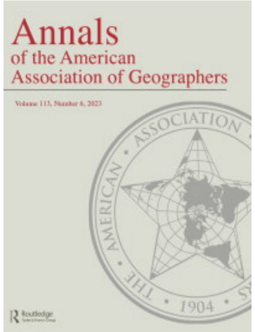

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The Heterogeneity of Ecosystem Services across the Riverine Landscape of the Koshi River Basin, Nepal

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A foundational tenet of the ecosystem services concept is that they arise from biophysical processes. Riverine landscapes are process-response systems where river flow and geomorphology generate a heterogeneous physical template that influences ecological processes, suggesting that the supply of ecosystem services in riverine landscapes should be congruent with the character and heterogeneity of the physical template. In this study, we examine the congruency between the physical template (river functional process zones; FPZs) and the supply of river flow dependent ecosystem services from riverine landscapes of the Koshi River Basin, Nepal. The supply of ecosystem services was congruent with FPZs. Social factors were shown to mediate the use and value of ecosystem services between FPZs. Heterogeneity of the physical template interacts with place, social activity, and demography to influence the use and potential value of ecosystem services across the riverine landscape. These spatial patterns of greater use of some types of riverine ecosystem services in certain areas of the riverine landscape are indicative of a highly coupled agricultural or "green loop" social-ecological system (SES) and show that maintaining riverine template heterogeneity is an important element of this green loop SES that supports 40 million people in the Koshi River Basin. *Key Words: Himalayan river system, physical river template, river networks, social-ecological systems.*

Ecosystem services are a well-established framework for identifying the benefits people obtain from nature and assessing the contributions of those benefits to human well-being (Kumar and Martinez-Alier 2011). Ecosystem services have been associated with biomes such as oceans, deserts, and mountains (Millenium Ecosystem Assessment [MEA] 2005). The ecosystem services supplied by riverine landscapes (including rivers, floodplains, and wetlands) are highly valuable: The economic value of ecosystem services supplied by rivers and their floodplains has been estimated to exceed US$25,681 ha^{-1} (Costanza et al. 2014). Moreover, approximately 25 percent of global terrestrial ecosystem services are supplied by floodplains (Tockner and Stanford 2002). Monetary or other values assigned to the ecosystem services of riverine landscapes illustrate their importance to society and aid decision-making about trade-offs between the use of riverine ecosystems and their ongoing capacity to continue to supply ecosystem services (De Groot et al. 2012; Costanza 2020).

A foundational tenet of ecosystem services is that they arise from biophysical processes in ecosystems (MEA 2005). While early research in ecosystem services recognized that the nature of ecosystem services differs among biomes (e.g., Daily 1997), the focus of much ecosystem service research to date has been about quantifying the supply and economic value of ecosystem services (e.g., Costanza et al. 2014). The link between biophysical processes and ecosystem services has recently been revived to include a spatial element that examines the supply of ecosystem services in relation to the physical character of landscapes at multiple spatial scales (cf. Rieb and Bennett 2020). Commensurate with the foundational tenet of ecosystem services, these studies show a nonuniform distribution of ecosystem services that varies within the underlying template of biophysical processes at spatial scales ranging from individual landscape units (Mitsch and Gosselink 2015) to continents (Schröter et al. 2019). Thus, heterogeneity or the spatial variation in biophysical processes (White and Brown 2005) suggests the supply of ecosystem services might be related to spatial

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variations in biophysical processes. Understanding the spatial distribution of ecosystem services avoids assumptions of spatial homogeneity and could provide better information for decision-making about use and conservation trade-offs.

In riverine landscapes, humans derive provisioning (fuelwood, hydropower, water for drinking and irrigation, etc.), regulating (climate regulation, groundwater recharge, water yield, carbon sequestration, etc.), supporting (habitat protection, habitat for birds and animals, soil formation, etc.) and cultural (tourism, cremation, religious bathing, etc.) benefits from intact riverine and flow-dependent ecosystems (Yeakley et al. 2016). However, rivers are heterogeneous landscapes because of biophsyical processes at multiple spatial scales (Gilvear et al. 2016). The supply of flow-dependent ecosystem services across a riverine landscape is a function of hydrogeomorphic complexity; that is, the complexity of the physical template of the riverine landscape (Thoms et al. 2017). Strong positive relationships between the diversity of physical river channel features and the supply of ecosystem services were demonstrated at the reach scale (i.e., less than one kilometer in length) in the River Allan, River Tyne, and Yana River by Large and Gilvear (2015). Similarly, Tomscha, Gergel, and Tomlinson (2017) showed different geomorphic reach types to be associated with specific ecosystem services. The emerging evidence suggests that heterogeneity of the underlying physical template should be a key consideration in understanding ecosystem services across riverine landscapes because different services will be supplied by different features of the physical template. Studies of the relationship between the character of the physical template and ecosystem services are restricted to reach or site scales of less than one kilometer, however (cf. Gilvear et al. 2016). Increasingly, the study and management of river systems has shifted from a reach- or site-based scale to a larger landscape or catchment/river basin scale that considers the entire river network (Gilvear et al. 2016). This shift is associated with a recognition that smaller scale approaches fail to address problems that contribute to longer term declines in the sustainability of rivers at the basin scale (Likens et al. 2009).

Many models explain the organization of the physical river template within a river network. The structure of the river template has been portrayed as a simple continuous downstream gradient (cf. the river continuum concept of Vannote et al. 1980) or a mosaic of hydrogeomorphic river zones that differ in length, physical composition, and spatial arrangement (Thorp, Thoms, and Delong 2006). The spatial pattern of the physical character of the river template reflects variations in hydrological regimes, sediment regimes, and valley conditions throughout a river network as well as a myriad of physical and ecological feedbacks. The riverine ecosystem synthesis (Thorp, Thoms, and Delong 2006) portrays river networks as a series of river zones that do not occur in a regular manner along river networks. These river zones or functional process zones (FPZs) have been shown to have unique physical properties and river features (Collins, Thoms, and Flotemersch 2014), biological communities (Elgueta et al. 2019), and food web character (Thoms, Scown, and Flotemersch 2018). Given the foundational tenet that biophysical processes generate ecosystem services, the type, abundance, and arrangement of ecosystem services across a river network is expected to be congruent with the type and distribution of FPZs in the river network (cf. Thorp et al. 2010).

This study investigates the spatial distribution of flow-dependent ecosystem services in relation to the spatial arrangement of the physical template (FPZs) in an entire river network. Given potential differences in the hydrogeomorphic character among FPZs, we expect that the supply, use, and value of ecosystem services will be congruent with the type and distribution of FPZs across the river network.

Study Area

The Koshi River Basin is a transboundary system draining the eastern Himalayas (Figure 1). Its headwaters are located in the Tibetan Plateau of China and, for most of its length, the Koshi River flows through Nepal before joining the Ganga River in India. The Koshi River Basin has a catchment area of 55,930 km^2 at the Nepal–India border, of which approximately 51 percent is in China and 49 percent in Nepal. Six major physiographic zones are found within the Koshi River Basin—the Tibetan Plateau, High Himalaya, High Mountains, Middle Mountain, Siwalik, and Terai, each with unique geology and topography (Dixit et al. 2009; Dhital 2015). The Trans-Himalaya (Tibetan Plateau and High Himalaya) covers 69 percent of the area of the basin, followed by the Middle Mountain (20 percent), High Mountains (5 percent), Siwalik (3 percent), and Terai (3 percent)

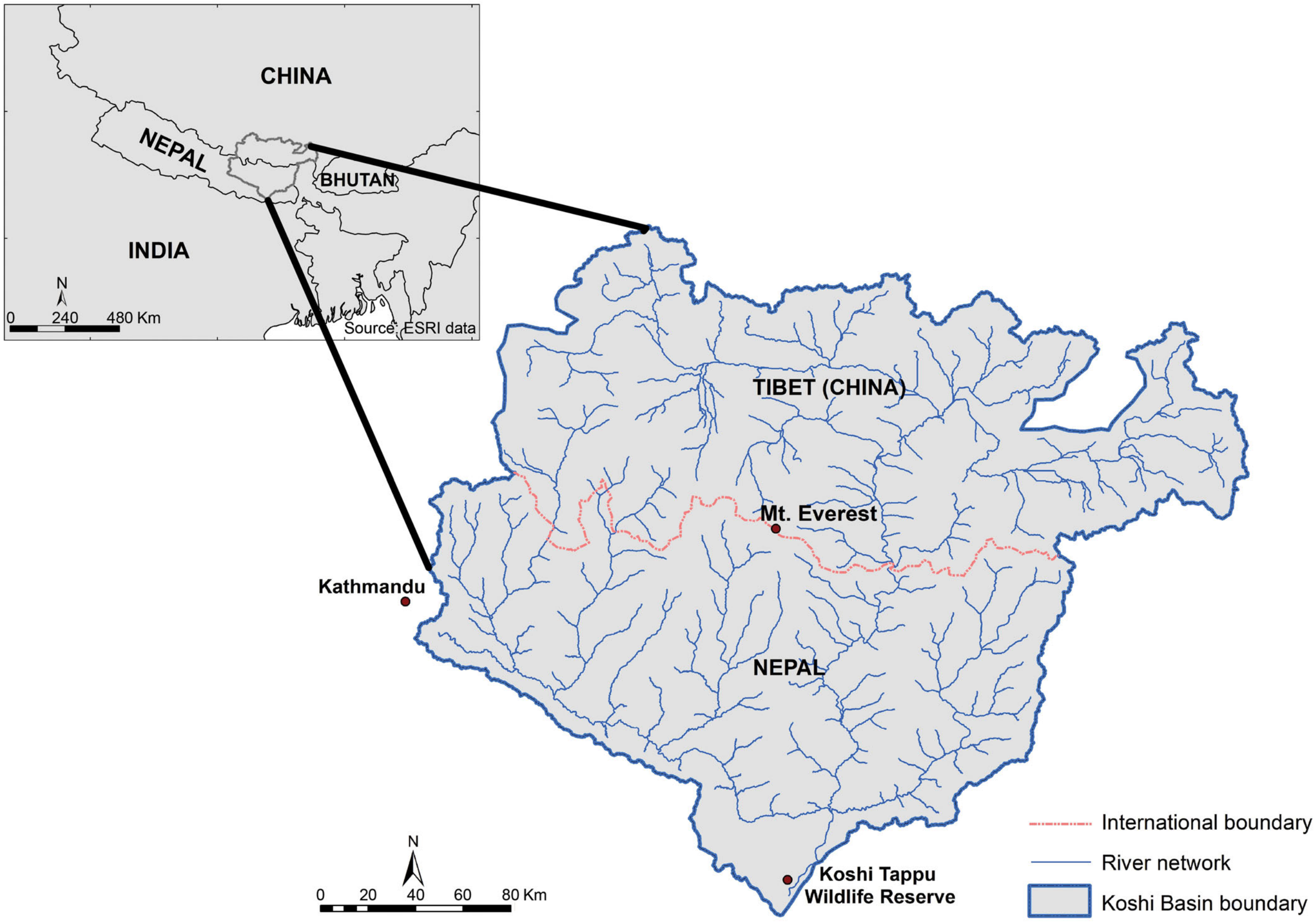

Figure 1. The Koshi River Basin and its location within Southeast Asia (inset).

