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Analysis of the climate change impact on water availability and the links between water pollution and economy for sustainable water resource management in Kaski District, Nepal

Saroj Kumar Chapagain[a,b,*], Anil Aryal[c,d], Geetha Mohan[a,e], Sadhana Shrestha Malla[a,e], Binaya Kumar Mishra[f] and Kensuke Fukushi[a,e]

[a] Institute for the Advanced Study of Sustainability, United Nations University, Tokyo 150-8925, Japan
[b] Institute for Integrated Management of Material Fluxes and of Resources, United Nations University, Dresden 01067, Germany
[c] Interdisciplinary Centre for River Basin Environment, University of Yamanashi, Kofu 400-8510, Japan
[d] Water Engineering and Management, Asian Institute of Technology, Klong Luang, Pathum Thani 12120, Thailand
[e] Institute for Future Initiatives, University of Tokyo, Tokyo 113-0033, Japan
[f] School of Engineering, Pokhara University, Lekhnath 33700, Nepal
*Corresponding author. E-mail: saroj@unu.edu, sarojchapagain77@gmail.com

SKC, 0000-0002-7348-2085

ABSTRACT

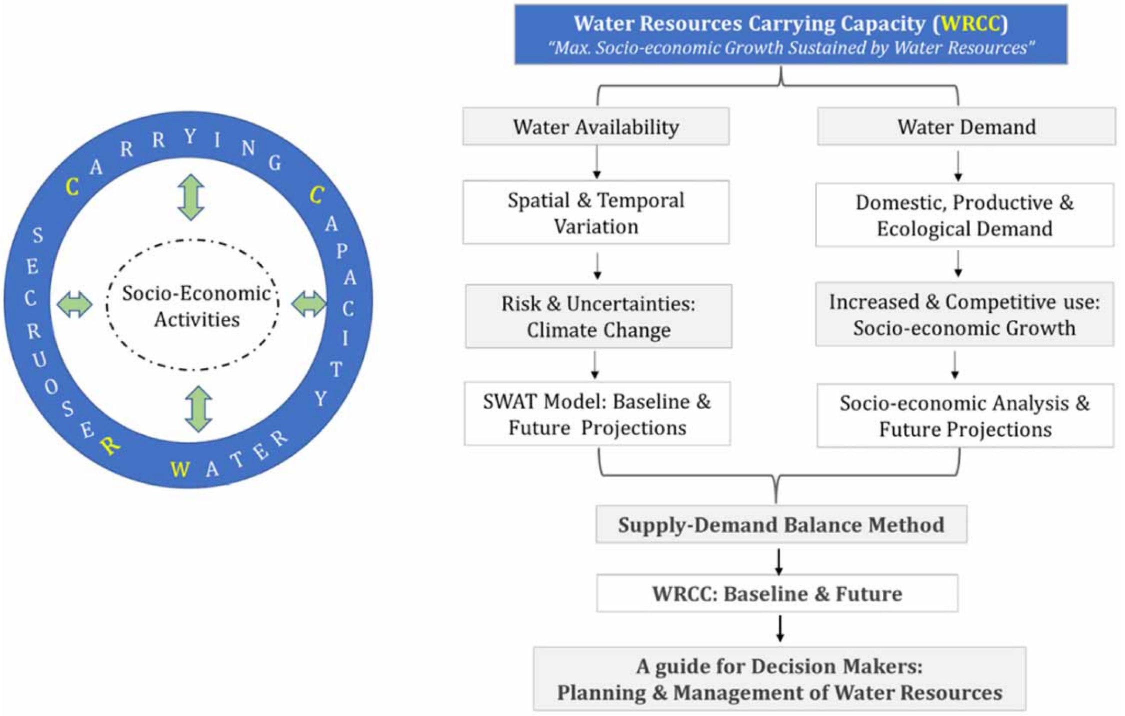
The newly enacted national water policy is envisioned as ensuring water sustainability in Nepal. Despite theoretical pertinence, questions remain about the effective implementation due to limited studies on key aspects of sustainability, such as water supply and demand, pollution, and impacts of climate change and socio-economic growth. This study analyses the current and future availability of water under climate change scenarios and determines water resources carrying capacity (WRCC) as the maximum socio-economic growth that can be supported in a case study on the Kaski District, Nepal. Annual average water availability was estimated to be 11,030.7 million cubic meters (MCM) for the baseline period (1992–2010), and 7,677.4 and 7,674.2 MCM for the future period (2022–2050) under the representative concentration pathway (RCP) 4.5 and 8.5 emission scenarios, respectively. For the baseline period, WRCC far exceeds the current population; therefore, water resources will not be a limiting factor for local socio-economic development. Nevertheless, sustainable water infrastructure development policies are necessary to ensure a reliable water supply able to cope with increasing seasonal variability and declining future water availability. A total of 30,049 tons of biological oxygen demand (BOD) loads were estimated based on the economic activities of the Kaski District in 2011, with the direct and indirect sectoral roles of water pollution determined for the first time. Rather than a single pollution control strategy based on pollution loads, multiple sector-specific strategies are necessary to effectively implement water pollution control policies.

Key words: environmentally extended input–output (EEIO), indirect water pollution, polluter pay, water policy, water resources carrying capacity (WRCC)

HIGHLIGHTS

- A decline in water availability and substantial seasonal variability is projected.
- Investing in water storage facilities and adequate supply systems are necessary for a reliable water supply.
- Sector-specific water pollution control measures should be considered.
- Analysis of direct and indirect sectoral pollution provides a strong basis for effective water pollution control policies.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water is vital for humans, and for economic development. Continued population and economic growth means an increased demand for water worldwide. The global water demand is projected to double to 6,900 billion m^3 in.2030 compared with 2005, over 40% higher than the existing reliable, sustainable water supply (Addam *et al.* 2009). The global water supply is further constrained by increasing pollution. United Nations (UN)-Water (2021) reported that nearly 2.3 billion people live in water-stressed countries, of which 733 million people are in high and critically water-stressed countries. Furthermore, 24–700 million people in some arid and semi-arid places are likely to be displaced due to intense water scarcity by 2030 (UN 2014a).

Water availability in the Asia-Pacific region varies greatly due to the wide range of climates, and water scarcity is a critical issue as this region holds approximately 36% of global water resources but accommodates 60% of the population (UN 2014b). The situation is further worsened by the rapidly growing economy, where excessive withdrawal of water resources, environmentally unfriendly production, and low levels of wastewater treatment are being practiced. Consequently, nine out of the 10 most polluted rivers are found in the Asia-Pacific region (Asian Development Bank: ADB 2020). The declining water quality and quantity call into question the continued growth of this region.

Nepal, in South Asia, receives an ample amount of precipitation (average 1,500 mm annually), but its distribution greatly varies with season and location. The majority (80%) of the total rainfall occurs within 4 months (June–September), resulting in a temporary excess of water, causing flooding and water-induced disasters. Rainfall in the remaining 8 months is insufficient and leads to drought and water scarcity in many parts of the country (Merz *et al.* 2003). As part of the Himalayan range, Nepal is often referred to as the water tower of South Asia; however, the Himalayas have undergone rapid deglaciation with climate change. Glaciers serve as important water sources for rivers in Nepal and India, especially during the dry season and rapid deglaciation is likely to have serious consequences on a regional scale on water resources (Shrestha & Aryal 2011). Concurrently, the changes in the rainfall pattern and the spatial variation, which is more pronounced in Nepal due to diverse topography and altitude, have been linked to the potential impacts on socio-economic activities (Panthi *et al.* 2015).

Climate change has made water resource management more challenging in this region (Aryal *et al.* 2019), confirming the need to assess the physical and socio-economic risks (Shrestha & Aryal 2011). Aside from climate change risks, water quality is deteriorating with the growth of socio-economic activities. This has reduced clean water availability, with a significant population forced to use contaminated water (Merz *et al.* 2003). The large population of this country is confronted with a poor water environment, and major cities, including the capital, face periodic or chronic water scarcity (Pandey 2021).

Increasing environmental stress is expected with rising socio-economic activities. Comprehensive policies that create a balance between socio-economic growth and the environment are essential. However, there is growing awareness of resource and impact decoupling, aimed at reducing environmental stress while increasing economic growth for sustainable development (United Nations Environment Programme: UNEP 2011). Despite considerable efforts, Nepal's attempts to manage water resources have not been effective, mainly due to a lack of integrated and coordinated approaches, linked to the fragmented and weakened institutions with overlapping scopes (Upadhyay & Gaudel 2018).

