Network analysis of water-related ecosystem services in search of solutions for sustainable catchment management: a case study in Sutlej-Beas River systems, India

Shuying Yu[a], Jian Peng[a], Pei Xia[a], Qi Wang[b], Robert C Grabowski[c], Adani Azhoni[d], Brij Bala[e], Vijay Shankar[f], Jeroen Meersmans[g]

[a] Laboratory for Earth Surface Processes, Ministry of Education, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

[b] Key Laboratory for Environmental and Urban Sciences, School of Urban Planning and Design, Shenzhen Graduate School, Peking University, Shenzhen 518055, China

[c] Centre for Water, Environment and Development, School of Water, Energy and Environment, Cranfield University, Cranfield MK43 0AL, UK

[d] Department of Civil Engineering, National Institute of Technology Karnataka, Surathkal, India

[e] Department of Agricultural Economics, COA, CSKHPKV, Palampur, Himachal Pradesh, India

[f] Civil Engineering Department, National Institute of Technology Hamirpur, Hamirpur, Himachal Pradesh, India

[g] TERRA Teaching and Research Centre, Gembloux Agro-Bio Tech, University of Liège, 5030 Gembloux, Belgium

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Abstract: Hydrological processes and ecosystem interactions are instrumental in sustaining local populations by providing various water-related ecosystem services (ES). Numerous studies gave priority to the theories and methods of building networks that emphasized different stakeholders. However, little study has examined the complex relationships among water-related ES themselves and how relevant human activities affect ES networks. To narrow this gap, in this study we quantified four critical water-related ES (flood mitigation, hydropower production, soil retention, and water conservation), set up six ES network types based on the synergy relationship, and further explored the effect of human activities on these networks. The results showed that among six ES network categories, networks with four fully linked ES occupied a large percentage of 23.20% while the network with one central ES linking two others accounted for the lowest percentage (9.28%). Compared with other ES, soil retention tended to be less centralized within the networks. In addition, land use intensity was found to greatly influence the ES networks compared with other indicators, especially for less complex networks. Our results highlighted the importance of network analysis in searching solutions for sustainable catchment management.

Keywords: Ecosystem services network; Water-related ecosystem services; Ecosystem synergy; Generalized additive model

1. Introduction

Ecosystem services (ES) are defined as the benefits that people obtain from ecosystems (Carpenter et al., 2006), and the direct and indirect contributions of ecosystems to human well-being (Kumar, 2012; Yu et al., 2021). Among them, water ecosystems play an essential role in maintaining water quality and quantity, supporting nutrient cycling, and providing energy for human consumption (Castello & Macedo, 2016). However, the consensus on describing these ES in the context of water resource management has not been achieved yet. There are terms of water-related ES (Lin et al., 2021a; Xia et al., 2021), water ES (Grizzetti et al., 2016; Hackbart et al., 2017), freshwater ES (Lin et al., 2021b; Chung et al., 2021), and riparian ES (Hanna et al., 2020), among which water-related ES is the most common in existing studies. It is acknowledged to usually cover water quantity (i.e. freshwater supply) and water quality (i.e. water purification) (Sun et al., 2023). Despite the importance of water-related ES in terms of contributing to the needs of human civilization and meeting local demands (Grill et al., 2015; Portela et al., 2021), many major global initiatives have overlooked the prospects of the water ecosystem in achieving sustainability (Basak et al., 2021). Therefore, it is in special need for quantifying water-related ES.

Understanding the complex linkages among the critical elements within the natural and human systems can greatly facilitate sustainability-oriented management (Grizzetti et al., 2016; Guerry et al., 2015; Grabowski et al., 2022; Peng et al., 2023). There are several methods attempting to reveal the intricate relationships between ES such as ecosystem service bundles (Spake et al., 2017). ES bundles, usually identified by cluster analysis, can reflect the close interactions of various ES. However, different types of interactions cannot be revealed, especially for those ES that are often bundled together in the same cluster. With the dendritic nature of water ecosystems, understanding process linkages requires an approach of network analysis, an effective tool for quantifying connections within specific ES in different local areas, which has been widely applied in the fields of natural resource management, socio-ecological matching, and adaptive governance (Bodin, 2017; Bodin et al., 2019; Dee et al., 2017).

Generally, the types of networks can be divided into two categories: 1) social-ecological networks (SEN), and 2) ecological networks (EN). As a pioneer, Bodin and his team have dramatically advanced the SEN research in recent decades (Bodin et al., 2017; Bodin and Tengo, 2012). Different from EN, the participants in SEN are separated into social actors, ecological actors, and others. The main steps to setting up SEN include defining the specialized social-ecological dependences, the social nodes and ecological nodes, and the links within the system (Felipe-Lucia et al., 2022; Simmons et al., 2019). By incorporating interdependencies, connections, and spatial scales, SEN can capture the complex interaction of various entities and solve multi-agent and cross-scale problems (Sayles and Baggio, 2017), such as the network connecting wild species, crops, and people on smallholder farms (Timberlake et al., 2022). However, most SEN studies remain at the abstract level, because quantifying SEN networks is quite challenging.

By comparison, there are fewer related elements in EN and the networks are more targeted at ES management. For example, Chung et al. (2021) explored the interrelationships between built and natural infrastructure in worldwide watersheds for cities by building freshwater ES networks. Networks between biodiversity, ecosystem functions, and ecosystem services have been examined to unravel how changes in land use will affect ecosystems and human wellbeing (Felipe-Lucia et al., 2020; Zhao et al., 2023). Special attention has been devoted to applying the EN approach for predicting ES vulnerability to species losses relevant to human threats (Keyes et al., 2021). Additionally, a large number of studies turn to ecological security patterns to set up EN (Dai et al., 2021). However, significant scientific gaps remain, including a lack of consensus on network framing rules, and the inclusion of ES trade-offs and synergies.

