Energy and Climate Change 2 (2021) 100060

Contents lists available at ScienceDirect

Energy and Climate Change

journal homepage: www.sciencedirect.com/journal/energy-and-climate-change

Water-energy-food nexus in India: A critical review

Nazar Kholod [a,*], Meredydd Evans [a], Zarrar Khan [a], Mohamad Hejazi [b], Vaibhav Chaturvedi [c]

[a] Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD, United States
[b] King Abdullah Petroleum Studies and Research Center, Riyadh, Saudi Arabia
[c] Council on Energy, Environment and Water, New Delhi, India

ARTICLE INFO

Keywords:
India
Water-energy-food nexus
Water scarcity
Review
Methods

ABSTRACT

India is one of the most water-stressed countries in the world. With the rapidly increasing population and growing energy demand, the country is already facing challenges in the interaction between water, energy, and food systems. Water scarcity could be a significant obstacle for meeting needs in India's growing cities, energy supply, and agricultural production. A key focus of this review paper is the interaction of water with energy and food. To provide a framework for spatial and temporal analysis of the nexus studies, we use the Global Change Analysis Model to identify the most water-stressed areas in India throughout 2050, as well as energy needs and land use. Then we review more than 100 studies to assess the evolution of competing demands for water, energy and food and identify research gaps in published water-energy-food (WEF) nexus studies. This review of published WEF nexus studies in India reveals that most studies are not designed to capture the interaction between multiple dimensions, which means they may underestimate water demands and water stress in the country. Only a few studies focus on future challenges and effects of climate change on water, energy, and food systems. The paper highlights the major gaps in the existing literature, contrasts them with large-scale, medium-resolution, modeled results on water scarcity, and provides recommendations for future research.

1. Introduction

India is the second most populous country in the world and is expected to become the most populous by 2025. According to United Nations' projections, India's population will reach 1.5 billion people in 2030 and over 1.7 billion by 2050 [88]. An additional 350 million people will need energy and food. In 2015, India consumed more energy than any other nation except China, the United States, and Russia [14], and the government is trying to expand electricity service to all citizens. The International Energy Agency (IEA) projects that India could add about 600 million new electricity consumers by 2040 [25]. India is one of the world's largest producers of rice, vegetables, fruits, and cotton [17]. Clearly, the country will need to expand food production or imports to feed the increasing population.

India is also one of the most water-stressed countries [22, 77] and its water resources are overexploited today, showing falling water tables [58]. This creates threats to the country's security because it puts stress on agriculture, the power sector, and industry. India's chronic water scarcity problems will become an even bigger challenge in the future [91].

About 600 million people in India face high to extreme water stress in India. NITI Aayog estimated that twenty-one major Indian cities will run out of groundwater by 2020. One hundred million people will be living in cities with no remaining groundwater [57]. The Indian government is trying to formulate and implement suitable strategies for better management of water resources, but risks remain very high. According to a report of the Intergovernmental Panel on Climate Change, India will be most significantly affected by climate change, given its huge population and levels of inequality [26]. Heat waves can seriously affect water availability for agriculture and the power sector.

To analyze the complex interactions between water, energy, and food, researchers and policy analysts use a nexus approach. Followed by Albrecht et al., we define "the WEF nexus as a systems-based perspective that explicitly recognizes water, energy, and food systems as both interconnected and interdependent." [2]. There are many studies that review WEF nexus importance, methodology, models, methods and applications [2, 15, 16, 27, 42, 63, 78, 84, 85, 89, 96], and this list is not exhaustive.

Previous studies have also provided some overview of WEF nexus research on India. For example, a book on the water-energy-food-

* Corresponding author at: 5825 University Research Court, Suite 3500, College Park, MD 20740, United States.
E-mail address: nazar.kholod@pnnl.gov (N. Kholod).

https://doi.org/10.1016/j.egycc.2021.100060
Received 28 May 2021; Received in revised form 26 August 2021; Accepted 3 October 2021
Available online 9 October 2021

security nexus [33] provides an excellent overview of the status of nexus issues in India. However, there is a need for a comprehensive review of existing WEF nexus studies in India to answer two key research questions. First, how does the existing literature assess the evolution of competing demands for water, energy and food in India? Second, what gaps in India exist in the WEF nexus space, particularly in the areas that will likely experience the greatest water stresses?

The paper is structured as follows. After this introduction, Section 2 provides an overview of the WEF nexus components and presents the results from GCAM on water demand and water scarcity in India. Section 3 describes the methodology and data sources used in this paper. Section 4 provides a review of the literature on WEF challenges in India focusing on demand sides of the nexus components. Section 6 summaries the major research gaps we found in the literature and provides concluding thoughts on future research directions.

2. Framing India's WEF challenges

The WEF nexus focuses on complex interactions, trade-offs, and synergies between the water, energy, and food systems (Fig. 1). Traditionally, the various dimensions of the nexus have been viewed independently. It is being increasingly realized that developments or challenges in one of these dimensions could have significant implications for the other dimensions of the nexus. For example, a lack of energy would hinder the withdrawal of adequate groundwater for irrigating crops. Similarly, the lack of water availability has already led to shutting down the power plants during peak summer months in arid regions of India as well as many other parts of the world. Clearly, while planning of food, water, and energy security, it is not enough to look at these systems independently. The inter-dependence of the systems, the trade-offs between them, and the synergistic opportunities could only be explored and better understood through viewing all these systems simultaneously within a common WEF nexus framework.

In order to frame the discussion on the WEF in India, we use several open-source tools which can shed light on the potential areas and drivers of water scarcity in the most water-stressed areas in India.

We use the Global Change Analysis Model (GCAM) [21, 22], developed by Pacific Northwest National Laboratory's Joint Global Change Research Institute to frame the challenges in the WEF nexus in India. GCAM is an integrated assessment model that represents the behavior of, and complex interactions between five systems: the energy system, water, agriculture and land use, the economy, and the climate. It represents 283 agroecological zones and 235 water basins, including 18 in India. Water withdrawals and consumption are represented across six economic sectors, including agriculture and the power sector. GCAM is widely used to analyze interaction of water with other sectors [11] under various scenarios [87].

India's population is projected to grow from 1.2 billion people in 2015 to 1.7 billion people in 2050. To feed the additional people, agriculture production will have to increase significantly. India's crop productivity is very low due to traditional farming practices, small landholdings, and limited investment in mechanization. The increase in agriculture production is going to be mainly on account of productivity enhancement through irrigation. This is reflected in the results which show that area under crops will grow by 6% between 2015 and 2050, while the water withdrawn for the same will grow by 42% during the