zones. Alluvial deposits dominate in the Terai, and sedimentary rocks are dominant in the Siwalik, whereas the Middle Mountain and High Mountains physiographic zones are dominated by sedimentary and metamorphic rocks. Crystalline rocks dominate in the High Himalaya physiographic zone, and fossiliferous sedimentary rocks dominate in the Tibetan Plateau. Elevation varies from 19 m above sea level (ASL) in the southern regions of the basin to 8,848 m ASL in the northern regions. Slopes range from 0° to 84° (Mishra et al. 2019). Precipitation is strongly influenced by the South Asian monsoon across most of the basin, but the Tibetan Plateau lies in the rain shadow. As a result, precipitation ranges from 207 mm per year in the trans-Himalaya region to 3,000 mm per year in the eastern mountains (Shrestha et al. 2017). The Koshi River Basin is characterized by a range of climatic conditions—from humid tropical conditions in the Terai physiographic zone to arctic conditions in the High Himalaya physiographic zone (Dixit et al. 2009). For example, temperatures in the northern regions of the Koshi River Basin can reach as low as −19 °C in winter, whereas in the southern regions, maximum temperatures of 45 °C have been recorded in summer. The long-term average annual discharge of the Koshi River at the Chatara hydrological station is 1,545 m^{3s-1} (Mishra et al. 2019).

A diversity of regional fluvial morphologies have been described in the Koshi River Basin (cf. Mahato and Shukla 2013; Kafle, Khanal, and Dahal 2015; Mishra et al. 2019). For example, in the upper basin, extensive fluvial flat lands (floodplains) and highly sinuous river channels are associated with wide valley surfaces and low channel slopes (Mishra et al. 2019). This contrasts to the highly constrained narrow valley, high-energy river systems associated with the High Himalaya physiographic zone. Relatively constrained fluvial systems, with narrow floodplain surfaces and bedload dominated river channels, are also characteristic of most of the High Mountains and Middle Mountain physiographic zones of the Koshi River Basin. Local variations in valley width are associated with increases in floodplain surface area, however, the relatively narrow valleys and steep adjacent slopes facilitate a high degree of coupling between underlying basin character and the presence of fluvial landforms (Mishra et al. 2019). In the lower elevation part of the basin, where the Koshi River emerges from the Himalayas, the suite of fluvial landforms changes. River systems become more dynamic with increasing valley widths and the multithread braided river channel transports large quantities of bedload material. The dynamic nature of the Koshi River in the southern regions of the basin is reflected with lateral channel movements of up to 115 km over the past 200 years (Kafle, Khanal, and Dahal 2015). In the Siwalik physiographic zone of the Koshi River Basin, the supply of bed load material has resulted in the construction of a megafan with a surface area greater than 15,000 km^2. Further downstream in the Terai physiographic zone, the Koshi River has a meandering channel and is associated with large floodplain surfaces (> 1,300 km^2) that are heavily cultivated (Danish et al. 2013).

The Koshi River Basin has been listed as a global biodiversity hot spot (Mittermeier et al. 2004). Important ecosystems and protected areas include snow and glacial landforms, barren land, rangelands, forests, wetlands, alpine meadows with grassland, water bodies and floodplains (Bhatta et al. 2015). There is also a diversity of land cover across the basin including grasslands (which occupy 40.34 percent of the land surface area), native forests (24.45 percent), and agriculture (12.45 percent). Other land covers in the Koshi River Basin include barren land (11.26 percent), snow and glaciers (9.45 percent), shrubland (1.52 percent), natural water bodies (0.5o percent), and urban areas (0.03 percent; Uddin, Wahid, and Murthy 2015). The natural resources of the Koshi River Basin also provide services including hydropower, water for domestic use, irrigation, floodplains for agriculture, and recreation and cultural sites (Shrestha et al. 2017). The Koshi River Basin has a total hydro potential of 22,350 MW (Khadka 2021). There are approximately 40 million people residing within the basin and population densities vary, from fewer than five persons per km^2 on the Tibetan Plateau to between 200 and 500 persons per km^2 in the Middle Mountain and Terai physiographic zones (Wahid et al. 2017). The livelihood of most of the population is dependent on the provision of ecosystem services with a direct link to water, including water-dependent agricultural activities within the basin (Hussain et al. 2018).

The Koshi River Basin can be described as a "green loop" system characterized by high direct dependence on local ecosystems, with little or no external economy through which to secure natural resources from elsewhere (cf. Cumming et al. 2014). Of the 40 million people within the Koshi River Basin, the majority (83 percent) are agriculturally dependent (Shrestha et al. 2017). Anaysis by the Koshi Basin Programme showed basin demography is closely related to regions of agricultural production and access to other natural resources. Thus, population densities are higher in the lowland regions of the basin—the Terai physiographic zone—compared to the mountainous Himalaya and the Tibetan Plateau physiographic zones. Within the Nepal section of the Koshi River Basin, the average population, according to the 2011 census, was 176 people per km^2. This varies across the basin, presumably with topography (Dixit et al. 2009). River valleys and their associated fertile floodplains are areas of higher population density.

Methods

The distribution, use, and value of ecosystem services among FPZs of the Koshi River Basin was determined using three steps (Figure 2). First, FPZs were identified. Second, an inventory of ecosystem services within the FPZs of the Koshi River Basin was constructed. Third, the relative use of each ecosystem service and their potential value among the FPZs of the Koshi River network was calculated.

Step 1: River Characterization and Identification of FPZs

The drainage network (streamlines), watershed boundary, flow direction and accumulation of the Koshi River Basin were prepared from the 30 m ASTER digital elevation model (ASTER DEM) using the Arc Hydro tool in ArcGIS.

Data collection sites were created at 5-km intervals along the drainage network of the Koshi River ($n = 1,272$) and became the focus for the extraction of fifteen hydrogeomorphic variables used to delineate

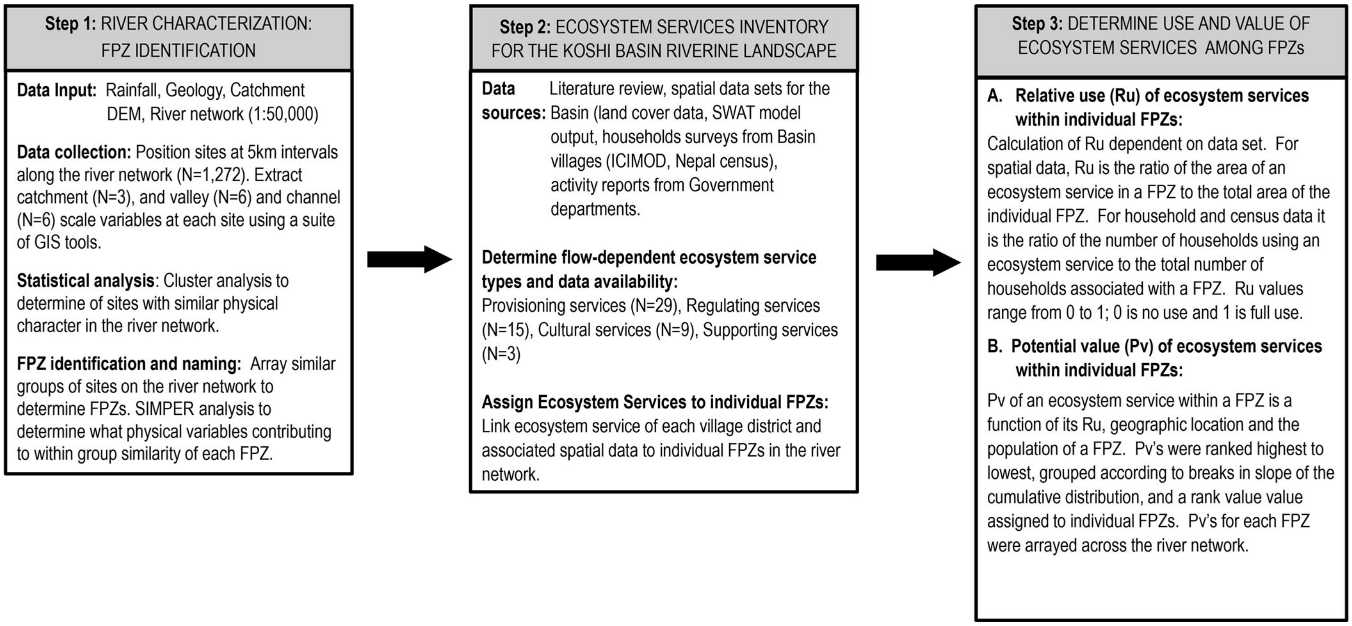

Figure 2. An approach to determine the congruency between the physical template and ecosystem services within the Koshi River Basin. *Note:* FPZ = functional process zone.