Nepal recently enacted the National Water Resources Policy (Ministry of Energy Water Resources and Irrigation MoEWRI 2020), emphasising integrated water resource management (IWRM), overcoming the failure of earlier water resources management plans to undertake coordinated and holistic approaches. This policy implements multiple integrated strategies for water resource management and recognises the pivotal role of water in socio-economic development. Water is considered a foundation for national prosperity, and its management is key to achieving several interconnected sustainable development goals (SDGs). Furthermore, the policy emphasises the need to address the challenges posed by increasing socio-economic growth and climate change, while ensuring a reliable supply of good quality water to all sectors and households.

However, several questions remain about the successful implementation of these policies under a paucity of data, especially for water availability, given the limited research and knowledge on the dynamics of water resources, climate change, and socio-economic activities. For instance, the current water policy undertakes water allocation strategies to satisfy the sectoral water demands. Effective implementation of the policy requires information on the local water availability, which usually varies with space and time. An earlier study reported seasonal and temporal changes in rainfall, with potential impacts on agriculture and livestock in the Gandaki River basin (Panthi *et al.* 2015). No research has yet described how changes in precipitation affect water availability. However, national water policy is concerned with the climate-induced challenges and highlights the need for further research.

Besides water availability, preserving the water environment and implementation of water pollution control strategies are equally important for ensuring the supply of good water quality, and the current water policy priorities polluter pay policies to water pollution controls. The polluter pay model, although a well-known method, has some practical limitations, such as bringing non-point pollution (agriculture) into the levying system. Furthermore, this system requires strict monitoring and enforcement for effective implementation (ADB 2008), which has yet to be developed.

Therefore, all adopted strategies must be carefully analysed and supported by detailed studies. A case study was carried out in Kaski District, Gandaki Province, Nepal, with the aim of providing inputs for decision makers to implement policies for water security at the local level. This work specifically focuses on (i) estimating water availability and demands, (ii) determining the water carrying capacity, expressed as the extent of socio-economic growth supported by the available water, (iii) establishing sectoral roles in water pollution, and (iv) providing policy measures for sustainable water supply and pollution control.

2. STUDY AREA

Kaski District is one of 77 districts of Nepal, situated in the Gandaki Province. It lies in central Nepal, part of the Gandaki River Basin (GRB). The basin is party snow fed, contains all agro-ecological zones of the country, and has a very diverse climate (Panthi *et al.* 2015), making it vulnerable to the impacts of climate change. Water resources management is crucial for a reliable water supply as this district is a popular tourist destination and has the largest metropolitan city in Nepal.

Geographically, the district lies 83 °40′ to 84 °12′ East longitude and 28 °06′ to 28 °36′ North latitude. It covers an area of 2,088.25 km^2, with an elevation of 450–8,091 masl. The district encompasses the country's largest metropolitan city, Pokhara-Lekhnath, and four rural municipalities of Rupa, Madi, Machhapuchhre, and Annapurna (Rimal *et al.* 2018) (Figure 1). Kaski District has a monsoonal climate that receives an average rainfall of 3,105.6 mm/year, averaged over 1975–2011. Approximately 80% of the total precipitation occurs in the monsoon season, June–September (Panthi *et al.* 2015). The Seti, Mardi, Madi, and Modi rivers (and their tributaries), as well as various lakes (Phewa, Rupa, Begnas, Dipang, Maidi), are the major water sources of this district (Rimal *et al.* 2018).

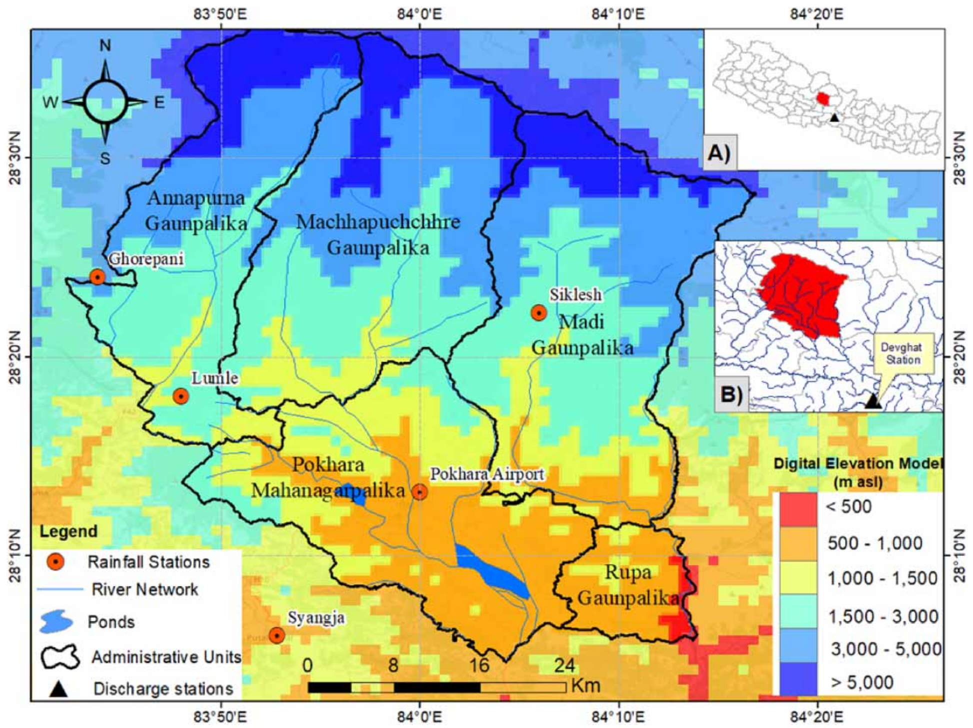


Figure 1 | Map of the study area of Kaski District in central Nepal. Inset (a) shows the study area location in Nepal and inset (b) shows a zoomed in version of the discharge station used for model calibration and validation (Devghat station represented by black triangle).

Water is abundant in this area; however, accessibility for domestic and agricultural use is still limited. For instance, Pokhara Metropolitan City (PMC), faces water supply shortages: as of 1971, PMC had a water supply of 6.5 and 3.4 million litres per day (MLD) in wet and dry seasons, respectively, against a demand for domestic water of 8.0 MLD. Similarly, in 2011, the average daily demand was 42.0 MLD, of which the Nepal Water Supply Corporation (NWSC) could supply 24.5 MLD in the wet season and 21.3 MLD in the dry season (NWSC 2011).

Agriculture dominates the local gross domestic product (GDP), contributing nearly 23% of the district GDP and providing 40.6% of the local employment (District Statistics Office: DSO 2017). Rice, maize, millet, wheat, and barley are the major cereal crops and apple, potato, bean, oil seed, and herbal products are the main cash crops. About 52% of the total cultivated land has access to irrigation, which is predominantly fed by surface water (rivers, lakes, and ponds), as per the national census of agriculture 2011–2012.

According to the manufacturing census 2011–2012, the district has 193 industrial establishments, engaging 4,205 employees and contributing 4.6% of the district GDP (DSO 2017). The district is popular with domestic and foreign tourists, and the tourism sector significantly boosts local socio-economic activities. It has a population of 492,098, per the 2011 Nepal census (DSO 2017). The district has experienced rapid urbanisation and attracts inter-district migration due to its abundant water resources, pleasant climate, better job opportunities, and easy access to services (Rimal *et al*. 2018).

To sustain the increasing socio-economic growth of the district, a reliable water supply must be ensured. Due to topographic, climatic, and socio-economic disparities, the ability of the water supply to sustain communities should be examined. The new Water Policy of Nepal promotes water resource management plans to be implemented at all levels of government: local, state, and federal. The Kaski District is used as a case study in this context, while the methods are applicable to other areas to analyse local water availability and pollution.

3. MATERIALS AND METHODS

3.1. Quantitative assessment of water availability

The total available water, water demand, and water carrying capacity, and their calculation methods are discussed in the subsequent sections.

3.1.1. Total available water

The Soil and Water Assessment Tool (SWAT) hydrological model can simulate a long period with varying watershed sizes, and has been widely used across Nepal by several researchers (e.g., Aryal *et al.* 2019; Pandey *et al.* 2020). The model was applied to estimate the total water availability for the GRB and then transferred to the entire Kaski District (study area) using Equation (1). The model was applied for the GRB since no hydrological station exists within the Kaski District, and this area has similar hydro-meteorological characteristics (Panthi *et al.* 2015). The input variables: rainfall, temperature, relative humidity, wind, digital elevation model (DEM), soil map, land use, and land cover were fed into the SWAT model to simulate the water availability for the baseline period (1992–2010). Water availability is expressed as an average monthly and annual basis. The average monthly was calculated in two steps, by first averaging each month over the baseline and projected years, and then, again, calculating the average over a year (i.e., 12 months). In contrast, the average annual availability of water was determined by calculating the average annual availability over the baseline year and future years.