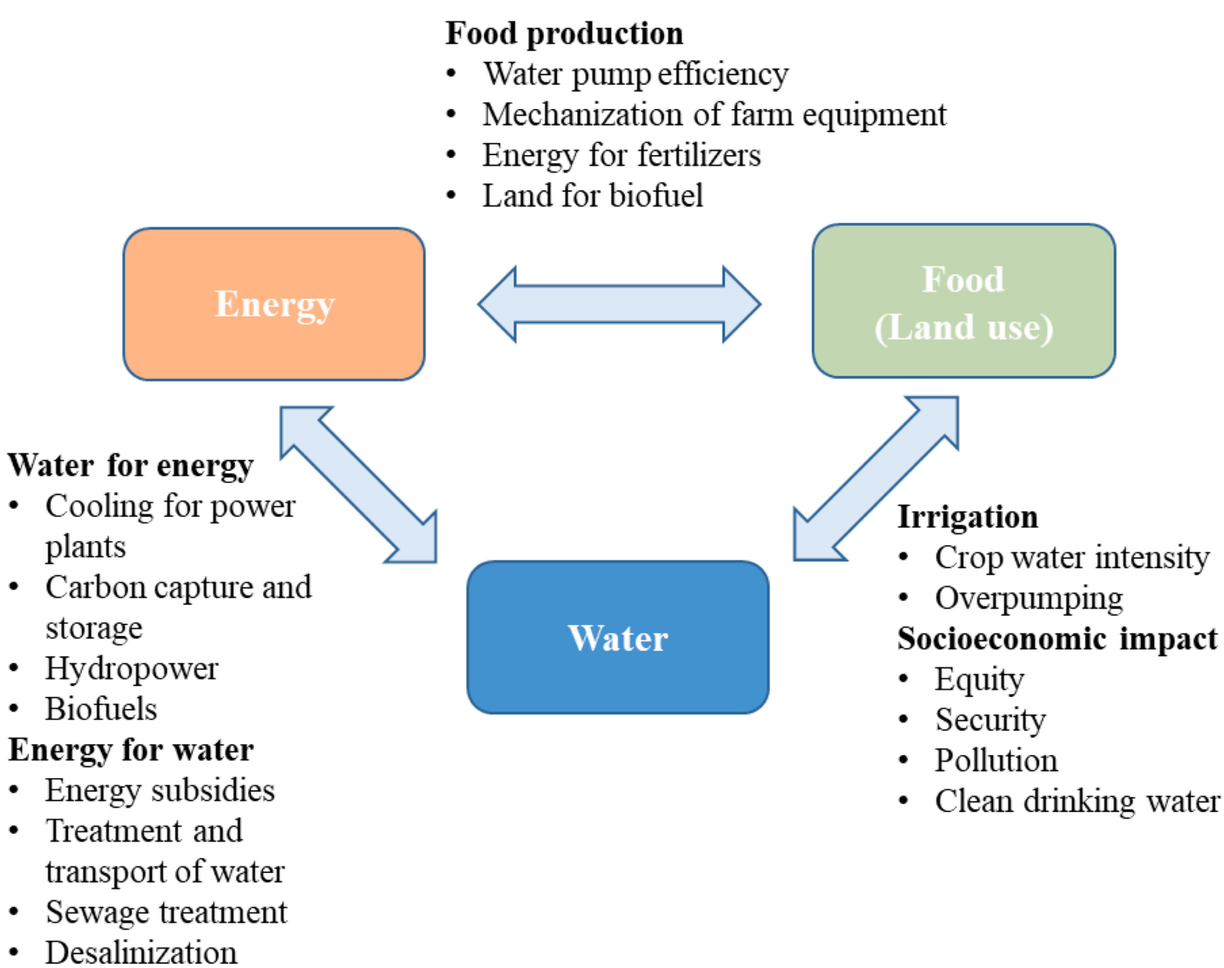


Fig. 1. Components of the WEF nexus in India. (Modified from [1].

same period (Supplement tables S5-S7). Growth in additional land for agriculture would be small.

The rest of this section focuses on water as the most important element of the WEF nexus in India. GCAM and its hydrological tools allow us to shed light on the potential areas and drivers of water scarcity in India. These results also provide a helpful frame to consider the detailed analysis of more bottom-up WEF studies in India, highlighting whether there are potential gaps in the geographical and sectoral coverage compared to the areas and drivers identified in large-scale, medium-resolution analysis.

Water supply is calculated using the Xanthos model [39, 60]. Xanthos produces outputs for various parameters including total runoff, average streamflow, potential evapotranspiration, and actual evapotranspiration [90]. We use the Tethys package to downscale water withdrawals from national to local scale [40, 61]. Tethys produces demands for six different sectors: irrigation, livestock, domestic, electricity (generation), manufacturing, and mining. Both Xanthos and Tethys produce outputs on monthly time-steps and 0.5-degree grid cells. Water scarcity is calculated as the ratio of water demands to water supply (runoff).

Fig. 2 shows the most water-stressed regions in India. Water scarcity grows dramatically across India through 2050 compared with today, but the greatest changes occur in the northwest and central-southern India.

Water scarcity in India comes from several factors. Demand grows significantly because of the population increase and economic growth. Overall, Fig. 3 shows that water demand growth is strongest in northern India, while the sectors experiencing the fastest growth include irrigation and livestock.

Agriculture, cities, and industry account for the largest changes in water withdrawals through 2050 (Fig. 4). Agriculture, as the far largest sector of water demand, will be specifically susceptive to climate change effects.

GCAM also provides projections on power generation in India and associated water withdrawal and consumption. The previously published GCAM results show that between 2010 and 2050 power generation and water withdrawal in India will increase by a factor of 9, while water consumption will grow by a factor of 5 [83]. We provided GCAM projections of electricity generation by technology in Supplement Table S4.

As this section shows, the GCAM ecosystem tools are very helpful to analyze future water, energy and land demands in India. However, while helpful, no single tool can shed light on all aspects of the WEF nexus in India and the results highlight the critical importance of bottom up WEF studies in India. There is a need for more robust assessment of the changes in the WEF nexus. Bottom-up studies and more detailed models can help clarify local trends and impacts, as well as options for mitigating water shortages.

3. Methodology and data

We compiled peer-reviewed publications in academic journals and book chapters. We searched the Scopus database for “India,” “water,” “energy,” “food,” and “nexus” in titles, abstracts, and keywords. The Scopus search resulted in 50 articles, conference papers, and book chapters. This low result could be explained by the fact that many nexus papers in India focus on dual-sector interactions, for example, water for energy, water for food, energy for water, and energy for food. A significant discussion on the WEF nexus in India is taking place in reports and other non-peer-reviewed publications. We also used Google Scholar to search for other studies on the WEF nexus in India, which resulted in over 19,000 items published between 2010 and 2021. We selected only full-text papers, which focus primarily on India; many other studies use India as an example in the text or references.

We also included studies from several prominent think tanks in India, such as the Center for Study of Science, Technology, and Policy (CSTEP), Integrated Research and Action for Development (IRADe), The Energy and Resources Institute (TERI), Council on Energy, Environment, and Water (CEEW), the Institute for Resource Analysis and Policy (IRAP). We

