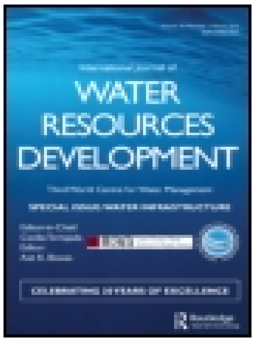

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Achieving water security in Nepal through unravelling the water-energy-agriculture nexus

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ABSTRACT

This article investigates water security in Nepal from the perspective of the water-energy-agriculture (food) nexus, focusing on pathways to water security that originate in actions and policies related to other sectors. It identifies promoting development of Nepal's hydropower potential to provide energy for pumping as way to improve water security in agriculture. Renewable groundwater reserves of 1.4 billion cubic meters (BCM), from an estimated available balance of 6.9 BCM, could be pumped to irrigate 613,000 ha of rainfed agricultural land in the Terai plains, with a potential direct economic gain of USD 1.1 billion annually and associated benefits including promotion of energy-based industry, food security and local employment. Governance also plays an important role in addressing water security. We conclude that a nexus-based approach is required for effective water management and governance.

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Water security; water-food-energy nexus; Nepal; groundwater; hydropower; agriculture; IWRM

Introduction

The concept of water security has received increased attention in recent years in both policy and academic debates (Cook & Bakker, 2012; Salam, Shrestha, Pandey, & Anal, 2017). Nepal has high annual rainfall, but still faces considerable challenges in ensuring water security. This is to a great extent the result of the high temporal and spatial variations in water availability as well as the lack of congruence between locations of water availability and water need (Water and Energy Commission Secretariat [WECS], 2005), but it is also related to governance issues. The challenges to water security in Nepal include ensuring improved access to safe drinking water and sanitation, providing sufficient water for irrigation, securing water for urban needs, and generating energy without compromising the water-dependent ecosystems.

Water security as a concept has evolved over time. In the 1990s, the concept was mainly human-centric (Cook & Bakker, 2012), but it is now becoming much broader. The Global Water Partnership (2000) has defined water security as 'access to adequate safe water at an affordable cost ensuring that the natural environment is protected and enhanced'; thus incorporating ecological dimensions. This approach has been further broadened by the

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Supplemental data for this article can be accessed here.

increasing recognition that water resources management is complex and intertwined with the development and social sectors (Biswas, 2004; Falkenmark, 2001). More recently, UN-Water (2013) defined water security as 'the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability', thus balancing the needs for water management related to socio-economic development, health, disasters and ecosystems. Further, it is now recognized that water security cannot be treated as a stand-alone issue. Attention is turning to the water-energy-food (WEF) nexus: the complex interactions within the wider framework of water, food and energy which mean that the actions in each sector can have effects in the others, and that water security, energy security and food security are closely linked (FAO, 2014). Rasul (2014) emphasized the role of the Hindu Kush Himalaya (HKH) ecosystem services in sustaining all three in downstream areas, and the importance of the nexus in South Asia resulting from the high dependency of downstream communities on upstream ecosystem services. In this wider framework, investment in water infrastructure and securing water is equally important to bring economic productivity and growth, and water security can be considered as the longer-term payoff of higher economic growth and lower poverty (Asian Development Bank [ADB], 2016; Rasul, Neupane, Hussain, & Pasakhala, 2019).

Despite having an estimated 7000 m^3 per person per year of water resources (FAO, 2016), Nepal's water security is thought to be among the weakest in Asia and the Pacific (ADB, 2016). Improving water security requires better understanding not only of water supply and demand but also of the linkages within the WEF nexus, and of the aspects within it which can be addressed to achieve overall improvements in water security. Most water security studies in Nepal have been context-specific. For example, Regmi (2007) looked into water security in the context of a farmer management irrigation system; there have been studies related to gender and poverty (Upadhyay, 2003) and agricultural insecurity (Dahal et al., 2015); and Biggs, Duncan, Atkinson, and Dash (2013) highlighted how poor governance has hindered Nepal in achieving water security. Some studies (e.g. Bradley & Bartram, 2013; Brown, Meeks, Ghile, Hunu, & Brown, 2013; Garrick & Hall, n.d.; Hanjra & Qureshi, 2010; Miyan, 2015; Thapa, Ishidaira, Pandey, Bhandari, & Shakya, 2018) have looked at water security as a small part of larger studies on geographical coverage and context.

This article assesses various aspects of water security in Nepal from the water-energy-agriculture (food) nexus perspective, following the framework shown in Figure 1. It looks at overall water availability and the challenges to and drivers of water insecurity, and then unravels the WEF nexus to reveal specific issues in selected water use sectors and other aspects related to water, and what development can be encouraged in other parts of the nexus that might improve water security and in turn contribute to the national economy. The article considers some specific measures to improve water security in different sectors and in particular provides some insight into the role of groundwater in agricultural water security and its relationship to energy provision, and the important role of governance in addressing water security using a holistic and integrated approach. It concludes by suggesting that a nexus-based approach is required for effective water management and governance, and that Integrated Water Resources Management (IWRM) and Integrated River Basin Management (IRBM) approaches need to be broadened to take into account the nexus between water, energy, and food production and security.

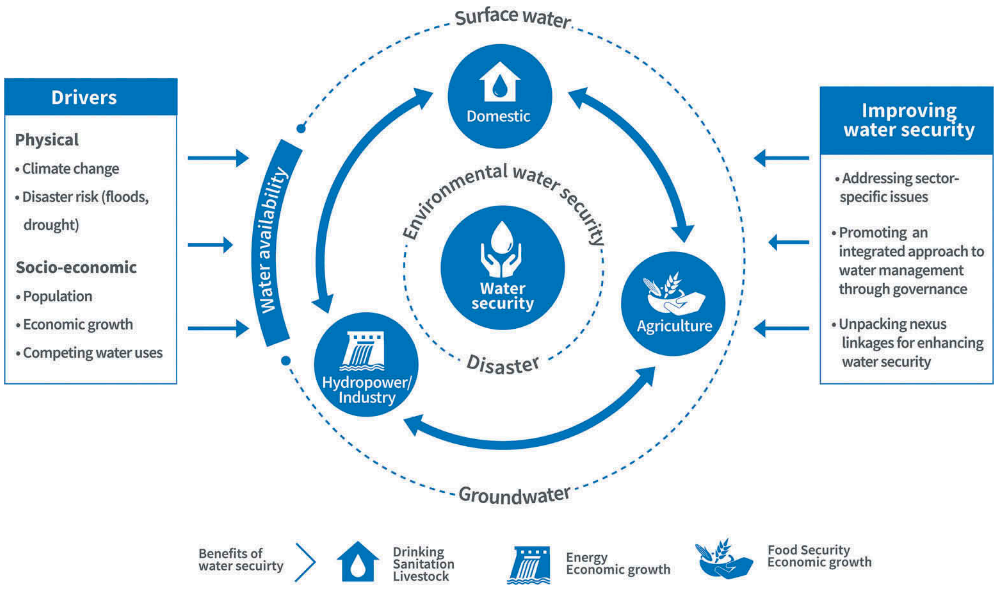

Figure 1. Conceptual framework used for analyzing water security.

Water availability

Nepal receives abundant precipitation annually, but it is distributed very unevenly as a result of both the monsoon climate (with marked temporal variation) and the extreme topography (leading to marked spatial variation). Water resources are available mainly in the form of surface water and groundwater, both of which have strong spatial and temporal variability.

