




Enhancing production and flow of freshwater ecosystem services in a managed Himalayan river system under uncertain future climate

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Abstract

Future climate change will likely impact the multiple freshwater ecosystem services (fES) provided by catchments through their landscapes and river systems. However, there is high spatio-temporal uncertainty on those impacts linked to climate change uncertainty and the natural and anthropogenic interdependencies of water management systems. This study identifies current and future spatial patterns of fES production in a highly managed water resource system in northern India to inform the design and assessment of plausible adaptation measures to enhance fES production in the catchment under uncertain climate change. A water resource systems modelling approach is used to evaluate fES across the full range of plausible future scenarios, to identify the (worst-case) climate change scenarios triggering the greatest impacts and assess the capacity of adaptation to enhance fES. Results indicate that the current and future states of the fES depend on the spatial patterns of climate change and the impacts of infrastructure management on river flows. Natural zones deliver more regulating and cultural services than anthropized areas, although they are more climate-sensitive. The implementation of a plausible adaptation strategy only manages to slightly enhance fES in the system with respect to no adaptation. These results demonstrate that water resource systems models are powerful tools to capture complex system dependencies and inform the design of robust catchment management measures. They also highlight that mitigation and more ambitious adaptation strategies are needed to offset climate change impacts in highly climate-sensitive catchments.

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1 Introduction

Healthy catchments provide multiple freshwater ecosystem services (fES) through their landscapes and rivers—e.g. water regulation and supply, water purification, flood abatement, maintaining aquatic fauna (Guswa et al. 2014; Brauman 2015)—which underpin economic development and social well-being (Hayat and Gupta 2016). Additionally, free-flowing rivers act as ecological networks that enable fES flows across regions (Schröter et al. 2018)—i.e. water regulation and nutrients cycling. Hence, conservation of nature is increasingly considered to be an investment in long-term sustainability rather than a constraint to economic development and the satisfaction of human needs (Liu et al. 2013; Crossman and Pollino 2018). However, biodiversity is declining globally, mainly due to human-induced changes in land use with resulting reductions of ecosystem services (ES) (IPBES 2019). Moreover, rivers around the world have been engineered into managed water resource systems through the construction of infrastructures (such as dams and sewage treatment works) and water abstractions and diversions. Water policies and management approaches (Adeloye and Dau 2019) for these engineered systems in many parts of the world currently allow for only limited consideration of the suite of fES which can be provided by the catchment since they focus on enhancing just the most direct services, i.e. water provisioning for human uses such as drinking, irrigation and hydropower production (Ncube et al. 2018; Grill et al. 2019).

Catchment processes and related fES (Runting et al. 2017; IPCC 2019) such as erosion control, flood protection, water purification and water supply (Tzilivakis et al. 2019), are likely to be impacted by future climate change. Spatial differences in temperature and precipitation changes will modify existing cross-sectoral trade-offs among and between water uses (e.g. irrigation, public water supply, hydropower, navigation, recreation, environmental needs) and fES (Dunford et al. 2015; Holman et al. 2016). The uncertainty in climate change projections cascades into spatio-temporal uncertainty in impacts (Koutroulis et al. 2018; Salmoral et al. 2019; Visser-Quinn et al. 2019), posing major adaptation challenges for catchment management to improve or maintain the delivery of fES in the future. Process-based modelling approaches are generally preferred to assess climate change impacts and define decision-making strategies for adaptation in relation to fES (Runting et al. 2017; Momblanch et al. 2019a). Most modelling studies that assess adaptation interventions in the landscape (Bangash et al. 2013; Dunford et al. 2015; Fan et al. 2016; Liu et al. 2017; Mandle et al. 2017; Huang et al. 2019; Underwood et al. 2019) with the intention to offset negative climate change impacts overlook river fES and their links to landscape services. This limits their capacity to support holistic solutions. Furthermore, most studies consider only a limited number of future emission scenarios and/or climate models so that adaptation options are not tested across the whole uncertainty spectrum. There is, therefore, an urgent need for research that provides evidence about the natural system and management-induced interdependencies to inform improved decision-making that is robust to uncertainty in the future climate. Water resource systems models, which integrate landscape and river processes while considering interactions between natural and anthropic dimensions including water infrastructures and their management, have the potential to fill that gap as they have previously proved useful in analysing the behaviour and performance of complex multi-objective water resource systems under climate change conditions (Höllermann et al. 2010; Booij et al. 2011; Poff et al. 2016; Bhawe et al. 2018; Momblanch et al. 2019b). Moreover, their

potential to assess fES has been demonstrated (Yates et al. 2005; Momblanch et al. 2016, 2017), although considering few services and in relatively simple systems.

This paper aims to understand how the spatial patterns of fES production change, from headwaters to lowlands, in a complex managed river system in the Western Himalayas in India under current and future climate, and explores the effectiveness of landscape and water management adaptation strategies to enhance fES productivity at catchment scale. We use a systems model (Water Evaluation and Planning tool, Seiber and Purkey 2015) that integrates hydrological processes, water management infrastructure, water users and water management practices and policy, to describe the spatial variability in indicators of fES production in the Sutlej-Beas system in northern India. This river system combines a complex and varied landscape, strongly climate-sensitive hydrology and significant nature-human interactions. The sensitivity of these fES indicators to future climate uncertainty is explored across the full range of plausible future scenarios, as represented by the full spectrum of representative concentration pathways (RCP) and global climate models (GCM). Finally, the effectiveness of selected adaptation measures across the different future emission scenarios are assessed and discussed in relation to future management practices and policies aimed at sustaining economic development and social well-being.