For calibration and validation of the model, the simulated river discharge was then compared with the data obtained from the Department of Hydrology and Meteorology (DHM) Nepal for the baseline period. After successful calibration and validation, the water availability for the near-future (2022–2050) period was estimated. The spatial and temporal characteristics (e.g., type of variable, source, Spatio-temporal resolution, and time period of acquired data set) of the input variables used in the SWAT model are provided in Table 1. The future projection was carried out under RCP4.5 (medium) and RCP8.5 (high) emission scenarios as these are realistic scenarios and serve as a useful tool for quantifying physical climate risk (Schwalm *et al.* 2020). River discharge was then estimated by feeding the bias-corrected (quantile mapping) climate data (rainfall, temperature) into the developed hydrological model. A detailed description of the method is available in Aryal *et al.* (2019).

$$Q_{Kaski} = Q_{Gandaki}\left(\frac{P_{Kaski}A_{Kaski}}{P_{Gandaki}A_{Gandaki}}\right)^{n} \tag{1}$$

where Q, P, and A are the water availability (in MCM: million cubic metres), precipitation (mm) amount, and area (km^2), respectively, of the respective watershed boundaries, that ranges from 0.5 to 0.8 with an increase in unit time.

SWAT is a continuous semi-distributed time-dependent hydrological model to assess the impact of different factors on the watershed. The model is simple to use and suitable for small to medium-sized watersheds. It has been widely adopted to estimate water availability in many river basins in Nepal (Aryal *et al.* 2019; Pandey *et al.* 2020), and is commonly used worldwide, enabling estimation of all forms of water, that is, surface water, groundwater, and snow water (Equation (2)) in the form of river discharge.

$$SW_t = SW_o + \sum (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \tag{2}$$

where SW_t represents the final soil water content (mm), SW_0 represents the initial soil water content (mm), R_{day} represents the daily precipitation (mm), Q_{surf} represents the daily surface runoff (mm), E_a represents the daily evapotranspiration (mm), W_{seep} represents the amount of water entering the vadose zone daily (mm) and Q_{gw} represents the daily return flow (mm).

Table 1 | Spatial and temporal characteristics of data used in the SWAT model

SN	Data type	Source	Time period	Resolution
1	Rainfall	DHM, Nepal	1981–2010	Daily
2	Temperature	DHM, Nepal	1981–2010	Daily
3	Discharge	DHM, Nepal	1992–2010	Daily
4	Land use land cover	ICIMOD, Nepal	2010	30 m
5	Digital elevation model	SRTM	2010	30 m
6	Geological map	DoG, Nepal	2010	30 m

DHM, Department of Hydrology and Meteorology; ICIMOD, International Center for Integrated Mountain Development; SRTM, Shuttle Radar Topography Mission; DoG, Department of Geology.

Calibration and validation of the model were performed at the Devghat Station (Figure 1) in 1992–2007 and 2008–2010, respectively. Three statistical indicators: coefficient of determination (R^2), percentage of volumetric bias (PBIAS), and Nash–Sutcliffe efficiency (NSE) were examined for this purpose. Details of the calibrated parameter are provided in Table S1 of Supplementary Materials.

3.1.2. Total water demand

The total water demand is estimated from the domestic water demand and productive water demand.

3.1.2.1. Domestic water demand. Domestic water use varies between rural and urban residents. In this study, domestic water consumption at 100 per capita per day was used for urban residents, following the minimum water requirement of the 2003 national building code (Ministry of Physical Planning and Works: MoPPW 2003), and rural domestic water consumption of 45 L per capita per day, as per the rural water supply and sanitation national policy (MoPPW 2004). Higher daily water use for the urban areas is estimated due to additional use for sanitation such as toilets and gardening. The total population of 492,098 and national average urban and rural populations of 17.1 and 82.9%, respectively, were used to calculate the residents for each category (Central Bureau of Statistics: CBS 2014).

3.1.2.2. Productive water demand. Water used for major economic activities is expressed as productive water use. This includes agriculture and livestock (primary industries), manufacturing (secondary industries), and hotel and restaurants (tertiary industries). Agricultural water use (irrigated water) was estimated for the major crops (rice, wheat, maize, millet, and barley) as well as cash crops (potatoes, oilseeds, and beans). The water use (m^3/year) for major crops was determined by multiplying the blue water footprint (m^3 per ton) for each crop (Shrestha *et al.* 2013) and the respective crop yield (tons/year). The blue water footprint refers to the amount of irrigated water used in a unit of crop yield production (ton). These values are taken for the district level from Shrestha *et al.* (2013), and the total crop yield of the district was from district agriculture statistics. Total water use by livestock was calculated by taking the per capita cattle water use (daily drinking water and service water) (Mekonnen & Hoekstra 2010) and the total livestock population in the district. The number of beef cattle, buffalo, goats, pigs, fowl, and ducks, obtained from the district agriculture and livestock statistics, were included in the calculation.

The manufacturing sectors comprised 198 establishments and provided a total gross output value of 5,893 million Nepalese Rupee (NPR) in 2011. The sector engaged 4,268 employees, with 1,992 employed in the food industries, as per the manufacturing census of 2011–2012. Water use in this sector was determined based on water use coefficients per employee (Malla *et al.* 2019). Hotels and restaurants are the major water users in the emerging tourism sector. Water use values for hotels and restaurants were obtained by taking water use coefficients as 100 L per bed, guided by the national building code (MoPPW 2003), and 50 L per restaurant seat.

3.1.2.3. Ecological water demand. The ecological water demand refers to the quantity of water needed to sustain freshwater ecosystems. This is usually performed by analysing environmental flow requirements and a range of methods are available including hydrological, hydraulic rating, habitat simulation, and holistic methods, at a regional, national, or continental level. These methods all require a long-term data set and flow velocity. Pastor *et al.* (2013) identified that 37% of the annual discharge is a good representative to estimate the quantity of water needed to meet environmental flow requirements. In the absence of data, the global average of 37% of annual discharge was adopted to estimate the ecological water demand. This amount likely varies within the seasons but is an important basis for the estimation.

3.1.3. Water resources carrying capacity

Water resources are a limiting factor for socio-economic development. Water resources are under immense pressure with increasing socio-economic growth. Therefore, is important to ascertain the maximum socio-economic growth that can be sustained by the available water resources. The quantitative analysis of water resources is often expressed as the water resources carrying capacity (WRCC), which serves as a useful tool for sustainable development planning in relation to available water resources (Yang *et al.* 2015; Yan & Xu 2022). Several definitions and methods are employed in WRCC analyses, which are broadly grouped into three categories: background analysis, supply and demand balance analysis, and recursive dynamic simulation (Li *et al.* 2010).

Background analysis estimates the carrying capacity of a region by using a comparable area with similar natural and social background. The approach is limited to a static historical background analysis and cannot be used for a dynamic process analysis as it is too simplistic and unable to represent complex natural social–economic systems. The ‘supply–demand balance analysis’ approach is used to determine the water-use quotas based on the total amount of regional water resources, the available resources, and the demand for water. A recursive dynamic simulation method is employed to reveal the WRCC analysis through computer simulation with dynamic simulation and mathematical economic analysis (Li *et al.* 2010). The requirements and performance of the methods increase from the first to the third methods, that is, (i) background analysis method (ii) supply–demand balance method, and (iii) recursive dynamic simulation method

In this study, the supply and demand balance method was adopted, which is widely used due to its simplicity and less data-demanding nature. Equation (3), following Ming (2011), was used to express WRCC at the population (number) scale:

$$P = \frac{W_s - W_E + P_{RA}A_R/P_I - R_{AI}A_I}{R_{DU} \times r + R_{DA} \times (1 - r) + U_P/P_I} \tag{3}$$

where P is the water resource carrying capacity (WRCC), expressed in population; W_s is the water supply, that is, total available water (m^3); W_E is ecological water (m^3); P_{RA} is the unit area agricultural average output value (NPR)/ha); A_R is the area of agricultural production (ha); P_I is the average industrial output value of per unit water (NPR/m^3); R_{AI} is the agricultural water consumption standard of the effective irrigation area (m^3/ha); A_I is the agricultural effective irrigation area (ha); R_{DU} is the urban–domestic water consumption standard $(l/p/d)$; R_{DA} is the rural–domestic water consumption standard; U_P is the per-capita industrial and agriculture output value (NPR/cap); and R is the urbanisation rate (%).