FPZs (Table 1). At each data collection site, watershed, valley, and channel scale variables were extracted using a series of GIS tools (Thoms, Scown, and Flotemersch 2018; Elegueta et al. 2019; Maasri et al. 2021). The watershed-scale variables were elevation, annual rainfall, and dominant geology (Table 1). Elevation was determined from the 30-m ASTER DEM digital National Elevation Dataset. Mean long-term annual rainfall data ($n = 30$ years) were obtained from rainfall stations in the Koshi River Basin from the Department of Hydrology and Meteorology of Nepal, and the Asian Precipitation–Highly Resolved Observed Data Integration Toward Evaluation (APHRODITE) data set allowed for spatial infilling in the Tibetan Plateau region of the basin. Geology data were from Chen et al. (2013) and assigned according to their rock type, erodibility, and potential sediment yield (cf. Thoms, Scown, and Flotemersch 2018). The valley-scale variables were valley width, valley floor width, the ratio of valley width to valley floor width, the left and right valley slopes, and down-valley slope, determined from the DEM of the watershed (Table 1). The six channel-scale variables were channel belt width, channel belt sinuosity, channel belt wavelength, channel sinuosity, planform class, and the number of river channels, determined from the streamlines of the basin (Table 1). Data sources used to derive the fifteen hydrogeomorphic variables used for the river characterization of the Koshi River are given in Table 1.

The data set of hydrogeomorphic variables (1,272 sites by fifteen variables) was analyzed using multivariate statistical techniques to identify groups of sites with similar physical characteristics. Sites were classified using the flexible unweighted pair-group method with arithmetic averages (UPGMA) fusion strategy, as recommended by Belbin and McDonald (1993), based on the fifteen variables. Groups of sites with similar physical character were selected from the dendrogram representation of the cluster analysis, whereby the least number of groups with maximum similarity was chosen. This step required the identification of an inflection point in the relationship between the number of groups in the classification and their corresponding similarity value (Thoms, Scown, and Flotemersch 2018). This analysis was also used to construct an FPZ nomenclature for the Koshi River Basin. Once identified, the sites were overlaid on the drainage network with their corresponding group nomenclature from the cluster analysis. Groups equate to FPZs. Sequences of the same group delineate FPZ segments in the river network—lengths of the river with similar valley–floodplain settings and river morphologies, inferred to be influenced by similar geomorphic processes (Thoms, Scown, and Flotemersch 2018). Finally, analysis of similarity (ANOSIM) and similarity percentage analysis (SIMPER) was used to determine differences in hydrogeomorphic variables and which hydrogeomorphic variables contribute to group similarity of each FPZ, respectively.

Table 1. Variables used to characterize functional process zones (FPZs) in the Koshi River Basin network

Variable	Scale	Data source
Elevation (m)	Watershed	The ASTER regional digital elevation model (DEM) is the primary elevation database, available from www.rds.icimod.org.
Geology	Watershed	The regional geology was extracted from Chen et al. (2013).
Mean annual precipitation (mm)	Watershed	The DHM and APHRODITE provide historical annual precipitation data, available at www.rds.icimod.org.
Valley width (m)	Valley	The valley width was derived from the DEM for the Koshi Basin (DEMKB); data available at www.une.edu.au.
Valley floor width (m)	Valley	The valley floor width was derived from DEMKB; data available at www.une.edu.au.
Ratio of the valley to valley floor width	Valley	The ratio of the valley to valley floor width was derived from DEMKB; data available at www.une.edu.au.
Left valley side slope	Valley	The left valley side slope was derived from DEMKB; data available at www.une.edu.au.
Right valley side slope	Valley	The right valley side slope was derived from DEMKB; data available at www.une.edu.au.
Down-valley slope	Valley	The down-valley slope was derived from DEMKB; data available at www.une.edu.au.
Width of the river channel belt (m)	Channel	The spatial geometry of streamlines within the Koshi basin was extracted from the DEMKB; data available at www.une.edu.au.
Wavelength of the channel belt width (m)	Channel	The spatial geometry of streamlines within the Koshi basin was extracted from the DEMKB; data available at www.une.edu.au.
Sinuosity of channel belt	Channel	The spatial geometry of streamlines within the Koshi basin was extracted from the DEMKB; data available at www.une.edu.au.
Sinuosity of the main river channel	Channel	The spatial geometry of streamlines within the Koshi basin was extracted from the DEMKB; data available at www.une.edu.au.
River channel planform class	Channel	Manually derived from Google Earth satellite image.
Number of river channels	Channel	Manually derived from Google Earth satellite image.

Note: DHM = Department of Hydrology and Meteorology; ASTER = Advanced Spaceborne Thermal Emission and Reflection Radiometer; APHRODITE = Asian Precipitation—Highly Resolved Observed Data Integration Toward Evaluation of Water Resource.

The floodplain area for all continuous FPZ segments was also determined. The valley floor area delineated for each FPZ segment was used as a surrogate for the floodplain area. Where two different FPZs met, valley floor polygons were split laterally across the valley at each site. The total floodplain area of each FPZ type and the distribution of floodplain areas among individual segments of each FPZ was calculated in ArcGIS.

Verification of the location of some FPZs that emerged in the Koshi River network was undertaken in several ways. First, a field-based study of nine random sites assessed the physical riverine landscape character according to the valley-scale hydrogeomorphic variables used in the classification. Second, the studies of Mahato and Shukla (2013) and Sinha et al. (2019) on the regional variability of fluvial landforms provided information on geology, topography, valley slopes, and valley dimensions as well as general descriptions of the physical character of river networks within the Koshi Basin. Collectively, these data form an independent, albeit limited, field-based verification of the FPZs delineated in the river network.

Step 2: Ecosystem Services Associated with FPZs of the Koshi River Basin

Four sources of information provided data on flow-dependent ecosystem services supplied by the riverine landscapes of the Koshi River Basin. First, a review of the ecosystem service literature for the region enabled the construction of a database of potential ecosystem services in the riverine landscape. Second, spatial data sets obtained from the International Center for Integrated Mountain Development (ICIMOD) provided land cover information for 2010 at a resolution of 30 m for the entire Koshi River Basin. These data sets were used as a proxy for ecosystem services. In addition, the Soil and Water Assessment Tool (SWAT) model, developed for the Koshi River Basin, also provided data on ecosystem services across the entire basin. SWAT is a basin modeling tool that can simulate water-dependent provisioning and regulating ecosystem services, and proxy variables, to estimate associated supporting and cultural services through river networks (cf. Crossman et al. 2013; Francesconi et al. 2016). Third, household surveys undertaken as part of the Poverty and Vulnerability Assessment (PVA; see http://rds.icimod.org/Home/DataDetail?metadataId=22324&searchlist=True) in 2011–2012 (Gerlitz et al. 2014) and the Nepal Census in 2011 (Central Bureau of Statistics [CBS] 2012), provided household-level data on the use of ecosystem services for each Village Development Committee (VDC) district in the Nepal section of the basin. Fourth, data obtained from various Nepalese government departments (e.g., Nepalese Tourism Board, Nepal Electricity) provided information on a variety of ecosystem services, including the location of dams, and cultural, tourism, and recreational sites and activities.

The source of information dictated how the supply or occurrence of individual ecosystem services within an FPZ was determined. The area or number of individual ecosystem services present within an FPZ segment was calculated from spatial data (i.e., the land cover and SWAT model data) and locational data from the Nepalese government. The use of household-level survey data first required VDCs to be linked to a specific FPZ. An FPZ shapefile was overlain on the VDC shapefile of the Koshi River network to determine the VDCs directly associated with a specific FPZ. Most VDCs were associated with only one FPZ. In situations where a VDC overlapped two FPZs, the areal proportion of a VDC within a FPZ was used to allocate the number of households associated with specific individual ecosystem services per FPZ. As a result, data from 726 VDCs (CBS 2012; Gerlitz et al. 2014) were used in this study of ecosystem services associated with the FPZs of the Koshi River. Ecosystem services identified and their accompanying information sources are given in Table 2.

Step 3: Use and Value of Ecosystem Services Among FPZs

There are many approaches to determine the use and value of ecosystem services (De Groot et al. 2012); most focus on economic valuation (e.g., Costanza et al. 1998). Evaluating the benefits of river ecosystem services differs according to discipline (i.e., environmental science, social science and economics), and is influenced by data availability (cf. Costanza and Farber 2002; Hanna et al. 2018). Most evaluations of the benefits from ecosystem services are economic, but this study took a different approach, developing two indicators of benefit—relative use and potential value—for individual FPZs in the Koshi River. Relative use describes whether an ecosystem service is used by people in the Koshi River Basin and value describes the importance and demand for the use of an ecosystem service by people in the Koshi River Basin.

The relative use of each ecosystem service is expressed as the ratio of either the area or number of individual ecosystem services to the total area or the total number of that ecosystem service across all FPZ segments. The relative use of ecosystem services determined from spatial data used the areal calculation and those ecosystem services determined from household-level census and PVA activity data used the numerical calculation. For example, the relative use of provisioning services was the ratio of the number of households using an ecosystem service within an FPZ segment to the total number of households associated with that FPZ. Similarly, the ratio of the number of cultural sites within an FPZ to the total number of cultural sites within the river network provided a relative use for cultural ecosystem services. By comparison, the relative use of supporting ecosystem services was the ratio of the area of an ecosystem service to the total area of an FPZ, whereas the relative use of regulating services was the ratio of the number regulating ecosystem services in an FPZ to the total number of that regulating service within the Koshi River Basin. Relative use of individual ecosystem services ranges from 0 to 1, where 0 represents that an ecosystem service is not used within an FPZ and 1 represents a situation where all households use a particular ecosystem service present within an FPZ. The total relative use of each ecosystem service group (provisioning, regulating, supporting, cultural) was the sum of all relative use values for each FPZ type. Similar methods have been used by Large and Gilvear (2015) and Tomscha, Gergel, and Tomlinson (2017) for determining the relative use of ecosystem services within smaller river reaches.