Topography and climate

Nepal's extreme topography heavily influences the pattern of precipitation. The elevation ranges from below 70 masl in the south to 8848 masl in the north, increasing rapidly within less than 200 km. As a result, Nepal has four main physiographic regions, with seven main climatic and ecological zones (Figure 2). The differences in climate and topography are reflected in differences in water availability and use, land use and land cover, population density and livelihood patterns. The Terai in the south is relatively flat, with a tropical to sub-tropical climate, good water resources and high net primary productivity, and thus high population density. The Terai is bounded by the low hills of the Siwaliks to the north, followed by the largest region of the Middle Mountains (Lesser Himalaya). The deep valleys and steep slopes encompass subtropical, temperate and subalpine zones and are dominated by anthropogenic activities, especially terraced agriculture and livestock farming, but with a low population density compared to the Terai. Hydropower production is mostly located in this region. The Higher Himalaya to the north is dominated by a sub-alpine to alpine climate, with rangelands, glaciers and snow peaks, fewer anthropogenic activities, and a low population density.

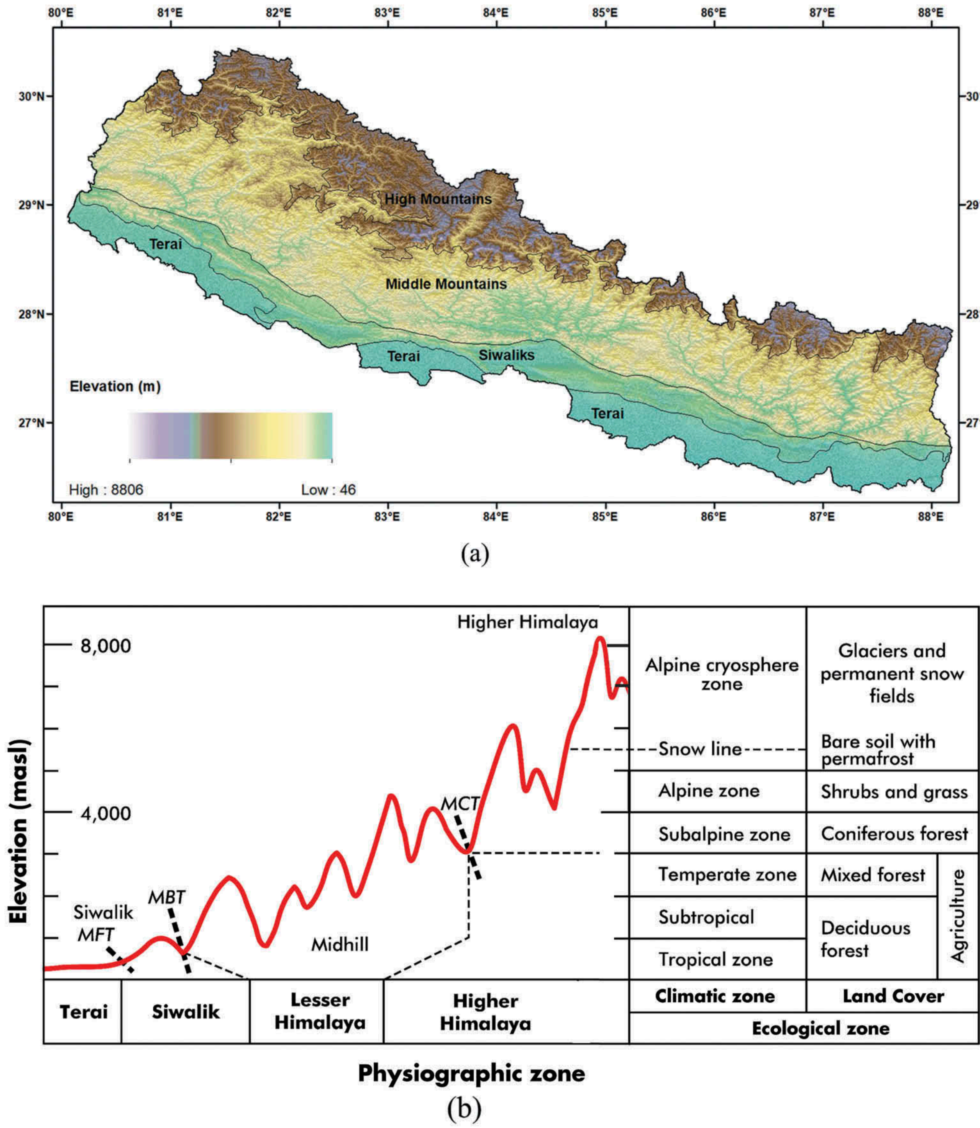

Figure 2. The Nepal Himalyas. (a) Physiographic zones. (b) Ecological zones along a typical south-north transect (source: Nepal, Flügel, Krause, Fink, & Fischer, 2017). (Notes: The Lesser Himalaya and Higher Himalaya are also known as the Middle Mountains and High Mountains, respectively. MFT = main frontal thrust; MBT = main boundary thrust; MCT = main central thrust; masl = metres above sea level.)

Precipitation in Nepal is dominated by the summer monsoon and the winter westerlies. Average annual precipitation (1971–2014) is 1450 mm (DHM, 2017), of which 80% falls in the monsoon season (June to September), and 20% during the other eight months (Figure A1 in the supplemental online resources). The spatial variation is also high, with average annual precipitation in different districts ranging from less than 300 mm in the northern mountains to more than 4000 mm in the eastern Middle Mountains (Figure A1). In the dry seasons, snow and glacier melt and groundwater sustain flow to the major rivers and provide the main source of water for different uses. Especially upstream, melt runoff in the pre-monsoon period (spring) supports irrigated agriculture along the river valleys.

Surface water availability

All the major river systems in Nepal are transboundary, originating in China and flowing through Nepal to join the Ganges in India (Figure A2). The total average annual runoff from all the river systems is estimated at 225 billion cubic metres (BCM), of which 172 BCM originates in Nepal (Table A1) (WECS, 2005). River flow is highly seasonable, with about 75% occurring in the monsoon season (June to September) (Figure A2). The high rainfall and river discharge lead to landslides, floods and flash floods in both mountain and Terai regions, but this is also a good time to plant major irrigated crops, such as paddy. Areas supported by year-round irrigation systems can grow more than one crop.

Groundwater availability

Groundwater is a reliable and flexible source of water for irrigation and other purposes, with many advantages compared to canal irrigation (Siebert et al., 2010). Groundwater is available in most parts of Nepal at varying depths and amounts. The southern Terai plains are in the groundwater saturated zone of the Indo-Gangetic Basin, whereas intra-mountain valleys such as the Kathmandu and Dang have isolated groundwater basins. The total volume of groundwater potentially available for extraction has been estimated by various authors using a variety of methods. Shrestha, Tripathi, and Laudari (2018) estimated annual renewable groundwater resources in the Terai at 8.8 BCM using measurements of seasonal fluctuations in the water table in shallow tube wells (2.5 m deep).

Despite this potential, groundwater use in Nepal remains relatively low. The AQUASTAT (2018) historical database on groundwater shows that it was almost nil in the 1980s, when groundwater extraction was already increasing in India, Bangladesh and Pakistan. Shrestha et al. (2018) estimated current groundwater extraction of 1.9 BCM/y in the Terai for irrigation, domestic and industrial use, compared to annual recharge of 8.8 BCM – an annual groundwater balance of +6.9 BCM/y (Table 1). This suggests a huge potential in renewable groundwater reserves.

