources with high spatial and seasonal variability (GoI 2014).

The multiple nexus interlinkages of water resources with land, energy and climate are strikingly evident in the case of irrigation. The massive surface water developments have altered the hydrology of the river basins and the intensive use of groundwater has depleted the water table leading to reduction in groundwater storage and availability across the country (WCD 2000; Rodell et al. 2009; CGWB 2014). The gross groundwater irrigated area of 60–70 Mha in India uses upto 120 000–150 000 GWh of electricity and 5–8 Mm³ of diesel to pump up 230–250 km³ of water annually (Mukherji et al. 2012). The introduction of subsidised electricity for groundwater irrigation directly led to increased and unregulated use of both power and groundwater use, depleting groundwater aquifers, increasing area under groundwater irrigation and further increasing power demands (Mukherji et al. 2012). Considerable advances in saline water intrusion is projected in the coastal stretches of India due to extreme groundwater withdrawal which can worsen with rise in sea level and increased water demands due to climate change (Sherif and Singh 1999; Bobba 2002). Of a total of 5723 groundwater blocks, 1615 are classified as semi-critical, critical or overexploited due to this heavy extraction (CGWB 2014). On the other hand, increased irrigation has led to salinity, alkalinity and water

logging issues in 8.4 Mha of agricultural land in the country (Ritzema et al. 2008).

Climate variability/change exerts additional constraints in the nexus that make the interrelationships more vulnerable and less predictable. It has been reported that climate change exacerbates the already reduced natural streamflow due to dams and water withdrawals in most parts of the country (Döll et al. 2012). The recent acute groundwater depletion in the Indo-gangetic plains primarily due to irrigation water withdrawals was also found to be influenced by the marked rise in temperature since 2008 (Panda and Wahr 2016). The increase in water demands and reduced water availability due to climate change is projected to decrease the area under irrigation substantially by 2030 (Taheripour et al. 2015). These interconnections in the ELWC nexus are more evident in the two-day black out incident in northern India on 30th and 31st July 2012 affecting over 600 million people. The delayed and deficit monsoon rainfall followed by increase in temperature resulted in abnormal increase in electricity demand (from agricultural and domestic sectors) and reduction in hydro power generation which triggered the abrupt shutdown of most of the power plants in the northern grid (IEA 2012).

The interventions in the water and land sectors through intensified irrigation have significant impacts on the regional and global climate through increased ET fluxes (Gordon et al. 2005; Asokan et al. 2010; Jarsjö et al. 2012; Jaramillo and Destouni 2015). The mean annual vapour fluxes have increased by 17 % (340 km^3) with marked seasonal variations (wet season—7 % and dry season—55 %) due to agricultural conversions in India, 2/3rd of which is attributed to irrigation (Douglas et al. 2006). The South Asian monsoon pattern is reported to be more sensitive to these irrigation-induced flux changes than to the climate impacts of land use change (Douglas et al. 2009). In the Mahanadi basin, irrigation is reported to enhance ET (by 40 mm year^{-1}) and reduce the annual average temperature (by $0.13 \text{ }^{\circ}\text{C}$) and runoff (by 32 mm year^{-1}) during 1956–2000 (Asokan and Destouni 2014). The changes in irrigation intensity across the basin induce high spatial variability in the fluxes (Asokan et al. 2010). In the Krishna river basin, an increase in ET (by 77 mm year^{-1}) is observed which is linked to the increased reservoir storage and irrigation during the twentieth century (Jaramillo and Destouni 2015).

Water resources are also affected by extensive land use land cover (LULC) conversion that includes deforestation, changes in the extent of cultivated lands and urbanisation by direct human interventions (Lambin et al. 2003). In India, a six-fold increase in population from 200 million to 1200 million during the past century along with rapid economic growth have resulted in significant LULC changes. The forest area has declined from 89 to 63 Mha and cropland area

has increased from 92 to 140 Mha during the period (Tian et al. 2014). These considerable LULC changes have led to significant changes in water fluxes (Gordon et al. 2005; Sterling et al. 2013). It has also been observed that emergent and expanding clusters of urban settlements, located most often along coastal zones and major waterways, have increased the demands and impacts on the water resources of India (McDonald et al. 2011). The water quality is also degrading in many parts of India due to changing land use. Surface and groundwater pollution, mainly from untreated sewage, industrial effluents, agricultural runoff and urban waste, is a major environmental issue in India that affects not only the fresh water availability but also the lives of millions of people (CGWB 2010; CWC 2011).

These interlinkages in the ELWC system through human interventions (Fig. 4) make the climate change impact assessment on water resources of the Indian subcontinent highly challenging.

CHALLENGES IN CLIMATE CHANGE IMPACT ASSESSMENTS ON WATER RESOURCE SYSTEMS

In the light of the above discussions, the challenges in assessing climate change impacts on water resources under human interventions are identified and detailed below. These can be distinguished as the uncertainties arising from data, climate change assessments and those from regional human interventions on the ELWC nexus.