2 Material and methods

2.1 Study area

The Sutlej-Beas system comprises the catchments of the Sutlej and Beas river basins (of 58,440 km² and 17,950 km², respectively), the rivers, water users, and the associated water infrastructures (Fig. 1), and spans from the Tibetan Plateau to the Plains of Punjab. The large elevation gradient in the system, from 160 masl to 7500 masl with a median of 4700 masl, causes a significant spatial variability in meteorological variables. Temperature decreases and precipitation increases with elevation to a maximum at around 2000 masl (Bookhagen and Burbank 2006). In the windward of the Himalayas, the Indian summer monsoon provides most of the annual precipitation (Bookhagen and Burbank 2010), and the Western disturbances contribute to snow accumulation above 2000 m above sea level (masl) during winter. This generates a highly seasonal hydrological regime. River flows are lower in winter as precipitation falls mostly as snow and accumulates in the snowpack. Flows gradually increase from March due to snow melt as the temperature rises. Glacier melt starts over summer when the seasonal snowpack depletes, and its contribution concurs with high runoff caused by monsoon rainfall, generating the highest river discharges. This pattern is similar but less marked in the Tibetan Plateau, which has a much drier climate as the Himalayas act as an orographic barrier (Wulf et al. 2016).

The steep slopes of the Himalayas are mainly covered by grasslands and bare land, while the Foothills are dominated by dense forests. The valleys comprise significant rainfed cropland, and the Plains are covered almost entirely with irrigated cropland and some urban areas. Young and thin soils are characteristic in the hilly parts of the catchments; however, as the slopes lessen, the soil gains depth. Two large reservoirs, Bhakra and Pong (with storage capacities of 8815 Mm³ and 8585 Mm³, respectively, based on data from the Bhakra Beas Management Board), regulate the water resources from the Himalayas and Foothills. These supply ~24,000 Mm³/year of water for irrigation to the command areas in the states of Punjab (38%), Haryana (36%) and Rajasthan (25%) through a complex canal network, ~225 Mm³/year for the city of Delhi, and are also used for hydropower generation and for the abatement of high summer flows. The Pandoh Dam in

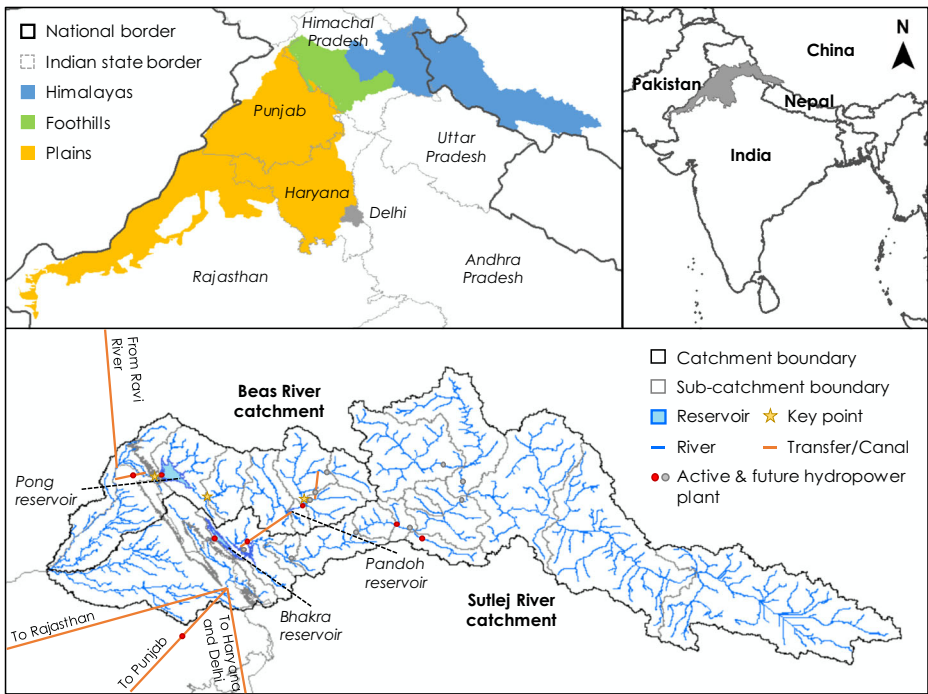


Fig. 1 General description of the study area. Top-right: Location of the study area and national borders (Bjorn Sandvik; thematicmapping.org). Top-left: geographical zones considered in the analysis of fES indicators and regional borders (GADM version 1.0; gadm.org). Bottom: Sutlej and Beas river catchments, sub-catchments and river network (delineated with GIS tools), main reservoirs (official shapefiles; National Institute of Hydrology Roorkee), water transfers and canals, active and future planned hydropower plants and key points to analyse river flow related fES in each geographical zone, i.e. Manali in the Himalayas, Nadaun in the Foothills and downstream Pong reservoir in the Plains

the middle reaches of the Beas allows the annual transfer of $\sim 4481 \text{ Mm}^3$ to the Sutlej River for hydropower production and redistributes the resources for canal irrigation. There are several other smaller run-of-the-river hydropower plants in the high reaches of the Sutlej and Beas rivers which have an obvious impact on downstream river flows, but do not drive the management of the system. The population within the catchment is low and mostly concentrates in the downstream Plains, representing a small fraction of the total water demand.

2.2 Systems model and data

The Water Evaluation and Planning (WEAP) tool is a generalized 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 hydrological processes (e.g. actual evapotranspiration, infiltration, runoff and snow melt and accumulation), water resources (i.e. surface water, snowpack, glaciers and groundwater), water demands (i.e. urban, hydropower, irrigation and environmental flows), water infrastructures (e.g. reservoirs, canals, hydropower barrages and inter-basin diversions) and management (e.g. irrigation scheduling, reservoir operation rules and environmental flow requirements). It uses a link and node structure to represent the various system components and processes and their spatial dependencies. For detailed information about WEAP capabilities and equations, refer to Seiber and Purkey (2015).

The Sutlej-Beas WEAP model used in this study (see model diagram in SM3a) is an improved version of the model developed by Momblanch et al. (2019b). It contains improved representation of irrigation water demands (i.e. addition of main crop rotations and irrigation schedules using the MABIA method (Seiber and Purkey 2015), hydropower water demands and related infrastructures. Even though the temporal resolution is kept at monthly, the new model version includes a better representation of the spatial variability of landscape parameters and meteorological variables through inclusion of a larger number of sub-catchments and elevation bands (i.e. 23 sub-catchments and 600 m elevation bands, resulting in 165 spatial elements) and data from regional climate models. For the Himalayas and their Foothills (Fig. 1) where topography strongly influences local hydro-meteorological processes, baseline meteorological data were generated through high-resolution 5-km grid dynamical downscaling of ERA-Interim reanalysis data using the Weather Research and Forecast (WRF) model by Bannister et al. (2019), including bias correction and validation; for the Plains, ERA-Interim data downscaled to ~0.5-degree resolution with RegCM4 was downloaded from CORDEX. Both datasets were spatially aggregated by sub-catchment and elevation band in their respective regions.