Table 1. Groundwater balance in the Terai region of Nepal, in billion cubic metres

Annual groundwater recharge	**8.8**
Annual groundwater extraction	
Irrigation from shallow tube wells	1.16
Irrigation from deep tube wells	0.15
Domestic use	0.46
Industrial use	0.16
Total	**1.93**
Annual balance (recharge minus extraction)	**6.9**

Source: Shrestha et al. (2018).

Challenges to water security

Despite its large water potential, Nepal has very low water security, with many people unable to access sufficient water to meet their domestic, agricultural and industrial needs. There are many factors contributing to this. Some of the more important are outlined below. They are divided into specific challenges in different water use sectors and overall management, and drivers that are likely to challenge overall water security in the future.

Challenges in specific water use sectors

Agricultural water security

Different factors hinder access to water in the hills, mountains and plains of Nepal. In the hills and mountains, the main problems are geophysical, with water mostly accessible in the valleys below the steep slopes, and rocky subsoil limiting the possibility of storage. Thus, rainfed agriculture is still the method of choice in most of this area. The plains areas of the Terai are mostly suitable for irrigation, but irrigation use remains low. A number of reasons can be identified:

- Most irrigation in the Terai is via canals that take water from small and medium-size rivers (originating in the Siwaliks and Mahabharat range) which dry up in winter and summer. Thus, the irrigation command area is much larger in the monsoon season than in summer and winter. Year-round irrigation coverage is low, and the area for growing winter and summer crops is relatively small.
- Energy constraints limit the ability of farmers to pump groundwater. Of the roughly 100,000 shallow tubewells in Nepal (most in the Terai), almost 80% use diesel pumps. Diesel is both expensive and dirty and puts pressure on foreign exchange. So far, the national grid has not reached all rural areas, and where it has reached, farmers have not always been able to access the subsidized farm power connection. And even where farm power is available, the electricity supply is intermittent and unreliable. This leads to a paradox of having plentiful groundwater at relatively shallow depths in most parts of the Terai, but low utilization of the resource due to high energy costs.
- Irrigation infrastructure in Nepal tends to be of a traditional type, which requires more labour and resources for repair and maintenance. Increasing erosion, landslides and sediment have further complicated repair and maintenance, making it more costly and reducing the command area for surface irrigation. Overall, irrigation systems in Nepal are running at low levels of both technical and allocative efficiency (Bhatta, Ishida, Taniguchi, & Sharma, 2006). Farm-level efficiency of use is also low due to use of the flooding method for irrigation, with high loss of water.
- Inappropriate crop choices also pose a problem for water security, for example when preference is given to water-intensive crops such as rice and sugarcane even in water-scarce areas.
- Financial constraints limit government investment in both new surface irrigation projects and the upkeep of existing projects.

- The incentive to invest in better water security for agriculture is limited by the fact that agricultural production in Nepal is unsubsidized and competes across an open border with subsidized production from India.

Hydro-energy security
Nepal has no fossil fuel reserves and limited potential for developing renewables like solar and windpower on a large scale, but it has large potential resources of hydropower. Ensuring water security for hydropower development mainly relates to ensuring investment for infrastructure to make the water available, as well as considerations related to competing uses, especially the environment. The main constraints are financial, political, and governance-related. As a small country, it is difficult for Nepal to generate enough capital to self-finance larger hydropower projects, even though it has successfully self-financed a number of small and medium-sized projects through the innovative mechanism of raising equity shares in the domestic markets. For larger projects, Nepal depends on bilateral or multilateral donors, and terms and conditions may not always be conducive for the hydropower producers, or the country. The market for surplus electricity is also a factor, with issues of cross-border trade and cooperation assuming importance, as well as questions of the larger political economy.

Urban and rural water security: the domestic sector
Nepal is the least urbanized country in South Asia but is now experiencing rapid urbanization, especially in Kathmandu and cities across the Terai. Urbanization creates new demands for water, and takes water away from agriculture and rural domestic needs to meet urban, residential, industrial and recreational needs (Narain, Khan, Sada, Singh, & Prakash, 2013). Urban water insecurity is a major emerging issue and is further complicated by issues of water pollution and solid waste management. The main impediment to urban water security is haphazard urban growth, which leads to the degradation of natural areas that used to recharge the groundwater. The other constraints are financial, managerial and technical.

Most of the rural population in the middle hills depends on springs for water for drinking and livelihood-related activities. In recent years, many of these springs have slowed or dried up.

Governance in the new federal context
In 2015, Nepal promulgated a federal constitution and in 2017 moved to federalism in the form of one country with seven provinces and 753 local government entities. Nepal is in the process of restructuring institutional arrangements and harmonizing policy in this context, and many plans and policies at provincial and local levels have yet to be finalized. How the administration develops will determine how Nepal uses its rich endowment of natural resources. The aim is to be as inclusive as possible, while foreseeing, averting and managing potential conflicts. Natural resources and water management fall under the purview of all three tiers (federal, state and local governments; Table A2). Conflicts might arise in using natural resources and sharing the costs and benefits. There may be conflicting interests in the various uses of water resources in different provinces when supply and demand is uneven. Although the constitution indicates the jurisdictions of each level of government, it has yet to clarify their precise responsibilities. The Local Government Operational Act of 2017 made these categories clear for local government,

but the distribution among provincial and federal governments is still being worked out. This should be further elucidated with the promulgation of the Electricity Act, Water Resources Act, Irrigation Act, and River Basin Master Plan.

Further drivers of water insecurity

A number of physical and socio-economic drivers of change could reduce water security in future. They can be divided into two main groups: physical (climate change and disaster risk); and socio-economic (population growth and competing water uses).

Climate change

The average annual maximum temperature for all Nepal increased by 2.4 °C (0.056 °C/y) over the 44 years from 1971 to 2014 (DHM, 2017). A reduction in glacier area of around 25% was recorded between 1980 and 2010 (Bajracharya, Maharjan, Shrestha, Bajracharya, & Baidya, 2014). Snowfall and glacier area affect the timing of river flow. Precipitation has also become more variable, with an increase in extreme precipitation events (Karki, Schickhoff, Scholten, & Böhner, 2017). These climatic changes can affect the quantity, quality and timing of water availability (MoPE, 2017) and thus reduce water security.

Climate change is likely to have a greater impact on water security in future. According to MoFE (2019), the climate change scenarios for Nepal suggest a significantly wetter and warmer climate towards the end of the century. Both the average annual mean temperature and the average annual precipitation are projected to increase (Figure A3). But pre-monsoon precipitation is projected to decrease, and extreme precipitation events to increase. These changes are expected to affect many sectors, including water, disaster management, energy, biodiversity, agriculture, health, urban planning, and livelihood-related activities (MoFE, 2019).

Disaster risk

According to MoHA (2018), more than 80% of the population of Nepal is at risk from natural hazards such as floods, landslides, windstorms, hailstorms, fire, earthquakes, and glacial lake outburst floods (GLOFs). Many of these natural hazards can affect water-related infrastructure and water availability. Hydropower especially can be affected by landslides, floods and GLOFs. GLOFs in high-altitude areas have affected small and medium-size hydropower projects (International Centre for Integrated Mountain Development [ICIMOD], 2011). In 1981, the Dig Tsho GLOF destroyed the nearly completed Namche Small Hydroelectric Project and caused further damage to downstream areas (ICIMOD, 2011). The small drinking water supply facilities in the mountains are affected by landslides and erosion, while in the downstream areas, irrigation and storage infrastructure is at high risk from sedimentation, floods and flash floods (MoPE, 2017).