3.2. Relationship between water pollution and economy

Besides availability, preserving water quality is becoming more challenging with the rise in socio-economic activities. Increasing water pollution has further challenged water scarcity issues. Water pollution has traditionally been investigated from a single category approach, which focuses on pollution from discrete economies, for instance, the textile industry, the food industry, hotels, and restaurants. However, this has not been effective in pollution control. The economy of a region consists of multiple sectors, interlinked through supply chains. Any changes in the demand of a sector (outputs) will directly influence other sectors’ economic demands. Thus, the environmental performance of sectors and water pollution needs to be analysed by going beyond a traditional approach, where the indirect roles of sectors, besides their direct pollution, should be considered. An environmentally extended input method was employed to establish water pollution and local economic activities for effective pollution control.

3.2.1. Environmentally extended input–output

Leontief’s input–output (I–O) model is conventionally used to describe the interconnections between sectors (Sanchez-Choliz 2003). The I–O model extended with environmental variables is increasingly used to couple the environmental and economy (Sánchez-Chóliz & Duarte 2005; Nguyen *et al.* 2018). In this study, the environmentally extended input–output (EEIO) method was used to analyse sectoral water pollution using biological oxygen demand (BOD) as a proxy water quality parameter. This method describes the dual roles of a sector as input supplier and receiver in the production process of an economy. Based on these roles, sectoral pollution is also distinguished into two categories: direct (i.e., a source of pollution) and indirect (i.e., a cause of pollution). Direct pollution is the pollutant load directly discharged by a sector in the production of total outputs that satisfy all demands, that is, the intermediate and final demands of an economy. In contrast, indirect pollution is the amount of pollutants discharged by a sector and other sectors to fulfill the inputs it requires. Unlike direct pollution, a sector’s indirect pollution is mainly caused by the inputs that they receive from the other sectors. This relationship is captured by the EEIO and assists decision makers in sustainable water pollution control policies.

Two sets of data, the I–O table and BOD discharge coefficient of sectors are required for the EEIO. The 2010–2011 national I–O table (26 × 26 sectors), was derived from the supply and use table (SUT) that originally consisted of 81 × 60 economic sectors from the ADB. The national I–O table was downscaled to the district level I–O table by employing the cross-industry location coefficient (CILC) method (Flegg *et al.* 1995). The revised I–O table was extended by adding the sectoral BOD discharge coefficient (kg/million NPR). The coefficient for manufacturing sectors was obtained from Chapagain *et al.* (2020), whereas other sectors were estimated indirectly by taking multiple pollution discharge variables. For example, the cultivated area and average BOD export coefficients from agricultural land were used to determine BOD loads from the agricultural sector, while BOD discharge of cattle farming (kg/day/cattle) and slaughtering activities (kg/tons of meat) from total cattle heads and meat quantity were used to determine the total BOD discharge from the livestock sector. For hotels and restaurants, total visitors and restaurant seats, together with BOD load per capita (visitor) per day and per seat were used. The computation of EEIO and extension of pollution loads in the conventional I–O is described in Chapagain *et al.* (2022).

A significant challenge of EEIO is the availability of data. This analysis is based on 2010–2011, I–O data, and the latest data will provide more accurate results. The extension of the I–O table was done by adding the BOD discharge intensity of the selected sector due to the widely used water quality indicator and relatively easy to estimate. However, it can be extended with other water quality parameters for characterising sectoral specific pollution. Therefore, developing pollution intensities for the large sector and the sub-sectoral levels and new water quality parameters will further strengthen such analyses.

4. RESULTS AND DISCUSSION

4.1. Quantitative assessment of water availability

4.1.1. Model calibration and validation

The hydrological model was calibrated and validated at the Devghat station of the Narayani River (Figure 2). Good model performance was demonstrated by a set of statistical indicators (Table 2), where the daily R^2 value was 0.90 for calibration and 0.88 for validation. The monthly R^2 was 0.96 and 0.95 for the calibration and validation, respectively. The daily PBIAS was +4.92% for calibration and −8.8% for validation, +4.95% for calibration and −0.09% for validation at the monthly scale, within the permissible limit (Aryal *et al.* 2019). Furthermore, NSE values for calibration (0.89 and 0.95) and validation (0.87 and 0.94) showed a good agreement of the model at both daily and monthly time scales.

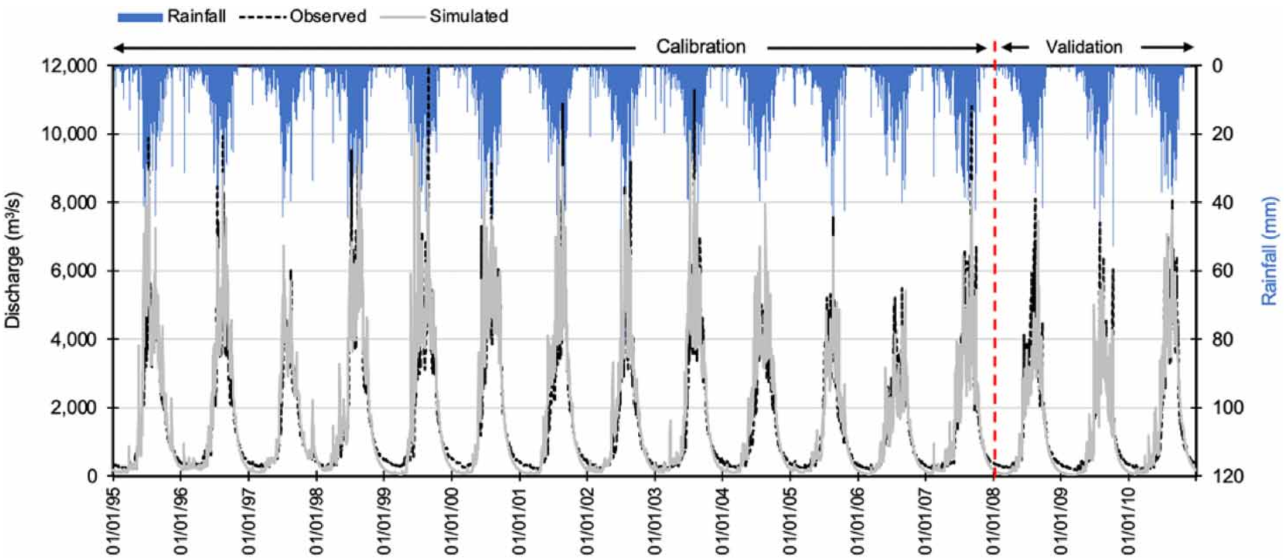


Figure 2 | Calibration and validation of SWAT at the Devghat station, Nepal.

Table 2 | Statistical performance of calibration and validation of the SWAT hydrological model

	Daily basis				**Monthly basis**				
Variable	R^2	**NSE**	**PBIAS**	**RSR**	R^2	**NSE**	**PBIAS**	**RSR**	**Performance**
Calibration	0.90	0.89	+4.92	0.33	0.96	0.95	+4.95	0.23	Very good
Validation	0.88	0.87	−8.8	0.35	0.95	0.94	−0.09	0.24	Very good

NSE, Nash–Sutcliffe efficiency; PBIAS, percentage of volumetric bias; RSR, root mean to square error (supply) to standard deviation (SD) ratio.

4.1.2. Total available water and its distribution

Total water availability under baseline and future emission scenarios is depicted in Figure 3. Monthly water availability in the baseline period was 12,152.1 MCM, while estimated availability was 16,951.6 MCM and 17,321.3 MCM under RCP4.5 and RCP8.5 emission scenarios, respectively. At the annual scale, average water availability for the baseline period was 11,030.7 MCM, while future projections were 7,677.4 MCM and 7,674.2 MCM under RCP4.5 and RCP8.5 emission scenarios, respectively. At the monthly time scale, water availability in the district increased by 4,799.5 MCM under the RCP4.5 emission scenario and by 5,169.2 MCM under the RCP8.5 emission scenario. This is likely due to the short-term effect of rising temperature, where accelerated melting takes place in the lower Himalayas. Such process is described as 'short seasons melting snow' and is considered to increase the stream flow for a short period of time (a month), and the effect is called as ice albedo feedback (Tandon 2021). However, at the annual scale, water availability was reduced by 3,353.3 MCM and 3,356.5 MCM under RCP4.5 and RCP8.5 emission scenarios, respectively.