Potential value of ecosystem services in FPZs was calculated as a function of the relative use of an ecosystem service within an FPZ, the geographic location of the FPZ, and the associated population density of the FPZ. Thus, the approach taken does not derive an economic value but integrates the biophysical context (the FPZ and its location within the river network) with the overall demand (relative use and population density of an FPZ) for an ecosystem service. Population density was determined for

Table 2. The ecosystem services associated with the riverine landscape of the Koshi River Basin

Ecosystem service type	Ecosystem services	
Provisioning	**Domestic water use** ●Δ	**Driftwood** Δ
	Timber/pole ●	**Branches/twigs** Δ
	Wood ●	**Grazing livestock** Δ
	Bamboo ●	**Hydropower** ■
	Thatch for roofing ●	**Irrigated agriculture** □
	Fuelwood/firewood ●	**Rain-fed agriculture** □
	Fishes Δ	**Water bodies** □
	Crab/snail/tortoise Δ	**Aggregate (sand-gravel-boulders)** □
	Game (Wild animals) Δ	**Forest** □
	Medicinal and ornamental plants Δ	**Alpine grassland/grassland** □
	Wild edible fruits Δ	**Shrubland** □
	Wild edible vegetables Δ	Transport
	Staple crops (paddy and wheat) Δ	Industry
	Cash crops (vegetable, potato, pulse) Δ	Paha (Agricultural field frog)
	Leaf litter Δ	Horticultural crops
	Foliage Δ	Fiber
	Forage/grass Δ	Bushmeat
	Fodder Δ	Natural plants
Regulating	**Climate regulation** □	**Biodiversity conservation** □
	Water yield □	**Habitat provision** □
	Nutrient regulation □	Hydrological cycle
	Groundwater recharge □	Water retention
	Sediment transport □	Water purification
	Sediment yield □	Seed dispersal
	Nutrient deposit □	Pollination
	Sediment retention □	Air quality regulation
	Carbon sequestration □	Pollution transport and dilution
	Flow regulation □	Flood protection
	Habitat-terrestrial □	Erosion control
	Habitat-aquatic □	Soil stability
	Habitat corridors □	Waste treatment
Cultural	**Cremation** ●	**Wildlife watching** □
	Research ■	Picnic
	Rafting/boating ■	Swimming
	Fishing ■	Social gathering (women)
	Pilgrimage ■	Traditional market
	Religious bathing ■	Sense of place
	Tourism ■	Traditional cultural practices
	Temple/religious site ■	Education
Supporting	**Aquatic habitat** □	Ecosystem resilience
	Terrestrial habitat □	Genetic diversity
	Habitat protection □	Pollination
	Nutrient cycling	Soil formation

Note: Ecosystem services in bold are those where data were available. The different symbols represent data sources: ● = 2011 Nepal census data; Δ = 2011 ICIMOD household survey data; ■ = Nepal government reports; □ = Spatial data (land cover and Soil and Water Assessment Tool).

each FPZ within the river network. For the Tibetan section, population data from the 2011 Chinese census were clipped according to their direct association with an FPZ. For the Nepal section, population data for each VDC (CBS 2012; Gerlitz et al. 2014) associated with an FPZ was used. Each FPZ was assigned a geographic location score, which ranged from 0 to 1, based on its elevation and climate, using the method outlined by Haines-Young, Potschin, and Kienast (2012). Potential values were grouped and groups of potential value groups were determined from the number and position of inflections present on the cumulative distribution curve of all potential values for the Koshi River Basin network and then ranked from low to high. A rank value was assigned to each FPZ and arrayed spatially on the river network. The spatial organization of ecosystem service rank values was undertaken to examine the association between FPZs and their ecosystem service value across the river network.

Statistical Analyses

The nonparametric Kolmogorov–Smirnov test was used to determine pairwise differences in the supply, relative use, and potential value of ecosystem services among FPZs within the Koshi River network. SIMPER analyses determined the contribution that each ecosystem service made to the mean similarity of the relative use and value within each FPZ.

Results

Functional Process Zones of the Koshi River Basin

Five FPZs emerged from the classification of the 1,272 sites in the Koshi River network (Figure 3A). These five FPZs explain 79.9 percent of the similarity between sites within this river network. FPZs had significantly different physical characteristics (ANOSIM: Global $R = 0.702$). From the cluster analysis, the first separation grouped sites via valley widths, explaining river channels contained in wide and narrow valleys. This corresponded to the low elevation floodplains in the Terai and the high elevation floodplains of the Tibetan Plateau, plus river channels associated with narrower river valleys (Figure 3A). Further into the dendrogram, sites were differentiated based on down-valley slopes and channel pattern (Figure 3A). Thus High Himalayan River channels were associated with narrow gorges, high down-valley slopes, and in-channel velocities. Braided river channels with multiple channels were associated with moderate down-valley slope. Meandering rivers were associated with relatively open valleys and well-developed floodplain surfaces (Figure 3A) and occur in the lower slopes of the southern Himalayan region.

The composition of the FPZs in the Koshi River Basin differed in terms of their total length and the number of individual segments (Table 3). The most abundant was the High Elevation Floodplain River FPZ covering 35 percent of the river network (Table 3). The next most abundant was the Meandering River FPZ, followed by the Braided River, High Himalayan River, and Low Elevation Floodplain River FPZs (Table 3). In terms of the number of individual segments comprising each FPZ, the Braided River FPZ had the highest number of single segments, followed by the High Himalayan River FPZ, the High Elevation Floodplain, the Meandering River FPZ, and finally the Low Elevation Floodplain River FPZ with one individual segment (Table 3).

The spatial organization of the five FPZs displayed a broad pattern within the Koshi River Basin (Figure 3B). Within the network, FPZs are arranged as a mosaic from the Tibetan Plateau through the Himalayas to the lowland regions of the Terai. Therefore, FPZs occupy discrete areas of the river network, and some FPZs repeat in different places within the river network. Braided River FPZs are most frequently adjacent to either Meandering River or High Elevation Floodplain River FPZs.

There is 3,278 km^2 of floodplain in the Koshi River Basin, which represents 5.86 percent of the total basin area and 80.00 percent of the total surface area of the riverine landscape in the basin. Floodplains are located in two distinct regions of the basin, the high and low elevation areas of the river network; that is, the Tibetan and Terai regions, respectively (Figure 3C). Overall, 72.33 percent of the floodplains in the Koshi River Basin are in the Tibetan Plateau (High Elevation Floodplain River FPZ).

The Occurrence of Ecosystem Services within FPZs

The literature review revealed eighty-six ecosystem services that had been previously identified to occur across the riverine landscape of the Koshi River Basin. Among the eighty-six ecosystem services, data were available for only fifty-six of these ecosystem services (Table 2) and for all FPZ types in the Koshi Basin. Of these, provisioning services are more abundant (twenty-nine) than regulating (fifteen), cultural (nine), and supporting (three) services (Figure 4A). The total abundance of ecosystem services was highest in the Low Elevation Floodplain River FPZ and lowest in the High Himalayan River and High Elevation Floodplain River FPZs (Figure 4B). There was a significant difference in the occurrence of supporting, regulating, provisioning, and cultural services among the FPZs (Kolmogorov–Smirnov test: $p < 0.01$ for all pairwise tests). Provisioning services dominated in the Low Elevation Floodplain River, Braided River, and

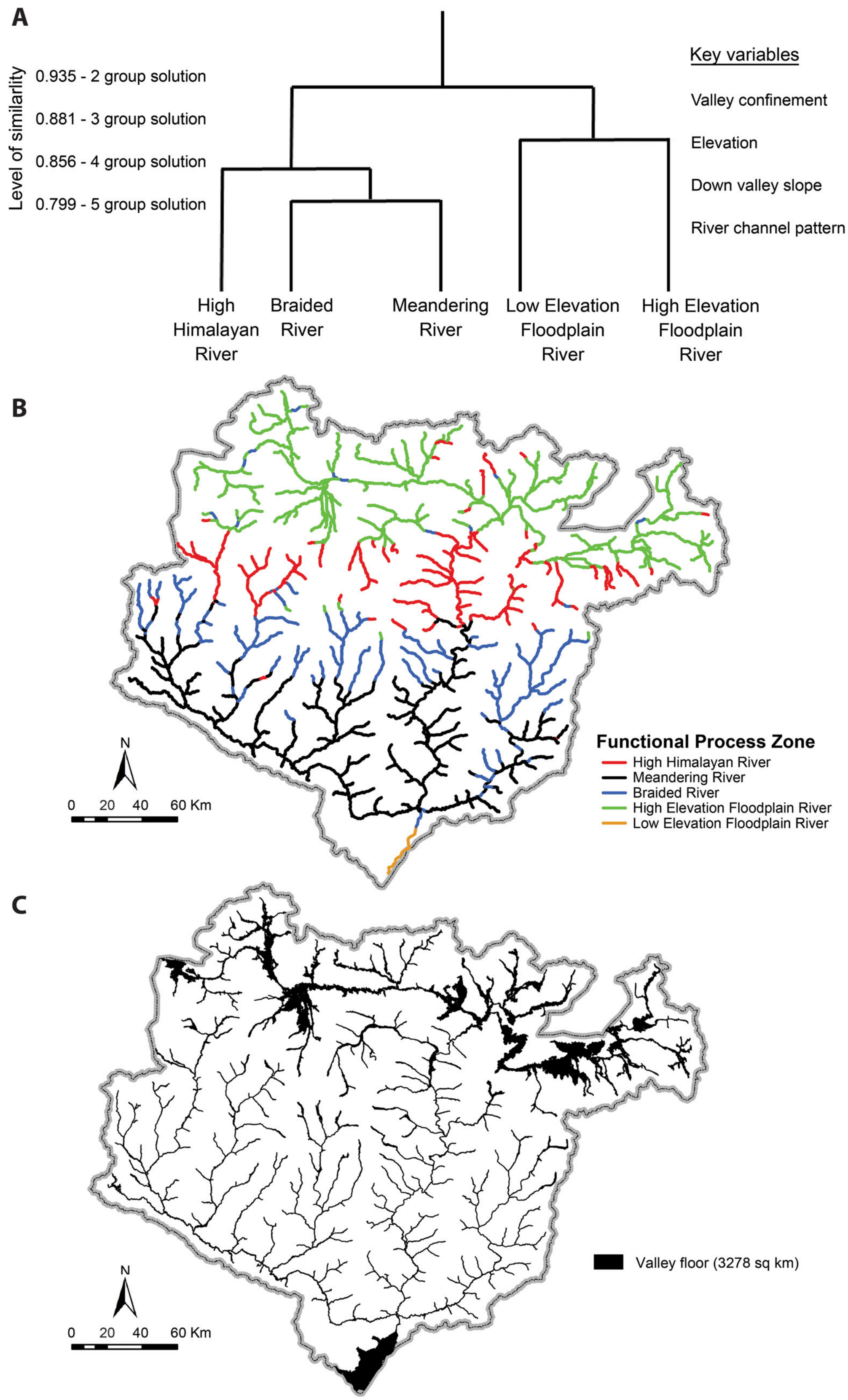

Figure 3. Elements of the riverine landscape of the Koshi River Basin. (A) The classification dendrogram of the Koshi River network used to derive functional process zones (FPZs). (B) Spatial organization of FPZs within the Koshi River network. (C) Distribution of major areas of valley floor.