Population growth

Nepal's population grew from under 10 million in 1961 to more than 25 million in 2011, and although this rate is slowing (the national average of 2.25%/y in 2001 dropped to 1.35%/y in 2011), the numbers are projected to grow for many years to come (Figure 3), with growth rates significantly higher in urban than in rural populations (Regmi, 2014). The larger population will probably need more water for drinking and domestic use, and

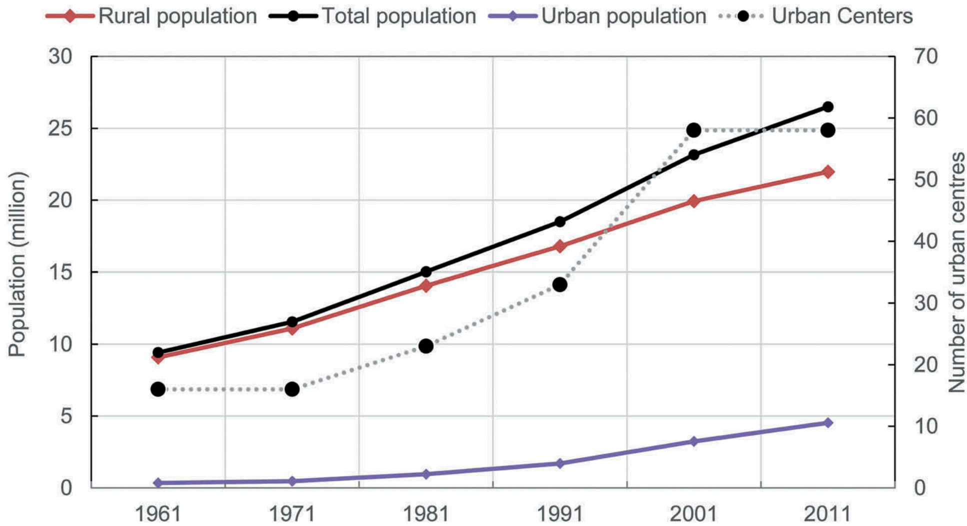

Figure 3. Growth in rural and urban populations in Nepal. Source: Data taken from CBS (2014).

for agricultural production to meet growing food requirements, and may bring higher vulnerability to water-induced hazards (Biggs et al., 2013). Economic growth, urbanization, globalization and higher standards of living are also increasing the per capita demand for water. Urban water security for drinking and other uses is likely to become a major problem. Population growth in India, where part of the commercial food in Nepal is produced, is also likely to create pressure on food security in Nepal and increase domestic demand for water for food production (Biggs et al., 2013).

Competing water uses

Competition among water users for limited resources can also lead to water insecurity for particular users and uses. Although the Water Resources Act (1992) prioritized water usages to avoid conflicts between multiple usages, conflicts still emerge. The most common are between riparian hydropower and other user groups when the minimum flow requirement for other uses and the riparian ecosystem are not being met. The hydropower projects are meant to release the minimum environmental flow mandated by the environmental impact assessment, but monitoring is not strict, and the conditions are often not met (Shrestha et al., 2016). One reason is that releasing the mandated flow can result in economic loss for the project (Rijal & Alfredsen, 2015).

In the Middle Mountains, springs remain a major source of water for drinking and domestic purposes. Perhaps 13 million people rely on springs as a primary source (Central Bureau of Statistics, 2012). However, in recent decades competition for this water due to the increasing population and changes in land-use patterns, together with infrastructure development and climate change, has led to a decline in spring flow: permanent springs have become seasonal, and some have dried up completely. The situation has become so grave that people are considering migrating away (Sharma et al., 2016; Tambe et al., 2012), and 28% of the population still has no access to safe supplies of potable water (Bartlett, Bharati, Pant, Hosterman, & McCornick, 2010).

Competing water uses can also lead to pollution of both surface and groundwater, with water used for cleaning and disposal of waste entering the supply for consumption and environmental use. Groundwater is polluted in many cities (Khatiwada, Takizawa, Tran, & Inoue, 2002) with more than 50% of the Kathmandu Valley affected by groundwater pollution (Shrestha, Semkuyu, & Pandey, 2016). Sewage disposal into freshwater also persists as a major issue in urban areas. The upsurge in city populations, coupled with poor urban planning, has led to large sewerage pipes being added to rivers as tributaries (Shrestha, Lamsal, Regmi, & Mishra, 2015). Other sources of contamination include factory waste and agricultural residues.

The water-energy-food (-environment) nexus

The WEF nexus can be defined as 'the very close links between these three sectors and the ways in which changes in one sector have an impact on one or both of the other sectors' (Nagle & Cooke, 2017), as well as how the sectors depend on each other. For example, water is an essential component in food and energy production; energy is used in numerous processes for supplying, treating and using water; and both water and energy are used for food production and transportation and along the entire agri-food supply chain. The multiple and competing uses for water, energy and food production mean there are important trade-offs that should be considered, often between sectors that are not coordinated. The nexus offers a conceptual approach to better understand and systematically analyze the complex interactions between the natural environment and human activities, and to work towards a more coordinated management and use of natural resources across sectors and scales (FAO, 2014). It can help identify and manage trade-offs and build synergies through our responses and therefore plays a vital role in livelihood security and socio-economic development (Rasul, 2014; Scott et al., 2019). Increasingly the environment is recognized as both a source and a consumer of water and energy in its own right, as reflected in the extension of the nexus concept to 'water-energy-food-environment'.

The key WEF nexus linkages in mountain regions are associated with hydropower generation and irrigation, both with important urban and rural implications, while in rural areas, the use of fuelwood for heating and cooking and rainfed agriculture for food production also play an important role (Scott et al., 2019).

Using the WEF nexus to address challenges to water security

Using the nexus concept in water security means unravelling the whole to reveal specific linkages between the sectors that affect water security, identifying challenges that have their source in sectors beyond simple water issues, and using these as a basis for developing specific recommendations for action. The nexus can be used to explore the interlinkages between the uses of water in different sectors (Rakhmatullaev, Abdullaev, & Kazbekov, 2017) and problems with ensuring water availability for different uses, such as hydropower and food production (Dhaubanjar, Davidsen, & Bauer-Gottwein, 2017; Rasul, 2014). Looking at water security from a nexus perspective can help us understand the wider implications and broaden the scope of interventions to include such things as water demand management, investment frameworks for public funding for improved surface irrigation, groundwater management, irrigation technologies and agricultural practices, as well as food procurement and trade policies (FAO, 2014).

In the following, we attempt to unpack the WEF nexus in Nepal by looking at each of the main water use sectors in turn – agriculture, energy, domestic and environment – and identifying the major challenges to water security and important linkages in the nexus with a view to identifying actions that can be taken to improve water security.

Agricultural sector

The agricultural sector is central to the WEF nexus. It is the main component in food production and a major user of water and energy. An estimated 65% of total agricultural production in Nepal comes from irrigated land (WECS, 2011). Agriculture accounts for 96% of total water withdrawal, with only 3.8% going to the domestic sector and a minimal amount to the industrial sector (AQUASTAT, 2018; WECS, 2011). However, despite considerable efforts by governmental and non-governmental agencies, a significant area of agricultural land remains under rainfed regimes (IMP, 2019; Poudel & Sharma, 2012), and much irrigated land has only seasonal access to water.