The historical and projected monthly water availabilities are shown in Figure 4. Water availability increases during both high (June–September) and low flow periods (March and April), and also reduces during the remaining low flow period (November–February) under the RCP4.5 emission scenario. However, under the RCP8.5 emission scenario, water availability in the district is projected to reduce during the low flow period (October–December) and increase in the rest of the months (including both low and high flow months). It is interesting to observe that different scenarios are projected to have different water availability during the low flow period. Such variations are likely due to the use of a large number of climate models to simulate the future climate under the lack of complete knowledge of the climate system (Aryal *et al.* 2019; Maharjan *et al.* 2021). During the baseline period, the monthly water availability in the Kaski District ranged from 1,976 to 36,715.8 MCM, corresponding to January and August, respectively, while it ranged from 1,113.6 MCM (January) to 48,405.3 MCM (August) under the RCP4.5 emission scenario and from 3,256.3 MCM (January) to 41,349.0 MCM (August) under the RCP8.5 emission scenario. The intra-annual water availability varied from −43.6 to +102.6% under the RCP4.5 emission scenario and from −8.9 to +245.2% under the RCP8.5 emission scenario. Noticeably, high water availability is observed during high flow months in the future, likely due to short-term extreme precipitation. A slight reduction in water availability is projected to occur during November (−1.4%) under the RCP4.5 emission scenario and October (−8.9%) under the RCP8.5 emission scenario, which is likely caused by increased evaporation as a result of rising temperatures. In addition, the results show variation in the water availability in the study area under different emission scenarios. The water availability is reduced under the RCP8.5 emission scenario compared with the RCP4.5 emission scenario and increased when compared to the baseline period. The variation in the monthly water availability under the different emission scenarios is the result of the uncertainties in the climate models simulation (Pandey *et al.* 2020).

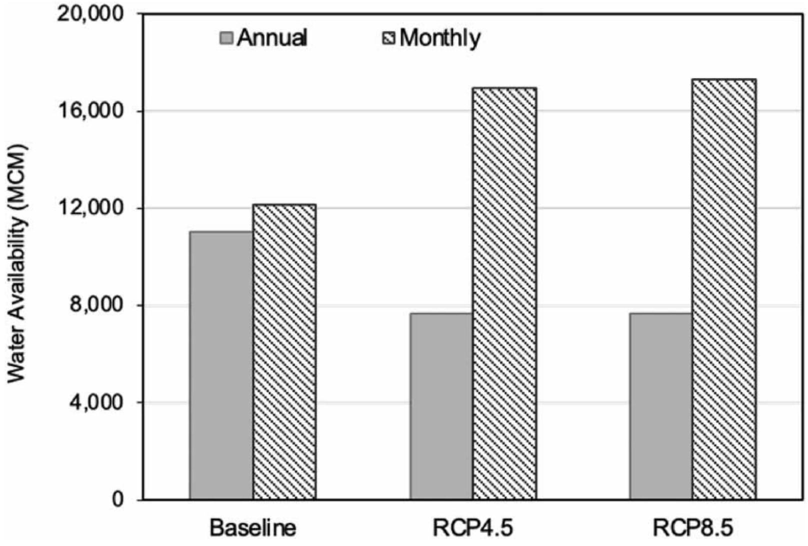


Figure 3 | The average annual and monthly water availability (MCM: million cubic metres) in Kaski District, Nepal, for a future period (2022–2050) under RCP4.5 and RCP8.5 emission scenarios compared with baseline (1992–2010).

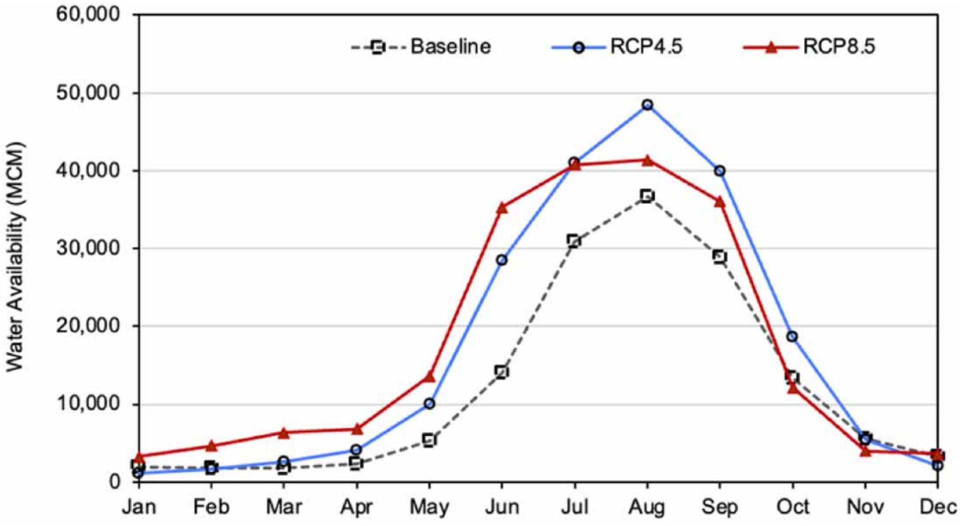


Figure 4 | Monthly water availability (million cubic metres) in Kaski District, Nepal, for baseline (1992–2010) and future (2022–2050) periods. For future periods, water availability is projected under RCP4.5 and RCP8.5 emission scenarios.

The inter-annual water availability for baseline and future periods is shown in Figure 5. Total water availability during the baseline period is declining at the rate of 11.9 MCM per year. In contrast, the annual water availability is increasing at the rate of +165.85 MCM and +35.55 MCM per year under RCP4.5 and RCP8.5 emission scenarios. However, mean annual water availability under RCP4.5 and RCP8.5 emission scenarios is projected to decrease by 35.44 and –31.83%, respectively, in comparison to the baseline period. The variability among the climate models is a plausible cause for the difference in the total water availability between the current and future scenarios. Moreover, the reduction in total water availability is also likely due to the melting snow across the Himalayas as a long-term effect, which in turn reduces the water supply, resulting in low water availability over time. Besides distinct wet and dry seasons pronounced under the climate change is also responsible to cause a high average monthly water availability than the annual average water availability.

4.1.2.1. Seasonal water availability. Future seasonal water availability shows an increasing trend compared with the baseline (Figure 6). Average water availability for the baseline period is 471.6 (December, January, February: DJF),

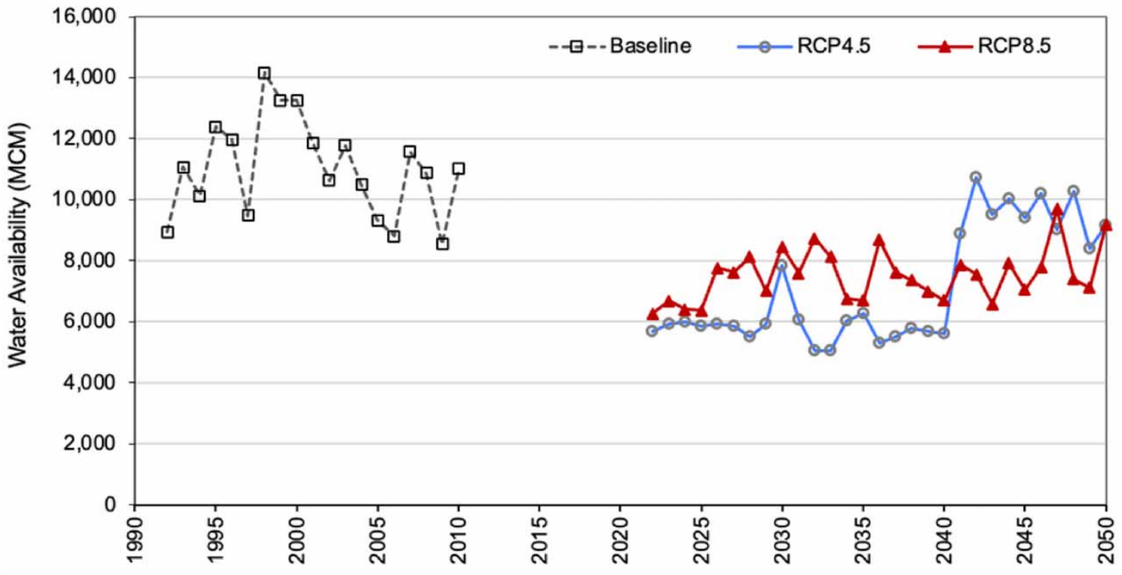


Figure 5 | Annual water availability (million cubic metres) in Kaski District, Nepal, for baseline (1992–2010) and future (2022–2050) periods under RCP4.5 and RCP8.5 emission scenarios.