The performance of the enhanced Sutlej-Beas system model was calibrated and validated against river flow in four river gauges and reservoir storage in Bhakra and Pong for different periods from 1989 to 2008 depending on data availability and excluding 2 years for warm-up. The indicators Nash-Sutcliffe efficiency, Pearson's correlation coefficient and percent bias show a generally good to excellent performance according to Moriasi et al. (2007) (SM3b) and are overall slightly better than in Momblanch et al. (2019b).

2.3 Climate change scenarios

We projected future climate using the delta change method that derives modelled average monthly anomalies for temperature and precipitation for each future time slice with respect to the modelled baseline period (i.e. 1989–2008; termed “historical” in the CMIP5 archive) and applies them to our baseline data (see Eqs. (1), (2), (3) and (4)). The delta changes were calculated from the outputs of every GCM within the Climate Model Intercomparison Project Phase 5 (CMIP5) available in the KNMI Climate Explorer (Trouet and Van Oldenborgh 2013) for RCP2.6 (26 GCM; see SM1a), 4.5 (35), 6.0 (19) and 8.5 (33) for the middle (2031–2050) and end of the century (2081–2100) and were spatially aggregated in the hilly region and the Plains. This resulted in 113 plausible projections of climate change (combinations of RCP x CMIP5 model) for each of the middle and end of the twenty-first-century horizons. For each CMIP5 model, RCP and time slice,

$$T_{t,y}^{\text{HiRes},F} = T_{t,y}^{\text{HiRes},B} + \Delta T_m^{\text{CMIP5}} \quad (1)$$

where $T_{t,y}^{\text{HiRes},F}$ is the high spatial resolution projected temperature (T) time series with time step t in the spatial element y ; $T_{t,y}^{\text{HiRes},B}$ is the baseline (superscript B) high-resolution temperature time series (WRF for the hilly region and RegCM4 for the Plains); and $\Delta T_m^{\text{CMIP5}}$ is the average monthly (m) temperature anomaly spatially averaged for the hilly region or the Plains as appropriate.

$$\Delta T_m^{\text{CMIP5}} = T_t^{\text{CMIP5},F} - T_t^{\text{CMIP5},B} \quad (2)$$

where $T_t^{\text{CMIP5},F}$ is the low spatial resolution (CMIP5) future (superscript F) temperature time series and $T_t^{\text{CMIP5},B}$ is the low-resolution temperature time series in the baseline period.

$$P_{t,y}^{\text{HiRes,F}} = P_{t,y}^{\text{HiRes,H}} * \Delta P_m^{\text{CMIP5}} \quad (3)$$

where $P_{t,y}^{\text{HiRes,F}}$ is the high spatial resolution projected precipitation (P) time series with time step t in the spatial element y ; $P_{t,y}^{\text{HiRes,B}}$ is the baseline high-resolution precipitation time series; and $\Delta P_m^{\text{CMIP5}}$ is the average monthly precipitation anomaly.

$$\Delta P_m^{\text{CMIP5}} = \frac{P_t^{\text{CMIP5,F}}}{P_t^{\text{CMIP5,B}}} \quad (4)$$

where $P_t^{\text{CMIP5,F}}$ is the low spatial resolution future precipitation time series and $P_t^{\text{CMIP5,B}}$ is the low-resolution precipitation time series in the baseline period.

The monthly delta change method was selected given the 226 combinations of RCP-time slice-GCM data that precluded dynamical downscaling to capitalize on the high-resolution WRF baseline. This method accounts for any simulated changes in the periodic patterns within the GCM simulations (timing and strength of the monsoon and western disturbances). The different time slices account for long-term trends in climate.

Initial values of area and depth for each glacier for each future time slice (2031 and 2081) were projected by Prasad et al. (2019) for climate change outputs from the GFDL-CM3 climate model under RCP8.5 using the Accumulation Area Ratio and Elevation Line Altitude methods (Tawde et al. 2017). The extrapolation of these variables to the other climate change scenarios is described in the supplementary material (SM1b).

2.4 Freshwater ecosystem services assessment

We used the Common International Classification of Ecosystem Services (CICES; Haines-Young and Potschin 2018) to identify the relevant fES for our study area as it provides a complete hierarchical description of ES. A summary of the fES included in the assessment is shown in Table 1. The selection of indicators was based on Maes et al. (2016), and their calculation considered the available outputs from WEAP (details are provided in the supplementary material, SM2).

Given the strong differences in climate, topography, land cover, etc. across the river basin, which are expected to influence fES production and flows of services, fES indicators were analysed across three distinct geographical zones, i.e. the Himalayas, the Foothills and the Plains (Fig. 1).

The values of the fES indicators in the climate change scenarios were normalized with respect to their value in the baseline. In this way, values of fES indicators lower (higher) than one represent an impairment (improvement) in the future delivery of the service, while values equal to one indicate no change.