- (a) *Absence of a resource inventory* Presently there is no comprehensive resource inventory in India to understand the inter-sectoral resource linkages and impacts. The impact assessment on water resources requires sufficient, reliable and long-term data on hydro-climate variables, existing water infrastructure, aquifer systems, land use and its dynamics, energy production and demands, sectoral water use pattern, population, water quality, type, quantity and source of pollution loads at desired spatial and temporal resolutions. The available data at present are spread across multiple government agencies with limited access. Being a state subject and most of the rivers being inter-state, much of the data on water are restricted in the public domain due to inter-state disputes. There is an urgent need to assimilate the inter-sectoral resource inventory data, capturing the changing resource use patterns, with the involvement of all concerned departments, institutions and stakeholders for a more dependable water resource assessment of the country.
- (b) *Uncertainties in assessing climate change and its impacts* These can arise from internal variability and

model, scenario and data uncertainties. GCMs and RCMs have high inter-model variability, bias and limited skill while projecting the fine-scale variables such as precipitation. The wet bias exhibited by most of the GCMs with regard to ISMR limits the ability of even multi-model assessments to reduce model uncertainties. The future emissions and evolution of climate will have higher levels of uncertainty under the present state of knowledge and available datasets. There are multiple datasets available on climate variables, derived using data from different sources and methods which have different uncertainty levels. The uncertainties that arise from these should also be a part of impact assessments.

- (c) *Failure of GCMs in capturing Indian Monsoon* The inability of most of the GCMs to capture the decreasing trend of ISMR, on which the entire water resources of the country depend upon, is a major challenge in assessing the impacts of climate change on the water resources of India.
- (d) *Heterogeneities in hydro-climate variables and resource use* Most of the hydro-climate variables exhibit high regional and seasonal variability. There is also high variability in resource availability and use. This necessitates compilation of existing resource and climate database at finer spatial and temporal resolutions making climate change impact assessments data intensive.
- (e) *Changing resource use pattern* Energy, land and water infrastructure development in India is among the largest in the world. There are considerable changes in the energy, land and water use patterns post 1970s with regards to their influence on regional and seasonal water availability, demand and quality. These changes to the resource base and their individual/inter-sectoral response to climate variability/change would be additional considerations while quantifying the impacts of climate change.
- (f) *Interlinkages in the ELWC system* ELWC are highly interdependent and influenced by geo-physical and socio-economic characteristics of a region. Our understanding of water as part of the ELWC system and their underlying processes and feedbacks is very limited. Being an indispensable component in the ELWC nexus, any change in the system affects both natural and anthropogenic water availability and use. On the other hand, water and land use are also recognised to affect the climate and hydrological cycle, the processes of which are still highly uncertain. Hence the assessment of the reciprocal impacts of climate change and water resource use is a challenging task which requires a holistic understanding of the ELWC system.

The considerable challenges for assessing the climate change impacts on the water resources of the country posed by extensive human interventions in the ELWC nexus can only be addressed by a systematic and inclusive approach which would involve:

- (i) identifying all the prominent links in the ELWC nexus in each of the river basins based on the current resource development using available data and research which may be the first step towards an integrated impact assessment.
- (ii) river basin-level resource and climate database inventory to be created by assimilating all available datasets from concerned departments and stakeholders in the country. The CWC has recently set up a 'Water Resources Information System of India' (India-WRIS) which can be upgraded for the purpose.
- (iii) preparation of guidelines for the assessment of the impacts of ELWC linkages and climate change on water resources for consistency in assessment.
- (iv) pilot studies to be initiated to explore the ELWC nexus and their impact on the water resources in some of the selected basins depending upon the availability of data and resources which can provide a guideline for future studies in other basins.
- (v) concerted research efforts to improve the skills of GCMs/RCMs for simulating the monsoons (especially ISMR) and other water fluxes. There is also a need to incorporate the prominent regional linkages in the ELWC nexus due to human interventions that influence the climate and regional water fluxes in climate/earth system modelling.

CONCLUDING REMARKS

The Indian water sector is highly dynamic, spatially heterogeneous and is one of the most developed/utilised resources in the world. The extensive human interventions on the water resource have also complexly interlinked it with the other resources of energy and land and the climate within the ELWC nexus. Climate change exerts additional pressures and uncertainties on the nexus. The consequent unprecedented levels of resource depletion have catalysed increasing scarcity and conflicts across the country which necessitate urgent research and policy interventions. In this regard, formulating coherent and integrated resource and climate change policies and relevant adaptation/mitigation measures in India would require (i) assessing the multiple interlinkages in the ELWC nexus, (ii) understanding the responses/impacts/feedbacks of the ELWC nexus and climate change and (iii) distinguishing and quantifying the impacts of global climate change from that of human

interventions on the water resources. The absence of a dynamic and comprehensive resource inventory, and uncertainties associated with assessing the climate change and its impacts add to the challenge. Recently, India has made major international commitments to mitigate climate change impacts and translating these into policies would require a concerted effort in addressing the challenges that have been highlighted in this paper.

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