For water-related ES, connected by hydrological processes, understanding the trade-offs and synergies among them is helpful for watershed ecosystem management. Trade-offs occur when the supply of certain ES is reduced by an increase of other ES, and often result from human specific demand preferences, while synergies represent the same change trend of two ES (Rodriguez et al., 2006). The interconnections in the environmental processes that influence ES in water ecosystems (Grabowski et al., 2022), and the increasingly complex spatial arrangement of connections due to human modification of river systems (e.g., canals and inter-basin transfers) can greatly influence local social-ecological systems (Ding et al., 2022). To a large extent, land use change and associated human activities have altered the interactions in the ecological system (Lin et al., 2021a; Lin et al., 2021b), which can be directly reflected by the characteristics of ES networks. Considering the compound reality in ecosystems, in this study we proposed an applicable network-based approach to facilitating cross-disciplinary engagement rather than advocating a crude one-size-fits-all approach. To fill this knowledge gap, Sutlej River and Beas River in India were taken as the study area with the following two objectives: 1) to construct networks among critical water-related ES, and 2) to figure out how human activities influence ES networks.

2. Methods

2.1 Study area and datasets

The study area (30°40'~32°31'N, 74°57'~77°58'E) is located around the Beas River and Sutlej River, covering three administrative areas: Himachal Pradesh, Punjab, and Haryana (Fig. 1). With a highly concentrated population, the downstream sector of the study area is widely-known as the granary of India due to its large modern agricultural irrigation area (Wang et al., 2022). The local hydrology is largely controlled by Himalayan snowmelt in the spring and summer. Heavy rain usually comes with the summer monsoon, which frequently triggers large scale downstream floods. Numerous media have criticized the severely degraded water quality attributed to daily disposal of excessive wastewater in the river and further influence the freshwater supply for urban areas. Thus, figuring out the status and relationships of local water-related ES is urgently needed.

The main datasets used in this study are introduced in Table 1, including land use and land cover (LUCC) data, road data, soil data, monthly precipitation data, DEM data, NDVI data, potential evapotranspiration data, dam site location and power generation data, and population data. All raster data were resampled with a unified 500 m resolution and the research unit was sub-catchment with a total number of 240 in the study area.

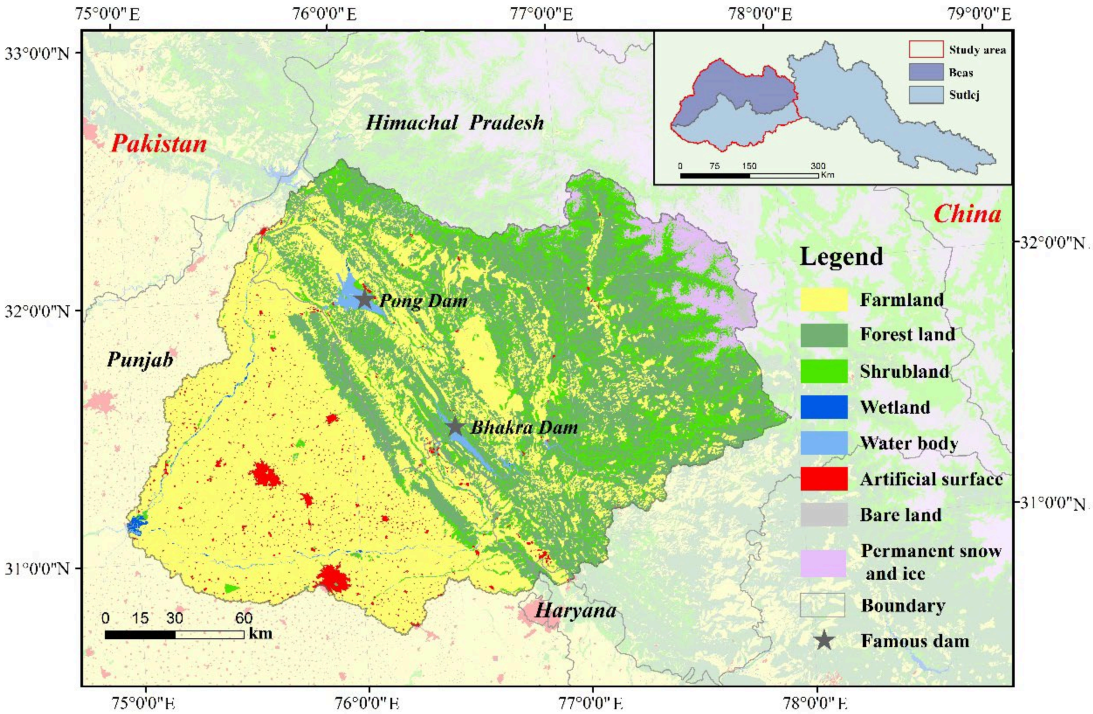


Fig. 1. Geographical location and land cover of the study area.

Table 1 Data sources used in this study

Dataset	Resolution	Source
Land use and land cover (LUCC)	30m Tiff	Globaland dataset http://globeland30.org/
Road	Shp	OpenStreetMap website https://www.openstreetmap.org/
Soil	1km Tiff	Harmonized World Soil Database (HWSD) https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/
Precipitation	1km Tiff	Climatic Research Unit https://crudata.uea.ac.uk/cru/data/hrg/
DEM	30m Tiff	SRTM dataset https://lpdaac.usgs.gov/products/srtmgl1v003/
NDVI	500m Tiff	MOD13A1 dataset https://lpdaac.usgs.gov/products/mod13a1v006/
Potential evapotranspiration	500m Tiff	MOD16A2 dataset https://lpdaac.usgs.gov/products/mod16a2v006/
Dam site location and power generation data	Shp	Global Power Plant Database https://datasets.wri.org/dataset/globalpowerplantdatabase

Population	1km Tiff	WorldPop dataset https://www.worldpop.org/

2.2 Conceptual framework

In local ecosystem, water supports the delivery of crucial ES and most of them can be directly appreciated by people via nature (Fig. 2). As a bridge connecting the social and ecological systems, ES can link the demands for freshwater and electricity of urban residents within the water ecosystem. However, with an increased urban population and intensive land use change, the interactions among the various kinds of social-ecological subjects are intricate and difficult to separate. In this study, it was more focused on the relationships among water-related ES and the human impact on their relationship network, which existed as several potential network types (Fig. 3).