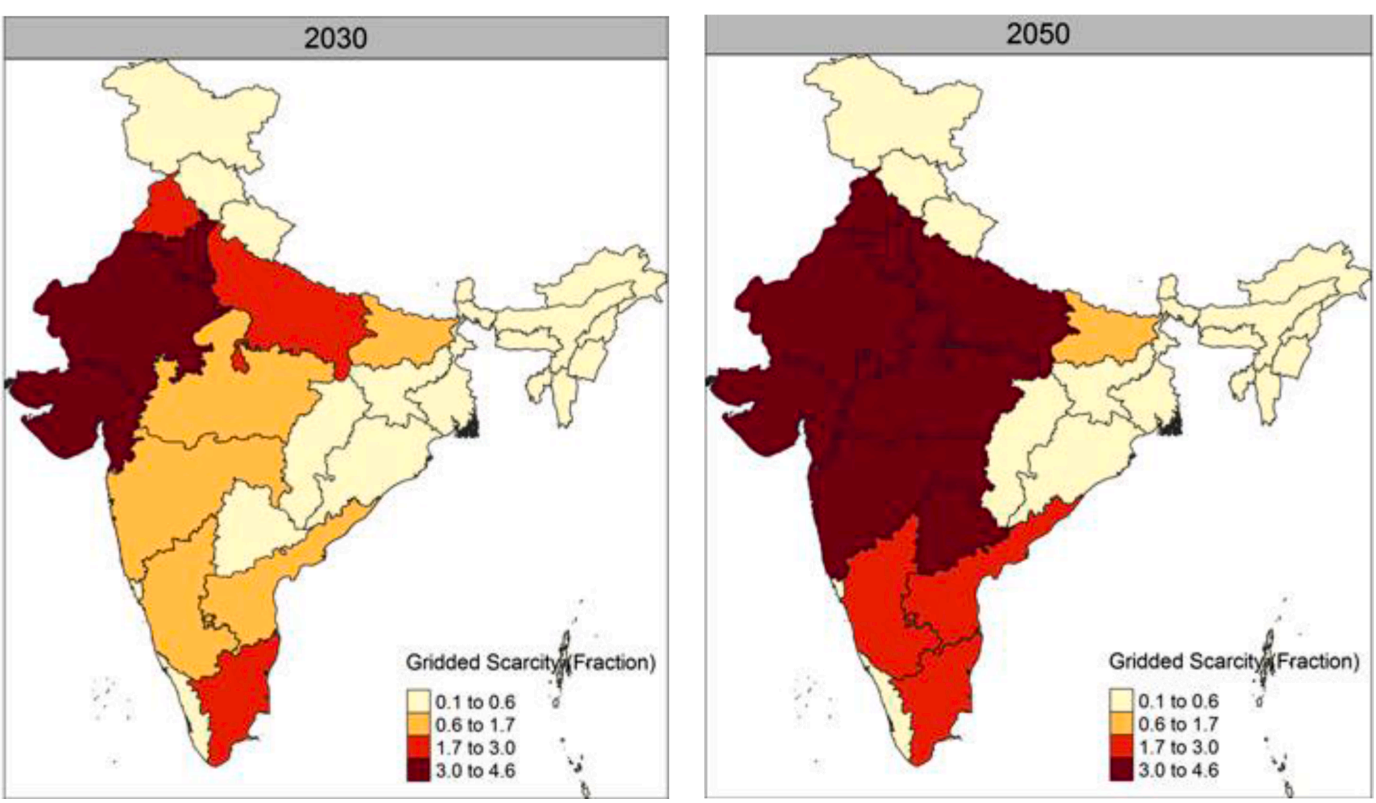
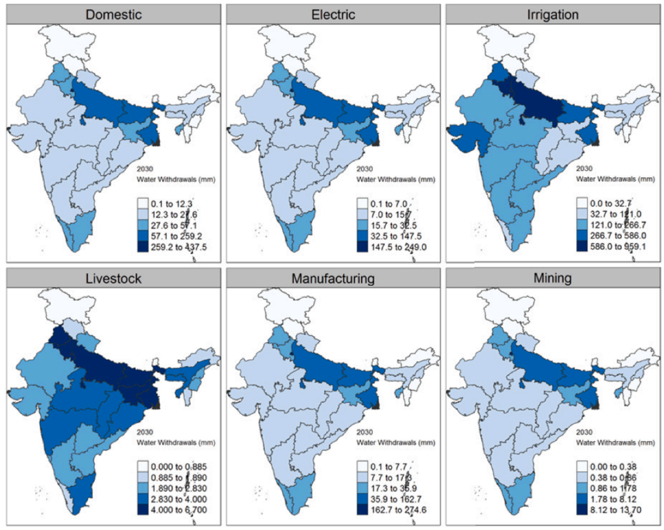
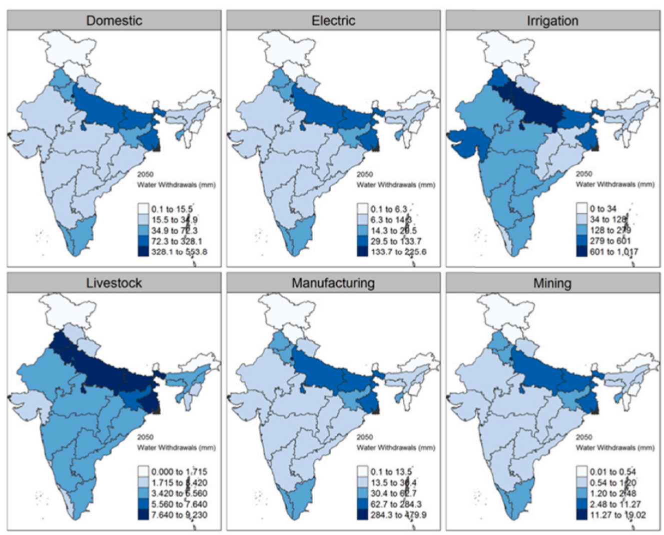


Fig. 2. Water scarcity in India, 2030 and 2050.



a) Water demand by sector, 2030.



b) Water demand by sector, 2050.

Fig. 3. Growth in water demand by sector, 2030 and 2050.Note the different scales of the spatial distribution of different demand types.

also analyzed studies from international research centers and organizations such as the International Water Management Institute (IWMI), the World Resources Institute (WRI), and the Columbia Water Center.

Finally, some studies do not use the nexus concept in the text thought they indeed focus on the WEF nexus. These papers are more difficult to identify because they do not show up in keyword searches, so we located some of them using by systematically reviewing references in the sources we considered (i.e., the snowball method). We should note, however, that the number of WEF nexus studies on India has been increasing very rapidly. More than half (57%) of all articles on the WEF nexus in India were published during the past five years; 43% of the studies were published during the past three years.

In total, we reviewed over 100 studies in this paper. All studies selected were analyzed regarding geographic coverage and timeframe (Section 4), and the nexus elements covered (Section 5). The Supplement provides additional data on the analyzed studies.

4. A review of the literature on WEF challenges in India

This section provides an overview of key WEF nexus studies in India. We try to answer the two research questions. First, how the existing literature assesses the evolution of competing demands for water, energy and food in the WEF nexus. More specifically, we will review what linkages between water, energy, and food (land use) exist and what the implications of this linkages are today and in the future. Second, what gaps exist in the water-energy-food nexus space, particularly in the areas that will likely experience the greatest water stresses? The supplement provides additional detail on methods, geographical focus, and timeframes of the published data.

The rest of the paper focuses on sectors and locations with the highest water scarcity to determine the areas of the focus in India.

This also allows us to highlight gaps in the knowledge of the WEF nexus impacts in the country.

4.1. Water-for-energy

The power sector uses water in thermal power plants as a coolant. Hydropower plants directly depend on water to run turbines. Two terms are used to describe water-for-power demand. Water withdrawal means water removed from the ground or diverted to a power plant from a surface-water source, while water consumption is the portion of withdrawn water not returned to the immediate water environment. Thermal power plants, which produce about 85% of all electricity in India, consume the largest share of water in the power sector.

Most of the papers on water-for-electricity in India focuses on India-wide problems in the power sector without geospatial detail. Some important topics are the reduction of water use for cooling, development of India-specific water withdrawal and water consumption coefficients and the analysis on policy measures. Several papers analyze future water demands in the power sector. For example, for the power sector, that has been the focus of many published papers, researchers have been using global average values in absence of India specific data. Chaturvedi et al. [12], on the other hand, presents a good example of research with India specific data points.

