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Untangling the water-food-energy-environment nexus for global change adaptation in a complex Himalayan water resource system

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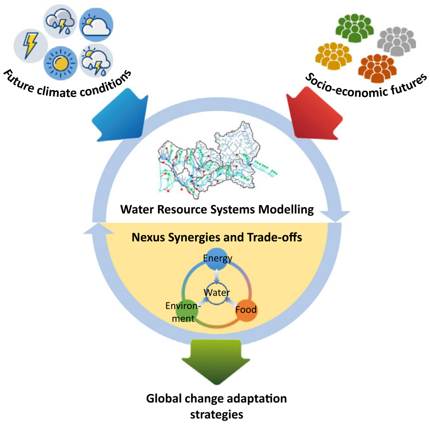
HIGHLIGHTS

- Water resource systems model is combined with nexus analysis.
- Socio-economic impacts on nexus components are greater than climate change.
- Complex scenario-specific synergies & trade-offs stress benefits of systems models
- Achieving balanced nexus components supports multiple SDGs.

GRAPHICAL ABSTRACT



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ABSTRACT

Holistic water management approaches are essential under future climate and socio-economic changes, especially while trying to achieve inter-disciplinary societal goals such as the Sustainable Development Goals (SDGs) of clean water, hunger eradication, clean energy and life on land. Assessing water resources within a water-food-energy-environment nexus approach enables the relationships between water-related sectors to be untangled while incorporating impacts of societal changes. We use a systems modelling approach to explore global change impacts on the nexus in the mid-21st century in a complex western Himalayan water resource system in India, considering a range of climate change and alternative socio-economic development scenarios. Results show that future socio-economic changes will have a much stronger impact on the nexus compared to climate change. Hydropower generation and environmental protection represent the major opportunities and limitations for adaptation in the studied system and should, thereby, be the focus for actions and systemic transformations in pursue of the SDGs. The emergence of scenario-specific synergies and trade-offs between nexus

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component indicators demonstrates the benefits that water resource systems models can make to designing better responses to the complex nexus challenges associated with future global change.

1. Introduction

In a context of rapid human development, in which water demands grow and diversify, the management of water resource becomes increasingly complex. The environmentally sustainable use of water has gained importance as a key requirement to protect future generations' access to reliable and safe water resources, thereby contributing to Goal 6 of the Sustainable Development Goals (SDGs) (United Nations, 2015). On the other hand, ensuring water supply for other uses such as irrigation and energy production is essential to achieving SDGs 2 (zero hunger) and 7 (affordable and clean energy).

Making water available in space and time for often competing water uses requires holistic approaches that account for all human needs and the protection of the environment as inextricably dependent variables (Cao, 2006; Bakker, 2012; Giupponi and Gain, 2017a). Many paradigms have been used to support water management that considers the interlinkages between all sectors (Gupta et al., 2013; Giupponi and Gain, 2017b). Integrated water resource management (Global Water Partnership, 2000) pursues multi-purpose management to maximise economic and social welfare by jointly managing land and water, but fails to represent interactions among sectoral policies (Hoff, 2011; Benson et al., 2015). It is widely recognised that agricultural policies have an impact on water and energy use; energy production strategies determine the amount of water (and food – i.e. biofuels) used to produce energy; water management defines the energy required to withdraw, transport and treat water; and environmental policies establish the limits to the use of natural resources and waste disposal for any economic activity. The water-food-energy (-environment) nexus accounts for these multiple relationships and considers water as a cross-cutting issue rather than a sector (Hoff, 2011; Gupta et al., 2013).

Future climate change jeopardises stability and sustainability of water supply (Azhoni et al., 2018; Flörke et al., 2018; Koutroulis et al., 2018). Not only will the hydrological balance be impacted, but environmental and social changes will also change the way water is used by different sectors. Thus, it is important to analyse both future climate and socio-economic changes (hereinafter called global change), considering their inherent uncertainty, to improve water security under global change through effective and robust water management alternatives (Holman and Trawick, 2011; Koutroulis et al., 2018). The nexus concept may be especially useful in that regard, helping to understand the conflicts and synergies between the different sectors, and supporting the design of water management adaptation measures that avoid sectoral approaches which can increase risk in other sectors (Rasul and Sharma, 2016).

Addressing the complex connections among nexus components (i.e. water, food, energy and environment) requires tools capable of representing the natural and social systems (Karabulut et al., 2016; Mohtar and Daher, 2016; Cai et al., 2018) and generating indicators that summarise nexus components, which are relevant for the studied system, meaningful for stakeholders, and enable the analysis of synergies and trade-offs. Water resource systems modelling platforms, such as WEAP (Yates et al., 2005a), MIKE-BASIN (DHI, 2011) and AQUATOOL (Andreu et al., 1996) have been used to address multi-sectoral water allocation problems including the environment (Sulis and Sechi, 2013) in numerous application across the world (e.g. Yates et al., 2005b; Labadie and Fontane, 2007; Medellín-Azuara et al., 2009; Sechi and Sulis, 2010; Meijer et al., 2012; Paredes-Arquiola et al., 2014; Chinnasamy et al., 2015). While many studies focus on climate change impacts on the water supply to different sectors (Booij et al., 2011; Sharma and De Condappa, 2013; Santos et al., 2015; Hernández-Bedolla et al., 2017) and test several water management adaptation policies (Kahil et al., 2015; Bhave et al., 2018), few studies comprehensively incorporate the influence of socio-economic changes on the system functioning (Vollmer et al., 2016) and nexus interrelations. Amin et al. (2018) project drinking water demands based on differing assumptions about population growth and change in living standards, but do not consider changes in other sectors. Höllermann et al. (2010) and Bhave et al. (2018) include future changes in several socio-economic sectors but focus on the performance of the water resource systems from a global water supply perspective without detailed consideration of inter-sectoral synergies and trade-offs.

The objective of the study is to develop and test a comprehensive framework for the analysis of the impacts of global change on the water-food-energy-environment nexus to support the development of adaptation policies for water resource management, using consistent future climate and socio-economic narratives for all relevant sectors, and accounting for their uncertainty. We use a systems modelling approach, implemented within the Water Evaluation and Planning System (WEAP) model, to simulate the effect of future climate and socio-economic changes under a wide range of combined scenarios. A set of indicators is proposed to untangle the existing synergies and trade-offs among nexus components and to provide the basis for improved decision making. The framework is tested for mid-21st century global change projections in a complex western Himalayan water resource system, which combines large irrigation and hydropower water demands with sparse drinking water supply infrastructures, and meltwater- and monsoon-driven hydrology.

2. Material and methods

2.1. Study area

The Beas and Sutlej river basins from their sources, in the western Himalayas and the Tibetan Plateau respectively, to their confluence define our study area. The total area of the system is around 76,400 km^2 (18,000 km^2 in Beas and 58,400 km^2 in Sutlej basin), of which 34,100 km^2 are in the Indian states of Himachal Pradesh and Punjab, and 42,300 km^2 in the Tibet Autonomous Region, China (Fig. 1). Elevations range from 160 m above sea level (masl) to almost 7500 m asl, with 50% of the system lying above 4700 m asl. The Tibetan and the upper Indian part of the basins are mainly covered by grassland and unvegetated steeply sloping land. The central parts of the basins have steep slopes that reduce downstream, with dense forests at the foothills and rainfed cropland in the valleys. The downstream part of the system is much flatter and covered almost entirely with irrigated cropland and some urban conurbations. Soils are young and thin in most of the study area, but gain depth in areas with gentle slopes.

The study area is influenced by the Westerlies that contribute to snow accumulation at medium to high elevations (above 2000 m asl) during winter, while in summer the Indian monsoon provides most of the annual rainfall (Bookhagen and Burbank, 2010). However, these climate phenomena weaken over the Tibetan Plateau, as the Himalayan crest acts as an orographic barrier, resulting in a much drier climate (Wulf et al., 2016). Thus, the average annual precipitation in the Tibetan Sutlej basin amounts only to 250 mm, while it is around 1200 mm in the Indian part. The corresponding value is 1500 mm in the Beas basin. The elevation gradients also cause significant spatial variability in the temperature, which decreases with elevation at a rate around 0.65 °C/100 m (Jain et al., 2008), producing a range of mean annual temperatures from −22.2 °C to 23.3 °C.