Water ecosystems support the delivery of crucial ecosystem services, such as fish production and water provisioning (Grizzetti et al., 2016). Thus, the content of water-related ES covers more than provision ES, but also regulation ES, support ES and cultural ES. Several key ecosystem services are also connected to the hydrological cycle in the river basin, for example water purification, water conservation and climate regulation. Although in reality, nearly all the important ES should be taken into consideration for the sustainable use and management of water resources, it is too complex to set up these kinds of ES networks and hard to explain. Thus, considering the social and ecological issues faced by Sutlej River and Beas River, we finally selected four critical water-related ES: flood mitigation, hydropower production, soil retention, and water conservation.

Within four selected water-related ES, the relationships are funny to explore. Water conservation, the ability of an ecosystem to keep water in the system, usually plays an essential role in retaining water (Li et al., 2021). However, the trade-offs between flood mitigation and water conservation seems to exist because the large water volume in the watershed may exert great pressure on flood mitigation although it can provide great natural condition for water conservation. Different from other three regulation ES, hydropower production serves as a provision ES with a close link to the demand of local stakeholders. Actually, terrestrial ecosystems influence these water-related ES to a large extent, especially land cover changes. For example, soil erosion decreases with increasing grassland patch density and water yield in summer increases as forest aggregation increased (Xia et al., 2021). Thus, in the context of intricate social-ecological systems, how are these water-related ES connected with each other is a valuable question to be studied.

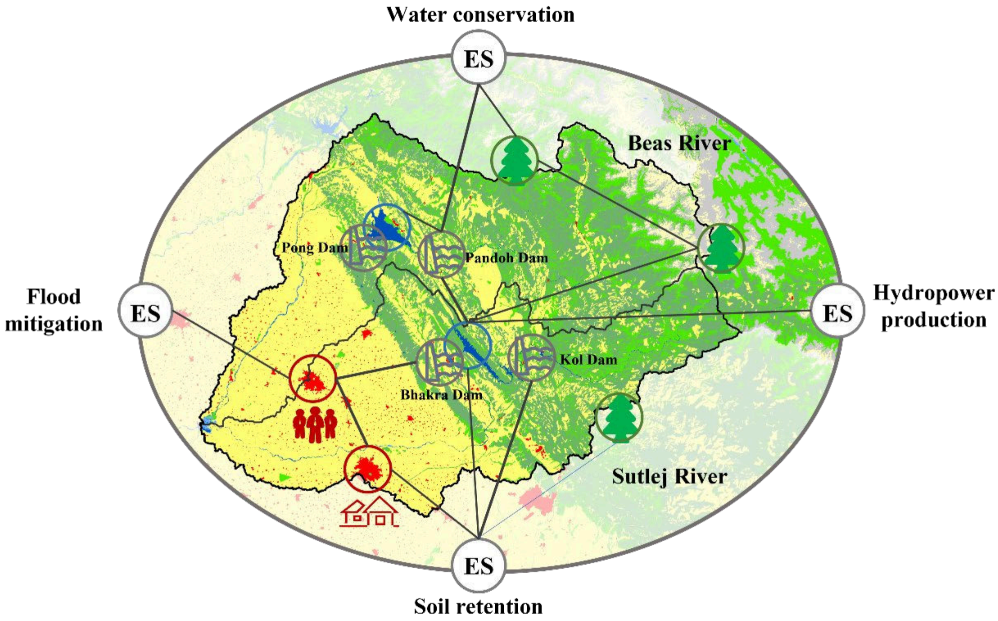


Fig. 2. A representation of the water-related ecosystem services (ES) provided by the Sutlej and Beas River systems, India.

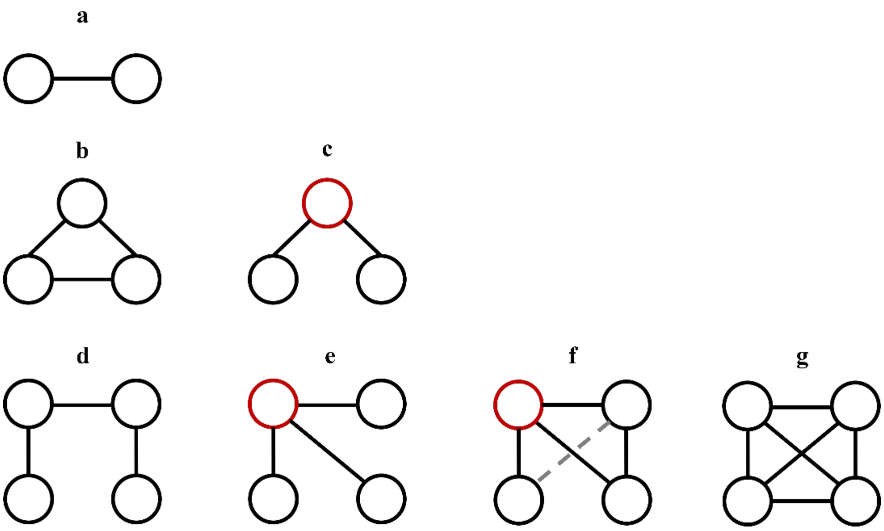


Fig. 3. Seven types of ES networks. The circle nodes represent simplified water-related ES, and the red circles are those playing an essential role in the whole network that are

defined as centralized nodes. The black lines represent the synergistic relationships between two ES while the gray dotted line represents the potential synergy between ES.

2.3 Quantifying water-related ecosystem services

Hydrological connectivity regulates the provision of interactive dynamic water-related ES that sustain local populations, yet it is increasingly being disrupted by the construction of dams, land-cover changes, and global climate change (Castello and Macedo, 2016; Lin et al., 2021a). Here, the four water-related ES were defined and calculated as follows. Since the value of different ecosystem services cannot be compared directly, the method of nature breaks in ArcGIS was used to display each water-related ecosystem service with the levels from low to high.