However, the issue of water availability by geographic location and increasing water scarcity in some areas remains an area of significant need in terms of the future research agenda. Some states with large power generation capacity and high-water stress are not sufficiently analyzed in the literature (e.g., Maharashtra). A good example of a paper that addresses this question is Luo et al. [41], although more are needed to cover the breadth of the topic. However, the world could shape in different ways, and these alternative development pathways could have significant implications for India's electricity generation and associated water demands.

One of the first papers that specifically focused on the water-for-electricity nexus is an intermodel comparison of water withdrawal and consumption for power generation by 2050 [83]. This study uses global median values for water withdrawals and consumption to estimate water demand by the power sector in India.

India operates older generation thermal power plants with open-loop, or once-through, cooling technologies. These cooling systems have an average water use intensity of about 80–160 m^3/MWh or around 40 to 80 times higher than the average modern close-loop, or recirculating, system [94]. To assess India's long-term electricity generation [12] developed India-specific dataset of water consumption withdrawal intensities by cooling technology and type of water (freshwater/seawater). They present a dataset of India-specific power plant distribution by cooling technology based on information from 185 power plant units, and technology-specific water withdrawals coefficients based on data of 41 power plant units [12].Many other studies [13, 41, 59, 82, 86, 93] use water consumption and water withdrawals coefficients to explore different future scenarios.

In recent years, researchers use more sophisticated tools to survey thermal power plants in India. For example, Luo et al. [41] use Google Maps to locate 358 power plants, which account for almost 99% of India's total thermal power capacity and analyze satellite images for all geolocated utilities to identify them by water source and cooling type. They found that 39% of the capacity is installed in high water-stress regions. Between 2012 and 2016, the 14 largest Indian thermal power companies could have earned over $1.4 billion of additional revenues from the sale of power but they did not due to water shortages.

For water consumption in 2010, the estimates range between 4 bcm [24], 3.7 bcm [83], 1.6 bcm [12], and 1.1 bcm in 2011 [41]. [41]. For water withdrawals in 2010, the estimates range from 49 bcm [49], 40 bcm [24] and 34 bcm [83] to 22 bcm [12], 18.0 bcm in 2014 [92], 18.8 bcm in 2015 [41]. Different assumptions on the distribution of cooling technologies and water intensity by India's power plants explain the difference of these results.

India has significant untapped hydro potential and several studies discuss water for hydropower plants and analyze the potential of large and small hydro projects [10, 23, 43, 56, 68, 70].

While many studies account for possible changes in the distribution of cooling technologies and decreasing intensities of water use, the issue of water availability for cooling by geographic location remains an important direction for future research. A study by [41] is a good example. The impact of climate change on future water availability is another important issue to consider in future studies. Another important direction of research is to further develop the database of India-specific water demand coefficient not only for fuel and cooling technologies but also for coal burning technologies as water requirements for subcritical, supercritical, and ultra-supercritical coal vary. With the emission mitigation challenges, nexus research focused on this sector becomes an important emerging area of research.

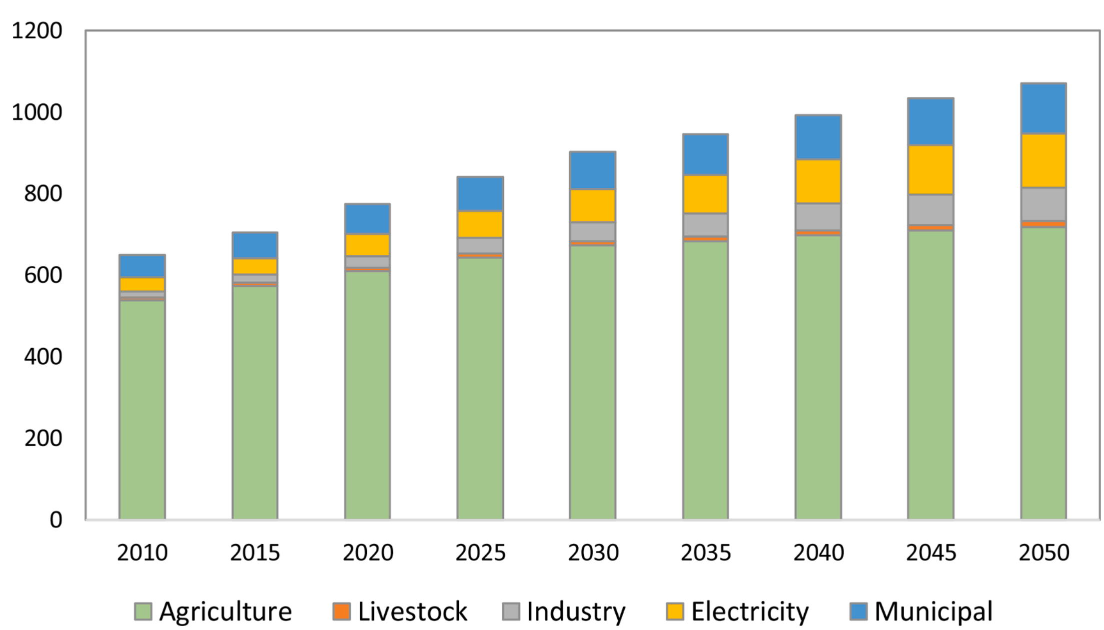


Fig. 4. Evolution of water withdrawals by sector of demand in India, billion m^3 (using GCAM output).

4.2. Energy-for-water

The energy-for-water nexus is one of the most debated issues in India. Researchers have discussed this type of nexus in the framework of the wider topic of water and energy management in India. Key study areas include energy subsidies, excessive energy consumption, renewable sources of energy for water. Most of the papers on this nexus link use qualitative methods.

Irrigation in India is the biggest source of water withdrawals, and inefficiencies in irrigation water use and the resultant lowering groundwater tables in many agricultural districts of India have often been attributed to the energy pricing policies. Energy pricing policies for irrigation has been an important area of nexus research in India for more than two decades. Indian utilities provide electricity for water pumps used by farmers at very low prices or even for free; diesel was also heavily subsidized. This almost-free energy for water has led to overexploitation of groundwater and wasteful use of energy. Many papers discuss the economic problems created by subsidized energy for water pumping, namely overirrigation and excess water consumption.

Subsidized energy for water pumping created many economic problems, in particular, overirrigation and excess water consumption. Many researchers discuss policies and implications of energy subsidies on water use in agriculture on the national levels [4, 6, 9, 30, 31, 36–38, 44, 71, 74].

The cost of irrigation water withdrawals has been a big political issue for India, resulting in significant energy subsidies for irrigation water. Many papers examine policies and implications of decisions on power demand in agricultural and implications for groundwater at the state level, namely in West Bengal [35, 51, 54, 55], Gujarat [20, 34, 72] Andhra Pradesh [30], Karnataka and Punjab [52]. In some cases, researchers study the impact of energy prices on water use at the water basin level [64, 69]. Clean drinking water is a rising concern in India because of significant energy use [29].

The practice of providing heavily subsidized energy for farmers, which led to overexploitation of water resources, have simulated debates about equity issues, for example, unequal access to water resources (Wagle et al., 2012 [6]) and trust in government [3]. Several researchers have noted that energy prices are very often are used in the political process before elections [4, 73, 74, 76, 80].