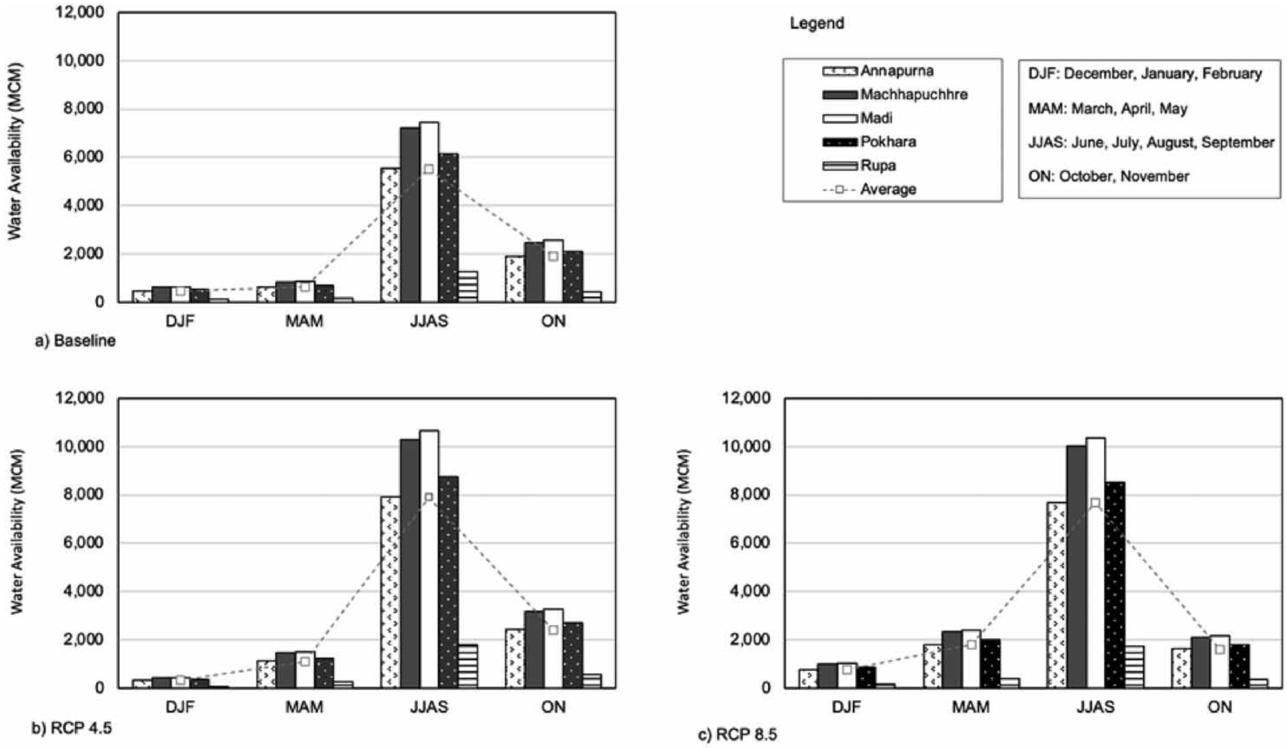


Figure 6 | Seasonal water availability in different administrative units for (a) baseline (1992–2010) and future (2022–2050) periods (b) under the RCP4.5 scenario and (c) the RCP8.5 scenario.

628.94 (March, April, May: MAM), 5,521.72 (June, July, August, September: JJAS), and 1,888.24 MCM (October, November: ON). For all seasons, Madi rural municipality has the highest water availability in the district, followed by Machhapuchhre rural municipality, which may be due to the high snow fed coverage area. Similarly, for all the seasons, Rupa rural municipality had the least water available in the district. The seasonal water availability ranged from 332.56 (DJF) to 7,887.95 MCM (JJAS), and from 770.81 (DJF) to 7,672.22 MCM (JJAS) under RCP4.5 and RCP8.5 emission scenarios, respectively. Numerous studies show the variability in seasonal water availability in different river basins of Nepal. They state that variation in precipitation and temperature contribute to future water availability in the study region. Research carried out in the Mahakali and Karnali River basin found that the annual discharge is projected to increase by 8.2% (2021–2045) and 6.4% (2040–2069), which corresponds to seasonal water availability.

4.1.2.2. Spatial water distribution. Aside from the seasonal variation, water availability also varies spatially within the district's administrative units (Figure 7). The average monthly water availability results show that Madi rural municipality has high levels of water availability (3,282.44 MCM), followed by Machhapuchhre rural municipality (3,177.09 MCM) in the baseline period. The monthly average water availability in PMC, Annapurna rural municipality, and Rupa rural municipality were 2,702.69; 2,437.17; and 5,52.71 MCM, respectively. In the high flow month (August), water availability among the administrative units ranged from 1,669.92 MCM (Rupa rural municipality) to 9,917.41 MCM (Madi rural municipality). In a low flow month (January), water availability among the administrative units ranged from 89.87 MCM (Rupa rural municipality) to 533.77 MCM (Madi rural municipality). Higher water availability was observed during the monsoon season in the northern regions of the district compared with the southern regions. The future spatial distribution of seasonal water availability is high at Madi and low in Rupa rural municipality. The large variation in spatial distribution needs to be addressed in the policies for equitable water distribution so that SDG targets are achieved.

The spatial change in future water availability (*provided in Figure S1 and Figure S2 of Supplementary Materials*) shows a reduction between November and February under the RCP4.5 emission scenario and between October and November under the RCP8.5 emission scenario. This change is projected to alter by −301.2 to +3,886.9 MCM under the RCP4.5 emission

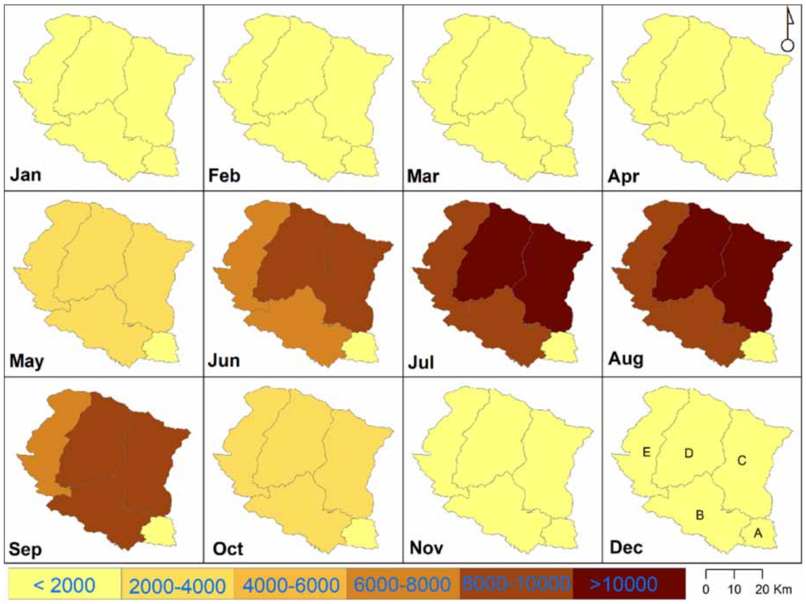


Figure 7 | Spatial distribution of monthly water availability (MCM: million cubic metres) for the baseline period (1992–2010). Here (A) Rupa Rural Municipality, (B) Pokhara Metropolitan city, (C) Madi Rural Municipality, (D) Machhapuchhre Rural Municipality, and (E) Annapurna Rural Municipality.

scenario and by −432.8 to +5,746.1 MCM under the RCP8.5 emission scenario. The maximum reduction is projected to occur in December in Machhapuchhre rural municipality, while the maximum increase is projected in June in Madi rural municipality under the RCP4.5 emission scenario. Similarly, under the RCP8.5 emission scenario, the maximum reduction and increase are projected to occur in Madi rural municipality in November and June, respectively. On average, the change in future water availability is projected to range from +962.6 to +1,296.4 MCM under the RCP4.5 emission scenario and from +235.1 to +1,396.3 MCM under the RCP8.5 emission scenario. The increase in the future water availability in the district might be attributed to the melting of ice and glaciers. Further, the future change in land use and the land cover pattern will also have a significant impact on water availability. Similar findings were found in a snow fed region of the Thuli Bheri River basin in Northwest of Nepal (Maharjan *et al.* 2021). The research clearly shows the Spatio-temporal variability in total water availability under climate change scenarios in the study site. Together with the national level, an appropriate water policy needs to be envisioned to cope with the challenges exerted by climate change at a local level.

4.1.3. Total water demand

Freshwater demand for various sectoral activities and domestic use in Kaski District is presented in Table 3. The agricultural sector is a major user that requires about 158.28 MCM, corresponding to 90.8% of the total water use. Agriculture requires a huge amount of water, and more than 80% of the population engages in agriculture in Nepal, accounting for 35% of the country's gross domestic product (Kong *et al.* 2019). The agricultural water demand will potentially increase with the expansion of irrigated land since the present coverage of irrigated land is about 52% of the total cultivated land (DSO 2017). At the same time, there is also increasing competition for water and the diversion of water for agriculture to domestic water use. Therefore, water allocation and management are crucial in this area.