2.5 Catchment management adaptation measures

A set of plausible adaptation strategies was defined with the aim of offsetting the negative simulated climate change impacts on fES taking account of existing projects and plans for the region such as the Himachal Pradesh Mid-Himalayan Watershed Development Project (World Bank 2017), Himachal Pradesh Reforestation Project (UNCC 2015), hydropower projects under investigation/formulation and technically feasible adaptation of water management rules (based on data from the Bhakra Beas Management Board and the National Institute of Hydrology in

Table 1 Summary of the assessed fES

| Type | fES ID | CICES classes | Definition |
|--------------|--------|--|---|
| Provisioning | 1 | Surface water for drinking | Average annual water supply to urban water uses |
| | 2 | Cultivated crops | Average annual crop production within irrigated command areas |
| Regulating | 3 | Freshwater used as an energy source | Average annual hydropower production |
| | 4 | Hydrological cycle and water flow maintenance—Snow regulation | Average annual snowfall as percentage of average annual precipitation |
| | 5 | Hydrological cycle and water flow maintenance—Groundwater regulation | Average annual recharge as percentage of average annual total runoff |
| | 6 | Mediation of flows—Flood protection | Proportion of maximum monthly precipitation that does not form surface runoff |
| | 7 | Mediation of flows—Control of erosion | Proportion of total erodible area that is snow-covered at times of rainfall |
| | 8 | Maintaining nursery populations and habitats | Median times interquartile range of the seasonal time series of Lotic-Invertebrate Index for Flow Evaluation (LIFE) scores. Available only for Himalayas and Foothills (see key points in Fig. 1) |
| Cultural | 9 | Physical and experiential interactions—Recreation and tourism | Fraction of time that flows are suitable for seasonal rafting activities |
| | 10 | Intellectual and representative interactions—Aesthetic | Glacier volume relative to the baseline in the Himalayas and fraction of time that flows are suitable for the activities in the Foothills and Plains (see key points in Fig. 1) |

India). The performance of the adaptation strategy was assessed in relation to its ability to enhance fES under a worst-case scenario for each RCP. The worst-case scenarios were determined as the CMIP5 simulation that provided the minimum weighted sum of fES across the three zones of the catchment through both the mid- and long-term climate change horizons (Eq. 5).

$$Min \sum_h \sum_z \sum_i w_{i,z} * fES_{i,z,h} \tag{5}$$

where $fES_{i,z,h}$ is the value of the normalized indicator with ID equal to i (1 to 10; Table 1) in zone z (Himalayas, Foothills and Plains) in the future time horizon h (middle and end of the century) and $w_{i,z}$ is the weight calculated as the percentage that each zone contributes to the total production of each fES in the catchment for the baseline period (see Fig. 2).

3 Results

3.1 Freshwater ecosystem services in the baseline

Although all zones of the catchment produce multiple services, their distinct natural and anthropogenic features result in clear hotspots for fES production. As shown in Fig. 2 (note that the percentages correspond to the weights used in Eq. (5)), the Himalayas stand out for their capacity to provide regulating services, especially flow regulation by the cryosphere (fES4) and erosion control (fES7), along with a significant supply of aquatic habitat (fES8) and

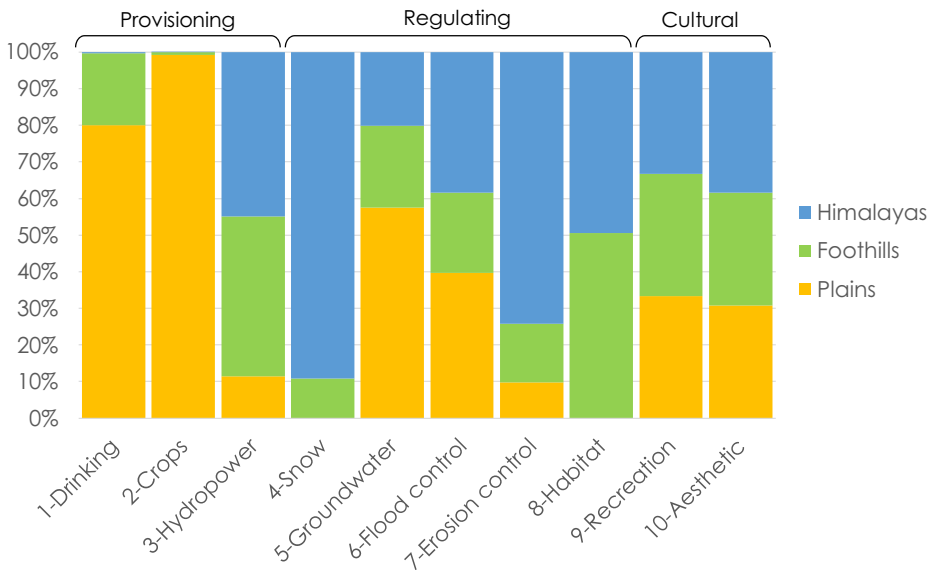


Fig. 2 Share of production of fES (1 to 10) in the study catchment between zones for the baseline period

cultural services (fES9 and 10). On the other hand, the Plains dominate the production of provisioning fES such as drinking water (fES1) and irrigated crops (fES2), which are greatly determined by the existence and management of reservoirs and irrigation canals, and flow regulation by groundwater (fES5), but not freshwater used as an energy source (fES3). The Foothills lay in an intermediate position in relation to the production of fES and, as opposed to the Himalayas and the Plains that are more polarized towards specific services, supply all of them. This shows their role as the interface between the natural mountainous and anthropized lowland ecosystems, resulting in a more multifunctional zone.

The existing spatial patterns result in relevant dependencies between fES. The Himalayas (and to a lesser extent the Foothills) regulate much of the water resources through snow accumulation and melt (fES4) that, given their low groundwater regulation capacity (fES5), support the high levels of provisioning services in the Plains (fES1 and 2) and the Foothills (fES3). This natural regulation is also important to ensure that rivers in the headwaters preserve their permanent character and provide services directly related to streamflow (fES8, 9 and 10) throughout the year, despite the existence of marked seasonality. In the Foothills and the Plains, where the influence of water management becomes stronger, streamflow-dependent services are driven by the particular functioning of the system. For example, the water transfers from the Beas to the Sutlej change the natural flows downstream of Pandoh Dam and determine the maintenance of aquatic habitats and cultural services. Similarly, the management of Bhakra and Pong reservoirs for irrigation supply and hydropower production influences these services.