Table 3. The character of functional process zones (FPZ) in the Koshi River network

FPZ	Total channel length (km)	Proportion of total (%)	No. of segments	Floodplain area (km^2)	Influencing variables identified via the SIMPER analysis	Physical character
High Himalayan River	739.4	13.40	42	471	• Valley confinement • Down-valley slope	Highly constrained sections of the river network associated with the High Himalaya physiographic zone, where river channels flow through narrow, deep valley sections that are dominated by steep bed slopes, like river channels in Canyon zones (cf. Schumm 1985).
Meandering River	1756.6	31.83	24	335	• Valley confinement • Down-valley slope • River channel pattern	Single-channelled sections of the river network with a sinuosity of less than 1.3, associated with moderate-to-low down-valley slopes; increases in river valley widths and lower down-valley slopes enable floodplain development.
Braided River	1069.2	19.37	56	175	• Valley confinement • Down-valley slope • River channel pattern	Sections of the river network dominated by relatively high-energy multichannelled river systems; these braided river settings have higher down-valley slopes and abundant sediment supply.
High Elevation Floodplain River	1913.1	34.66	22	1900	• Valley confinement • Elevation	Floodplain dominated zones occur in those areas of the river network with extended river valley widths; high elevation floodplains are in the Tibetan Plateau region of the Koshi River Basin.
Low Elevation Floodplain River	40.6	0.74	1	397	• Valley confinement • Elevation	Floodplain dominated zones occur in those areas of the river network with extended river valley widths; low elevation floodplains are in the Terai region of the Koshi River Basin.

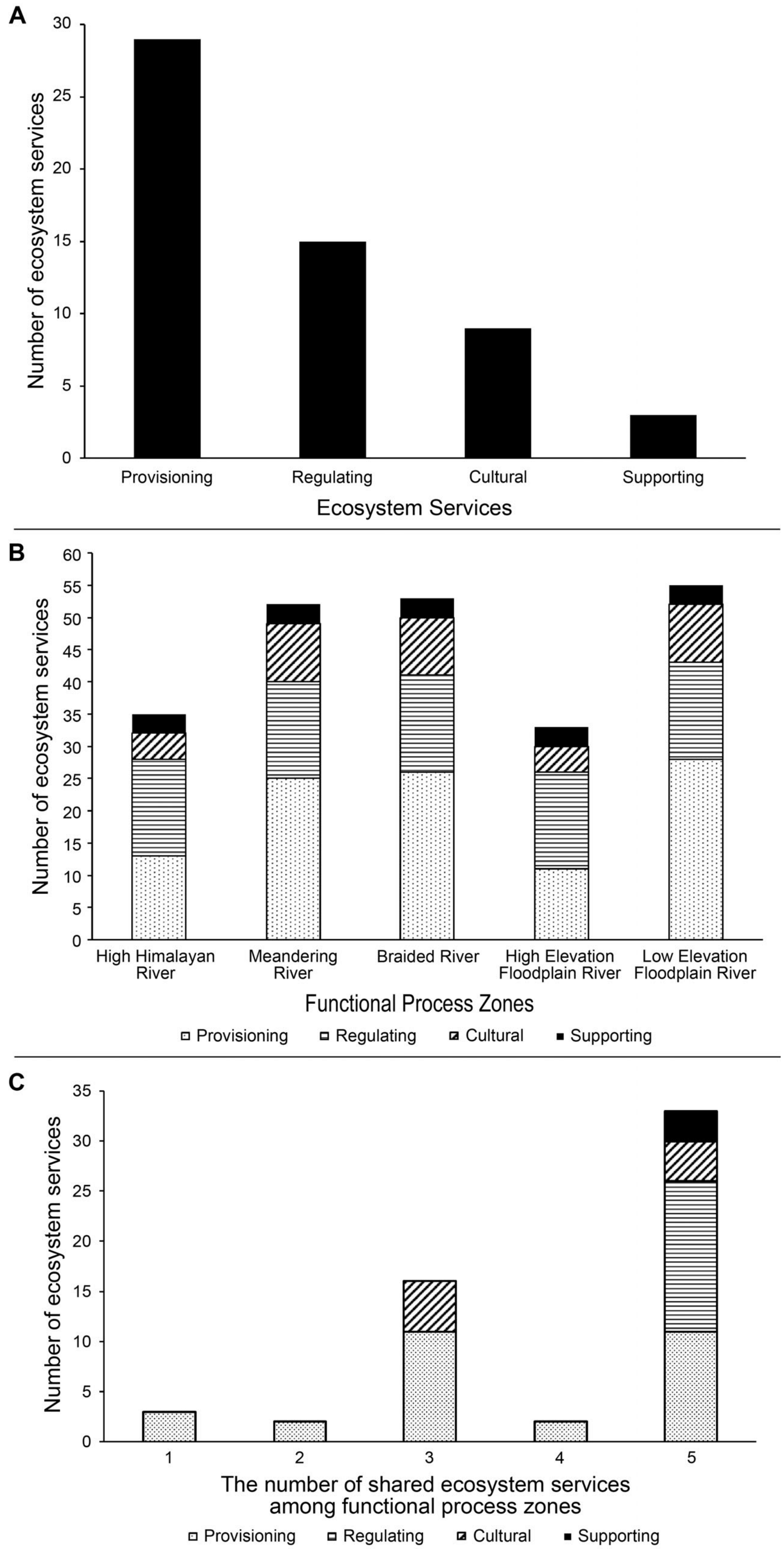

Figure 4. Ecosystem services of the Koshi Basin riverine landscape. (A) The abundance of ecosystem services. (B) The abundance of ecosystem services in the functional process zones (FPZs). (C) The number of ecosystem services shared among the FPZs of the Koshi Basin, where five means that an ecosystem service occurs in all FPZ types.

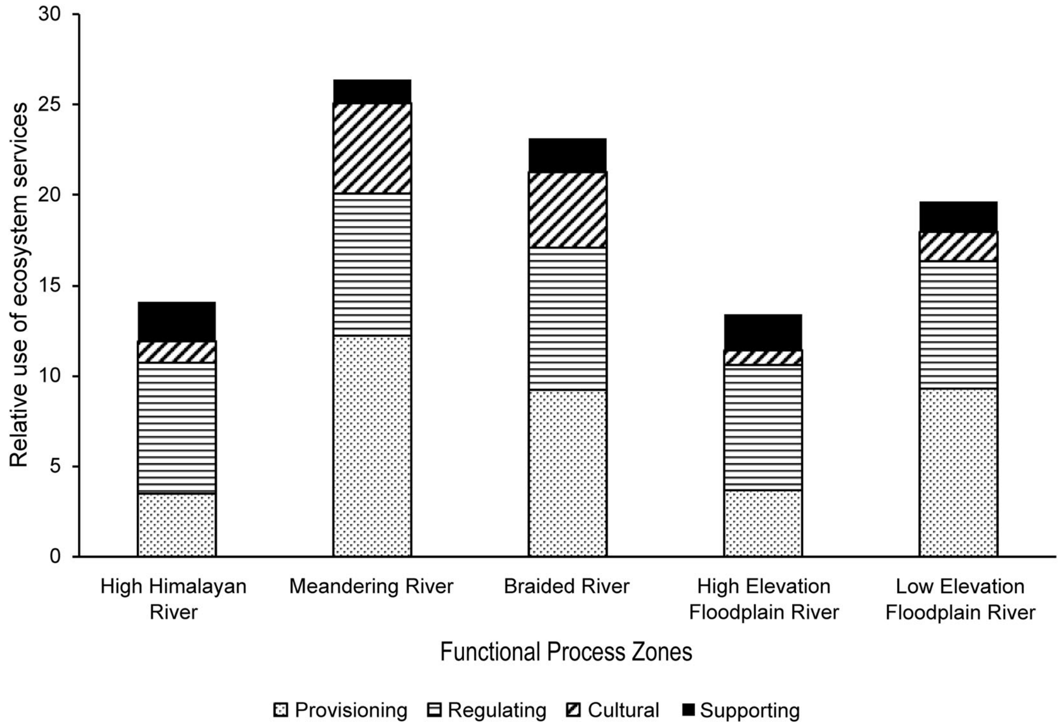

Figure 5. The relative use of ecosystem services within the functional process zones of the Koshi River Basin.

Meandering River FPZs, whereas regulating services were relatively more abundant in the High Elevation Floodplain River and High Himalayan River FPZs (Figure 4B). Cultural and supporting services were relatively evenly distributed among the five FPZs of the Koshi River Basin (Figure 4B).