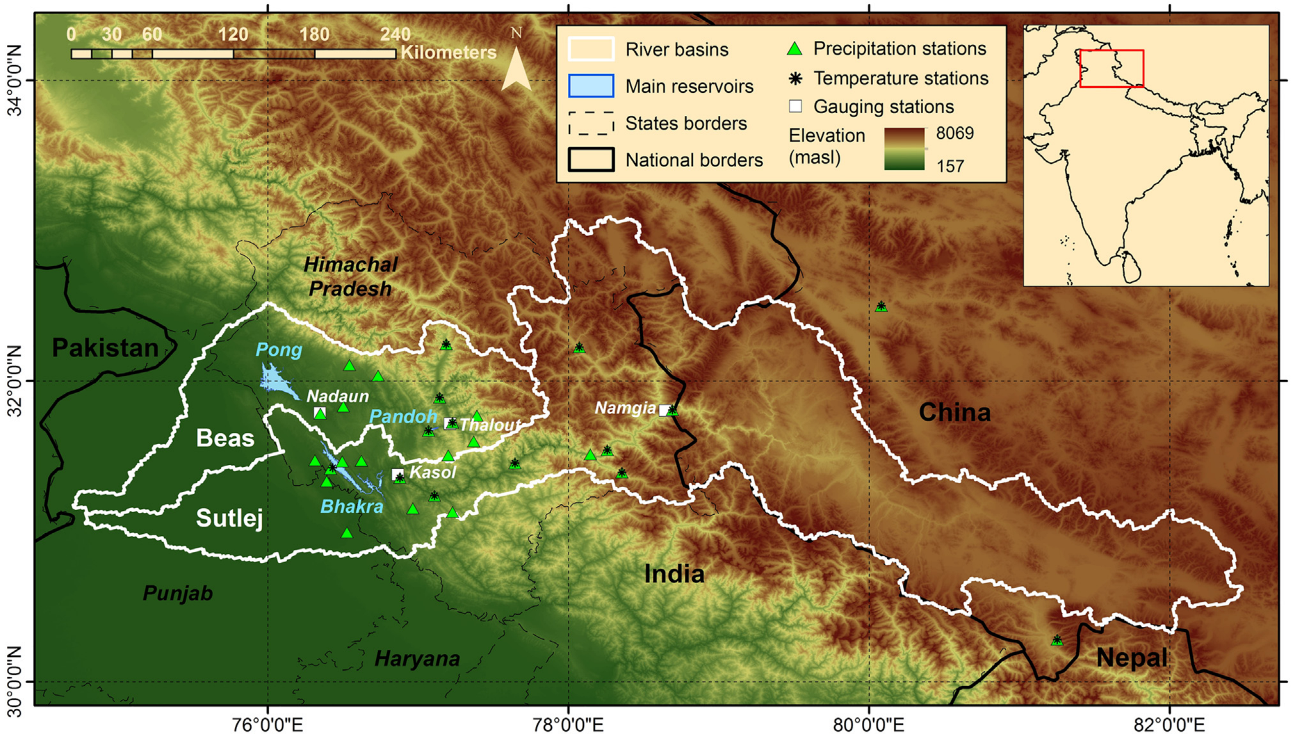


Fig. 1. Beas and Sutlej river basins (delineated with GIS tools), climate and flow monitoring networks (National Institute of Hydrology Roorkee), main reservoirs (official shapefiles; National Institute of Hydrology Roorkee), national (Bjorn Sandvik; thematicmapping.org) and regional borders (GADM version 1.0; gadm.org), and topography (Digital Elevation Model from the Shuttle Radar Topography Mission; Jarvis et al., 2008).

The hydrological regime is highly seasonal. Low flows occur in winter when precipitation falls mostly as snow. With warmer temperatures around March–April, flows start to increase due to snowmelt. Over summer, as seasonal snowpack is depleted, glacier melt starts contributing to runoff which occurs concurrently with monsoon rainfall, bringing about the highest river discharges. This flow pattern is less marked in the Tibetan part of the study area, but the timing is similar.

Water management in the system is multipurpose. Two large reservoirs downstream of the Himalayas, Bhakra and Pong (with storage capacities of 8815 Mm^3 and 8585 Mm^3 respectively), are managed to supply water downstream for irrigation (mainly to the Punjab plains and other nearby states), for hydropower generation, and for the abatement of high summer flows. Of the 12,763 Mm^3 mean annual runoff yielded by the Beas basin upstream Pong reservoir only 8485 Mm^3/year actually flows into the reservoir, as 4278 Mm^3/year is transferred from the Pandoh dam, located in the middle reaches of the Beas (see Fig. 1), to the Sutlej River for hydropower production. Bhakra reservoir receives around 16,354 Mm^3/year, which include the Sutlej runoff and the water transfer. Average annual releases from Bhakra and Pong to supply irrigation demands are around 10,318 Mm^3 and 7913 Mm^3, respectively. The population is mostly concentrated in the downstream plains, and their domestic water needs represent a small fraction of the total water demand.

2.2. General framework for global change impact analysis and adaptation

The proposed framework (Fig. 2) uses the water resource systems modelling approach as its central element to, firstly, assess the range of impacts of climate change on hydrology under several future climate scenarios and, secondly, analyse the range of impacts of global change by combining the climate change scenarios that generated the most extreme hydrologic conditions (driest and wettest) in the previous step with a set of socio-economic scenarios. The final model outcomes show the range of impacts of global change on all sectors of the system which are used to derive indicators that represent each nexus component. Finally, the resulting indicators are assessed to uncover the synergies and trade-offs among water-related sectors that will inform water management adaptation measures.

2.3. Systems model and data

The Water Evaluation and Planning System (WEAP; Yates et al., 2005a) is a generalised simulation model for the analysis of water resource systems, which solves multi-sectoral water allocation problems based on demand priority and supply preferences. It represents different water sources (i.e. surface water, including snow and glacier runoff, and groundwater), water demands (i.e. urban, hydropower, irrigation and environmental flows) and how they are related by means of water infrastructures (i.e. reservoirs, canals and wells). For detailed information about WEAP capabilities and equations refer to Seiber and Purkey (2015). Fig. 3 shows the elements included in the WEAP model of the study area, which have been refined through consultation with key local stakeholders, and are described in detail below.

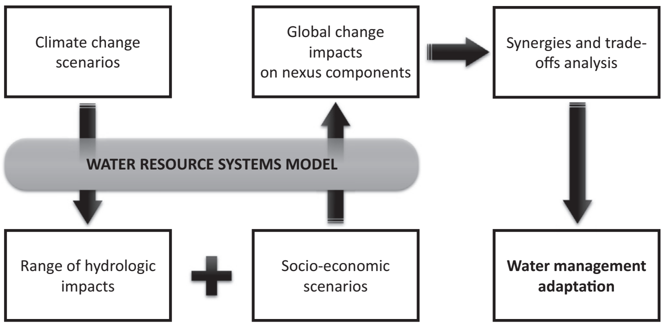


Fig. 2. Framework for global change impact analysis combining water resource systems modelling and water-food-energy-environment nexus approaches.