3.2 Assessment of climate change impacts on freshwater ecosystem services

3.2.1 Climate change projections

Future climate projections for the Sutlej-Beas system show a consistent pattern across the three zones of average annual temperature increases and associated uncertainty that

increase with time and RCP (Fig. 3a). The similar patterns in the Plains in relation to the hilly region (Foothills and Himalayas, which are based on the same delta change factors) demonstrate the limited capacity of GCM to capture spatial variability at the regional scale due to their low-resolution (~0.75° to ~3.75° in this study). Although the change in the median average annual precipitation within the projections in each RCP-time slice mostly increases, there is much greater spread across CMIP5 models, with some models giving significant positive and negative changes (Fig. 3b). Moreover, while the absolute magnitude of the changes in the temperature projections across RCPs is very similar in the three zones (with few model outliers), the variability of precipitation projections is much higher in the Foothills and Himalayas, particularly at the end of the century, which indicates the variable performance of individual CMIP5 models in representing the complex interactions between atmospheric circulation systems and the orography. Interestingly, the differences in the statistical distributions of projected climate variables (i.e. median and quartiles) between RCP4.5 and 6.0 are small, and the highest uncertainty is due to CMIP5 models.

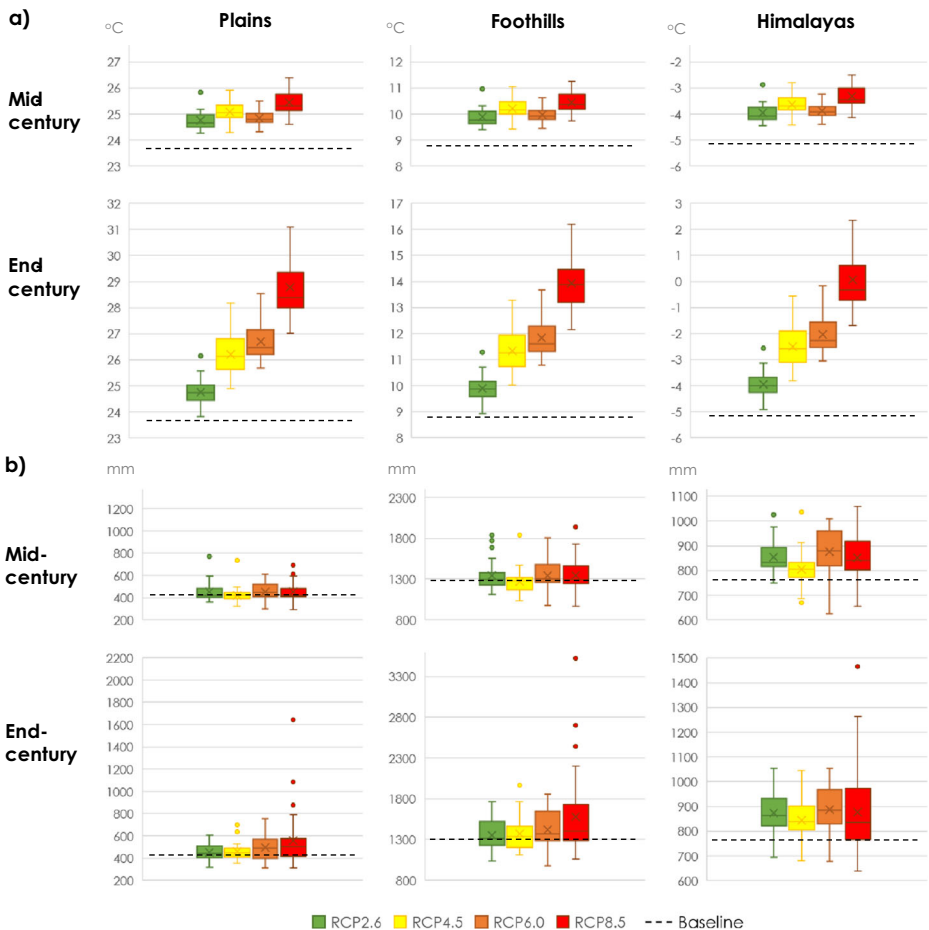


Fig. 3 Variability of **a** future temperature (°C) and **b** future precipitation (mm) under climate change scenarios

3.2.2 Climate change impacts

The ensemble median of fES indicators in each zone and future time horizon shows little change in most fES under climate change (Fig. 4). In fact, the median across climate change scenarios is practically one in the Plains for all fES and only suffers small variations in the Foothills. This insensitivity is particularly marked in the Plains where climate change will barely affect precipitation and the reservoirs have a strong influence in some services. The largest impacts affect streamflow-dependent cultural services, i.e. fES8, fES9 and fES10. The changes in fES2, fES3 and fES4 are less pronounced, showing only slight variations in the Himalayas and Foothills, especially by the end of the century. The decrease in flow maintenance by snow (fES4) implies a decrease in glacier nourishment and, therefore, glacier recession in the long term. This is reflected in the median of fES9, which increases by the middle of the century most likely due to increased flows from snow and glacier melt but tends to reduce towards the end of the century as glaciers deplete and their contribution to runoff decreases. The increase in crop production and hydropower in the hills can also be related to accelerated glacier melting.

The uncertainty in the climate change scenarios is propagated through the water resource systems model and leads to uncertain impacts on fES (Fig. 4). Uncertainty is low in the Plains throughout time and high in the Foothills and the Himalayas, increasing towards the end of the century. The higher uncertainty in the hills can be due to the natural character of these zones that makes them much dependent of hydro-meteorological processes, as well as the more uncertain climate projections which produce more extreme forcing conditions. Looking at particular services, the aesthetic enjoyment (fES10) and the habitat maintenance service (fES8) show large uncertainty in potential impacts in all zones, and so do the cultivated crops (fES2). However, there is a clear difference between the Foothills and Plains where the impacts are either positive or negative, and the Himalayas where these services are negatively impacted under practically all scenarios. This is mainly induced by the existence of water infrastructures in the Foothills and the Plains that are managed differently depending on the spatial differences of climate change (e.g. more or less precipitation in the Plains combined with more or less