Some ecosystem services occurred in all FPZs. Overall, eleven provisioning services, fifteen regulating services, four cultural services, and three supporting services were common to all FPZs (Figure 4C). Of the remaining fifteen provisioning services, two were shared between two FPZs: hydropower in the Meandering River FPZ and Braided River FPZ and wild edible fruits in the Braided River FPZ and Low Elevation Floodplain River FPZ. Two provisioning services (forest and shrubland) were shared among four FPZs, however (High Himalayan River, Meandering River, Braided River, and Low Elevation Floodplain River FPZs), and the remaining eleven services were shared among three FPZs (Meandering River, Braided River, and Low Elevation Floodplain River FPZs). By comparison, five cultural services (rafting/boating, fishing, pilgrimage, religious bathing, and the presence of temples) were shared among three FPZs (Meandering River, Braided River, and Low Elevation Floodplain River FPZs). The provisioning services of game, wild edible vegetables, and driftwood were unique to the Low Elevation Floodplain River FPZ (Figure 4C).

Use and Value of Ecosystem Services among FPZs

The relative use of the fifty-six ecosystem services differed significantly among FPZs (Kolmogorov–Smirnov test: $p < 0.01$ for all pairwise tests). Overall, relative use of ecosystem services was higher in the Meandering River FPZ compared to the Braided River FPZ, Low Elevation Floodplain River FPZ, High Himalayan River FPZ, and High Elevation Floodplain River FPZ (Figure 5). Relative use of the four ecosystem service groups also differed among the five FPZs. The relative use of provisioning services was highest in the Meandering River FPZ and the relative use of regulating services was highest in the High Himalayan River FPZ (Figure 5). By comparison, the relative use of cultural services was highest in the Meandering River FPZ, whereas the relative use of supporting services was highest in the High Himalayan River FPZ (Figure 5).

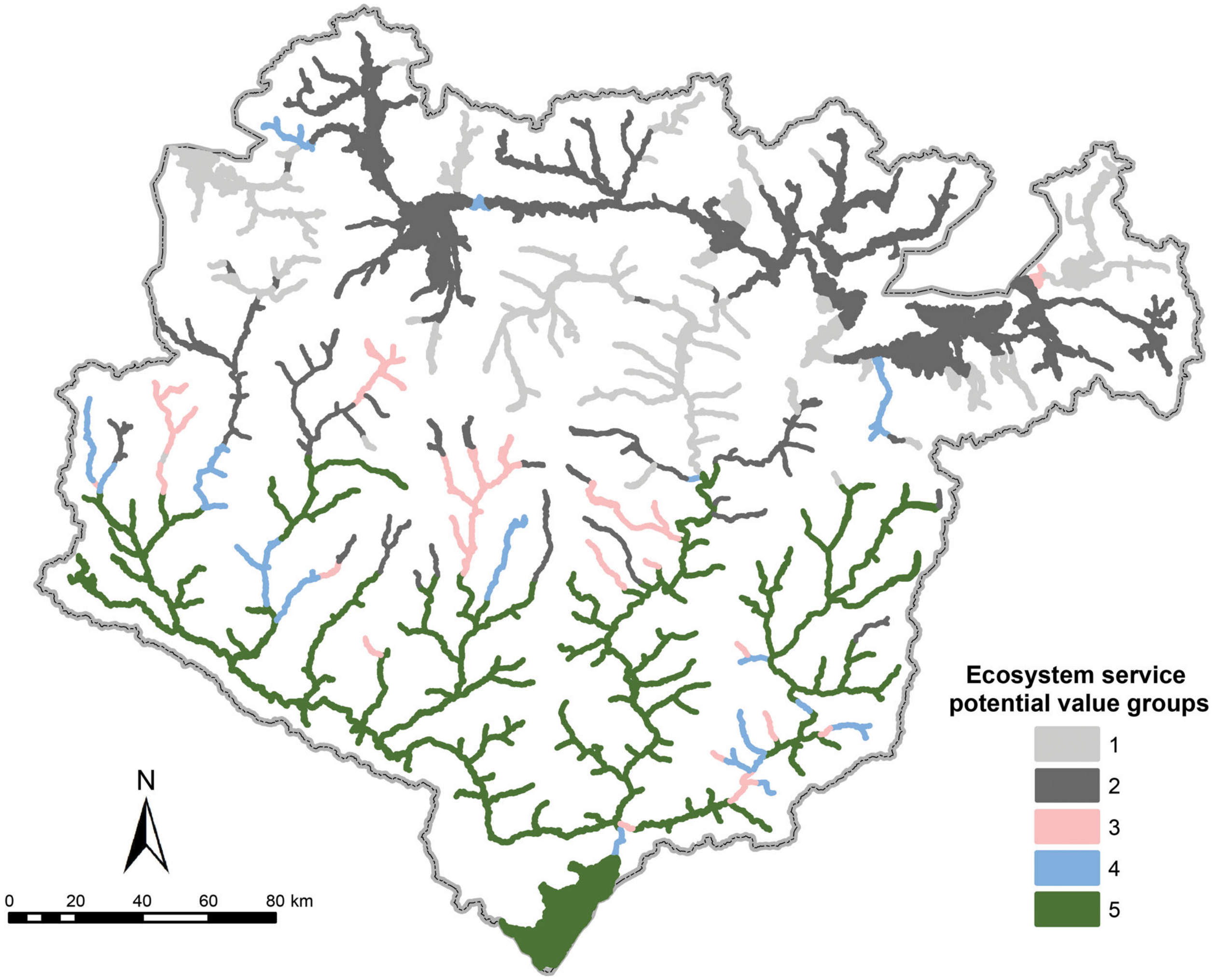

Figure 6. The distribution of the potential value of ecosystem services across the Koshi River Basin. Groups are explained in the text but in general, represent a continuum of lower (Group 1) to higher (Group 5) potential values.

The potential value of ecosystem services varied significantly among most of the FPZs (Kolmogorov–Smirnov test: $p < 0.01$ for all pairwise tests). Of the ten pairwise FPZ comparisons, only two were not significantly different from one another; that is, the potential value of ecosystem services in the High Elevation Floodplain River FPZ and High Himalayan River FPZ. In decreasing order of potential value (where higher numbers are greater potential value), median potential value of ecosystem services was 3.3 for the High Elevation Floodplain River FPZ, 17.5 for the High Himalayan River FPZ, 505.1 for the Braided River FPZ, 4,245.0 for the Meandering River FPZ, and 9,899.0 for the Low Elevation Floodplain River FPZ.

Five groups of potential values for ecosystem services emerged from an analysis of the cumulative distribution of potential values: Group 1, 15 to 18; Group 2, 19 to 30; Group 3, 30 to 53; Group 4, 54 to 132; and Group 5, more than 132, where higher numbers represent greater potential value. The spatial distribution of these groups varied across the Koshi River Basin drainage network (Figure 6). In terms of length, Group 5 occupied 2,015 km or 35 percent of the river network and was the dominant potential value. This was followed by Group 2 (1,987 km or 34 percent), Group 1 (1,110 km or 19 percent), Group 3 (355 km or 6 percent), and Group 4 (303 km or 5 percent). In terms of riverine landscape area, however, 51 percent of the riverine landscape was occupied by Group 2, followed by Group 5 (23 percent), Group 1 (22 percent), Group 3 (2 percent), and Group 4 (2 percent).

The spatial distribution of the five potential value groups (Figure 6) shows Group 5 to be located predominantly in the lower elevation regions of the river network, and associated with the Low Elevation Floodplain River and Meandering River FPZs. In contrast, the lowest potential value of ecosystem services (Group 1) was located mainly in higher elevation regions of the basin in the High Himalayan River FPZ (Figure 6). Overall, the High Elevation Floodplain River FPZ was associated predominantly with Group 2. The Braided River and High Himalayan River FPZs were mostly associated with Groups 3 and 4. A broad pattern of increasing potential value in ecosystem services from the Tibetan Plateau through to the lowland regions of the basin is evident (Figure 6). There are areas of the river network that interrupt this general pattern, however, suggesting a nonuniform distribution of the potential value of ecosystem services across the river network. Some potential value groups are repeated with distance along the river network in association with the distribution of FPZs in the river network. Thus, the similarity between the spatial distribution of FPZs and ecosystem service potential value group was low, with a 15.85 percent similarity between the two for the Koshi River Basin drainage network.

Discussion

A foundational premise of river science is that the physical river template and associated biophysical processes are heterogeneous (Gilvear et al. 2016). Given the relationship between biophysical processes and ecosystem services, the supply of ecosystem services is not expected to be uniform throughout the river network. Studies of flow-dependent ecosystem services, however, have not examined heterogeneity in the river template and have been reach or site based. This study of the Koshi River Basin has found a direct relationship between the heterogeneity of the river template and the supply, use, and value of ecosystem services at the spatial scale of an entire river network. The approach of uncovering congruence between FPZs and ecosystem services in this river network is directly transferable to other river basins, regardless of their size. Knowledge of the heterogeneity in the supply, use, and value of ecosystem services in a river network will support evidence-based decision-making about river conservation activities and the use of river resources. The findings of this study advance our knowledge of ecosystem services in riverine landscapes in three areas, each of which is discussed next.

Congruency between the Physical Template and Ecosystem Services

A unique assemblage of ecosystem services exists among the five FPZs of the Koshi River Basin. Significant statistical differences among all FPZs confirm the congruency between the physical template and the supply of ecosystem services. Similar congruencies have been shown to occur in terrestrial landscapes, namely for agricultural (Qiu et al. 2020; Rieb and Bennett 2020), forested (Grêt-Regamey et al. 2014), and urban systems (Haase, Frantzeskaki, and Elmqvist 2014; Qiu et al. 2017). In general, these terrestrial-based studies support the foundational tenet that ecosystem services are generated by biophysical processes (Potschin et al. 2016). Our study of the Koshi River Basin demonstrates that this congruence also occurs in riverine landscapes.