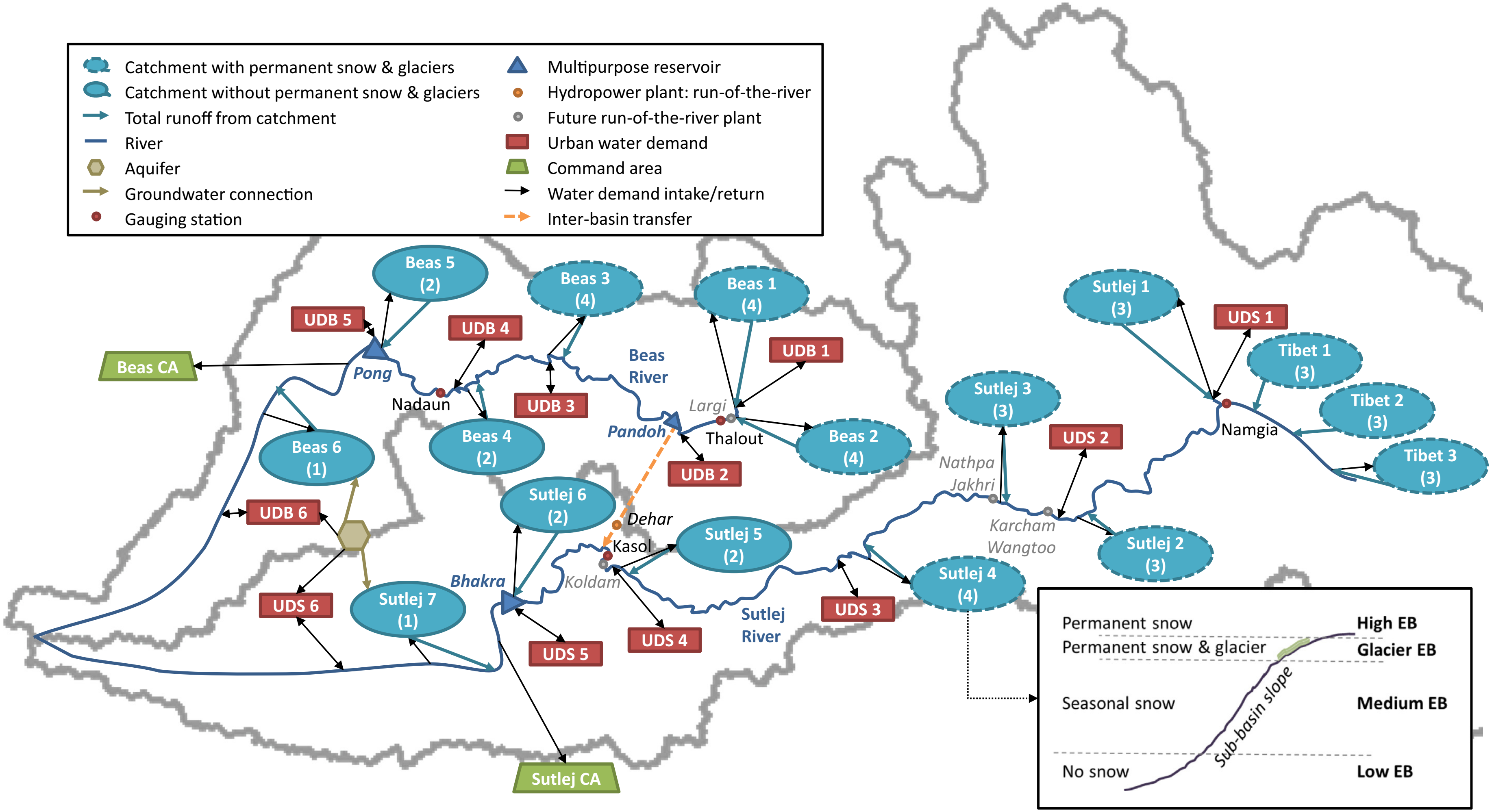


Fig. 3. Conceptualisation of the study area and subdivision of catchments into elevation bands (number of elevation bands per catchment shown in brackets).

Catchments (represented as ellipses in Fig. 3) are defined according to the availability of river flow gauging stations, the location of main water management infrastructures and a balanced spatial discretisation of the study area. In order to represent the variability of meteorological inputs and hydrological processes with elevation, catchments are subdivided in two to three elevation bands depending on their elevation range, informed by historical snow cover maps from MODIS (MOD10A1). Glaciers are considered separately to snow-covered areas in relevant catchments to model their temporal evolution (Fig. 3), with average elevation, area and initial depth of glaciers in each catchment obtained from unpublished work and expert judgement. Each elevation band is represented as an individual element that contributes to the river flows and receives water from the river for irrigation, if needed. Meteorological, land cover and soil data are entered for each elevation band in each catchment, and total runoff is calculated using the two-compartment soil water balance (Yates et al., 2005a). The upper compartment simulates evapotranspiration based on the Penman-Monteith equation and crop/vegetation coefficients (Allen et al., 1998; Howes et al., 2015) and considering rainfall (and irrigation on agricultural land), runoff, interflow and soil moisture variation. Base flow and soil moisture changes are simulated in the lower compartment.

Precipitation and temperature data were collected from the Bhakra Beas Management Board for 27 weather stations in India, and from the China Meteorological Administration for 2 stations in China. Relative humidity and wind gridded data were obtained from the NASA Science Mission Directorate's Satellite and Re-analysis research programs SSE Release 6.0 (https://asdc-arcgis.larc.nasa.gov/sse/). Cloudiness fraction, calculated as the fraction of daytime hours with no clouds, was derived from sun duration available at some weather stations. Meteorological inputs were extrapolated to each elevation band from the closest station or as the average of overlapping grid cells. Additionally, seasonal temperature lapse rates are used to extrapolate temperatures to each elevation band according to Jain et al. (2008), while a fixed precipitation gradient of 0.026 mm/100 m is used (Hegdahl et al., 2016). The ESA CCI Land cover product (Hollmann et al., 2013) for 2000 and the Digital Soil Map of the World (Land and Water Development Division - FAO, 2003) are used to describe the spatial variability of vegetation and soil characteristics.

Regarding socio-economic data, urban water demands (rectangles in Fig. 3) were obtained at district scale combining population – as per the Census of India of 1991 (Ministry of Home Affairs, 2011) – and daily consumption per capita – 40 l and 135 l in rural and urban areas, respectively (Water Aid India, 2005). Irrigation demands are calculated by WEAP in the catchments containing agricultural land based on the soil moisture deficit. Irrigation supplies via canals to downstream Command Areas (CA) outside of the catchment boundaries (Sutlej CA and Beas CA in Fig. 3) are estimated through calibration of the simulated releases from Bhakra and Pong reservoirs. Data on hydropower plants, water transfers and the main reservoirs has been obtained from the Beas Bhakra Management Board, augmented by the Water Resources Information System of India (www.india-wris.nrsc.gov.in). Those hydropower plants built after the end of the baseline period (June 1987–May 2007) are only active in the model in future scenarios. Groundwater extraction for irrigation and drinking water supply is considered in the plains of Sutlej and Beas rivers (i.e. in catchments Sutlej 7 and Beas 6, and urban demands UDS 6 and UDB 6 in Fig. 3) as an alternative source to surface water.

The model was calibrated and validated against measured discharge at four gauging stations and measured water storage in Bhakra and Pong reservoirs using Nash-Sutcliffe Efficiency (NSE), Pearson's correlation coefficient (R), and Percent bias (PBIAS) as performance indicators for different periods from 1987 to 2007 (Table SM1) depending on data availability. The period from June 1985 to May 1987 was used for warm-up to remove the effect of the initial conditions. A monthly time step was selected in the simulations which covers the concentration time of the study area – around 12 days in winter and 6 days in summer (Wulf et al., 2016) – and ensures that water balances are met in the system nodes at every time step.

2.4. Climate change scenarios

Climate change impacts are analysed for the mid-21st century, as it spans the long-term planning horizon usually considered by water industry and regulators (Alsharhan and Wood, 2003) and allows glacier area to be assumed to be constant in the north western Himalayas (Bolch et al., 2012). To express the climate change uncertainty, the 25th, 50th and 75th percentiles of temperature and precipitation seasonal projections for the Tibetan Plateau and South Asia from an ensemble of 42 CMIP5 global climate models (GCMs) for the Representative Concentration Pathway (RCP) 4.5 emissions scenario in 2065, as presented in the IPCC 5th Assessment Report (Christensen et al., 2013), were considered (see Table SM2 for details on the projections of precipitation and temperature). All combinations of the three percentiles of seasonal projected changes in precipitation and temperature are applied to the baseline monthly time series to generate a set of nine climate change (CC) scenarios (Table 1) for the time-slice 2055–2075 (20-year period around 2065), representative of a wide GCM uncertainty range and partially capturing temperature and precipitation changes consistent with RCP2.6 and RCP6.0 (Fig. 4). WEAP simulations are initially performed with all nine CC scenarios, and those that are identified as the most extreme in terms of producing the minimum and maximum mean annual runoff generated upstream Pond and Bhakra reservoirs are selected for the next stage of the analysis, which concerns the joint implementation of projected climate and socio-economic changes. This reduces the computational load and facilitates the analysis of results while ensuring that the range of uncertainty in future water availability in the system is covered.