Researchers also analyzed options for providing power for water pumps from renewable sources [62], especially focusing on whether solar-powered pumps are viable [19, 75] or not [7, 8, 67]. Another important question is whether it will actually lead to more groundwater depletion because there will no longer be a surrogate price for water consumption. Other aspects of the energy-for-water nexus have received less attention. Some examples include energy requirements for wastewater treatments [79] and wastewater use [48], and desalinization of water [47].

The link between energy and water is underrepresented in some states that will experience severe water stress. For example, Rajasthan, Haryana, and Karnataka are among the largest agricultural producers with severe water scarcity, but the link between energy and water is not sufficiently analyzed in the academic literature. Another significant gap in the energy-for-water studies is the limited number of publications on future impacts of economic development and the expansion of irrigated agriculture on groundwater and surface water levels. Some good examples of studies that address these issues are [43, 80, 81].

4.3. Water-for-food

Agriculture consumes about 80% of water withdrawals in India (Fig. 4). With its fast-growing population, India is experiencing growth in demand for irrigation water to produce food. The importance of the water-for-food or, in other words, water use in agriculture, is extremely important in the Indian context because of the need to feed a growing population particularly in regions with significant water constraints.

Previous studies show that the growth in food production has been achieved through the intensification of irrigation, often through the use of finite groundwater. Another way of looking at this is that since the Green Revolution in the 1960s, the increase in food production has been associated with a decline in groundwater availability ([5].

Many of the papers on water use in agriculture analyze the effects of climate change [28, 32, 45, 95]. To develop adaptation strategies, many researchers use dynamic crop simulation models to simulate yield impacts under different climate change scenarios. This portion of the nexus is one of the most well studied overall. However, scholars usually do not use the word "nexus" when they analyze water-for-food issues. As a result, we did not find many papers with keywords "nexus", "water", and "food."

This isolated focus on water demand in agriculture limits our understanding of the interactions with other sectors. One of the important directions of research is to look at competition for water from agriculture, the power sector and cities. The growing demand for water in agriculture will exacerbate water shortages in other sectors. A recent paper by Mukherji concludes that solutions to India's groundwater problems need to be embedded within the current context of its water-energy-food nexus [53].

4.4. Energy and land use

Similarly to many other nexus areas, we located only a few papers, which specifically focus on the energy-food nexus. One possible explanation is that most of the papers that analyze energy-for-food issues focus on water issues. Some examples of papers on the interaction between energy and land use in the nexus framework include studies on the land-use competition for the production of biofuels [18], or production of renewable energy without hurting agriculture [46]. This is a potentially important gap given the growth in policies to promote the use of biomass in India since bio-energy will play a growing role in India in the next decades. Deep decarbonization scenarios in the power sector often rely heavily on bioenergy, particularly with bio-energy carbon capture and storage (CCS) to achieve negative emissions. This implies large-scale plantations of dedicated bioenergy crops. The linkages between bio-energy crops, agricultural crops, and land use have not been explored significantly in India. With the growing recognition of the importance of climate change in India, the impact of the bio-energy debate on various nexus dimensions will only increase. It is critical to understand these interlinkages, given that dedicated bio-energy crops have a significant water footprint.

4.5. Water-energy-food

There is a growing body of academic literature with an analysis of all three dimensions of the WEF nexus. For example, [65] analyze the growing demand for water for energy and food in South Asia, and look for possible integrated solutions that support multiple uses of water. [50] use a systems modeling approach to explore global change impacts on the nexus in a complex Himalayan water resource system to uncovers existing synergies and trade-offs to identify general strategies for water management adaptation.

Researchers only recently have started analyzing the nexus using integrated assessment tools. The first example of this kind of study is [5], which analyzes three nexus sectors (water, food, and energy) from the perspective of the agricultural sector. This study includes the assessment of water resources, water consumption by agriculture, crop production and energy use for irrigation. This study covers data for several decades and provides insights into sub-regional issues. [81] analyze future groundwater availability and associated surface flows to formulate policy approaches for o improving water sustainability. The authors combine measurements with integrated modeling to evaluate the effects of climate change on water availability, the efficiency of irrigation and the effect of energy subsidies on water demand in some water-stressed areas of India.

As Momblanch et al. show, socioeconomic impacts on nexus components are greater than climate change [50]. Thus, the results from integrated assessment models could be complemented with the analysis of social-economic and political implications using qualitative methods, which are well-developed and accepted in India. J. Rising argues that integrated assessment models can provide insights that can support the development of hydroeconomic optimization models using intertemporal decision-making and economic valuation [66].

The critical need for India is to develop comprehensive studies of various special and temporal resolutions focusing on all components of the WEF nexus. Integrated assessment studies should be tested and supported by detailed studies which are critical to providing downscaled information on impacts and challenges.

5. Discussion and conclusion

The analysis of the interactions between water, energy, and food is a fast-growing area of scientific research in India. The importance of the WEF nexus is rapidly increasing because of the many effects that one element of the nexus may have on two others. In looking at the composite scarcity results from Xanthos and Tethys, as described earlier, water scarcity is likely to grow dramatically across India across multiple dimensions: including geography and the extent of use across different sectors.

The analysis of the published studies revealed that the evolution of some critical WEF nexus linkages have been intensively researched in India. Several most advanced areas include the exploration of available water resources, water demands in the power sector, and energy use to provide water in several sectors, especially in agriculture. The water component of the nexus has been intensively explored for decades and India has one of the most developed hydrology schools in the world. As a result of this success, many papers tend to analyze the WEF nexus issues from the position of water. The analysis showed that in most cases studies do not use comparable scales and do not show comparable data. As a result, it is difficult or impossible to compare these studies. The gaps are so large in the existing studies that it is not possible to do a meta-analysis comparing results as the studies cover different sectors and scales. Ultimately, understanding the energy-water-food nexus in India requires a matrixed approach that includes:

- Multiple nexus dimensions, preferably at once;
- Drivers behind the growth in water demand and scarcity, including climate change and population and economic growth, as well as changing patterns of consumption;
- Geographic differences;
- Differences over time;
- Technologies and policies that can help reduce the impact of water scarcity.

The review of published papers on the WEF nexus in India has revealed some major gaps in the analysis of WEF nexus issues in India. The four most important issues are:

Comprehensiveness of nexus analysis: Despite the growing number of the nexus papers, the complexity of the nexus is not adequately analyzed in published studies. Most researchers focus only on one or two elements in the nexus rather than having a holistic view of the nexus challenge. The nature of the nexus should be explored from a wider perspective and should include all interactions between water, energy, and land use. A more comprehensive methodological approach is needed to analyze the full nexus.

Future drivers: Most studies to date look at historical data. The few that do look at the future do not typically look at the major drivers of change in demand for water and energy. For example, climate change is an important driver regarding changing precipitation patterns and snowpack. The impacts of climate change and their interactions with various elements of the nexus framework have received little attention in the literature. With climate change expected to put pressure on water resources, as well as the way energy is produced and used, this aspect needs to be better represented in India-specific analysis. Static analysis, as currently dominating the literature, is a useful starting point. But analyzing scenarios related to regional impacts of development and climate change, both on demand and supply side, will be important to better understand the future uncertainties related to various dimensions of WEF nexus.