The main source of irrigation water is surface water from rivers, glacier and snow melt, lakes, wetlands and springs, although groundwater irrigation is increasing. Surface irrigation covers about 80% of the total irrigated area; the other 20% is irrigated through groundwater or mixed systems (FAO, 2016). The irrigation command area varies from 90% of the system in the wet season to 25% in the dry season, with year-round irrigation less than 38%, due to the high seasonal variation in water availability (WECS, 2011). Extraction of water lies well below the potential. Less than 7% (15 BCM) of the total average annual river runoff of 225 BCM is used for irrigation (Bharati, Gurung, Jayakody, Smakhtin, & Bhattarai, 2014; WECS, 2005), and in the Terai alone, less than one-third of annual groundwater recharge is extracted for agriculture (Table 1). The ability to extract water for irrigation is directly linked to the availability of reliable and affordable electricity for pumping, and thus to the energy sector.

Water security in agriculture essentially means access to sufficient water for irrigation. The overall cereal yield in Nepal is 2.6 MT/ha, far lower than the regional and global average (World Bank, 2018), indicating overall low productivity. Access to year-round irrigation is vital to improve crop yields; at present most irrigation schemes function in the monsoon but not in winter and spring, when the need is greatest. A fully controlled irrigation system can have two or three times the yield of rainfed and monsoon-irrigated regimes (ADB, 2014).

Energy and industrial sectors

Energy sector

Water is the primary input for hydro-based energy generation, which provides 99.5% of Nepal's electricity production (Nepal Electric Authority, 2015). At the same time, hydropower is itself important for water security, as energy is used to pump water to meet various water demands, including domestic and industrial demand in the cities, and agricultural water demand in rural areas. Nepal has a great potential for hydropower development, thanks to the high precipitation and steep topography, along with perennial rivers fed by glaciers and snow in the high mountains. It is estimated at 83,000 MW (Shrestha, 2016), of which 43,500 MW is thought to be economically and technically feasible (Dixit, 2008). Only a fraction of this has been exploited so far. The present generation is close to 1050 MW, with a further 7950 MW planned in 209 projects licensed for construction and now at different stages of completion (Department of Electricity Development, 2019). Nepal still imports 450 MW of power from India and produces an additional 54 MW from diesel fuel (MoEWRI, 2018).

Despite its high per capita potential for electricity production, Nepal has a supply deficit, and its per capita consumption is among the lowest in Asia. Thirty percent of rural households still lack access to electricity (MoF, 2018). Most of the population still relies on traditional energy sources for cooking and heating, and these sources comprise 69% of total energy consumption. Electricity demand is increasing by approximately 7% per year (Nepal Electricy Authority, 2015), mainly for rural electrification, industry and domestic use. The demand forecast for 2033 is around 5785 MW (Figure A4).

Hydropower is seen as a potential medium to support the national economy, but could also provide substantial revenue at the local level. Similarly, access to energy can open up opportunities for many other electricity-dependent sectors. But the country faces several challenges in hydropower development, a major one being seasonality. Production is largely dominated by run-of-the-river projects, which produce less during the dry season, when demand is highest, and a surplus in the rainy season, when demand is lower (Sharma & Awal, 2013). Only one of the 73 operating projects is a storage type (Department of Electricity Development, 2019). It is estimated that even if all of Nepal's potential is exploited, dry-season production would amount to only 11,300 MW (Shrestha, 2016). The seasonality is likely to be aggravated by climatic and other environmental change.

Achieving water security in the hydropower sector implies making sufficient water available in the form of run-of-the-river flow or storage infrastructure to produce the full electricity requirement.

Industrial sector

Industrial growth outside the energy industry is very limited. Industry contributes only 5.4% of GDP, down from 10% 20 years ago (MoF, 2018), and represents only 36% of total power consumption, less than household consumption (45%). Investment is low, with only 54% of investment in the industrial sector going to energy-based industries (MoF, 2018). To some extent, lack of industry to provide a consumer base for power means lack of incentive to increase electricity production, while lack of reliable electricity suppy means lack of incentive for industrial growth. However, as energy projects come on line, there is likely to be an upsurge in industrial growth, leading to economic development, which will further stimulate an increase in hydroelectricity production. But this will also increase competition among water users, as both hydropower production and industries themselves will have higher water requirements, in competition with the domestic water use, agriculture and the environment. It may also affect water supply through increased pollution. Achieving water security for industry will require increasing the total volume of available water and/or increasing water use efficiency.

Domestic sector

The domestic sector predominantly uses water for drinking and sanitation and to supply livestock. As of the last census, 85% of Nepal's population had access to basic water supply services, and 62% to basic sanitation facilities (Central Bureau of Statistics, 2012). Domestic water is mainly supplied through surface or groundwater schemes implemented by government and community-based organizations. But the water supply remains strongly seasonal, with more limited access to drinking water in the dry season.

In the mid-hills, springs are the main source of domestic water. In many cases, spring water is collected in storage tanks and accessed via taps. In some cases, stored water is pumped to a higher level and supplied by gravity flow to individual houses or community taps. Spring discharge is also used for small-scale irrigation on hill slopes. But there is increasing evidence that springs are drying up; they are becoming seasonal, and their discharge is dropping. A study by Sharma et al. (2016) found that one-third of the springs in Kavre District have dried up, and Chapagain, Ghimire, and Shrestha (2019) found that spring discharge had declined by over 30% in the last 30 years in one mid-hill region.

In the plains of the Terai, the major source of drinking water is groundwater, which meets close to 90% of the drinking water demand in the region (ADB and ICIMOD, 2006). Only 14% of households have access to piped water, while about 80% pump water from the 800,000 shallow and drinking tubewells in the region (Kansakar, 2005; MoWSS, 2016; Sarwar & Mason, 2017). Tubewells and shallow wells are commonly used to supplement the limited supply of municipal water in cities, including Kathmandu, where groundwater levels have dropped considerably due to excessive use to meet the increasing demand of the growing population (Pandey, Chapagain, & Kazama, 2010).

Domestic water supply has close connections with energy, agriculture and the environment, as provision of domestic water is strongly affected by the energy available for pumping, by land use and land cover change affecting recharge, by extraction of surface and groundwater for competing uses, and by availability of storage infrastructure. Ensuring domestic water security will require addressing all of these.

Environmental sector

The entire ecosystem depends on water for its function, but is itself also a major component of water supply, for example through capturing runoff, providing storage in soil and root systems, and recycling water to the atmosphere. A healthy ecosystem is essential for the water supply, and water is essential for a healthy ecosystem. Nepal's 2005 National Water Plan made supporting water-dependent ecosystems a major priority (WECS, 2005). These ecosystems can be disturbed by upstream water uses, infrastructure development and pollution. For example, if water is diverted from a stretch of river for hydropower production, the lack of year-round flow along that stretch can affect the local ecosystem, especially fish and other riparian life. Environmental flow assessments provide an understanding of the amount of flow required in a river system to support the freshwater ecosystem. They should include an understanding of wet- and dry-season flows, natural high flows, extreme low flows, floods and interannual variability, all of which determine the flow regimes of river systems (Manandhar, 2016). In urban areas, rapid unplanned urbanization with direct disposal of household waste and sewerage into rivers has also harmed river ecosystems (Karn & Harada, 2001). Discharge from industry can also affect water quality and dependent ecosystems in downstream areas.

Maintaining water security for the environment means ensuring that sufficient flows of water are retained to maintain ecosystem function. Plans for water extraction for use in other sectors must be balanced against the need to protect ecosystems and their dependent biodiversity.