2.5. Socio-economic scenarios

The socio-economic changes implemented in our modelling framework are based on selected Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2017). Specifically, SSP1 (Sustainability), SSP2 (Middle of the Road) and SSP5 (Conventional Development) are analysed. These SSPs are selected to account for a range of uncertainty associated with the future evolution of economic and social patterns while also having a narrative consistent with the RCP4.5 emission scenario. With this scenario combination a range of plausible futures is explored that captures low to medium challenges for climate change adaptation and low to high challenges for mitigation (O'Neill et al., 2014). SSP3 (Fragmentation) is excluded from the analysis as it is more relevant to high-end climate change scenarios (Hanasaki et al., 2013). SSP4 (Inequality) is also excluded, as it is less representative at the catchment scale (due to its main characteristic being the inequalities between developed and developing countries).

SSPs are represented in WEAP through the modification of key variables which define water demands (Table 2). The changes projected for

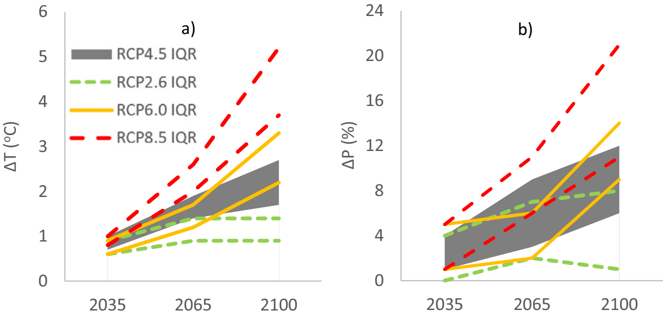


Fig. 4. Interquartile range (IQR) of RCP4.5 and its comparison with IQR of RCP2.6, 6 and 8.5, for (a) temperature and (b) precipitation.

Table 1
Climate change scenarios considered by combination of projected 25th, 50th and 75th percentile changes in precipitation (ΔT) and temperature (ΔP) by 2065 with respect to the baseline period.

	ΔP 25th	ΔP 50th	ΔP 75th
ΔT 25th	CC1	CC2	CC3
ΔT 50th	CC4	CC5	CC6
ΔT 75th	CC7	CC8	CC9

the mid-21st century are applied uniformly along the period 2055–2075. National (or regional, where national data are not available) data on population, crop land, and hydropower demand evolution per SSP are acquired from the IIASA database (Riahi et al., 2017). Per capita water consumption and irrigated area per SSP are projected from the global model results of SSP municipal water demand and irrigated area from Hanasaki et al. (2013). The socio-economic input variables bring a systemic approach to the analysis, as they have been produced considering the nexus interdependencies of the different variables according to the SSP narratives (Samir and Lutz, 2014; Riahi et al., 2017). Socio-economic changes are also reflected in the WEAP variables of environmental flows and flood abatement capacity through interpreting the SSP narratives (Table 2). For example, in SSP1 which is characterised by high environmental awareness, an environmental flow regime downstream Pandoh is imposed based on the monthly average flows series upstream in which each monthly value is reduced to the nearest lower quartile of the upstream flow series in order to keep the main characteristics of the hydrograph (Acreman, 2016). In contrast, in SSP5 which is associated with increasingly intensive agriculture and management of water systems and a lack of environmental concern, we consider that environmental flow requirements will be set at a minimum flow regime. In the case of flood abatement, SSP1 favours natural flood management (i.e. afforestation of sparse vegetation or grassland areas) whereas SSP5 adopts infrastructure-based measures focused on increasing the abatement storage in Bhakra and Pong reservoirs.

The most notable changes in SSP1 with respect to the baseline concern the environmental flow requirements and hydropower demand which both increase significantly. For SSP2, the growth of hydropower and drinking water demands stand out, with the irrigation demand increase being also important. The expansion of irrigated cropland is the most substantial feature of SSP5.

2.6. Nexus analysis

The nexus analysis requires the definition of all components based on the problem addressed and the specific study area. For the purpose of defining adaptation policies for water resource management in the Beas and Sutlej river basins, the energy component covers the hydropower production; the food component refers to productivity of irrigated crops; the environment is represented by the maintenance of the flow regime downstream Pandoh reservoir relative to upstream flows; and the water component includes drinking water and flood abatement. With that definition of nexus components, we ensure that the analysis targets the main water-related sectors in the study area using the indicators derived from WEAP outputs in Table 3. All indicators are expressed as percentages to facilitate comparison.

We define the concept 'Nexus Status' (NSt) to summarise the nexus assessment in each scenario Eq. (1) shows the general expression proposed to calculate NSt and its application to the Beas-Sutlej system assuming that all nexus components are equally relevant, thereby using an equal weighting:

$$\mathrm{NSt} = \sum_{1}^{\mathrm{No.\ \ Nex.Comp}} w_k \cdot \bar{I_k} = 0.25 \cdot \frac{I_1 + I_2}{2} + 0.25 \cdot I_3 + 0.25 \cdot I_4 + 0.25 \cdot I_5 \quad (1)$$

Table 2
Summary of changes in WEAP variables by SSP scenario, where 'lpcd' is litres per capita per day.

	Baseline		Future					
	Source	Description	Source	Region	Description	SSP1	SSP2	SSP5
Population	Ministry of Home Affairs, 2011	District-specific	Riahi et al., 2017	India	% increase with respect to baseline	23.2%	45.4%	22.9%
Consumption per capita (lpcd)	Water Aid India, 2005	Rural: 40 Urban: 135	Hanasaki et al., 2013	World	Linear law based on use efficiency & GDP	Rural: 158 Urban: 200	Rural: 158 Urban: 253	Rural: 158 Urban: 200
Cropland	Hollmann et al., 2013	Catchment specific	Riahi et al., 2017	Asia	% area change with respect to baseline	−4.7%	11.2%	25.2%
Irrigated area	Hollmann et al., 2013	Catchment specific	Hanasaki et al., 2013	World	% increase with respect to baseline. Power law of time based on growth rate	3.6%	19.3%	42.3%
Hydropower demand	BBMB and India-WRIS	Power plant-specific	Riahi et al., 2017	Asia	% increase with respect to baseline	286%	364%	116%
Environmental flows	Expert judgement	No minimum flows	SSP interpretation[a]	–	Management strategy	Mimic natural flow duration curves	As in baseline	10% of flow upstream Beas-Sutlej transfer
Flood abatement	Expert judgement	Hedging rules for abatement in reservoirs	SSP interpretation[a]	–	Management strategy	Natural flood mitigation (afforestation) and baseline hedging rules	As in baseline	Modified hedging rules

[a] Based on SSPs narratives.

Table 3
Definition and calculation of nexus indicators for each nexus component, where 'i' represents the number of nodes of each type included in the model (i.e. urban centres for drinking water demands; reservoirs for flood abatement; irrigation command areas for irrigation demands; and hydropower plants for energy production), 't' represents the number of simulated months (i.e. 240 months, from June 1987 to May 2007 for the baseline and June 2055 to May 2075 for future scenarios).

Nexus component	Nexus indicator definition and calculation
Water	Drinking water supply as % of demand met (I_1): $\dfrac{\sum_i \sum_t \dfrac{\mathit{Drinking\ water\ supplied}_{i,t}}{\mathit{Drinking\ water\ demanded}_{i,t}}}{\mathit{No.i} \cdot \mathit{No.t}} \cdot 100$ Abatement capacity of reservoirs (I_2): $\dfrac{\sum_i \sum_{t:[May-Sept]} \dfrac{\mathit{Storage\ capacity}_i - \mathit{Stored\ volume}_{i,t}}{\mathit{Storage\ capacity}_i - \mathit{Conservation\ volume}_{i,t}}}{\mathit{No.i} \cdot \mathit{No.t}} \cdot 100$
Food	Irrigated crop production as % of maximum potential production (I_3): $\dfrac{\sum_i \sum_t \mathit{Irrigated\ crop\ production}_{i,t}}{\sum_i \sum_t \mathit{Maximum\ irrigated\ crop\ production}_{i,t}} \cdot 100$
Energy	Energy production as % of maximum generation capacity (I_4): $\dfrac{\sum\limits_i \sum_t \mathit{Hydropower\ energy\ produced}_{i,t}}{\sum_i \sum_t \mathit{Hydropower\ production\ capacity}_{i,t}} \cdot 100$
Environment	Natural flow maintenance downstream of Beas-Sutlej link (I_5): $\dfrac{Q_{50}\ \mathit{average\ monthly\ flow}\vert_{\mathit{downstream\ link}}}{Q_{50}\ \mathit{average\ monthly\ flow}\vert_{\mathit{upstream\ link}}} \cdot 100$

where w_k is the weight (from 0 to 1) of nexus component k, ensuring that $\Sigma w_k = 1$; and $\bar{I}_k$ is the average of all nexus indicators representing the nexus component k.