Focus on water-stressed regions: Finally, strategically, it is important to focus on the water-stressed regions. We highlight that researchers have looked at various levels - national, state, as well as basin level in the nexus research in India. But understanding the nexus challenges in water-stressed regions has not been a focus for most of the research. This is true looking at existing scarcity, and even more true regarding where scarcity will be greatest in the future. Though it is critical to view the nexus related challenges across all basins and states in India, we argue that the WEF nexus in water-stressed regions is an important research gap and should be accorded a higher priority at least in the near future.

Need for robust India-specific data: The WEF nexus plays out at various levels and in various contexts. For a better understanding of nexus elements across levels and contexts, robust India-specific data is critical. Very few papers in the literature we assessed use India-specific water data. India-specific data would be important for deriving robust conclusions and insights for many different contexts and policy questions that India needs to answer and should ideally be collected and shared by researchers for their specific research context.

In other words, we know already that major pinch points are emerging in India related to the WEF nexus. Some cities are running out of water for household use because of all the other demands placed on water in the region coupled with drought. Thermal power plants in some regions are needing to curtail their production because of a lack of cooling water. The implications of solar water pumps and increased bioenergy production are not well understood today, but still are proceeding to grow rapidly because of policy and pricing incentives. These near-term pinch points are an indication of the future, but mitigation future scarcity requires a more comprehensive analysis of all dimensions of the EWF nexus and its underlying drivers. It is critical to consider how things may change with time and geography in order to provide decision-makers with clear evidence for adaptation strategies.

Our research aims at summarizing the key insights from India-specific WEF nexus research, as well as highlighting the gaps that need to be addressed in future research. We hope that a strategic approach on WEF nexus research in the water-scarce country will be able to better inform policymakers to address the myriad challenges of India's water, energy, and food systems at various levels of governance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the United States Agency for International Development (Contract DE-AC36–08GO28308). PNNL is operated for DOE by Battelle Memorial Institute under contract DE-AC05–76RL01830.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2021.100060.