（1） Flood mitigation

Flood mitigation reflects the ecosystems' ability to moderating floods, which has a close relationship with terrestrial ecosystems in the context of water management (Fu et al., 2013). The Soil Conservation Service curve number (SCS-CN) method is widely used to calculate runoff for a single event. In this study, an event with rainfall greater than 50 mm in 24 hours was regarded as a flood, and flood mitigation service was calculated as follows (Fu et al., 2013):

$$\mathrm{Flood_{mit}} = \left(P_{ev} - \frac{(P_{ev} - 0.2S)^2}{P_{ev} + 0.8S}\right) \times storm_{days} \tag{1.}$$

where $\mathrm{Flood_{mit}}$ represents the service of flood mitigation (mm); P_{ev} represents the rainfall in a single event (mm); $storm_{days}$ represents the days with floods in one year; and S represents the amount of rainfall maintained by the ecosystem, derived as follows:

$$\mathrm{S} = \frac{1000}{CN} - 100 \tag{2.}$$

where CN is curve number, a coefficient related to land use, soil moisture, etc., which ranges from 0 to100 according to the existing literature.

（2） Hydropower production

Dams in the study area are mostly used for power generation and irrigation, implying that hydropower production is important in local water-related ES. The Global

Power Plant Database provides hydropower plant locations. Site interpolation and zonal statistics were done with the help of ArcGIS 10.6. Then, we summed the installed capacity of the hydropower dams in each sub-watershed (Chung et al., 2021).

（3） Soil retention

Soil erosion destroys the original soil structure, leads to soil degradation, and reduces ecosystem productivity, negatively affecting socio-economic and ecological aspects (Wang et al., 2022; Lu et al., 2022). Considering the undulating terrain and intensive human activity, soil retention is an important ES in this region. The commonly used Revised Universal Soil Loss Equation (RUSLE) was applied to calculate the service of soil retention (Wang et al., 2022).

$$A = R \times K \times LS \times (1 - C \times P) \tag{3.}$$

where A represents the service of soil retention in 2020; R represents rainfall erosivity factor; K represents soil erodibility factor; L represents slope length factor; S represents slope factor; C represents land cover and vegetation management factor; and P represents cropping practice factor.

（4） Water conservation

Water conservation plays an essential role in retaining water resource, purifying water quality and regulating runoff. The water yield module of the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model was applied due to its advantage in enabling large spatio-temporal scale modeling based on the principle of water balance. Allowing for the surface runoff, we finally used the following equation to estimate the amount of water conservation (Li et al., 2021).

$$WS = \min\left(\frac{1{,}249}{Velocity}\right) \times \min\left(1{,}0.9 \times \frac{TI}{3}\right) \times \min\left(1, \frac{Ksat}{300}\right) \times Y_{xj} \tag{4.}$$

where WS represents the service of water conservation (mm); $Velocity$ represents the coefficient of flow rate; $Ksat$ represents saturated water conductivity of soil (cm/d), calculated by Neuro Theta software; TI represents dimensionless topographic index; and Y_{xj} represents water yield. TI and Y_{xj} were calculated as follows.

$$TI = \log(\frac{watershed\ pixel\ count}{soil\ depth\ \times percent\ slope}) \tag{5}$$

where $watershed\ pixel\ count$ refers to the pixel number of the catchment, $soil\ depth$ refers to the soil thickness, and $percent\ slope$ refers to the percent slope.

$$Y_{xj} = \left(1 - AET_{xj}/P_x\right) \times P_x \tag{6}$$

where AET_{xj} represents the actual evapotranspiration for the grid x of land-use type j and P_x represents the annual precipitation for the grid x.

2.4 Network analysis

The Root Mean Square Error (RMSE) can represent the difference between predicted and observed values, which has been widely applied to quantify synergies and trade-offs between ES (Bradford and D'Amato, 2012). Commonly, the larger the RMSE value, the weaker the synergy between ES. To observe the change of the synergy between ES, four ES were processed with the min-max standardization. It is worth mentioning that in the network analysis, we focused on the relative comparison rather than the absolute value. Therefore, only links with the top 50% synergy values in all sub-catchments were retained for each ES pair, and a water-related ES network was thus formulated. For four ES, there are seven network types, the quantitative structure of which matters a lot for ES management.

To describe the characteristics of networks, two network indexes were additionally calculated: network density and network centrality. The network density reflects the close relationship among four ES in the network. The greater the number of association relationships in the network, the greater the network density. In this study, the network density was defined as the ratio of the number of connections present to the maximum number of connections among ES that can exist in the entire network. The network centrality can demonstrate the status and role of each ES in the network (see red circles in Fig. 3). The more central an ecosystem service is in the network, the greater its influence in the network, and the more it can affect other ES. Here, network centrality was defined as the ratio of the summed number of ES directly associated with each ecosystem service in the network to the maximum number of ES that are likely to be directly connected.

The nonlinear responses of network indexes to human activity associated variables were explored with the generalized additive model (GAM, using the 'gam' function in the R package 'mgcv'). GAM can flexibly fit the relationship between the response and explanatory variables by smooth functions and penalized regression splines without prior knowledge, so as to choose a specific response function (Ziter et al., 2019).

3. Results

3.1 Spatial patterns of water-related ecosystem services

Spatial patterns of four critical water-related ES are shown in Fig. 4, and the comparison of two rivers is depicted in Fig. 5. Both watersheds showed poor performance in terms of flood mitigation in the downstream sub-catchments. It is noted that sub-catchments with large water areas often had better flood mitigation performances. Hydropower production was greater in the Sutlej catchment, with the highest production sub-catchments clustered in the Himalayan foothills (Fig. 4). Sub-catchments in the Beas River had substantially lower hydropower generation potential, with its top 25% barely reaching the median for Sutlej River (Fig. 5). The majority of local sub-catchments had high levels of soil retention, especially concentrated in the downstream of the study area. Similar to the spatial pattern of soil retention, water conservation also showed better conditions in the downstream areas.