The Pearson's correlation test has been previously successfully used to identify synergies and trade-offs (Raudsepp-Hearne et al., 2010; Erb et al., 2011; Luukkanen et al., 2012; Hicks et al., 2013). Here, it is used to disentangle the synergies and trade-offs between nexus component indicators, by calculating a correlation matrix which shows the level of consistency between pairs of nexus indicators under each global change scenario. Positive correlation occurs if the annual values of two indicators show similar variation with time. Negative correlation arises if the temporal variability of the indicators is opposing (i.e. one increases when the other decreases or vice versa).

3. Results

3.1. Calibration and validation

Fig. 5 demonstrates that the model has a satisfactory to very good ability to simulate river flows and reservoir volumes (according to the generally accepted performance rating criteria for NSE and PBIAS of Moriasi et al. (2007)), indicating that the model may be useful to explore global change impacts and inform water management adaptation. Performance indicators for calibration show a slightly better fit for Beas streamflow with NSEs above 0.7, while in the Sutlej basin NSEs are above 0.6. For the validation period, values remain similar. Biases in discharge are generally low, and decrease downstream. The model fit for the reservoir storage for Pong in the Beas is lower (NSE 0.52) than for Bhakra reservoir in Sutlej (NSE 0.69), especially for the validation period, partly reflecting the greater uncertainty in observed storage in Pong compared to water levels in Bhakra, and the shorter observational period. However, R and PBIAS have acceptable values for both reservoirs.

The analysis of hydrologic components shows that the Sutlej runoff is strongly influenced by snow melt as it represents 56% of the mean annual runoff generated upstream Bhakra dam. Glaciers play a much less relevant role with ~4% contribution. For the Beas, meltwater is less important with 17% and 1.7% of the mean annual runoff generated upstream Pong being provided by snow and glacier melt, respectively. Seasonally, both basins are dominated by the effect of the Monsoon, getting >50% of the annual runoff during that season (June to August).

3.2. Climate change impacts on hydrology

All CC scenarios project an increase in the mean annual runoff generated by the catchments upstream Pong and Bhakra reservoirs compared to the baseline, ranging from ~2% for the CC7 to ~10% for CC3, reflecting the balance between the increased precipitation, snow and glacier ice melt, and evapotranspiration (Fig. 6). Changes in mean annual runoff (Fig. 6b) between the baseline and CC scenarios are mostly associated with increases in summer flows and the peak flow in August and less pronounced increases in spring (March to April) runoff. In the CC scenarios, the peak in snowmelt occurs earlier compared to the baseline (April instead of May, Fig. 6c) causing the increase in total runoff in April, but there is a reduction of annual snowmelt due to weakened snowfall and, thereby, less snow accumulation. The reduced snowpack and higher temperatures cause increased glacier ice melt from June to October which, together with higher summer precipitation, leads to the higher summer runoff (Fig. 6b). This effect is much more marked in CC7 due to the combination of the largest temperature and lowest precipitation increases. However, overall melt water declines under CC as the increase in glacier melt does not offset snowmelt losses. Hence, the model indicates that augmented precipitation causes the resulting mean annual runoff to increase, even though actual evapotranspiration also increases.

Future precipitation in winter, as one of the main drivers for glaciers growth in western Himalayas, is not projected to increase by mid-21st century. That combined with increased glacier melt translates into an overall negative glacier mass balance. For the Beas basin, CC3 and CC7 produce reductions of 63% to 65% in the total volume of glaciers with respect to the baseline, while the Sutlej basin experiences reductions between 61% and 65%.

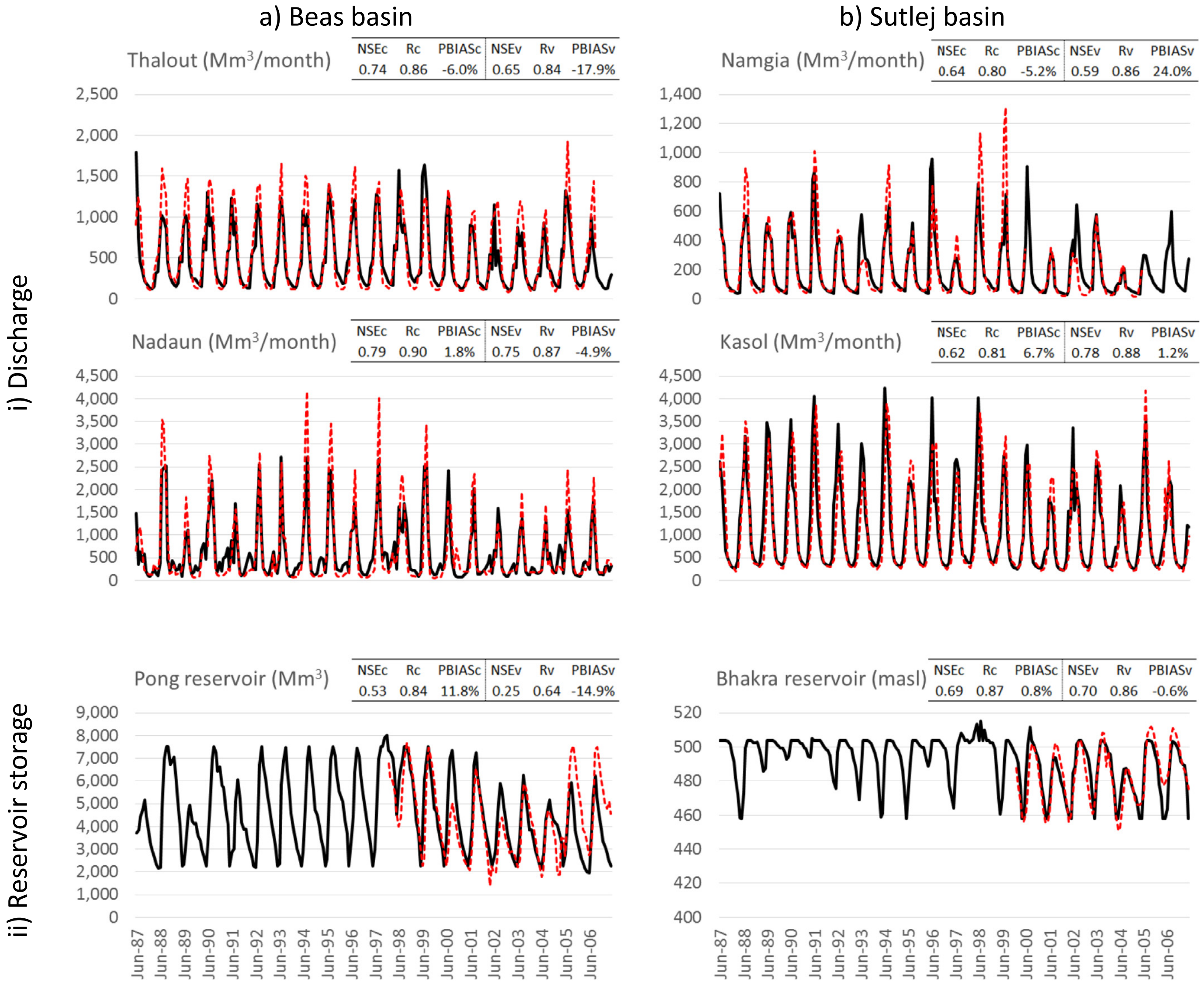


Fig. 5. Simulated (solid line) and observed (dotted line) monthly (i) discharges and (ii) reservoir storage for the calibration and validation periods in (a) Beas and (b) Sutlej basins. Model performance indicators with the subscripts 'c' and 'v' refer to the calibration and validation periods, respectively.