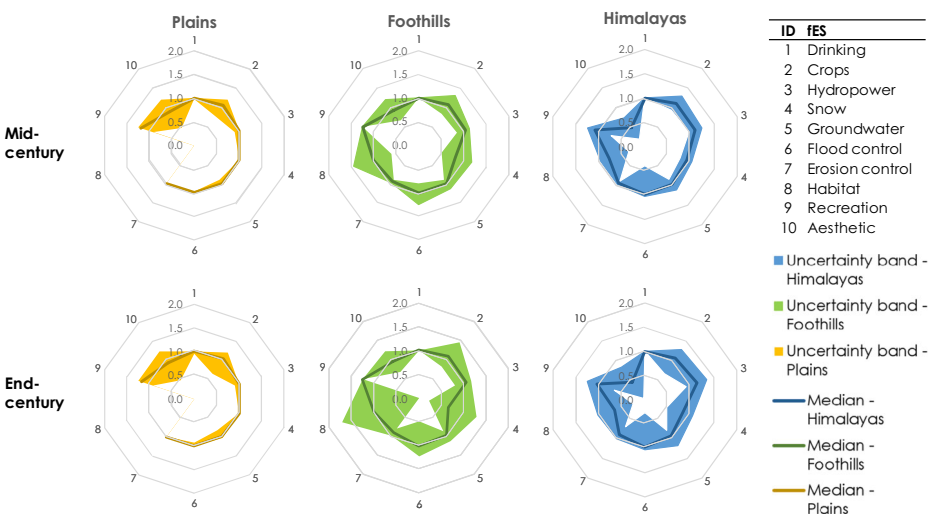


Fig. 4 Impacts of climate change on fES relative to the baseline across the RCP and CMIP5 uncertainty (bands) and median of the uncertainty distribution (lines) for each zone in the catchment and each future time horizon

precipitation in the hills) and result in distinct functioning of the system across scenarios that can improve or worsen fES. Linked to the engineered character of the study area, water provisioning for drinking (fES1) does not suffer any impact in any zone under any scenario as meeting urban water supply has the highest priority in the management of the system.

3.2.3 Worst-case scenario identification

The fact that some fES increase with climate change still results in practically no scenarios improving with respect to the baseline (1 out of 113, see values above 20 in SM1a). However, there are scenarios which show a clear deterioration. The worst-case scenarios under each RCP are presented in Table 2, where the weighted sum of fES across the century corresponding to no impacts would be 20 (i.e. all fES equal to one in the middle and end of the century). Results show an overall negative impact of climate change on fES that tends to increase with higher-end RCPs. However, the magnitudes of the impacts are comparable for RCP4.5 and 6.0 as anticipated by the similarities in their climate projections.

Breaking down the results of the worst-case scenarios by fES and climate change horizon (Fig. 5), we can see the specific services improving with climate change and those that are most impaired. The direction of the relationship with climate change is not consistent across the RCPs, which reflects the changing relative importance of temperature and precipitation changes. Considering the zonal weighting of each fES, the most negatively impacted services are fES2, 3, 4, 7, 8 and 10. These are also the ones that show the largest variability across RCPs, indicating nonlinearities in their responses to climate change. Adaptation measures should, therefore, be directed to enhance these services. However, flow regulation by snow (fES4) is the result of snow precipitation balance and cannot be managed in any way; that limits the improvable services to fES2, 3, 7, 8 and 10. Since adaptation should avoid deteriorating other fES, the measures will focus on strengthening the target services in the existing hotspots rather than changing their overall spatial pattern in the baseline. For example, food production (fES2) measures will focus on the Plains where this service is strongly provided.

3.3 Effectiveness of adaptation measures under the worst-case scenarios

According to the previous results, a multi-sectoral adaptation strategy directed to reduce the negative impacts of climate change on fES2, 3, 7, 8 and 10 under the worst-case climate scenario for each RCP while minimizing unavoidable trade-offs with the other services was tested. Given the target fES and the identified synergies and trade-offs, the strategy included the following set of measures:

Table 2 Worst-case scenarios in relation to fES production and corresponding zone-weighted sum of fES across climate change horizons

| RCP | Worst-case CMIP5 | Weighted \sum fES |
|------------|------------------|---------------------|
| No impacts | – | 20.00 |
| 2.6 | GFDL-CM3 | 19.08 |
| 4.5 | GFDL-CM3 | 18.45 |
| 6.0 | GFDL-ESM2G | 18.60 |
| 8.5 | CMCC-CMS | 17.46 |

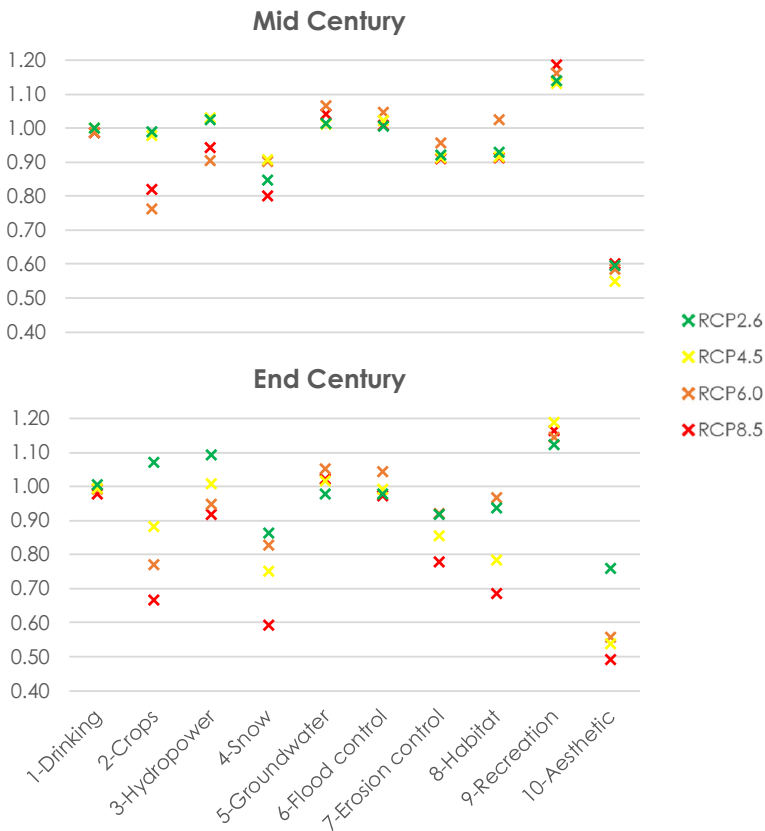


Fig. 5 Values of zone-weighted sums of fES for each worst-case scenario by climate change horizon