Landscape structure is a mediator of the supply of ecosystem services (cf. Tamy et al. 2016; Rieb and Bennett 2020). The review and meta-analysis of Mitchell, Bennett, and Gonzalez (2015; Mitchell, Suarez-Castro, et al. 2015) suggests landscape structure affects how ecosystem services are supplied across landscapes. Within riverine landscapes, Thorp et al. (2010) hypothesized that large-scale hydrogeomorphological differences would influence the supply of ecosystem services. For example, floodplains are known hot spots that generate a wide range of ecosystem services such as fertile soils and carbon storage (Tockner and Stanford 2002). The importance of riparian and floodplain areas in supplying bundles of ecosystem services, at local spatial scales, has been shown by Tomscha, Gergel, and Tomlinson (2017), Van Looy et al. (2017), and Hornung, Podschun, and Pusch (2019). By comparison, river channel environments that experience extreme disturbances, from extended periods of drying or flooding, intermittently supply a limited array of ecosystem services (cf. Ruiz, Alonso, and Vidal-Abarca 2021). Large-scale regional differences in hydrogeomorphology and the supply of ecosystem services are evident in the Koshi River Basin. The extensive floodplain ecosystems that characterize the Low Elevation Floodplain River FPZ, located in the Terai region, supply a greater number of ecosystem services compared to the other FPZs. This dominance is primarily from the enhanced supply of provisioning services (Figure 4). In contrast, the supply of provisioning services in the High Himalayan River FPZ is reduced (Figure 4), presumably because this FPZ is dominated by a high-energy river channel system constrained within narrow bedrock controlled valleys, with no floodplains and limited riparian areas. In contrast, the Meandering River and Braided River FPZs are less controlled by valley widths, and have some floodplain areas and a greater ability to supply provisioning services. Thus, regional-scale differences in the physical template of the Koshi River Basin, as expressed by the presence of FPZs, are associated with variations in the supply of unique bundles of ecosystem services.

The influence of structure on biophysical processes is a function of landscape composition and location or place (Phillips 2018). In terms of riverine landscapes, composition can be represented as the number of FPZs, each with a different physical character or hydrogeomorphology; and, place is the position of FPZs within the stream network. Place factors, including climate and biological production, represent the local or regional environmental context. FPZs have been shown to have a nonuniform distribution along river networks (cf. Thoms, Scown, and Flotemersch 2018) and some FPZs repeat downstream. According to the riverine ecosystem synthesis of Thorp, Thoms, and Delong (2006; Thorp et al. 2010), however, similar FPZs are considered to have equivalent biophysical features and processes, thus they might have equivalent ecosystem services regardless of place. In the Koshi River Basin, the two floodplain-dominated FPZs differ in terms of their ecosystem service assemblages. Overall, the Low Elevation Floodplain River FPZ supplies a greater number of provisioning ($n = 28$) and cultural ($n = 9$) ecosystem services compared to the High Elevation Floodplain Rivers FPZ ($n = 11$ for provisioning services, $n = 4$ for cultural services). In terms of provisioning services, only 40 percent were found in both floodplain FPZs. The main differences between the two floodplain FPZs relate to those provisioning services supplied by various vegetation communities and reflect the influence of broader environmental factors like elevation, temperature, and photosynthetic activity (Mitsch and Gosselink 2015). The Tibetan region of the Koshi Basin, with an average elevation of 4,380 m ASL, has lower mean annual temperatures and a significant snowpack coverage compared to other regions of the basin (Dixit et al. 2009). All of these factors have the potential to limit the occurrence of certain floodplain vegetation communities and the ability to supply provisioning ecosystem services. Thus, not all floodplains are the same and place is a factor influencing the ability to supply ecosystem services regardless of the type of FPZ or physical template.

Landscape heterogeneity—the spatial variation in the organization of components in a landscape—affects the supply of many ecosystem services (Rieb and Bennett 2020). Landscape heterogeneity influences ecosystem interactions and regulates ecosystem responses to extrinsic and intrinsic stressors (Turner and Gardner 2015), subsequently influencing the supply of ecosystem services. For example, Qiu and Turner (2015) showed landscape heterogeneity to affect the supply of hydrologic ecosystem services and explained surface-water quality conditions in the Yahara River in Wisconsin. In the Yahara River catchment, surface-water quality was negatively correlated with percent cropland and positively correlated with the percent forest, grassland, and wetland in the basin. In general, empirical and theoretical evidence indicates landscape configuration (e.g., distribution of land uses, proximity of source and buffer ecosystems) mediates the transport of water and nutrients across agricultural landscapes (Kreiling et al. 2020), thereby affecting hydrologic ecosystem services (Qiu and Turner 2015).

Heterogeneity is a feature of the physical template of riverine landscapes, as evident by the character and organization of FPZs. The distribution of FPZs in the Koshi River Basin does not support the traditional clinal or gradient models of river system organization. Rather, there is a mosaic structure, as hypothesized by the river ecosystem synthesis (cf. Thorp, Thoms, and Delong 2006; Thorp et al. 2010). For example, High Elevation Floodplains River was the dominant FPZ in the upper reaches of the Koshi River network. This FPZ transitioned into the gorge-like High Himalayan River FPZ, and eventually further downstream into the Low Elevation Floodplain River FPZ. Because of the relationship between the physical template and ecosystem services, there is also "mosaicked" heterogeneity in the supply of ecosystem services. This occurs as the nonuniform distribution of ecosystem services across the riverine landscape of the Koshi River Basin.

Although the supply of ecosystem services was most abundant in the Low Elevation Floodplain River FPZ, the Braided River and Meandering River FPZs located in the midsections of the basin were both abundant in terms of the supply of ecosystem services. Distinct zones of unique assemblages of ecosystem services exist across the riverine landscape of the Koshi River Basin. This knowledge is fundamental to improving management of the basin, especially for assessing the environmental impacts of future water developments and for the process of decision-making around trade-offs.

The Social-Ecological Riverine Landscape

Heterogeneity of ecosystem service use is also a feature of the Koshi riverine landscape. Significant statistical differences in total relative use values among all FPZs infer congruency between the physical template and ecosystem service use. The character of heterogeneity in total relative use, however, did not match that of ecosystem service supply. Ranking FPZs in terms of total relative use showed the Meandering River FPZ to have the strongest use, followed by the Braided River FPZ, Low Elevation Floodplain River FPZ, High Himalayan River FPZ, and High Elevation Floodplain River FPZ. By comparison, the rank order for ecosystem service supply had the Low Elevation Floodplain River as the FPZ with the greatest supply, followed by the Braided River FPZ, Meandering River FPZ, High Himalayan River FPZ, and High Elevation Floodplain River FPZ. There are two components of heterogeneity: compositional and configurational (Lovett et al. 2005). Compositional heterogeneity is the number, type, and abundance of spatial units in the landscape, whereas configurational heterogeneity is the spatial arrangement of those units (Lovett et al. 2005). Thus, a mismatch in configurational heterogeneity occurs between ecosystem service use and supply in the riverine landscape of the Koshi River Basin.

Studies assessing relationships between the supply and social demand (use) of ecosystem services have increased over the past decade (Bennett et al. 2021). Most are focused on agricultural landscapes. Regardless of the landscape, mismatches between ecosystem service supply and demand have been proposed to reflect the ability to access, receive, and modify the benefits from ecosystems (cf. Hanna et al. 2020); community demographics and types of ecosystem service bundles available (Flotemersch et al. 2019); and social preferences for particular bundles or individual ecosystem services (Martín-López et al. 2012). Patterns of differential use of ecosystem services that emerge from diverging social preferences toward ecosystem services will influence configurational heterogeneity of ecosystem service use. Differences in the relative use of bundles of provisioning, regulating, supporting, and cultural ecosystem services occur among FPZs, regardless of whether the ecosystem services might be present in multiple FPZs. Overall, the relative use of provisioning and cultural services was dominant in the Meandering River FPZ while regulating and supporting services were dominant in the High Himalayan River FPZ, compared to other FPZs (cf. Figure 5). In addition, differential use of individual ecosystem services occurred within FPZs, and this differed among FPZs. In terms of provisioning ecosystem services, despite being more abundant in the Low Elevation Floodplain River FPZ ($n = 28$) compared to other FPZs ($n = 11$, 12, 25, and 26 for the High Elevation Floodplain River, High Himalayan River, Meandering River, and Braided River FPZs, respectively) actual use was dominated by those individual services associated with agricultural activities. In the remaining FPZs, all provisioning ecosystem services were used in similar proportions, with an enhanced total relative use. Thus, social factors have an influence on the heterogeneity of relative use of ecosystem services.

The concept of value is central to the science and practice of managing riverine landscapes (Gilvear et al. 2016). Despite a well-developed body of theory and evidence that explores concepts of value in different ways across different disciplines and landscapes, our knowledge of the value of ecosystem services within riverine landscapes is limited (Basak et al. 2021). A degree of congruency was also observed between the physical template and ecosystem service value. Differences in potential value were only recorded between two FPZs. As result, there was a marked simplification of the configurational and compositional heterogeneity of the potential value of ecosystem services compared to the heterogeneity of the relative use and supply of ecosystem services.

Valuation of ecosystem services has primarily been conducted within the context of the economic value of these services to society (Costanza et al. 1998). Economic analyses can be hindered by limited data, especially in remote regions like the Himalayas. The approach taken in this study is similar to the contingency analysis of Castro et al. (2011) and relies on the availability and relative use of ecosystem services as well as demographic information—the transfer of benefits to society. Given the spatial demography of the Koshi Basin, we would expect heterogeneity in the value of ecosystem services to reflect basic demographic patterns, with enhanced ecosystem values in the Low Elevation Floodplain River FPZ and those river valleys with easy access, such as the Meandering River and Braided River FPZs. Overall, our findings show marked difference between the upper and lower regions of the Koshi River Basin. Higher ecosystem service values in the lower regions of the basin reflect the greater supply, use, and population using these services compared to the upper regions.