Out of the nine climate change scenario runs, CC3 and CC7 have the highest and lowest water availability in the system, respectively, based on the mean annual runoff generated in the Sutlej and Beas basins upstream of the Bhakra and Pong reservoirs, although they span only 7% around the ensemble mean of the nine CCs (mean annual runoff in CC3 is ~3% higher than the ensemble mean and ~4% lower than the ensemble mean in CC7). Further analysis focuses on the combination of these two climate change scenarios with the socio-economic changes.

3.3. Nexus analysis of global change impacts

The projections of nexus indicators under climate and socio-economic changes are shown in Fig. 7. The drinking water indicator (I_1) has high values (>97%) across all socio-economic scenarios, as meeting urban water supply is the highest priority in the system in all scenarios. Similarly, irrigated crop productivity (I_3) improves in all SSP scenarios compared to the baseline, even in SSP2 and SSP5 in which the irrigation demand increases due to significant irrigated land expansion (Table 2). The natural flood mitigation measure of afforestation in SSP1 is generally slightly less effective at flood abatement than modifying the reservoir hedging rules to increase flood storage capacity employed in the other SSPs, but still helps to maintain the abatement capacity indicator (I_2) under climate change at a level similar to the baseline. Installed hydropower potential increases in both SSP1 and SSP2 (Table 2), but SSP2 is better able to exploit the increased capacity than SSP1 with the nexus indicator for energy (I_4) increasing to >75% in SSP2. However, this is associated with little improvement in the environmental indicator (I_5), which increases the most in SSP1. The improved status of I_5 in SSP1 compared to baseline conditions, arises from the imposition of a flow regime flow downstream of the Beas-Sutlej transfer that mimics the upstream flows.

While SSP2 and 5 both maximise the nexus indicators for drinking water provision and irrigated crop productivity, this is at the expense of environmental flows (SSP 2 and 5) and energy production (SSP5). SSP1 presents the most balanced situation in which all nexus indicators are above 50%. The water (I_1) and food (I_3) nexus components are insensitive to the uncertainty in climate change (as shown by the range of each indicator value between CC3 and CC7 for each SSP in Fig. 7), while the water (I_2), energy (I_4) and environment (I_5) components show uncertainty between the climate scenarios. This reflects the

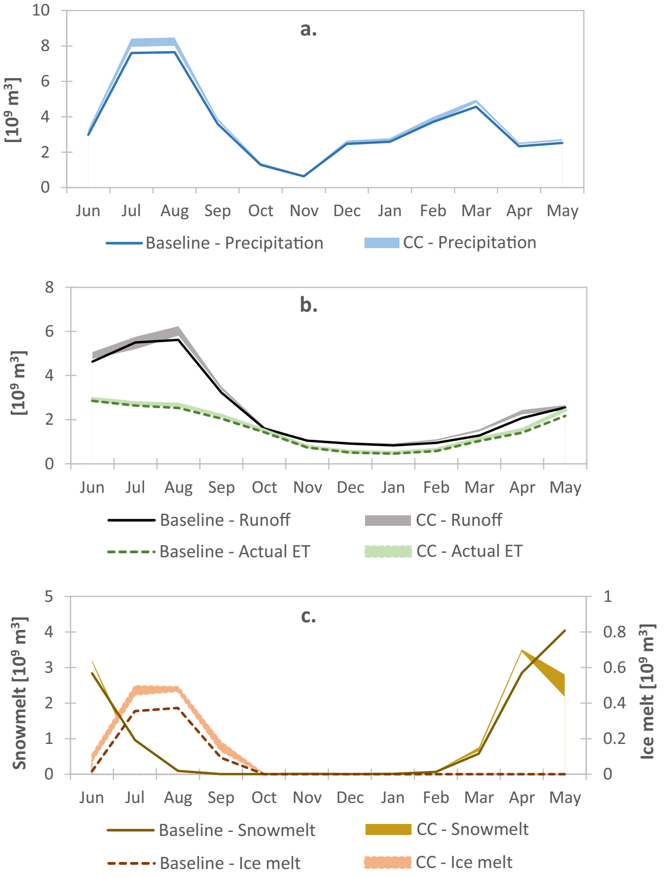


Fig. 6. Seasonality of average monthly hydrological variables for the baseline period and for the range of CC scenarios (CC3–CC7), for a. precipitation, b. mean annual runoff generated upstream Pong and Bhakra and actual evapotranspiration, and c. snowmelt and ice melt.

combined consequences of seasonal water scarcity and the supply priorities in the system, which prioritises meeting drinking and irrigation demands ahead of other water uses.

Table 4
Nexus Status (NSt) for all analysed global change scenarios.

	CC3	CC7
SSP1	69.8%	69.3%
SSP2	68.2%	68.5%
SSP5	60.3%	58.7%

The nexus status values for the six global change scenario combinations are presented in Table 4. Across the scenarios, NSt is higher under CC3 than under CC7, as most nexus components are positively correlated with water quantity, and is highest under SSP1. However, while both climate change scenarios project an increase in water availability in the study area, NSt values for SSP5 are both lower than the baseline value of 60.4%. Variations in NSt between the SSPs are larger than between the CCs, demonstrating the greater overall impact of the socio-economic scenarios on the nexus components.

While the nexus status and its separate indicators provide information about the impacts associated with the future global change scenarios, they alone lack informative content to support the definition of robust and globally efficient adaptation. Fig. 8 shows the correlation matrixes between the annual series of nexus indicators under each simulated global change scenario to identify synergies and trade-offs between the nexus components. Statistically significant correlations (Pearson's coefficient higher than 0.5 or lower than −0.5) are highlighted in bold. Positive correlations (synergies) indicate that both indicators increase (or decrease) at the same time, while negative correlations (trade-offs) imply opposing directions of change. However, these interdependencies are linked to the magnitudes of the socio-economic changes and, thereby, the interpretation of synergies and trade-offs requires an understanding of the functioning of the system under each scenario. Surprisingly, most trade-offs emerge under SSP1 while SSP5 does not show any significant correlations between nexus indicators. This demonstrates that despite SSP1 maximising NSt, its high environmental requirements and hydropower demand generate more tensions.

Due to the topology of the system, most synergies and trade-offs are indirectly driven by the management of the inter-basin water transfer which defines the flow releases from Pandoh reservoir to the downstream Beas River and to the water transfer to the Sutlej. Directly related