Water use by livestock is estimated as 2.72 MCM. The manufacturing withdraws, which is about 0.33 MCM. The district contains 198 industrial establishments, with 4,268 employees, contributing 4.6% of the district's GDP in 2011–2012 (DSO 2017). The food and beverage industries are the major water-consuming industries, accounting (0.19 MCM) for more than half of the total water consumption of all the sectors. In the service sector, about 0.2 MCM water is utilised by hotels and restaurants annually. With rising socio-economic activities in the district, hotels, restaurants, and manufacturing sectors are growing rapidly, which is likely to increase the demand for water. Besides water quantity, there will be an increasing concern for maintaining high quality water while increasing the supply for domestic and industrial purposes.

Table 3 | Estimated water demand in the Kaski District

SN	Category	Water demand (MCM)	Variable
1	Domestic water	9.77	Total population: 492,098
	Rural residents	*3.07*	Urban population: 17.1%
	Urban residents	*6.70*	Rural population: 82.9%
2	Agriculture and livestock	161	
	Agriculture	*158.28*	Irrigated area: 12,182 ha
	Livestock	*2.72*	Beef cattle head: 70,340 Buffalo head: 118,683 Pig head: 9,123
3	Manufacturing industries	0.33	Number of establishments: 198 Number of employees: 4,268 Gross output: 5,892.5 (million NPR)
	Food industries	*0.11*	
	Beverage industries	*0.08*	
	Fabricated metal industries	*0.07*	
	Textile industries	*0.01*	
	Others	*0.06*	
4	Hotels and restaurants	0.20	Number of hotel beds: 7,240
5.	Ecological water	4,081	37% of the total annual water supply

4.1.4. Water carrying capacity

The WRCC was determined by Equation (3), using average annual water availability for the baseline period as input. The analysis determined the WRCC population to be 127 million, 254 times higher than the existing population of the Kaski District. This clearly shows that water is not a limiting factor for the socio-economic development of this district. The findings confirm that water is abundant in this region, and quantifies the extent of socio-economic growth that can be supported by the available water resources. These results can guide local water policies and provide an example of how a similar approach can be adopted in other parts of the country.

Despite the large WRCC, the current water supply for domestic and productive use is still limited in this case study. This situation is likely to be more pronounced with diverse seasonal and spatial variations in rainfall, and the wide range of inter-seasonal discharges, that is, high flow and low flow in the future. To ensure a consistent and reliable supply of water throughout the areas and seasons, water storage facilities are necessary. The Global Water Partnership: GWP (n.d.) reported that Nepal has one of the lowest dam storage capacities in Asia, and the country's water services are hindered by inadequate infrastructure and low investments. This study emphasises that investment in sustainable water infrastructure is necessary to ensure an adequate supply of water in the future.

4.2. Water pollution and economic sectors

A total of 30,049 tons of BOD was produced by economic activity in Kaski in 2011. Agriculture and livestock contributed the largest amount of direct BOD discharge (29,930 tons); 99.6% of the total discharge. The huge contribution of this sector is mainly due to its high BOD loading coefficient, and as a dominant sector in the local economy. The significant role of livestock is globally recognised; however, pollution levels vary with livestock farming methods and treatment practices (Wen 2016). Hotels and restaurants discharged 74.3 tons of BOD, the second largest BOD loading sector. Manufacturing sectors released 41.6 tons of BOD, among which, the food, textile, and paper industries produced a dominant share.

Apart from direct pollution, the indirect role of each sector in BOD production, either from itself or other sectors in acquiring its inputs was analysed. BOD distribution among major sectors in Kaski District is provided in Table S2 of the Supplementary Materials. Indirect pollution is often overlooked in conventional studies, however, evaluating a sectoral performance considering the supply chain is increasing in environmental planning. In Kaski District, agriculture had high indirect pollution, with 58.7% of the total BOD discharge (30,049 tons), followed by the manufacturing sector, and hotels and restaurants, responsible for 27.6 and 3.3% of total BOD, respectively.

The agriculture and livestock sector has a major role in pollution, being the highest contributor to both direct and indirect BOD discharge The high indirect BOD discharge of the sector reflects its heavy reliance on its own sector, characterising it as a self-polluting sector. On the other hand, the manufacturing sectors had a much greater role in BOD discharge indirectly, which was linked to the high dependence on other sectors for raw materials. Similarly, hotels and restaurants released 3.3% of the total BOD indirectly, much higher than the amount of BOD released directly. Since the sector relies on the agriculture and livestock sector and manufacturing industries for its inputs. Other service sectors such as transportation, finance, and administrative, contributed 10.4% of total BOD discharge indirectly, while their direct BOD discharge was much lower (0.002%).

The agriculture and livestock sector is the major water polluter in the district; however, most efforts concentrate on wastewater discharge from other sectors such as manufacturing industries, hotels, and restaurants. These results indicate that targeting manufacturing sectors by introducing stringent standards will not be sufficient for achieving a good water environment. Therefore, all economic activities, including both point and non-point polluters, should be targeted. Nepal's recent water resource policy (MoEWRI 2020) emphasises that the polluter pay policy complies with the discharge standards, while polluters are subjected to fees and penalties for not meeting these standards. The policy is widely used in wastewater discharge, however, it is not equally fair for all economic sectors. The study results show that agriculture and livestock are a major polluters, but the polluter pay model might be difficult to apply to this sector due to its non-point pollution nature. If the sector is brought under the criteria, and pollution fees are determined by estimating BOD loads based on their BOD discharge coefficient, it would not fair and competitive due to the much higher cost per unit sectoral output compared with the manufacturing and service sectors. Therefore, alternative strategies should be sought that encourage polluters to reduce their pollution loads. For agriculture and livestock, good agricultural practices and proper waste handling should be targeted. We recommend that policy should focus on turning livestock waste into compost or biogas, for which technical and financial assistance should be given. This EEIO analysis provides a backdrop for decision makers to consider several measures, being aware of the close link between agriculture and livestock to other sectors. For indirect water pollution, all economic activities should be looked at from a broad perspective and multiple measures should be opted in pollution control policies.

5. CONCLUSIONS AND POLICY RECOMMENDATIONS

This study explores current and future water availability and analyses the relationship between water pollution and the economy for sustainable water management in Kaski District, Nepal. Several new insights are presented which will contribute to the effective management of water resources. The average annual water availability for baseline periods was 11,030.7 MCM, while future predictions are 7,677.4 and 7,674.2 MCM under RCP4.5 and 8.5 emission scenarios, respectively. Annual water availability is projected to be reduced in the future, while the difference between high and low flows will be more pronounced. Water availability data were used for determining WRCC as a decision-making tool, in conjugation with water demands and socio-economic variables. The high WRCC demonstrates that water is not a limiting factor in this area in the near-future. However, due to declining water availability and more pronounced high and low flows in the future, investment in water storage facilities and adequate supply systems are recommended to ensure a reliable water supply.

Water pollution was investigated by coupling BOD discharge and sectoral activities, for both direct and indirect discharge. The agriculture and livestock sector was a major BOD polluter, accounting for 99.6% of the total BOD discharge, followed by hotels and restaurants, and manufacturing industries. The manufacturing sector and hotels and restaurants caused greater indirect pollution discharge compared with their direct BOD discharge, due to their high dependence on agriculture and livestock. Pollution controls must focus on the agriculture and livestock sector (i.e., major polluters), which is often ignored. The polluter pay policy is difficult to apply to major polluters as non-point pollution is harder to track and quantify. If the sector is brought into polluter pay criteria, then, considering their pollution per unit outputs, the fee will be very high, and may not be affordable. Better consideration of appropriate strategies for all sectors and sub-sectors in controlling water pollution is necessary, whereby policymakers must consider multiple control measures for specific sectors. For example, technological solutions such as turning livestock waste into biogas and animal feedstuffs, and providing technical and financial support to facilitate this, are necessary. Moreover, providing awareness and training to local farmers to opt for the right dose and mode of fertiliser application is helpful. In the case of wastewater from manufacturing industries and hotels and restaurants, clean technologies should be encouraged, and polluter pay policies with strict wastewater discharge standards could be employed. Sectors such as construction, transportation, and finance do not cause pollution directly, however, they cause significant water pollution indirectly. This provides a new avenue for decision makers to reconsider and expand pollution control measures, however, the addition of more water quality parameters and sub-sectoral levels will further enhance the analysis. We recommend similar studies representing large water basins and socio-economic activities to complement and foster the implementation of sustainable water resource management policies.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

ADB 2008 *Thailand: Capacity Building for Pollution Taxation and Resources Mobilization for Environmental and Natural Resources Sector-Phase II*. Technical Assistance Report 4667 THA, Bangkok, Thailand.