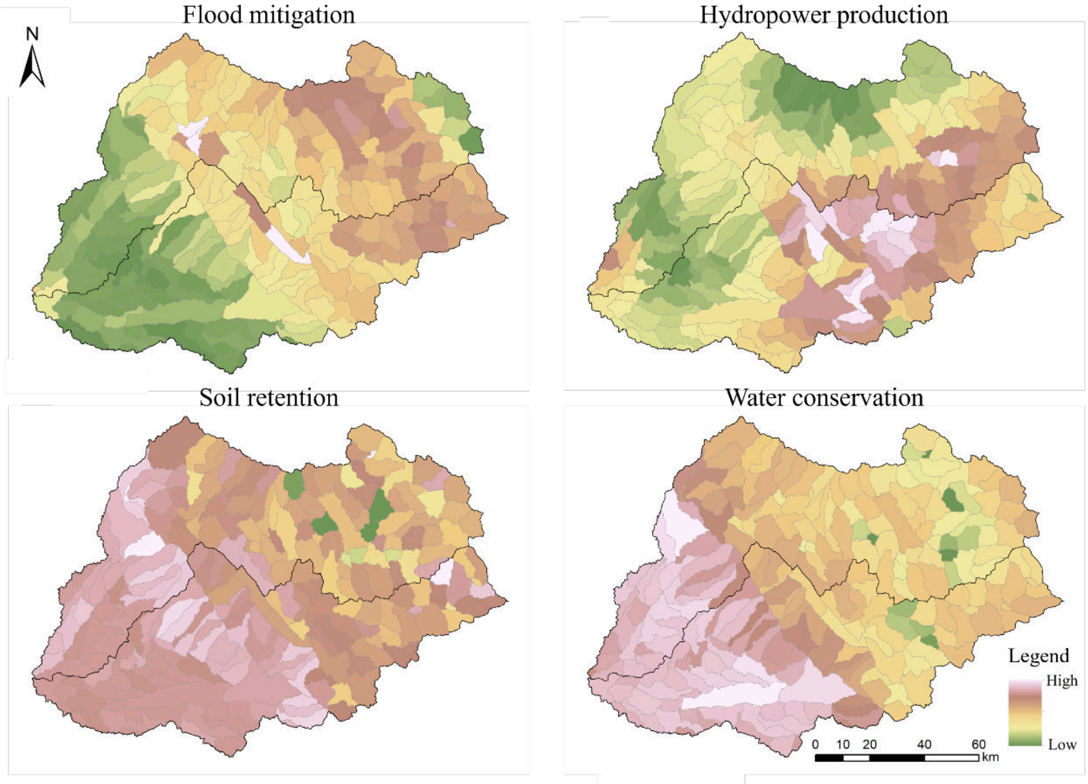


Fig. 4. Spatial patterns of four water-related ecosystem services

Comparing Beas River and Sutlej River, in general, most ES in Sutlej River performed better than those in Beas River, except in terms of flood mitigation (Fig. 5). It could also be deduced that there was an obvious trade-off or synergy phenomenon, which reinforced the importance of building ES networks.

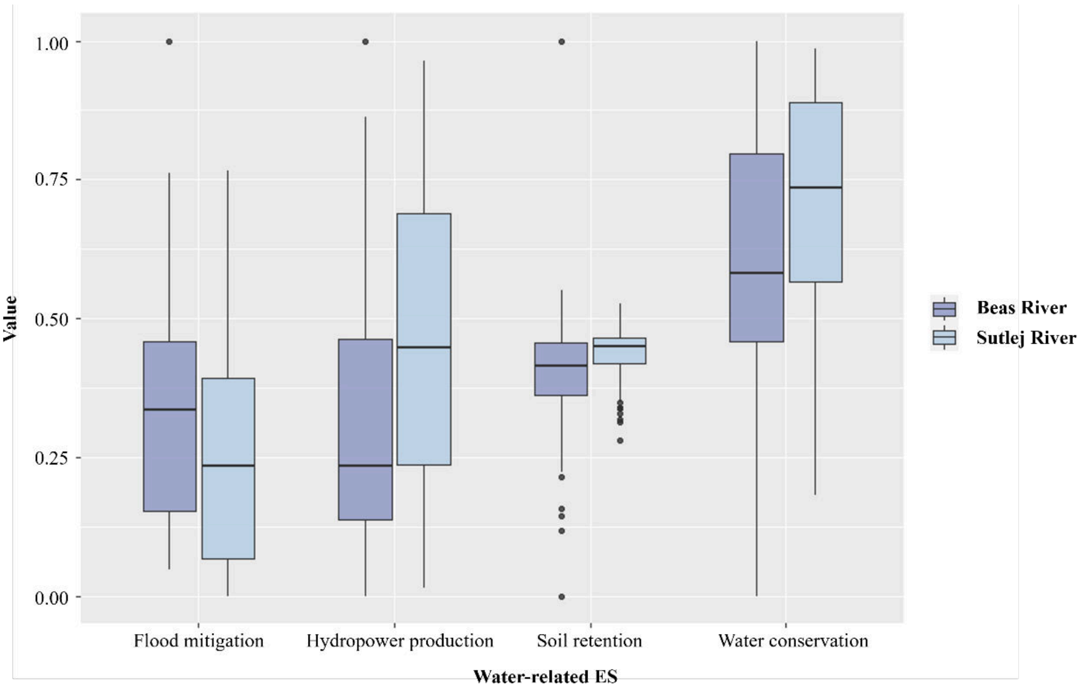


Fig. 5. Comparison of four water-related ecosystem services between Sutlej River and Beas River

3.2 Water-related ecosystem services networks

A total of 194 ES networks were identified among the whole 240 sub-catchments, which were divided into six types (Fig. 6). For all sub-catchments, the most frequently occurring type was f with four or five links, representing 23.71% of all the networks. In this network type, the four water-related ES were closely connected with each other. The second most common network type (corresponding to 23.20%) was g where all ES were completely connected. Networks with one centralized node and three links (type e) accounted for 18.56%, and there were no networks centralized by soil retention but 28 centralized by hydropower production, indicating the relative importance of hydropower production in the local areas. It was also noted that in two-node networks of type a, there were only networks between flood mitigation and soil retention (10 for the number of networks, the same as below), between soil retention and water conservation (6), and between hydropower production and soil retention (9), all of which connected with soil retention. In terms of type b, where three water-related ES were fully linked with each other, interactions among flood mitigation, soil retention, and water conservation were found most frequently (17 out of 24).