- fES2: Optimized irrigation schedule for rice based on soil moisture deficit (Vatta et al. 2018). The irrigation is applied when the soil moisture depletion reaches 30% of the readily available water and amount is set at 50% of the readily available water.
- fES3: Commissioning of run-of-the-river hydropower plants that have been under investigation or formulation during or shortly after the baseline period (future hydropower plants in Fig. 1).
- fES7: Based on the proposed projects in the Himachal Pradesh Mid-Himalayan Watershed Development Project, this measure considers the afforestation of bare soil areas of medium to high elevation bands (i.e. 2800 to 5200 masl) which have seasonal snow during the baseline. The afforested area in each elevation band is the minimum value between 50% of bare land area, 5% of the total area of the elevation band and 100 km².
- fES8 and 10: Setting of minimum flows downstream of Pandoh and Pong reservoirs to the 10th percentile of baseline river flows in Nadaun and downstream Pong reservoir (key points in Fig. 1), respectively.

As shown in Table 3, the implementation of the adaptation strategy increases the targeted fES in almost all cases and also benefits other services. However, the improvement is not sufficient to bring the overall level of fES production back to baseline levels. Only fES6 under RCP2.6 and fES8 under RCP 6.0 improve with respect to the baseline conditions. Results also indicate

that the effectiveness of the tested adaptation strategy decreases with higher-end climate changes as shown at both the weighted-average fES and individual fES levels.

4 Discussion

Understanding where fES originate, their delivery pathways and how they may change in the future is critical to designing and assessing adaptation needs to maintain livelihoods. This study has shown that the production of fES in complex hydro-meteorological catchments is unevenly distributed, with certain fES tending to polarize in space within zones with particular characteristics. Although enhanced in our highly complex Himalayan river basins, this differentiation caused by the spatial contrasts in climate, topography, soils and land cover and also policies, which shape social-ecological dynamics (Raudsepp-Hearne et al. 2010; Saidi and Spray 2018), is likely to occur in other catchments. However, despite this spatial polarization in the production of some fES, the natural capacity of the different zones to deliver a range of services suggests that they are all inherently multifunctional and, therefore, able to support sustainable development (Wilson 2010; Balzan et al. 2018; Lorilla et al. 2019).

Assessing the importance of each service in a multifunctional system is subjective and scale-dependent, with serious implications for fES management responses to climate change. Making decisions considering multiple ES requires the allocation of weights, often subjectively, to the different ES to reflect their relative importance for the decision-maker or stakeholder. This subjectivity is especially important for those fES which are difficult to economically value (Irvine et al. 2016; Cord et al. 2017) such as cultural. There are many approaches to such multi-criteria decision-making, which should ideally involve multiple perspectives and stakeholders in the weighting (Koschke et al. 2012; Langemeyer et al. 2016; Derak et al. 2017), although we used equal weighting for all fES in the present study in a large trans-national system. Moreover, there is likely to be strong a scale dependence to the relative importance and prioritization of ES which should be taken into account to inform

Table 3 Change in individual fES indicators and their zone-weighted sum under the worst-case climate change scenarios with and without adaptation measures

| fES | RCP2.6 | | RCP4.5 | | RCP6.0 | | RCP8.5 | |
|--------|---------------|--------------|---------------|--------------|---------------|--------------|---------------|--------------|
| | No adaptation | Adaptation | No adaptation | Adaptation | No Adaptation | Adaptation | No adaptation | Adaptation |
| 1 | 2.005 | <i>2.007</i> | 1.993 | <i>1.999</i> | 1.977 | <i>1.983</i> | 1.963 | <i>1.971</i> |
| 2 | 2.058 | <i>2.117</i> | 1.859 | <i>1.949</i> | 1.530 | <i>1.603</i> | 1.485 | <i>1.557</i> |
| 3 | 2.116 | <i>2.193</i> | 2.038 | <i>2.120</i> | 1.852 | <i>1.939</i> | 1.861 | <i>1.959</i> |
| 4 | 1.709 | 1.709 | 1.656 | 1.656 | 1.730 | 1.730 | 1.392 | 1.392 |
| 5 | 1.989 | 1.985 | 2.024 | 2.019 | 2.114 | 2.109 | 2.062 | 2.057 |
| 6 | 1.980 | 2.016 | 2.012 | <i>2.035</i> | 2.089 | <i>2.097</i> | 1.979 | 1.976 |
| 7 | 1.835 | <i>1.851</i> | 1.766 | <i>1.783</i> | 1.876 | <i>1.888</i> | 1.686 | <i>1.699</i> |
| 8 | 1.773 | <i>1.793</i> | 1.698 | 1.679 | 1.990 | 2.095 | 1.595 | <i>1.649</i> |
| 9 | 2.263 | <i>2.296</i> | 2.318 | 2.313 | 2.305 | <i>2.330</i> | 2.348 | <i>2.358</i> |
| 10 | 1.354 | <i>1.497</i> | 1.083 | <i>1.088</i> | 1.142 | <i>1.152</i> | 1.089 | 1.055 |
| ∑fES | 19.08 | 19.46 | 18.45 | 18.64 | 18.60 | 18.93 | 17.46 | 17.67 |
| Change | 0.38 | | 0.20 | | 0.32 | | 0.21 | |

The change is relative to the “no adaptation” scenario. Figures in italics indicate improvement of fES with adaptation, and bold indicate improvement with respect to the baseline

governance across multiple jurisdictions and scales, as the social value of some fES can become more important at smaller scales, for example, supporting food production under climate change to ensure subsistence agriculture in remote rural communities within mountainous areas, despite its small relative importance in the system.