References

[1] H. Adnan, The Status of the Water-Food-Energy Nexus in Asia and the Pacific, Thailand, UN-ESCAP 58 (2013).
[2] T.R. Albrecht, A. Crootof, C.A. Scott, The Water-Energy-Food Nexus: a systematic review of methods for nexus assessment, Environ. Res. Lett. 13 (2018), 043002.
[3] M. Alkon, J. Urpelainen, Trust in Government and Subsidy Reform: evidence from a Survey of Indian Farmers, Stud. Comp. Int. Dev. 1-28 (2018).
[4] R. Badiani, K.K. Jessoe, S. Plant, Development and the Environment: the Implications of Agricultural Electricity Subsidies in India, J. Environ. Dev. 21 (2012) 244–262.
[5] B. Barik, S. Ghosh, A.S. Sahana, A. Pathak, M. Sekhar, Water–food–energy nexus with changing agricultural scenarios in India during recent decades, Hydrol. Earth Syst. Sci. 21 (2017) 3041–3060.
[6] N. Bassi, Assessing potential of water rights and energy pricing in making groundwater use for irrigation sustainable in India, Water Policy 16 (2014) 442–453.
[7] N. Bassi, Solar Pumps Are Not Viable, Econ. Politic. Week. L. (10) (2015) 63–66.
[8] N. Bassi, Solarizing groundwater irrigation in India: a growing debate, Int. J. Water Resour. Dev. 34 (2018) 132–145.
[9] C. Bowe, Horst, D.V. der, Positive externalities, knowledge exchange and corporate farm extension services; a case study on creating shared value in a water scarce area, Ecosystem Services 15 (2015) 1–10.
[10] S. Buechler, D. Sen, N. Khandekar, C.A. Scott, *Re*-linking governance of energy with livelihoods and irrigation in Uttarakhand, India, Water (Switzerland) 8 (2016).
[11] K. Calvin, P. Patel, L. Clarke, G. Asrar, B. Bond-Lamberty, R.Y. Cui, A. Di Vittorio, K. Dorheim, J. Edmonds, C. Hartin, GCAM v5. 1: representing the linkages between energy, water, land, climate, and economic systems, Geoscientific Model Development 12 (2019). Online.
[12] V. Chaturvedi, P.N. Koti, R. Sugam, K. Neog, M. Hejazi, Cooperation or rivalry? Impact of alternative development pathways on India's long-term electricity generation and associated water demands, Energy 192 (2020), 116708.
[13] V. Chaturvedi, R.K. Sugam, P. Nagarkoti, K. Neog, Energy-Water Nexus and Efficient Water Cooling Technologies For Thermal Power Plants in India: An Analysis Within an Integrated Assessment Modelling Framework, Council on Energy, Environment and Water, New Delhi, 2018.
[14] EIA, International Energy Outlook 2018, U.S. Energy Information Administration, Washington DC, 2018. Available at, https://www.eia.gov/outlooks/ieo/.
[15] A. Endo, I. Tsurita, K. Burnett, P.M. Orencio, A review of the current state of research on the water, energy, and food nexus, J. Hydrol. Region. Stud. 11 (2017) 20–30.
[16] A. Endo, M. Yamada, Y. Miyashita, R. Sugimoto, A. Ishii, J. Nishijima, M. Fujii, T. Kato, H. Hamamoto, M. Kimura, Dynamics of water–energy–food nexus methodology, methods, and tools, Curr. Opin. Environ. Sci. Health 13 (2020) 46–60.
[17] FAO, 2018. India at a glance. Food and Agriculture Organisation of the United Nations, Available at http://www.fao.org/india/fao-in-india/india-at-a-glance/en/.
[18] H. Gunatilake, D. Roland-Holst, G. Sugiyarto, Energy security for India: biofuels, energy efficiency and food productivity, Energy Policy 65 (2014) 761–767.
[19] E. Gupta, The impact of solar water pumps on energy-water-food nexus: evidence from Rajasthan, India, Energy Policy 129 (2019) 598–609.
[20] R.K. Gupta, Water and energy linkages for groundwater exploitation: a case study of Gujarat State, India, Water Sci. Tech. 45 (2002) 151–166.
[21] M. Hejazi, J. Edmonds, L. Clarke, P. Kyle, E. Davies, V. Chaturvedi, M. Wise, P. Patel, J. Eom, K. Calvin, Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework, Technol. Forecast. Soc. Change 81 (2014) 205–226.
[22] M.I. Hejazi, J. Edmonds, L. Clarke, P. Kyle, E. Davies, V. Chaturvedi, M. Wise, P. Patel, J. Eom, K. Calvin, Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies, Hydrol. Earth Syst. Sci. 18 (2014) 2859–2883.
[23] T. Hennig, Damming the transnational Ayeyarwady basin. Hydropower and the water-energy nexus, Renewable Sustainable Energy Rev. 65 (2016) 1232–1246.
[24] IEA, World Energy Outlook International Energy Agency, Paris (2012). Available at, http://www.worldenergyoutlook.org/weo2012/.
[25] IEA, India Energy Outlook, World Energy Outlook Special Report. International Energy Agency, Paris, 2015. Available at, http://www.worldenergyoutlook.org/media/weowebsite/2015/IndiaEnergyOutlook_WEO2015.pdf.
[26] IPCC, Global Warming of 1.5 °C. Special Report, Intergovernmental Panel on Climate Change, Geneva, 2018. Available at, https://www.ipcc.ch/sr15/.
[27] S. Kaddoura, S. El Khatib, Review of water-energy-food Nexus tools to improve the Nexus modelling approach for integrated policy making, Environ. Sci. Policy 77 (2017) 114–121.
[28] Y. Kang, S. Khan, X. Ma, Climate change impacts on crop yield, crop water productivity and food security–A review, Prog. Nat. Sci. 19 (2009) 1665–1674.
[29] V.P. Katekar, S.S. Deshmukh, A. Vasan, Energy, drinking water and health nexus in India and its effects on environment and economy, J. Water and Climate Change (2020).
[30] C. Kimmich, Linking action situations: coordination, conflicts, and evolution in electricity provision for irrigation in Andhra Pradesh, India, Ecol. Econ. 90 (2013) 150–158.
[31] C. Kimmich, J. Sagebiel, Empowering irrigation: a game-theoretic approach to electricity utilization in Indian agriculture, Utilities Policy 43 (2016) 174–185.
[32] K. Krishna Kumar, K. Rupa Kumar, R. Ashrit, N. Deshpande, J. Hansen, Climate impacts on Indian agriculture, Int. J. Climatol. J. R.Meteorol. Soc. 24 (2004) 1375–1393.
[33] D. Kumar, N. Bassi, A. Narayanamoorthy, M. Sivamohan, The Water, Energy and Food Security Nexus: lessons from India for Development, Routledge. Earthscan Stud. Natur. Resour. Manage. Ser. (2014).
[34] D.M. Kumar, O.P. Singh, Market instruments for demand management in the face of scarcity and overuse of water in Gujarat, Western India, Water Policy 3 (2001) 387–403.
[35] M. Kumar, N. Bassi, M. Sivamohan, L. Venkatachalam, Agriculture in West Bengal: can the new policies trigger a second Green Revolution? Rev. Dev. Change 18 (2013) 37–51.
[36] M.D. Kumar, Impact of electricity prices and volumetric water allocation on energy and groundwater demand management: analysis from Western India, Energy Policy 33 (2005) 39–51.
[37] M.D. Kumar, C.A. Scott, O.P. Singh, Inducing the shift from flat-rate or free agricultural power to metered supply: implications for groundwater depletion and power sector viability in India, J. Hydrol. (Amst.) 409 (2011) 382–394.
[38] M.D. Kumar, C.A. Scott, O.P. Singh, Can India raise agricultural productivity while reducing groundwater and energy use? Int. J. Water Resour. Dev. 29 (2013) 557–573.
[39] X. Li, C.R. Vernon, M.I. Hejazi, R.P. Link, L. Feng, Y. Liu, L.T. Rauchenstein, Xanthos–A Global Hydrologic Model, J. Open Res. Softw. 5 (2017).
[40] X. Li, C.R. Vernon, M.I. Hejazi, R.P. Link, Z. Huang, L. Liu, L. Feng, Tethys–A Python Package for Spatial and Temporal Downscaling of Global Water Withdrawals, J. Open Res. Softw. 6 (2018).
[41] T. Luo, D. Krishnan, S. Sen, Parched Power: Water Demands, Risks, and Opportunities for India's Power Sector, Working Paper. World Resources Institute, Washington, DC, 2018. Available online at, http://www.wri.org/publication/parched-power.
[42] D. Mabrey, M. Vittorio, Moving from theory to practice in the water–energy–food nexus: an evaluation of existing models and frameworks, Water-Energy Nexus 1 (2018) 17–25.
[43] C.G. Madhusoodhanan, K.G. Sreeja, T.I. Eldho, Climate change impact assessments on the water resources of India under extensive human interventions, Ambio 45 (2016) 725–741.
[44] R.P.S. Malik, Water-Energy Nexus in Resource-poor Economies: the Indian Experience, Int. J. Water Resour. Dev. 18 (2002) 47–58.
[45] R. Mall, R. Singh, A. Gupta, G. Srinivasan, L. Rathore, Impact of climate change on Indian agriculture: a review, Clim. Change 78 (2006) 445–478.
[46] P.R. Malu, U.S. Sharma, J.M. Pearce, Agrivoltaic potential on grape farms in India, Sustain. Energy Tech. Assess. 23 (2017) 104–110.
[47] S. Manju, N. Sagar, Renewable energy integrated desalination: a sustainable solution to overcome future fresh-water scarcity in India, Renewable Sustainable Energy Rev. 73 (2017) 594–609.
[48] L. Miller-Robbie, A. Ramaswami, P. Amerasinghe, Wastewater treatment and reuse in urban agriculture: exploring the food, energy, water, and health nexus in Hyderabad, India, Environ. Res. Lett. 12 (2017).
[49] B.K. Mitra, A. Bhattacharya, X. Zhou, A critical review of long term water energy nexus in India, Inst. Glob. Environ. Strat. Jpn. (2014). Available at, http://nexusconference.web.unc.edu/files/2014/04/mitra-bijon.pdf.
[50] A. Momblanch, L. Papadimitriou, S.K. Jain, A. Kulkarni, C.S. Ojha, A.J. Adeloye, I. P. Holman, Untangling the water-food-energy-environment nexus for global change adaptation in a complex Himalayan water resource system, Sci. Total Environ. 655 (2019) 35–47.
[51] A. Mukherji, The energy-irrigation nexus and its impact on groundwater markets in eastern Indo-Gangetic basin: evidence from West Bengal, India, Energy Policy 35 (2007) 6413–6430.
[52] A. Mukherji, Managing energy-irrigation nexus: insights from Karnataka and Punjab states in India. Advances in Groundwater Governance, Taylor & Francis Group, London, 2018, pp. 289–306.
[53] A. Mukherji, Sustainable Groundwater Management in India Needs a Water-Energy-Food Nexus Approach, Appl. Econ. Perspect. Policy (2020).
[54] A. Mukherji, A. Das, The political economy of metering agricultural tube wells in West Bengal, India, Water Int. 39 (2014) 671–685.
[55] A. Mukherji, B. Das, N. Majumdar, N.C. Nayak, R.R. Sethi, B.R. Sharma, Metering of agricultural power supply in West Bengal, India: who gains and who loses? Energy Policy 37 (2009) 5530–5539.
[56] H. Nautiyal, S. Singal, A. Sharma, Small hydropower for sustainable energy development in India, Renewable Sustainable Energy Rev. 15 (2011) 2021–2027.
[57] NITI Aayog, Composite Water Management Index: a Tool for Water Management. The National Institution for Transforming India, New Delhi. Available at (2018). http://www.niti.gov.in/writereaddata/files/document_publication/2018-05-18-Water-index-Report_vS6B.pdf.
[58] D.K. Panda, J. Wahr, Spatiotemporal evolution of water storage changes in India from the updated GRACE-derived gravity records, Water Resour. Res. 52 (2016) 135–149.
[59] J. Parikh, P. Ghosh, Energy, Food and Water Nexus – Analysis in Macroeconomic Consistency Framework, Integrated Research and Action for Development (IRADe), New Delhi, 2017.
[60] PNNL, Xanthos, Pacific Northwest National Laboratory, 2017. Available at, https://github.com/JGCRI/xanthos.
[61] PNNL, Tethys, Spatiotemporal downscaling model for global water withdrawal (2018). Available at, https://github.com/JGCRI/tethys.
[62] P. Purohit, Financial evaluation of renewable energy technologies for irrigation water pumping in India, Energy Policy 35 (2007) 3134–3144.