There were the most sub-types in type f, which in total had ten kinds of combinations. For type f networks with only one centralized node, water conservation played a more important role and no networks were centralized by soil retention. For type f networks centralized by two ES nodes, the frequency of co-centrality of flood mitigation and water conservation, and hydropower production and water conservation were the highest. There were no type d networks in the study area, indicating that networks connected by two equally important ES were rare. Among all networks, soil retention showed less dominance compared with the other three water-related ES, which could, to a certain extent, indicate that it might be a lower priority when considering the distribution of the restricted finance that was available for the overall maximization of

ES conservation.

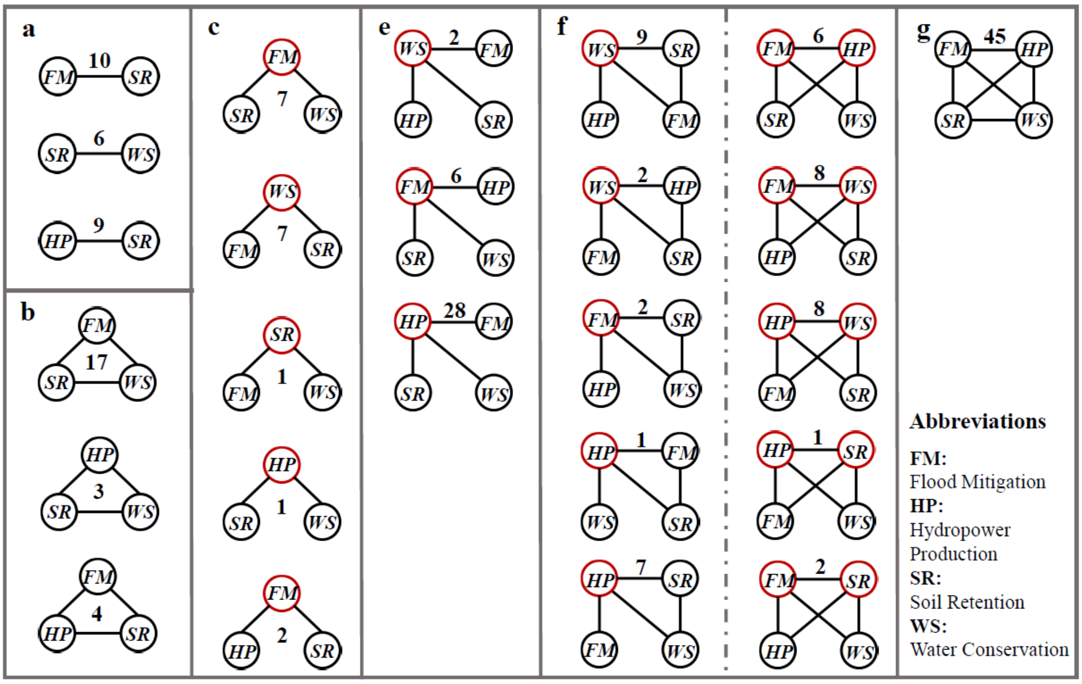
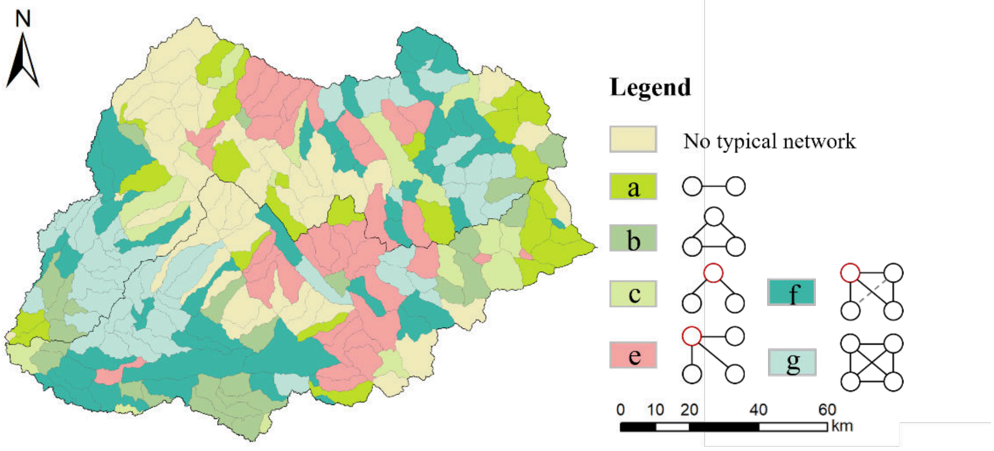


Fig. 6. All kinds of water-related ES networks of sub-catchments. The black node represents the ES and the red nodes are the ES with more links than the others. The number of each type of network is next to the sub-figure.

The spatial patterns of ES networks and their associated indexes (network density and network centrality) are shown in Fig. 7a with the corresponding boxplot in Fig. 8. Generally speaking, most of the sub-catchments without typical ES networks belonged to the Beas River, where type g had the highest percentage (20.31%), which mainly gathered in the downstream area with relatively higher urbanization. By comparison, type e and type f were equally highly represented among networks (18.75% in total) in Sutlej River, with type e concentrated in the middle basin and type f located mainly in the downstream area. Comparing Fig. 7b and Fig. 7c, it could be found that there was only subtle difference in the spatial pattern of network density and network centrality, which had a relatively low values in the downstream areas, with high values gathering mainly in Beas River.