The findings of this study reveal that the production and flow of services along the river network are modified by the influence of associated water infrastructures, in our case reservoirs and inter-basin water transfers. For example, the large reservoirs in the Foothills that support the high levels of provision of water supply and food production in the Plains provide a regulation service that compensates for the low levels of flow regulation by groundwater systems in the impermeable geology of the Himalayas. These reservoirs may also offset the future loss of flood abatement capacity in the upstream zones with climate change. The fES production can also positively influence downstream water management as some services may be beneficial for the operation of the water resource system. For example, the Himalayas provide a significant control of erosion through the protection that permanent snow cover provides to bare soil from direct rainfall (fES7), which benefits downstream hydropower production and irrigation by reducing sediment-related damage to infrastructure and loss of storage capacity (Terrado et al. 2014; Ashagre et al. 2018), although this has not been directly modelled in this study. Moreover, current and future states of the fES are a function of both the spatial patterns of climate change (and associated direct impacts) and the spatial interdependencies of fES flows induced by the river and infrastructure management. The clear evidence of the multiple feedback loops between landscape and river fES and the sensitivity of fES flows to the existing water management and infrastructures highlights the importance of integrated approaches, such as systems modelling, for climate change impact assessment (Harrison et al. 2016; Momb Blanch et al. 2017; Rosenzweig et al. 2017). However, these approaches entail simplifications in the representation of real complexity and the estimation of indicators that describe the behaviour of the system (Brown et al. 2015). Therefore, it is important that simplifications are based on robust assumptions that ensure the credibility of the outputs. For example, the habitat maintenance service (fES8) is derived from LIFE score time series, which can be related to the delivery of supporting ecosystem services (Ncube et al. 2018). By incorporating both the LIFE score median and the interquartile range, the proposed indicator accounts for general trends of change and the resilience of the service linked to macro-invertebrate diversity (Visser et al. 2019).

The high uncertainty in climate change projections, due to emissions and climate model uncertainty, in the Sutlej-Beas catchments translates into a wide range of impact magnitude such that the future direction of change in most fES is conflicting under different scenarios, making the identification of the “best” adaptation solution difficult if not impossible. Uncertainty issues are intrinsic to all adaptation studies and have led to the emergence of a range of decision-making paradigms (Green and Weatherhead 2014; Yousefpour and Hanewinkel 2016; Roelich and Giesekam 2019). In our study, we use a precautionary approach that considers the worst possible state as the basis for identifying catchment management responses but which risks over-adaptation if the future climatic impacts turn out to be less severe. Alternative approaches, such as robust decision-making which look for solutions that perform satisfactorily across all scenarios (Bhave et al. 2016) or dynamic adaptive policy planning (Roelich and Giesekam 2019), take a more uncertainty-based perspective and allow for the development of no-regret adaptation strategies but may lead to under-adaptation.

Uncertainty in future change is not restricted to climate but also to socio-economic change (O'Neill et al. 2017). Changes in land use, population, agricultural practices and energy demand, among many other socio-economic variables, will have important implications for water resources

availability and demand in catchments. Many recent studies have demonstrated that the combined impacts of future climate and socio-economic changes can be more severe than climate change impacts alone (Hanasaki et al. 2013; Arnell and Lloyd-Hughes 2014; Holman et al. 2019; Momblanch et al. 2019b). However, analysing climate change alone, as in this study, is the preliminary stage to a full global change impact assessment that helps to understand the relative importance of climate and socio-economic components in each specific case. This helps to avoid climatisation of the problem (i.e. overemphasis of climatic factors to justify global change impacts) as a way of discharging decision-makers from accountability for their decisions (Wine and Davison 2019). In this study, we implemented an adaptation strategy that was based on the assumption that responses compatible with current projects and plans for the study area could be implemented under all futures. However, the ability to adapt is also conditioned by the future socio-economic context, as the associated economic, political and social conditions can enhance or deteriorate the enablers and disablers of adaptive capacity (Azihoni et al. 2018).

While this current study has focussed on adaptation to reduce the impacts of climate change on fES, it has reinforced the societal benefits of mitigation due to multiple dimensions of the limits for adaptation. Firstly, adaptation is unable to address losses in some strongly climate-dependent fES, such as the flow regulation provided by the snowpack or cultural services provided by the glaciers as part of the Himalayan landscape. Secondly, the ability of adaptation to fully negate climate impacts reduces with increasing magnitude of climate change. Finally, there are major limits to the effectiveness of nature-based solutions such as afforestation (Dadson et al. 2017) to compensate for the weakening of the regionally and internationally important flow regulation function of the spatially extensive snowpack (and glaciers). Moreover, transitioning from our current trajectory of greenhouse gas emissions to those consistent with the Paris Agreement (similar to RCP2.6) is expected to require extensive implementation of land-based mitigation measures, which are included in 148 of the 160 (Intended) Nationally Determined Contributions, with afforestation and reforestation being central (Forsell et al. 2016). Large-scale implementation of these type of mitigation measures can lead to trade-offs and conflicts with some fES such as water (Cunningham et al. 2015) and food provisioning (Lee et al. 2019). Under such circumstances, investment in or modification of the engineered infrastructures becomes the most effective means to replicate the regulation service delivery. Hence, addressing climate change through adaptation and mitigation poses important and diverse management challenges to maintaining multifunctional fES production and delivery. A holistic systems-based approach that considers the interdependencies between fES, natural and anthropic systems and management responses is essential to inform the design of mitigation and/or adaptation responses. This will help to avoid or minimize unintended detrimental consequences on fES and help to ensure that fES continue to underpin future societal well-being.

5 Conclusions

This study has analysed the spatial distribution and flow of fES in a managed river system in the Western Himalayas in India under historical conditions and has explored their sensitivity to climate change uncertainty across the twenty-first century. The systems modelling tool WEAP has been used to account for the natural and management-induced dependencies between fES and to design and test an adaptation strategy to enhance fES under a precautionary approach.

The balance between natural and anthropogenic features in different parts of the catchment greatly determines the spatial distribution of services. Natural zones deliver more regulating and cultural services than anthropized areas, and these are more climate-dependent due to the

lesser influence of water infrastructures. Thus, combined adaptation and mitigation measures may be necessary to offset the negative impacts of climate change on fES. In this context of emerging trade-offs, water resource systems models are able to capture complex landscape-river feedbacks and assist decision-makers to prioritize and design robust measures to enhance the production and delivery of fES which sustain long-term human development.

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Data Availability Data underlying this study can be accessed through NERC's Environmental Information Data Centre at <https://doi.org/10.5285/715db0b2-1d63-4842-ab80-f0f33b39e5e0>.

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