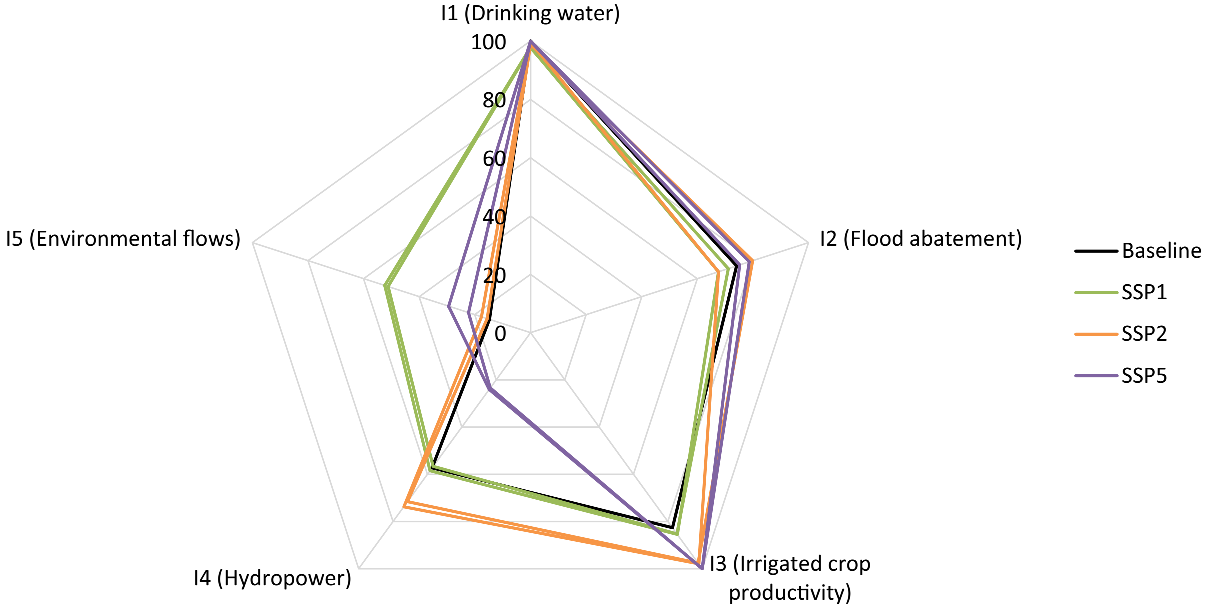
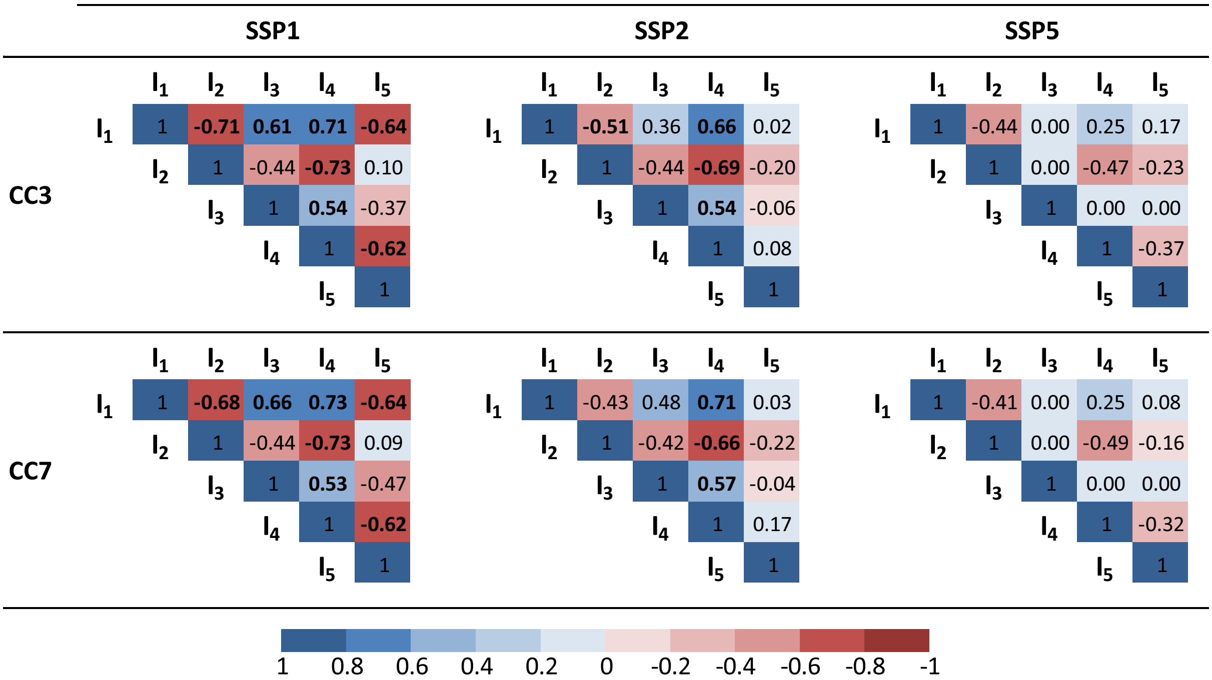


Fig. 7. Nexus indicators for the baseline, and the integrated future climate (CC3 and CC7) and socio-economic scenarios.



		SSP1					SSP2					SSP5				
		I_1	I_2	I_3	I_4	I_5	I_1	I_2	I_3	I_4	I_5	I_1	I_2	I_3	I_4	I_5
CC3	I_1	1	**-0.71**	**0.61**	**0.71**	**-0.64**	1	**-0.51**	0.36	**0.66**	0.02	1	-0.44	0.00	0.25	0.17
	I_2		1	-0.44	**-0.73**	0.10		1	-0.44	**-0.69**	-0.20		1	0.00	-0.47	-0.23
	I_3			1	**0.54**	-0.37			1	**0.54**	-0.06			1	0.00	0.00
	I_4				1	**-0.62**				1	0.08				1	-0.37
	I_5					1					1					1
CC7	I_1	1	**-0.68**	**0.66**	**0.73**	**-0.64**	1	-0.43	0.48	**0.71**	0.03	1	-0.41	0.00	0.25	0.08
	I_2		1	-0.44	**-0.73**	0.09		1	-0.42	**-0.66**	-0.22		1	0.00	-0.49	-0.16
	I_3			1	**0.53**	-0.47			1	**0.57**	-0.04			1	0.00	0.00
	I_4				1	**-0.62**				1	0.17				1	-0.32
	I_5					1					1					1

Fig. 8. Pearson's correlation matrix between annual series of Nexus indicators under CC3 and CC7, and SSP scenarios.

to that effect is the Energy (I_4) - Environment (I_5) trade-off in SSP1. Because the Sutlej power plants (at Dehar and Bhakra) provide higher power production potential than the Pong power plant on the Beas (Fig. SM3), water that is used for environmental purposes downstream of Pandoh represents a loss of hydropower production. Combined high flow requirements and hydropower demand in SSP1 (Figs. SM3 and SM5) also limits the supply to drinking water demands in the Beas catchment upstream of the water transfer generating the trade-off Water (I_1) - Environment (I_5). On the other hand, more water transferred from Beas to Sutlej to increase hydropower production in SSP1 and SSP2 gives rise to the trade-off between Water (I_2) - Energy (I_4) since, for the same inflow, Bhakra reservoir provides less abatement than Pong (Fig. SM4) due to its elevation-storage characteristics. The trade-off Water (I_1) - Water (I_2) in SSP1 results from the combination of all the above trade-offs, as the coverage of drinking water supply in the upper Beas River improves if environmental restrictions are loosened (i.e. inter-basin transfers are increased) but the flood abatement is impaired.

In order to satisfy increased energy demands, part of the resources from the upper Sutlej have to be compromised to increase energy production in the Sutlej power plants, which results in the reduction of coverage to irrigation demands in the upper Sutlej River (Fig. SM2). Hence, more water transferred from the Beas simultaneously improves the coverage of these demands and energy production, generating the Food (I_3) - Energy (I_4) synergy which is consistent across SSP1 and SSP2. Similarly, the Water (I_1) - Energy (I_4) synergy arises with changes in the water transfers (Fig. SM1), but is only significant under SSP1 and SSP2 scenarios due to the large increases in the energy demand. Finally, significant synergies unfold between Water (I_1) and Food (I_3) nexus components in SSP1. However, this is a virtual synergy resulting from the functioning of the system that tries to share the supply deficits between the demands with similar priority, because consumptive demands (e.g irrigation) are always exclusive and, thereby, rivals.

3.4. Water management adaptation

Analysis of the synergies and trade-offs that are consistent within SSPs points to the components with key importance for the system. The co-existence of large hydropower and environmental flow demands are the main triggers of nexus tensions in the Beas-Sutlej system and give rise to the major opportunities and limitations for adaptation. Hence, these sectors should be at the centre of the planning strategies for future actions and transformation to adapt to mid-21st century global change in the system.

Without adaptation, the current hydropower production structure locks-in the requirement for large water transfers and impairs environmental conditions downstream of Pandoh dam and the flood abatement capacity. While increasing the hydropower potential in the Beas basin could reduce the magnitude of water transfers, alternative measures to foster other types of clean energy production would help to reduce the Energy-Environment trade-off and contribute to the target of affordable and clean energy (SDG 7). Relaxing nexus tensions in the system would increase the reliability of water supply to other sectors such as irrigated agriculture or the environment to the benefit of the local economy. Environmental requirements could also be optimised to minimise the impacts on drinking and irrigation water demands which rely on the unregulated flows generated in the headwaters of the Beas and Sutlej basins, based on detailed studies about the habitat needs of the main aquatic species, as well as the cultural and religious values associated to river flows. Simultaneously, measures to increase water security in the upper parts of the basins could compensate the negative effects of the environmental restrictions.