Improving water security in Nepal

Water security is still a key issue for many people in Nepal, in spite of the theoretically high physical availability of water. The impediments to water security result mainly from economic and institutional factors rather than physical water scarcity, as outlined in the previous sections. The issues and potential measures to address them can be summarized for each water use sector, but specific measures will also affect other issues and lead to outcomes in other sectors. Furthermore, the move towards integrated management of water resources and approaches to water governance will also play an important role in achieving water security. These aspects are discussed in the following sections.

Addressing sector-specific issues

The issues identified in specific sectors from a range of studies over many years are summarized in Table 2, together with potential measures to address them. The major issues are presented in more detail in the preceding sections, and others are included in the table for completeness. It is beyond the scope of this article to go into details on all these topics; rather, we provide an overview, with details especially of issues that benefit from using a nexus approach. Although presented sector-wise, the issues and measures take into account the linkages in the WEF nexus following the water security framework presented in Figure 1.

Unpacking nexus linkages to improve water security

The nexus among groundwater, energy, and irrigation has been highlighted in a number of studies (Mukherji, 2007; Shah, Scott, Kishore, & Sharma, 2004). One of the clearest results of the analysis using a nexus approach to water security is the recognition that in Nepal this nexus offers one of the most accessible opportunities to address water security, which is to increase the water available to agriculture by increasing the extraction and use of groundwater to levels up to annual recharge through increased production of affordable energy. The approach is made possible by the high rainfall and recharge and the aquifer conditions, and the resulting increase in both production and the productivity of agriculture would also improve food security. Access to irrigation can be boosted primarily through investments in the energy sector to exploit the country's potential for hydropower and increase the coverage of the energy supply network, and on a smaller scale

Table 2. Measures to improve water security in different sectors.

Sectors	Major issues	Water security measures
Agriculture	• Access to water in mountains and hills • Lack of water for irrigation in the plains • Energy availability and access for water extraction • Water loss • Climate variability and change • Drying spring sources • Access to markets	• Increasing water supply through infrastructure and rejuvenation of springs • Groundwater pumping using grid electricity and off-grid solar power • Small and local-scale water storage and rainwater harvesting • Inter-basin water transfer • Irrigation technologies, farming technologies (demand management) • Formal and informal water markets
Domestic	• Access to drinking water • Drying spring sources • Urban water supply systems • Sanitation	• Spring conservation and management through hydro-geological and community approaches; small and local-scale water storage and rainwater harvesting • Increasing water supply (inter-basin water transfer) • Sustainable use of groundwater in an urban context
Hydropower	• Seasonality of water availability • Hazard risks (landslides, glacial lake outburst floods) • Sedimentation • Climate change and variability (e.g. extremes) • Maintaining environmental sustainability	• Multipurpose water storage infrastructure • Public–private partnerships • Considering downstream water uses for irrigation, environment and domestic water uses • Multi-hazard risk assessment
Industry	• Access to water • Overuse of groundwater • Water pollution and contamination	• Sustainable use of groundwater • Reducing pollution and maintaining the ecosystem • Optimization of industrial processes to minimize water use
Environment	• Pollution • Seasonality of water flow • Diversion of water for hydropower • Lack of compliance with environmental flow requirements • Groundwater exploitation in urban areas	• Regulatory framework in place with proper monitoring • Environment management plan based on environmental impact assessment • Promoting aquatic movement across water infrastructure • Effective monitoring and compliance

through investment in solar power irrigation systems. The rationale behind this approach and the potential benefits are presented in more detail below, followed by a range of other actions to improve water security.

Exploiting the nexus between groundwater and agriculture in the Terai

The net area of cultivated, irrigated and irrigable land in the Terai, hill and mountain areas of Nepal is shown in Table 3. At present only 1.1 million of the 3.5 million hectares of cultivated land (31%) is irrigated, but a further 1.3 million hectares could be irrigated if water can be made available (IMP, 2019). Nearly half of all cultivated land and most irrigable land lies in the fertile alluvial plains of the Terai, popularly known as the granary of Nepal. Close to 60% of potentially irrigable land already receives some irrigation, about half from surface water, a quarter from groundwater, and the rest from conjunctive use of surface and groundwater, but more than 600,000 ha of land that could be irrigated still supports only rainfed agriculture. Furthermore, half of the present irrigation in the Terai is through surface irrigation schemes which are mostly fed by small and medium-sized rivers. But there is considerable fluctuation in the net command areas between the monsoon and dry seasons, with large areas receiving no water in the dry season and thus unable to grow winter and

Table 3. Irrigated and potentially irrigable land in Nepal (source: IMP, 2019).

Category	Terai		Hills		Mountains		Total ('000)
	ha ('000)	%	ha ('000)	%	ha ('000)	%	
Cultivated agricultural land	1,594	44.8	1,566	44.0	401	11.3	3,561
Potentially irrigable land	1,480	65.3	627	27.7	159	7	2,265
Present area irrigated							
Surface water	*434*		*170*		*41*		*654*
Conjunctive use	*207*		–		-		*207*
Groundwater	*226*		*8*		-		*234*
Total	866	79.8	178	16.4	41	3.8	1,085
Net potential irrigable land	613	51.4	448	38.5	118	10.1	1,180

spring crops. Even in areas growing monsoon crops, timely onset of the monsoon is critical, as there may not be enough irrigation water if the monsoon is late.

The estimated annual recharge of groundwater in the Terai is 8.8 BCM, but less than a quarter of this is currently extracted, leaving a potential balance of 6.9 BCM that could be used for irrigation (Table 1). More water could be used both to increase the overall irrigated area and to increase the seasonal coverage of irrigation in areas already receiving some water through conjunctive use of surface and groundwater in the dry season. Year-round irrigation would help boost both yields (which are among the lowest in the plains areas of South Asia) and cropping intensity. A recent study suggests that with sufficient water, the plains of the lower Gangetic basin can support 2.5 crops per year without threat of long-term depletion, compared to the 1.2 to 1.5 crops per year grown in the Terai at present (Shah, Rai, Verma, & Durga, 2018). Not only could more crops be planted, water availability would facilitate effective use of other agricultural inputs such as fertilizers, pesticides and improved crop varieties, also leading to higher crop productivity and production. Use of such inputs in conditions of water stress may not improve yields and can even be counterproductive (Khunthasuvon et al., 1998).

There are two main factors to be considered when proposing to increase groundwater extraction to support agriculture: the sustainability of extraction amounts, and how to ensure a regular and uninterrupted supply of energy for extraction.

Sustainability of extraction was explored using calculations based on expansion of irrigated area by the full potential of 613,000 ha in Terai (Table 4). The crop water requirement differs from crop to crop, and by variety, soil type, and season. However, a conservative estimate shows that on average 5000–10,000 m^3/ha of water is required to cultivate cereal crops in South Asia (Facon, 2000; Haavisto, Santos, & Perrels, 2018), giving a maximum of 613 MCM for summer (dry-season) rice. Although water is abundant for growing rice in the monsoon season, delayed onset of the monsoon can require supplementation with groundwater, estimated at 307 MCM. Finally, irrigation would enable cultivation of winter crops such as wheat and barley, requiring a further 490 MCM. The total 1.4 BCM required to cultivate three crops per year on all the potentially irrigable land

Table 4. Estimated groundwater requirement to irrigate irrigable land in the Terai (author's calculation based on Facon, 2000; Haavisto et al., 2018; IMP, 2019).