(a) Spatial pattern of networks



(b) Network density

(c) Network centrality

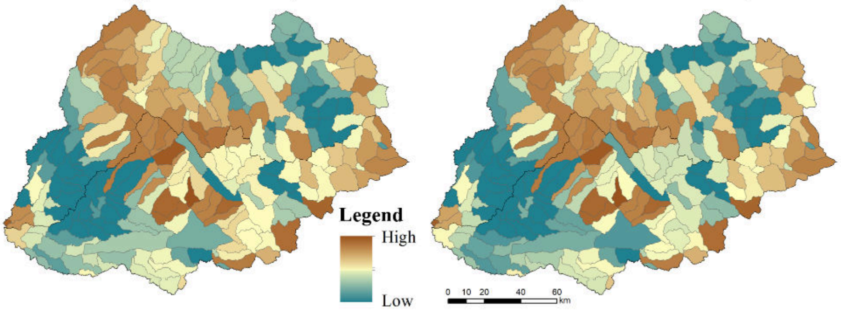


Fig. 7. Spatial patterns of water-related ES networks and associated indexes

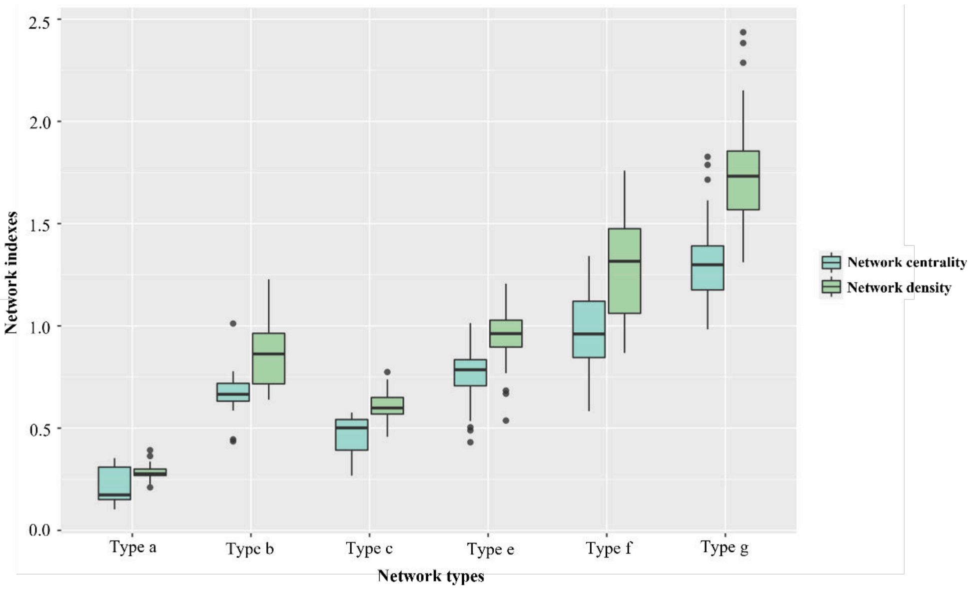


Fig. 8. Boxplot of network indexes for different water-related ES network types

According to Fig. 8, network centrality had a lower average value than network density in all network types. In general, the values of network indexes increased with the increasing number of nodes and links, except for type b. Compared with type c, type b was fully connected with obvious better performance. This implied that to a certain extent, local water-related ES might benefit from the complexity of the network, which enabled higher network resilience.

Compared with other human activity associated factors, such as population density, road density and nighttime light intensity, land use intensity had a more significant nonlinear impact on the network (with edf = 5.842 for network intensity and edf = 5.746 for network centrality, both $p < 0.001$). Inspired by this, the six categories of ES networks were explored separately using GAM (Fig. 9). Significant relationships between network centrality and land use intensity were identified for two network types (type a and type e), although the characteristics of the two relationships between network centrality and land use intensity were quite different. In type a, the relationship tended to be nonlinear with two peaks, indicating that an appropriate range of land use intensity ought to be further explored for effective improvement of ES networks. However, the relationship in type e was linear, highlighting the features of one ES dominated networks.

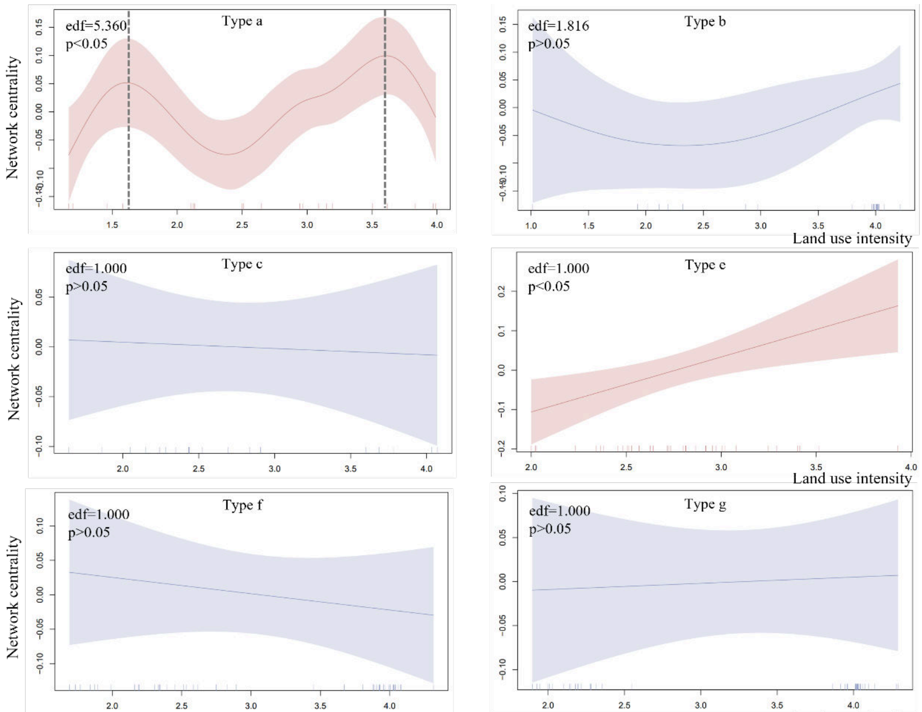


Fig. 9. Correlations between network centrality and land use intensity across various

water-related ES network types

4. Discussion

4.1 Understanding ecosystem services networks

Six ES network types were identified in Beas River and Sutlej River, which could help to understand the underlying interactions among multiple ecosystem services (Wang et al., 2022; Basak et al., 2021). The different characteristics of ES network types facilitates the insights into the further management of catchments. For catchments belonging to type a with only two ES nodes, achieving the balance between these two ES is critical to ecosystem conservation. The results showed that the high land use intensity might be related to low network indexes. Thus, figuring out the accepted range of land use intensity can contribute to better network improvement. Compared with other types, the number of involved stakeholders is relatively smaller and these areas can serve as the policy demonstration area. For type b, these sub-catchments had fully connected water-related ES, most of which had a close relationship among flood mitigation, soil retention, and water conservation, emphasizing the relative importance of these ES and their interactions. Thus, ES equality should be prioritized when implementing compensation and conservation measures. Type c had a centralized ES node linking the others, and this centralized node was more likely to be flood mitigation and water conservation, emphasizing their essential role in the corresponding sub-catchments where priority could be given to protecting these two ES when financial budgets were restricted.