ADB 2020 *Transforming Urban–Rural Water Linkages Into High Quality Investment*. Asian Development Bank, Manila, Philippines.

Aryal, A., Shrestha, S. & Babel, M. S. 2019 Quantifying the sources of uncertainty in an ensemble of hydrological climate-impact projections. *Theoretical and Applied Climatology* **135** (1–2), 193–209.

CBS 2014 *Population Monograph of Nepal. Volume 1(Population and Dynamics)*. Government of Nepal, Central Bureau of Statistics, National Planning Commission Secretariat, Kathmandu, Nepal.

Chapagain, S. K., Mohan, G. & Fukushi, K. 2020 An extended input–output model to analyze links between manufacturing and water pollution in Nepal. *Water, Air, & Soil Pollution* **231** (12), 570.

Chapagain, S. K., Mohan, G., Rimba, A. B., Payus, C., Sudarma, I. & Fukushi, K. 2022 Analyzing the relationship between water pollution and economic activity for a more effective pollution control policy in Bali Province, Indonesia. *Sustainable Environment Research* **32** (1), 1–14.

DSO 2017 *Rural Municipality/Municipality's Profile of Kaski*. District Statistics Office, Pokhara, Nepal. [In Nepali].

Flegg, A. T., Webber, C. D. & Elliott, M. V. 1995 On the appropriate use of location quotients in generating regional input–output tables. *Regional Studies* **29** (6), 547–561.

GWP n.d. *The Post-2015 Development Agenda Nepal Stakeholder Perspectives on A Water Goal and its Implementation*. Global Water Partnership, Global Secretariat, Stockholm, Sweden.

Kong, B., Deng, W., Wang, Q. & Yu, H. 2019 Investigation and evaluation of agricultural water use in a least developed country–a case study in Koshi River basin, Nepal. *Water Policy* **21** (3), 658–675.

Li, X. G., Wei, X. & Lu, Y. D. 2010 Optimising the allocation of groundwater carrying capacity in a data-scarce region. *Water SA* **36** (4).

Maharjan, M., Aryal, A., Talchabhadel, R. & Thapa, B. R. 2021 Impact of climate change on the streamflow modulated by changes in precipitation and temperature in the north latitude watershed of Nepal. *Hydrology* **8** (3), 117.

Malla, R., Sapkota, A. & Prajapati, P. 2019 Estimation of water use coefficient for assessing industrial water demand of various industries of Kathmandu valley. *Journal of Environment Science* **5**, 21–26.

Mekonnen, M. M. & Hoekstra, A. Y. 2010 *The Green, Blue and Grey Water Footprint of Farm Animals and Animal Products, Value of Water Research Report Series No. 48*. UNESCO-IHE, Delft, The Netherlands.

Merz, J., Nakarmi, G., Shrestha, S. K., Dahal, B. M., Dangol, P. M., Dhakal, M. P., Dongol, B. S., Sharma, S., Shah, P. B. & Weingartner, R. 2003 Water: a scarce resource in rural watersheds of Nepal's middle mountains. *Mountain Research and Development* **23** (1), 41–49.

Ming, L. 2011 The prediction and analysis of water resource carrying capacity in Chongqing Metropolitan, China. *Procedia Environmental Sciences* **10**, 2233–2239.

MoEWRI 2020 *National Water Resources Policy-2077*. Ministry of Energy, Water Resources and Irrigation, Government of Nepal, Kathmandu, Nepal. [in Nepali].

MoPPW 2003 *Nepal Building Code, NBC 208*. Ministry of Physical Planning and Works, Government of Nepal, Kathmandu, Nepal.

MoPPW 2004 *Rural Water Supply and Sanitation National Policy & Rural Water Supply and Sanitation National Strategy 2004*. Ministry of Physical Planning and Works, Government of Nepal, Kathmandu, Nepal.

Nguyen, H. T., Aviso, K. B., Kojima, N. & Tokai, A. 2018 Structural analysis of the interrelationship between economic activities and water pollution in Vietnam in the period of 2000–2011. *Clean Technologies and Environmental Policy* **20** (3), 621–638.

NWSC 2011 *Management Information Report*. Nepal Water Supply Corporation, Pokhara, Nepal.

Pandey, C. L. 2021 Managing urban water security: challenges and prospects in Nepal. *Environment, Development and Sustainability* **23** (1), 241–257.

Pandey, V. P., Dhaubanjar, S., Bharati, L. & Thapa, B. R. 2020 Spatio-temporal distribution of water availability in Karnali-Mohana Basin, Western Nepal: climate change impact assessment (Part-B). *Journal of Hydrology: Regional Studies* **29**, 100691.

Panthi, J., Dahal, P., Shrestha, M., Aryal, S., Krakauer, N., Pradhanang, S., Lakhankar, T., Jha, A., Sharma &, M. & Karki, R. 2015 Spatial and temporal variability of rainfall in the Gandaki River Basin of Nepal Himalaya. *Climate* **3** (1), 210–226.

Pastor, A. V., Ludwig, F., Biemans, H., Hoff, H. & Kabat, P. 2013 Accounting for environmental flow requirements in global water assessments (preprint). *Hydrology and Earth System Science Discussions* **10**, 14987–15032.

Rimal, B., Zhang, L., Keshtkar, H., Sun, X. & Rijal, S. 2018 Quantifying the spatiotemporal pattern of urban expansion and hazard and risk area identification in the Kaski District of Nepal. *Land* **7** (1), 37.

Sanchez-Choliz, J. 2003 Analysing pollution by way of vertically integrated coefficients, with an application to the water sector in Aragon. *Cambridge Journal of Economics* **27** (3), 433–448.

Sánchez-Chóliz, J. & Duarte, R. 2005 Water pollution in the Spanish economy: analysis of sensitivity to production and environmental constraints. *Ecological Economics* **53** (3), 325–338.

Schwalm, C. R., Glendon, S. & Duffy, P. B. 2020 RCP8. 5 tracks cumulative CO2 emissions. *Proceedings of the National Academy of Sciences* **117** (33), 19656–19657.

Shrestha, A. B. & Aryal, R. 2011 Climate change in Nepal and its impact on Himalayan glaciers. *Regional Environmental Change* **11** (1), 65–77.

Shrestha, S., Pandey, V. P., Chanamai, C. & Ghosh, D. K. 2013 Green, blue and grey water footprints of primary crops production in Nepal. *Water Resources Management* **27**, 5223–5243.

Tandon, A. 2021 *Carbon Brief: Climate Change has Driven 16% Drop in 'now Meltwater' From Asia's High Mountains*. Available from: https://www.carbonbrief.org/climate-change-has-driven-16-drop-in-snow-meltwater-from-asias-high-mountains/ (accessed 16 June 2022).

UN 2014a *Interaction Decade for Action 'WATER FOR LIFE' 2005–2015*. Available from: https://www.un.org/waterforlifedecade/scarcity.shtml (accessed 16 January 2022).

UN 2014b *Interaction Decade for Action 'WATER FOR LIFE' 2005–2015*. Available from: https://www.un.org/waterforlifedecade/asia.shtml (accessed 16 January 2022).

UNEP 2011 In: *Decoupling Natural Resource use and Environmental Impacts From Economic Growth, A Report of the Working Group on Decoupling to the International Resource Panel* (Fischer-Kowalski, M., Swilling, M., von Weizsäcker, E. U., Ren, Y., Moriguchi, Y., Crane, W., Krausmann, F., Eisenmenger, N., Giljum, S., Hennicke, P., Romero Lankao, P., Siriban Manalang, A. & Sewerin, S., eds). United Nations Environment Programme, Nairobi, Kenya.

UN-Water 2021 *Summary Progress Update 2021: SDG 6—Water and Sanitation for all*. UN Water Technical Advisory Unit, Geneva, Switzerland.

Upadhyay, S. N. & Gaudel, P. 2018 Water resources development in Nepal: Myths and realities. *Hydro Nepal: Journal of Water, Energy and Environment* **23**.

Wen, Y., Schoups, G. & van de Giesen, N. 2017 Organic pollution of rivers: combined threats of urbanization, livestock farming and global climate change. *Scientific Reports* **7** (1), 43289.

Yan, B. & Xu, Y. 2022 Evaluation and prediction of water resources carrying capacity in Jiangsu Province, China. *Water Policy*. Uncorrected proof. doi: 10.2166/wp.2022.172.

Yang, J., Lei, K., Khu, S. & Meng, W. 2015 Assessment of water resources carrying capacity for sustainable development based on a system dynamics model: a case study of Tieling City, China. *Water Resources Management* **29** (3), 885–899.

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