Crop	Water requirement (MCM) for 613,000 ha of irrigated land
Summer rice	613
Supplement for monsoon rice	307
Winter crops (e.g. wheat, barley)	490
Total	**1,410**

in the Terai is still only 20% of the calculated recharge surplus and thus within sustainable amounts. This would leave a considerable potential for additional irrigation of land which already receives some surface irrigation but not year round, enabling additional crops to be grown in winter and summer (before the monsoon).

Exploiting these groundwater resources requires access to a reliable and affordable supply of energy. This can be achieved primarily by exploiting a greater part of the country's potential resources for hydropower, as outlined under 'Energy Sector' earlier. A rough estimate is that the energy requirement would be on the order of 153,000 kWh per day, equivalent to 15 MW (to pump 1410 MCM per year from a depth of 10 m at 70% efficiency). On a smaller scale, solar-powered irrigation systems can be used to help smallholder farmers irrigate their lands and reduce dependence on the national grid. Solar pumps have an advantage over hydroelectricity in many rural areas where electricity infrastructure is still limited, especially to farmland. Linking farms to the electricity grid increases costs, and the fragmented parcels add complexity. Shah et al. (2018) suggested that solar-powered pumps are a good option for groundwater pumping in the Terai, while in future a combination of grid electricity and solar power could help maximize opportunities (Mekhilef, Faramarzi, Saidur, & Salam, 2013). Constructing large irrigation systems takes a huge amount of resources and a long time, but a distributed energy approach with local pumping using hydropower and solar power irrigation systems could provide immediate benefits.

The potential additional revenue from irrigation of the additional 613,000 ha was estimated from the difference between the market price of the average rainfed yield of monsoon rice cultivated at present, and the value of three crops (monsoon rice, summer rice and winter wheat) grown over the whole area with year-round irrigation (Table 5). An estimated additional USD 2.2 billion (NPR 220 billion) could be generated as direct gross benefit. A conservative estimate puts production costs at 50%, based on values of 40–55% reported for rice-wheat-dominated agriculture in the Indo-Gangetic Plain (Jat et al., 2014). Thus, net direct benefit could be on the order of USD 1.1 billion. This is equivalent to 4.5% of national GDP in 2017. There would also be indirect benefits, such as local employment, and gains in the markets for inputs and outputs. Further, Nepal imports a huge amount of cereals, vegetables and fruit, mostly (over 70%) from India. Currently, Nepal exports agricultural commodities equivalent to USD 190 million and imports agricultural commodities equivalent to USD 950 million, a net deficit of USD 860 million (calculated from World Integrated Trade Solution, 2018). If water security in agriculture is achieved, the additional agricultural production could easily fill the trade deficit gap and help achieve food security. Irrigated summer crops generally have higher productivity than monsoon crops because of the greater solar radiation, and are also less vulnerable to diseases and pests. Where markets are accessible, as in the Terai, farmers also have the opportunity to grow higher-value cash crops like fruits and vegetables. For example, solar pumps introduced for irrigation in Saptari District of Nepal increased the cropping intensity and yields and helped farmers switch from cereal to vegetable production and fish farming, with a potential increase in farm income (Mukherji et al., 2017; personal communication, Nabina Laamichhane, ICIMOD, 18 April 2019).

Table 5. Potential yield gains following groundwater irrigation of the 613,000 hectares in the Terai growing rainfed crops at present.

Crop	Average rainfed yield (MT/ha)	Maximum irrigated yield* (MT/ha)	Additional yield with irrigation (MT/ha)	Additional production with irrigation (1000 MT)	Market price** (NPR/kg)	Current revenue (NPR millions)	Revenue with irrigation (NPR millions)	Additional revenue (NPR millions)
Summer rice (April to June)	0	3.9		2391	47	0	112,000	112,000
Monsoon rice (June to October)	3.3	3.9	0.6	368	63	127	150,000	23,000
Winter wheat (November to March)	0	2.9		1,778	48	0	85,000	85,000
Total				**4,535**		**127**	**347,000**	**220,000 (USD 2.2 billion)**

Source: *FAOSTAT (2019); **MoALD (2017); MoAD (2019).
Notes: Price of coarse rice is for summer rice, and fine rice for monsoon rice; USD 1 = NPR 100 in 2017.

Other benefits and approaches

The potential for using power to pump groundwater on a large scale increases the overall incentive for increasing hydropower production. This is likely to generate an excess of power, offering further opportunities, such as using electricity in agricultural storage and processing, developing power-dependent industries, increasing domestic consumption through innovative uses such as cooking in place of LPG and wood, and selling to nearby markets, all of which can contribute to revenue generation, employment and local development.

Using groundwater can also have other direct and indirect benefits. One is the potential to reduce the intensity of flooding in the monsoon season, as suggested by the Ganges Water Machine hypothesis of Revelle and Lakshminarayana (1975). The hypothesis is that lowering the water table in the pre-monsoon season could allow higher recharge during the monsoon, using water that would otherwise contribute to flooding. It was suggested as a mechanism for storing excess water in the monsoon season in aquifers in the eastern Gangetic basin where the terrain is too flat to construct large water storage structures. The hypothesis has been tested using empirical data for West Bengal (Mukherji, Banerjee, & Biswas, 2018), Bangladesh (Shamsudduha, Taylor, Ahmed, & Zahid, 2011), and India as a whole (Chinnasamy, 2016). All these studies found that lowering the shallow aquifers before the monsoon allowed more water to infiltrate at the beginning of the monsoon season. Thus, withdrawing large amounts of water from the aquifers in the Terai during the dry winter and summer seasons could have the additional benefit of reducing flooding intensity when the excess water is used for recharge. This implies that care must be taken to ensure that the recharge pathways are maintained and possibly proactively managed, which has further implications for farming practices and infrastructure construction.

There are other methods that can be used to increase water supply. For example, the Nepalese government has made a dedicated effort to increase water supply through inter-basin transfer by bringing water from the Melamchi watershed to the Kathmandu Valley

(Bhattarai, Pant, & Molden, 2005). At a local scale, promoting rainwater harvesting and artificial recharge of shallow and deep aquifers could also ease the water supply, at least during the monsoon and the months right after (Shrestha, 2009). Possibilities for improving water security include a dedicated spring conservation programme, water storage of various sizes to hold rainfall and recharge groundwater, and springshed management approaches (Shrestha et al., 2017).

In urban areas, the nexus approach makes it clear that integrated solutions are needed that look at issues like drinking water provision, stormwater management, and management of wastewater and solid waste. Improving urban water security requires that urban development planning consider supply and demand management, maintaining natural and human-made recharge structures and strict control of haphazard groundwater exploitation.

Promoting an integrated approach to water management through governance: IWRM and the nexus approach

Water insecurity in Nepal, in the face of abundant theoretical availability, is linked to problems of supply and demand, in which water governance plays an important role (Neupane, 2011). Using water resources sustainably requires water governance that uses a holistic and integrated approach to the management of water and related resources. Nepal's Water Resources Strategy (WRS) of 2002 (WECS, 2002) and National Water Plan (NWP) of 2005 (WECS, 2005) envisage using IWRM. WRS 2002 was developed using a participatory approach with social, economic and environmental sustainability principles, with the overall aim of improving the living standard of the Nepalese people in a sustainable way. The NWP 2005 was developed to implement the activities identified in WRS 2002. The NWP recognizes the broad objectives of the WRS and lays down short-, medium- and long-term plans for the water resources sector, including investment and human resource development. It attempts to address environmental concerns, and includes an environmental management plan. This plan is designed to maximize positive impacts and minimize or mitigate adverse impacts in line with environmental sustainability concerns. The NWP also adopts IWRM principles for the development of water resources in a holistic and systematic manner. However, although the WRS and the NWP were formulated one-and-a-half decades ago, implementation of IWRM has been slow. As suggested by Suhardiman, Clement, and Bharati (2015), some of the prominent challenges to implementation are lack of coordination among government institutions, lack of clarity on the mandates of key institutions, and lack of strong political will, with water issues fragmented among different ministries in the past. This also indicates that water governance is a key issue.