Type e had obvious spatial agglomeration characteristics compared with the others, and a linear relationship between network indexes and land use intensity. In these sub-catchments, the increasing of land use intensity can help the improvement of ES networks. With the large proportion of type f and type g, the network complexity in these sub-catchments was high. These networks were closer to reality compared to the simpler networks, such as type a. However, local water management should still pay special attention to these networks and figure out the common features to initiate proper targeted policies. To achieve this, recording precisely localized data for accurate ES assessment is an essential premise, such as monitoring water flow paths of each sub-catchment and upstream inflow capacity (Sun et al., 2023). Due to the increasing urbanization, the conflicts between social development and ecological conservation may be severer than before, asking for more collaborative management efforts.

4.2 A dilemma for sustainable catchment development

Sutlej River and Beas River, located adjacent to each other and sharing similar environmental conditions, are characterized by the dilemma of balancing intensive human activities and critical water-related ES conservation. The main differences between the two rivers lie in their importance and interactions with neighboring areas. Flowing through the historic crossroads region of Punjab in northern India and Pakistan, Sutlej River has encountered sovereignty conflicts in water management (Varay et al., 2017; Setia et al., 2020; Roy et al., 2021). Therefore, the conditions related to disturbance by human activities in Sutlej River are more complex compared with those of Beas River.

According to the above results, it could be found that in general, Sutlej River had higher water-related ES than Beas River. The ES network types were more diversified, but with relatively low network density and network centrality. This implied that for local government, when regulating the ES in the two rivers, the focus should be tailored according to the objective situation. Based on our results, for each kind of sub-catchment the priority for protecting local ES had been identified, especially revealing the important ES in networks. By this way, the human-ecological system supported by ES networks can link biophysical processes and human benefits. It should be noted that ES networks are discussed at the scale of sub-catchment, which requires the downscaled efforts to relevant sub-catchment, such as fine-scale data recording and monitoring for reliable ES assessment (Portela et al., 2021). This improvement can contribute to both the specialized sub-catchment management and general basin conservation to a large extent. However, there are simultaneously more problems than local protection such as the ownership of management rights and the finical balance among various departments. Sutlej-Yamuna Link (SYL) is a famous local program known for its controversy among various stakeholders, which intends to link Sutlej River and Yamuna River. The linkage is of great significance for local freight and irrigation (Roy et al., 2021). Under such circumstances, it is difficult for Punjab to share water resources with other states. Apart from this, like other built infrastructure, once the SYL is established successfully, it is likely to affect the structure of ES networks by increasing water use, establishing business links and providing employment opportunities, which will finally intensify the human influence. The construction of the SYL will not only directly affect water-related ES in Sutlej River, but also unavoidably exert high pressure on Beas River. Such a programme starkly reveals the conflicts among different stakeholders, and the difficulty of balancing the social infrastructure and ecological protection (Garue et al., 2021; Vercruysse et al., 2022).

Built (or grey) infrastructure has been proven to exert pressure on natural ecosystems and the search for new approaches, like natural infrastructure, is deemed to be effective (Chung et al., 2021; Palmer, 2010). From the view of hydrological processes, the construction of engineering projects is liable to change ecological processes and natural systems and leads to degradation of water-related ES. Regarding the direct users of water-related ES, city residents by their nature spatially have a high demand within a small rang (McDonald et al., 2014; Romulo et al., 2018; Xu et al., 2022). Therefore, closer attention and greater priority should be devoted to how to combine water-related ES networks with urban development demands. Before that, the jurisdictional relationship of different city entities over different sub-catchments should be clearly defined to ensure that discussions can be productive and constructive decisions can be made.

4.3 Limitations and future research directions

To investigate the ES networks, four critical local water-related ES were selected in this study, and their relationships within sub-catchments were summarized using six different types of ES networks. While the main objective of building ES networks has been achieved, there are still several limitations. First of all, only four critical water-related ES have been considered. However, in many studies, water-related ES covered a wide range of ES category, such as freshwater supply and sediment deposition, which are more in line with the real world. Once more kinds of ES are integrated into the networks, the types of ES networks will increase and more useful information can be extracted in further studies. In addition, it should be noted that we focused on the relative relationships among ES rather than the absolute values of the ES themselves or their trade-offs or synergies. Thus, the links between two ES do not have certain values to describe the strength of their connections, i.e., the nodes and links of ES networks were treated equally. However, in many network studies, how to assign values to different nodes and links is complex and worth exploring. In future studies, it can be focused on quantifying the strength of links and taking more kinds of ES into consideration, including various ES that exist in addition to water-related ES.

5. Conclusion

Identifying and maintaining the complex inter-relationships of various water-related ES plays a vital role in sustaining local ecosystems due to the hydrological connectivity across multiple spatial scales and jurisdictional boundaries. Taking Beas River and Sutlej River as the study area, we quantified four critical water-related ES and built the networks among them based on the values of synergies. The results showed that there was an obvious spatial agglomeration of low flood mitigation and hydropower production but high soil retention and water conservation in the downstream areas, and ES in Sutlej River were overall higher than ES in Beas River. There were six network categories in total, of which the network with all the four ES nodes fully linked with each other represented the largest proportion. Within all the networks, soil retention tended to be less centralized compared with the other ES. In addition, land use intensity was found to obviously influence the network indexes. This study advanced the ES network research by categorizing ES network and quantifying network indexes.

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Competing interests

The authors declare no competing interests.

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Yu, Shuying

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