4. Discussion

The importance of the Himalayas, sometimes referred to as the "water towers of Asia", to the hydrological behaviour of their associated river basins leads to the common use of hydrological models to assess global change impacts (Khadka et al., 2014; Neupane et al., 2014; Ali et al., 2015; Li et al., 2015; Soncini et al., 2016; Adnan et al., 2017; Stigter et al., 2017), which seldom represent the effects of anthropogenic infrastructure (e.g. reservoirs, inter- and intra-basin diversions) and abstractions on river flows. However, understanding the combined consequences of current and future natural and anthropogenic forcing on river basins is critical for the assessment of water supply reliability, ecosystem services, and for developing adaptation strategies to support society, rural livelihoods and the regional economy (Viviroli et al., 2011). In this study, we use the water resource systems model WEAP to integrate climate and socio-economic changes and examine the consequences of a wide range of plausible futures in a complex regionally-important river basin system that combines diverse hydrological drivers (rainfall, seasonal snowpacks and glaciers); major consumptive (irrigation) and non-consumptive (hydropower) water demands; and complex multi-functional infrastructure (reservoirs, diversions, and impoundments).

In a first stage, the impacts of climate change on future water availability are analysed. Seasonal changes in precipitation and temperature based on the 25th, 50th and 75th percentiles of a 42 CMIP5 GCM ensemble for RCP4.5 are used to represent a credible uncertainty range, although we acknowledge that such an approach will not fully represent the inter-model and intra-seasonal variability within the CMIP5 ensemble for the Tibetan and South Asia regions (Koutroulis et al., 2016) and the representation of the complex meteorological phenomena of the region (Mathison et al., 2015). Another way to address uncertainty would be to synthesise several possible realisations of the ensemble projections (e.g. 1000) and analyse those to generate the range of impacts (Soundharajan et al., 2016). Our wettest and lowest temperature increase climate change scenario generated the greatest water resource availability (as given by simulated mean annual runoff generated upstream Pong and Bhakra reservoirs), while the driest and hottest future climate scenario results in the lowest. This somewhat contradicts Remesan and Holman (2015) whose highest simulated total discharge using the HySim model was under their wettest and hottest climate change scenario in the Beas basin, but reflects different model representations of seasonal snowpacks and glaciers and the complex interactions between temperature and evapotranspiration (influenced by soil moisture) and snowmelt (with elevation) (Kingston et al., 2011; Remesan and Holman, 2015). According to our findings, an increase in total annual water resources availability with respect to the baseline is projected for the mid-21st century in the Beas-Sutlej Himalayan system, which is mostly evident in the pre-monsoon and monsoon seasons. A combination of higher monsoon precipitation, the advance of the snowmelt season and increased ice melt caused by rising temperatures drive the changes in mean annual runoff. Most of these signals are in agreement with hydrological studies in the region (i.e. Beas, Sutlej or upper Indus basin), such as the early response of snowmelt and the overall reduction of total snowmelt contribution to runoff (Jain et al., 2010; Sharma et al., 2013; Su et al., 2016). Nonetheless, many studies suggest future reduction in river flows during the monsoon period (Immerzeel et al., 2010; Jain et al., 2010; Sharma et al., 2013; Lutz et al., 2016), albeit with large variability in the reported changes. Differences in the results may be due to the underlying assumptions of each study, particularly regarding the future climate forcing data for the monsoon period; the hydrological models; and the projection of glacier changes into the future. For example, while WEAP represents glacier depth dynamically over time (but not glacier extent), glaciers are not represented within the models of Jain et al. (2010) and Sharma et al. (2013); whereas Immerzeel et al. (2010) and Lutz et al. (2016) estimate the future extent and depth of glaciers based on continuous mass balance simulations. Although we only simulate the mid-21st century, our results indicate a gradual depletion trend of glaciers in the studied basins throughout the examined time-period which is expected to continue to the late 21st century following continuous temperature increases. This aligns with longer term studies which show a dramatic reduction in glacier melt contribution to total runoff by the end of the century in the western Himalayas under RCP4.5 (Immerzeel et al., 2013; Su et al., 2016). Thus, an examination of the same system for a later time-frame – when the vital hydrological input of the glaciers in the system has been lost or considerably reduced – could possibly reveal a significant shift in the magnitude and seasonality of runoff and other hydrological components, with major implications for the future nexus components.

The inclusion of future socio-economic scenarios in the analysis brings about large differences in the behaviour of the Beas-Sutlej system with respect to the baseline. Despite the simulated increase in water resources availability in the studied area by mid-21st century, model results indicate that supply problems may arise because of the increase in sectoral water demands and policy changes. That is in line with Hanasaki et al. (2013) and Arnell and Lloyd-Hughes (2014) who demonstrated that socio-economic changes will be the main drivers of water scarcity impacts in the future. WEAP results are used to derive nexus indicators which show that the examined socio-economic scenarios have a considerable impact on nexus components for the studied system and, thus, on the aggregated nexus status. The most environmentally sustainable socio-economic scenario, SSP1, shows the most balanced situation among nexus components and provides the highest overall NSt driven by the selection of equal weighting for all nexus components. While this choice is coherent with the holistic nature of the nexus concept and the attainment of multiple SDGs, other combinations of weights could be defined to stress the relevance of a specific sector which would produce different NSt results across scenarios. Hence, the choice of weights should be subject to discussion with stakeholders and aligned with the ultimate objective of the analysis. Interestingly, SSP1 is the scenario for which the largest synergies and trade-offs between nexus indicators are found. These findings highlight the inter-sectoral trade-offs that need to be made in order to have an improved overall nexus. These compromises can be more evident within a sustainable development framework, where concurrently managing the limited land and water resources to secure environmental quality while satisfying the remaining nexus components to support multiple societal goals is challenging (van Vuuren et al., 2017). The identification of the major trade-offs also stresses the need for transformative measures (Zimm et al., 2018) which relate to the energy and environment sectors in the studied system.

The scenario-dependent variability in our nexus results shows that the consideration of alternative socio-economic developments is of paramount importance when assessing global change impacts to design robust adaptation strategies (Holman et al., 2018). This study demonstrates the benefits that combining water resource systems modelling and nexus assessment provides for representing the consequences of socio-economic changes on both water demand and water resource management, and the water use interdependencies (synergies and trade-offs) between sectors. Additionally, while a systems modelling approach entails a compromise between the complexity of system representation (through integration of hydrology, water use and management) and the complexity of individual process representation (Loucks and van Beek, 2017), such models are a valuable tool for co-production of adaptation scenarios. By facilitating the development of a shared view of a river basin system and its complexity, and through incorporating diverse perspectives into the conceptualisation of problems and solutions (Clark et al., 2016), water resource systems models can support the development of adaptation strategies that take a holistic, as opposed to sectoral, perspective and lead to better designed responses to the complex nexus challenges of future global change.

5. Conclusions

This study analyses the impacts of global change on the water-food-energy-environment nexus in a complex water resource system and uncovers the existing synergies and trade-offs to identify general strategies for water management adaptation. Pathways for emissions and socio-economic development account for the uncertainty in global change and support informed solutions related to water security.

In the studied system with seasonal water scarcity and water excess, future changes in nexus components of energy (as hydropower), environment (as environmental flows) and (to a lesser extent) flood abatement are responsible for most synergies and trade-offs. The impacts of socio-economic change, through changing water and energy demands and water management, are shown to be greater that the direct impacts of climate change in the mid-21st century. This highlights the need to consider different socio-economic scenarios, complementary to a representative range of climate change scenarios, within a systems modelling framework to ensure that the consequences of – and uncertainty in – global change are adequately captured. Consideration of multiple scenarios, therefore, emerges as a prerequisite for robust adaptation policy making and relevant action planning. Additionally, co-production of models and indicators, and the interpretation of results with relevant stakeholders are essential to ensuring the appropriate representation of the complex human-environment system of a river basin and its associated management practices and policies.

Overall, this study shows how a coupling between water resource systems modelling and water-food-energy-environment nexus approaches helps to inform actions and transformations for adaptation that account for economic growth, equity and sustainability. This approach can assist in advancing towards the attainment of the Sustainable Development Goals given the emerging water security challenges resulting from future changes in water availability, water demands and environmental protection.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.11.045.

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