Although IWRM promotes an integrated approach to water, land, and other related resources, in practice it has only been implemented at large scales and has only been tested in a few selected projects; the current challenge is to demonstrate improvement of existing water management practices (Biswas, 2008). Suhardiman et al. (2015) suggest that the current discourse on IWRM in Nepal highlights the need to shift the emphasis from national policy formulation to local, adaptive, pragmatic approaches to IWRM. It remains to be seen how IWRM can help solve the water crisis, support water-based adaptation and livelihoods, and deal with climate-change-related challenges at different scales.

The WEF nexus and IWRM are linked, but they have different approaches and focus (Ringler, Bhaduri, & Lawford, 2013). IWRM is specifically water-sector-oriented, and is less concerned with linkages with other sectors, whereas the nexus approach not only takes into account all the different users and uses of water, it specifically considers the linkages among water, energy and food and looks at the trade-offs and synergies, and the possibilities they offer for increasing water security through actions in other sectors. Although IWRM attempts to involve all sectors of water management, the nexus approach treats water, energy and food equally and also considers their interdependencies (Rasul et al. 2014). Essentially, IWRM deals with the entire life cycle of water, and provides tools for implementation, while the nexus approach deals with the life cycle of water and other related processes, including energy, land and food, and suggests pathways for intervention.

Biggs et al. (2013) suggested that while the principles of IWRM and water security have some complementarity, given the limited uptake of IWRM to date, perhaps an alternative framing such as the nexus-based approach is required for effective water management and governance. The scope for greater merging of nexus thinking within IWRM has been discussed in some detail by Benson, Gain, and Rouillard (2015). They conclude that:

> Scope exists within current IWRM practice to better shift water governance from prioritizing *inter alia* demand management and resource efficiency towards securing an acceptable quality and quantity of water for all users and ecological protection: all key objectives of IWRM. A critical issue is how best to balance water, agricultural, and energy security at multiple scales. Current nexus arguments still remain highly ambiguous on this subject, inferring a need for strategic policy guidance and institutional structures across multilevel governance. (p. 768)

This study illustrates how the nexus approach can be used to identify pathways to water security that originate in actions and policies related to other sectors, specifically the encouragement of generation of hydropower to provide affordable energy for pumping groundwater to support agriculture. Exploiting the groundwater requires cross-sectoral policy coherence among the agriculture, energy and water sectors. The IWRM and IRBM approaches which the Nepal government has adopted as policy need to be broadened to recognize the nexus between water, energy and food production and security. Further, rainfall and temperature patterns are likely to be affected by climate change, and additional adaptive water management practices may be necessary to help achieve water security. The nexus approach has also been discussed as an important tool in adaptation to climate change (Rasul & Sharma, 2016). The framework proposed in Figure 1 could be helpful for integrating these different aspects. The ultimate aim of the WEF nexus approach is also to use the framework as a tool for assessing environmental livelihoods (Biggs et al., 2015).

The key linkages identified using the nexus approach will vary according to the regional, national and local conditions in the area of interest. Particularly from a water perspective, a river basin approach is crucial, as it is fundamental in terms of the linkages among water resources and water uses (Lawford et al., 2013) in both upstream and downstream areas (Nepal, Pandey, Shrestha, & Mukherji, 2018; Nepal et al., 2019). As with IWRM, the aim should be to broaden the approach of IRBM to encompass WEF linkages at the river basin level (Hooper, 2003). The governance framework needs to be designed in such a way that the intersectoral linkages are not only taken into account but fundamental to policy development and the identification of interventions. The recent creation of a Ministry of Energy, Water Resources, and Irrigation at the central level is a promising step in this direction and should be helpful for settling water, energy and irrigation-related issues at the provincial and local levels.

Conclusion

Water security continues to be a major concern in Nepal in all sectors, despite the abundance of annual rainfall. Water demand is likely to increase with population growth, urbanization, industrialization, more intensive agriculture and increasing standards of living, while water supply may itself be affected by changing climatic patterns.

Addressing water security requires new and innovative approaches based on our better understanding of water not as a 'stand-alone' good but as one aspect of an integrated system. The WEF nexus concept recognizes that water, energy, food and other land-based resources are interlinked and have complex interactions, leading to synergies and trade-offs. The present study shows how using this concept to investigate linkages to water security in different water use sectors can help identify specific approaches that can be used to address water security in other sectors. Specifically, Nepal's plains contain large and mostly untapped reserves of renewable groundwater, which can be used to increase the water supply to irrigated agriculture, and this can be achieved primarily by introducing policies to promote development of Nepal's hydropower potential to provide reliable, affordable energy for pumping. The estimated potential direct economic gain from providing year-round irrigation to the unirrigated agricultural area in the Terai is on the order of USD 1.1 billion, equivalent to 4.5% of Nepal's annual GDP in 2017. There would also be indirect benefits in terms of generation of local employment, boost to markets, and reduction of imports. In terms of the nexus, the energy sector would itself benefit from the incentive to increase hydropower production provided by the enlarged consumer base for pumping, while disaster risk reduction could benefit from the reduced flooding intensity when the excess water is used to recharge the aquifer. Other linkages, such as promotion of solar power for pumping, with benefits to smallholders and industry, are mentioned and remain to be further explored.

The study also laid out the main problems in other water use sectors, including the drying up of springs in the mid-hills, which impacts domestic water use as well as livestock farming, and the problems resulting from rapid urbanization, whereby urban water security is threatened by the haphazard and uncontrolled use of groundwater, combined with reduction in recharge due to construction. Some measures to address these, such as springshed management, are suggested, but the detailed linkages within the nexus play a less marked role, and more detailed analysis lies beyond the scope of this article.

Nexus considerations also highlight areas for caution. For example, using groundwater to address water security issues in any sector requires also assessing the potential environmental impact and level of sustainable extraction, and ensuring that recharge pathways are protected and pollution is avoided. In particular, pumping of large quantities of water for industrial and urban use needs to be carefully monitored and controlled by government agencies. Environmental use needs to be given special consideration, in terms of both water-dependent ecosystems and biological diversity.

Water governance plays an important role in addressing water security. Using water resources sustainably requires water governance that uses a holistic and integrated approach to the management of water and related resources. Nepal's water policy envisages using IWRM, but implementation of the approach has been slow. The nexus and IWRM concepts are linked but have different approaches and focus. We suggest that a nexus-based approach is required for the implementation of effective water management and governance, and that IWRM and IRBM approaches need to be broadened to take into account the nexus between water, energy, and food production and security. The new federal structure poses a further challenge in this, with responsibilities and provisions at different levels still to be finalized. This includes a need for a clearer jurisdiction for all three tiers of the government. However, it also offers opportunities as new policies and implementation pathways are formulated at different levels of governance. The creation of a combined Ministry of Energy, Water Resources, and Irrigation at the central level is a promising first step.

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