[63] A. Purwanto, J. Sušnik, F.X. Suryadi, C.d. Fraiture, Water-energy-food nexus: critical review, practical applications, and prospects for future research, Sustainability 13 (2021) 1919.
[64] G. Rasul, Water for growth and development in the Ganges, Brahmaputra, and Meghna basins: an economic perspective, Int. J. River Basin Manage. 13 (2015) 387–400.
[65] G. Rasul, N. Neupane, A. Hussain, B. Pasakhala, Beyond hydropower: towards an integrated solution for water, energy and food security in South Asia, Int. J. Water Resour. Dev. (2019) 1–25.
[66] J. Rising, Decision-making and integrated assessment models of the water-energy-food nexus, Water Security 9 (2020), 100056.
[67] M. Sahasranaman, M.D. Kumar, N. Bassi, M. Singh, A. Ganguly, Solar Irrigation Cooperatives: creating the Frankenstein's Monster for India's Groundwater, Econ. Politic. Week. L.III (2018) 65–68.
[68] W. Schwanghart, R. Worni, C. Huggel, M. Stoffel, O. Korup, Uncertainty in the Himalayan energy–water nexus: estimating regional exposure to glacial lake outburst floods, Environ. Res. Lett. 11 (2016), 074005.
[69] C.A. Scott, B. Sharma, Energy supply and the expansion of groundwater irrigation in the Indus-Ganges Basin, Int. J. River Basin Manage. 7 (2009) 119–124.
[70] S.H. Shah, R.B. Gibson, Large dam development in India: sustainability criteria for the assessment of critical river basin infrastructure, Int. J. River Basin Manage. 11 (2013) 33–53.
[71] T. Shah, Climate change and groundwater: india's opportunities for mitigation and adaptation, Environ. Res. Lett. 4 (2009), 035005.
[72] T. Shah, Towards a Managed Aquifer Recharge strategy for Gujarat, India: an economist's dialogue with hydro-geologists, J. Hydrol. (Amst.) 518 (2014) 94–107.
[73] T. Shah, S. Bhatt, R.K. Shah, J. Talati, Groundwater governance through electricity supply management: assessing an innovative intervention in Gujarat, western India, Agric. Water Manage. 95 (2008) 1233–1242.
[74] T. Shah, M. Giordano, A. Mukherji, Political economy of the energy-groundwater nexus in India: exploring issues and assessing policy options, Hydrogeol. J. 20 (2012) 995–1006.
[75] T. Shah, N. Durga, G.P. Rai, S. Verma, R. Rathod, Promoting Solar Power as a Remunerative Crop, Econ. Politic. Week. 52 (45) (2017) 14–19.
[76] T. Shah, C. Scott, A. Kishore, A. Sharma, Energy-irrigation Nexus in South Asia: Improving groundwater Conservation and Power Sector Viability, IWMI, 2004.
[77] T. Shiao, A. Maddocks, C. Carson, E. Loizeaux, 3 Maps Explain India's Growing Water Risks, World Resources Institute, Washington DC, 2015. Available at, http://www.wri.org/blog/2015/02/3-maps-explain-india%E2%80%99s-growing-water-risks.
[78] G.B. Simpson, G.P. Jewitt, The development of the water-energy-food nexus as a framework for achieving resource security: a review, Front. Environ. Sci. 7 (2019) 8.
[79] P. Singh, A. Kansal, Energy and GHG accounting for wastewater infrastructure, Resour. Conserv. Recycl. 128 (2018) 499–507.
[80] R.P. Sishodia, S. Shukla, W.D. Graham, S.P. Wani, J.W. Jones, J. Heaney, Current and future groundwater withdrawals: effects, management and energy policy options for a semi-arid Indian watershed, Adv. Water Resour. 110 (2017) 459–475.
[81] R.P. Sishodia, S. Shukla, S.P. Wani, W.D. Graham, J.W. Jones, Future irrigation expansion outweigh groundwater recharge gains from climate change in semi-arid India, Sci. Total Environ. 635 (2018) 725–740.
[82] S. Srinivasan, A. Kanudia, N. Roshna, N. Dharmala, J. Asundi, Impact of power sector growth on water resources, (CSTEP-Report-2018-02). Center For Study of Science, Technology and Policy (CSTEP), Bangalore, 2018.
[83] S. Srinivasan, N. Kholod, V. Chaturvedi, P.P. Ghosh, R. Mathur, L. Clarke, M. Evans, M. Hejazi, A. Kanudia, P.N. Koti, B. Liu, K.S. Parikh, M.S. Ali, K. Sharma, Water for electricity in India: a multi-model study of future challenges and linkages to climate change mitigation, Appl. Energy 210 (2018) 673–684.
[84] K.G. Stylianopoulou, C.M. Papapostolou, E.M. Kondili, Water–energy–food Nexus: a focused review on integrated methods, Environ. Sci. Proc. (2020) 46, p.
[85] F. Tashtoush, W. Al-Zubari, A. Shah, A review of the water–energy–food nexus measurement and management approach, Int. J. Energy and Water Resour. 3 (2019) 361–374.
[86] TERI, Integrated Modelling Study of the Food-Energy-Water Nexus in India, The Energy and Resources Institute, New Delhi, 2018. Project Report No. 2016MS01.
[87] S.W. Turner, M. Hejazi, K. Calvin, P. Kyle, S. Kim, A pathway of global food supply adaptation in a world with increasingly constrained groundwater, Sci. Total Environ. 673 (2019) 165–176.
[88] UN, Department of Economic and Social Affairs, World Population Prospects. United Nations, New York, 2017. Available at, https://esa.un.org/unpd/wpp/Download/Standard/Population/.
[89] A.M. Urbinatti, L.L. Benites-Lazaro, C.M.d. Carvalho, L.L. Giatti, The conceptual basis of water-energy-food nexus governance: systematic literature review using network and discourse analysis, J. Integr. Environ. Sci. 17 (2020) 21–43.
[90] C.R. Vernon, M.I. Hejazi, S.W. Turner, Y. Liu, C.J. Braun, X. Li, R.P. Link, A global hydrologic framework to accelerate scientific discovery, J. Open Res. Softw. 7 (2019).
[91] World Energy Council, Water For Energy, World Energy Council, London, 2010.
[92] WRI and IRENA, 2018 a. Water Use in India's Power Generation: impact of Renewables and Improved Cooling Technologies to 2030. World Resources Institute (WRI) and the International Renewable Energy Agency (IRENA), Available at http://irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENAIndiapowerwater2018pdf.pdf.
[93] WRI and IRENA, Water Use in India's Power Generation: Impact of Renewables and Improved Cooling Technologies to 2030. Methodology and Data Sources, b, World Resources Institute (WRI) and the International Renewable Energy Agency (IRENA), 2018. Available at, http://irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_power_water_2018_methodology.pdf?la=en&hash=C1726E07286F34010EB878321F72C471F0C4427C.
[94] WWAP, The United Nations World Water Development Report 2014: Water and Energy, United Nations World Water Assessment Programme, Paris, UNESCO, 2014.
[95] E. Zaveri, S.G. Danielle, F.-.V. Karen, F. Steve, B.L. Richard, H.W. Douglas, P. Alexander, E.N. Robert, Invisible water, visible impact: groundwater use and Indian agriculture under climate change, Environ. Res. Lett. 11 (2016), 084005.
[96] C. Zhang, X. Chen, Y. Li, W. Ding, G. Fu, Water-energy-food nexus: concepts, questions and methodologies, J. Clean. Prod. 195 (2018) 625–639.