Riverine landscapes are coupled and complex social-ecological systems (Pingram, Price, and Thoms 2019; Weigelhofer et al. 2021). Congruency between the physical template and the supply, use, and value of ecosystem services provides evidence for this coupling. The Koshi River Basin is a green loop system (cf. Cumming et al. 2014) characterized by the direct dependence of mostly agricultural communities on local flow-dependent ecosystem services providing benefits to people within the Koshi River Basin. The majority of communities are centered on the riverine landscapes of the basin. The differential patterns of ecosystem service heterogeneity, however, highlight the character of the coupling between the natural and human subsystems. The supply of ecosystem services reflects the primacy of the physical template. The place or location of FPZs and their associated ecosystem services, social values of associated bundles of ecosystem services, and demography, however, have a marked and differential influence on the use and value of the ecosystem services. These spatial differences between supply, use, and value are also indicative of a developing coupled agricultural or green loop social-ecological system (cf. Hamann, Biggs, and Reyers 2015).

Riverine Landscapes as Complex Adaptive Systems: A Model for the Koshi River Basin

The social-ecological landscape of rivers is increasingly conceptualized as a complex adaptive system by virtue of its hierarchical organization and ability to adjust multiple forms to an array of physical, ecological, and social processes (Thoms and Sheldon 2019). Identifying and understanding the various interactions between biophysical and social drivers, processes, and interrelated states that comprise social-ecological riverine landscapes is challenging. Conceptual models aid in understanding this complexity. Flow chain models demonstrate interactions between various components of complex adaptive systems at multiple spatial scales. Flow chain models have been used to demonstrate the efficiencies of environmental flow regimes on biophysical processes (Yarnell and Thoms 2022) and the ecological concept of disturbance in urban river systems (Grimm et al. 2017). Flow chain models have four basic components representing the interplay of biophysical and social characteristics in riverine landscapes: *Drivers* are the main agents of change, *functions* are a series of controllers or processes that are governed by the agents of change, *templates* are those surfaces (both abiotic and biotic) on which drivers and functions act, and finally there are a series of *responders*, which are sets of processes or actors that are parts of the social-ecological environment present across the riverine landscape.

A flow chain model of the Koshi River Basin (Figure 7) shows the supply, use, and value of ecosystem services of the riverine landscape to be the product of multiple biophysical and social interactions. The flow regime is the main driver that acts on the geomorphological structure of the riverine landscape, and this can be expressed as FPZs with similar hydrogeomorphic characteristics. The output of this interaction directly influences the assemblage of ecosystem services that can be supplied by the riverine landscape—the type, abundance, and position in the network (cf. Thoms, Scown, and Flotemersch 2018). Controllers, such as population density, social values, and geographic location or place, influence the supply, use, and value of ecosystem services in the riverine landscape. Controllers interact via a series of feedbacks between the supply of ecosystem services and their use and value. Overall, this framework helps to understand the complex relationships between flow, the physical template (ecological), and ecosystem services (social) within coupled social-ecological riverine landscapes.

The flow chain representation of the interactions between the physical template and ecosystem services is a heuristic model of the Koshi River Basin

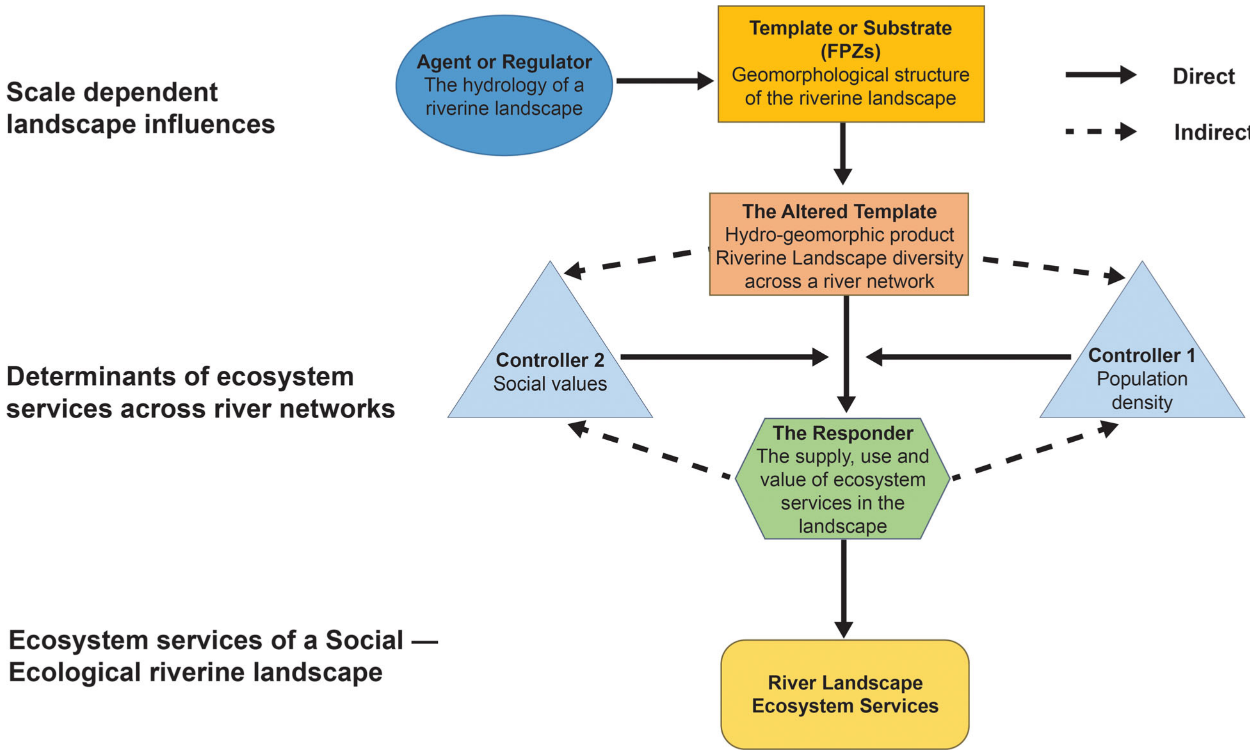

Figure 7. A flow-chain model for describing process interactions and the character of ecosystem services across riverine landscapes (modified from Thoms et al., 2017). The flow-chain model has four basic components: the abiotic or biotic agent or regulator of change, or driver; the template or substrate on which the driver acts; controllers of the driver or agent of change; and an entity or process that responds to the driver or agent of change. Responders can be sets of processes, ecosystem services, organisms, or parts of the physical environment. *Note:* FPZ = functional process zone.

riverine landscape. Like any landscape model, there are limitations, and it could be improved with additional data. Our study was fortunate to have ecosystem service data for all FPZs identified in the basin, but data were not available for all individual FPZs. This is especially important in mountainous regions where access can be restricted. Understanding variations among similar FPZs located in different regions of the basin is important for considering finer level interactions between the physical template and ecosystem services. Variations in data availability were also noted across the four ecosystem service groups. Provisioning and regulating services (Table 2, Figure 4) dominated the ecosystem services for the Koshi Basin. This could reflect bias in the sampling design. The distribution among the four ecosystem service types in the Koshi Basin, however, is similar to that reported from other studies in different geographic regions (cf. Bennett, Peterson, and Gordon 2009; Burkard et al. 2009; Ezenwaka and Grave 2014; Kamlun and Arndt 2019). In the Koshi River Basin, the contribution of the four ecosystem service types was 51.8 percent, 26.8 percent, 5.4 percent, and 16.1 percent for provisioning, regulating, supporting, and cultural services, respectively, compared to the mean across nine other studies of 40 percent, 29 percent, 20 percent, and 11 percent, respectively. This could suggest that our sampling of ecosystem services across the four types was sufficient.

Summary

The Himalayas are a biodiversity hot spot (Chettri et al. 2008) identified as a global conservation priority region (Brooks et al. 2006). The Koshi River Basin is a large river system draining the Himalayas and home to more than 40 million people, many of whom depend on the ecosystem services of its riverine landscape. The supply of ecosystem services (e.g., supporting, provisioning, regulating, and cultural) provided by the riverine ecosystems contributes to the well-being of the populations that reside in the basin and the basin communities further downstream in India. Despite the multidimensional (ecological, sociocultural, and economic) importance of ecosystems to human society, there have been limited efforts to assess the provision of ecosystem services in the riverine landscape of the Himalayas. Efforts to manage flow-dependent ecosystem services must be cognizant of the physical template and social interactions in controlling the spatial distribution across riverine landscapes.

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References

Basak, S. M., M. S. Hossain, J. Tusznio, and M. Grodzinska-Jurczak. 2021. Social benefits of river restoration from ecosystem services perspective: A systematic review. *Environmental Science and Policy* 124:90–100.

Belbin, L., and C. McDonald. 1993. Comparing three classification strategies for use in ecology. *Journal of Vegetation Science* 4:341–48.

Bennett, E. M., J. Baird, H. Baulch, R. Chaplin-Kramer, E. Fraser, P. Loring, P. Morrison, L. Parrott, K. Sherren, K. J. Winkler, et al. 2021. Ecosystem services and the resilience of agricultural landscapes., In *Advances in ecological research*, ed. D. A. Bohan and A. J. Vanbergen, 1–43. New York: Academic Press.

Bennett, E. M., G. D. Peterson, and L. J. Gordon. 2009. Understanding relationships among multiple ecosystem service. *Ecology Letters* 12:1394–1404.

Bhatta, L. D., B. E. H. Van Oort, N. E. Stork, and H. Baral. 2015. Ecosystem services and livelihoods in a changing climate: Understanding local adaptations in the Upper Koshi, Nepal. *International Journal of Biodiversity Science, Ecosystem Services and Management* 11:145–55.

Brooks, T. M., R. A. Mittermeier, G. A. B. Da Fonseca, J. Gerlach, M. Hoffmann, J. F. Lamoreux, C. G. Mittermeier, J. D. Pilgrim, and A. S. L. Rodrigues. 2006. Global biodiversity conservation priorities. *Science* 313 (5783):58–61. doi: 10.1126/science.1127609.

Burkard, B., F. Kroll, F. Muller, and W. Windhorst. 2009. Landscapes capacities to provide ecosystem services—A concept for land-cover based assessments. *Landscape Online* 15:1–22.

Castro, A. J., B. Martin-Lopez, M. Garcia-Llorenete, P. A. Aguilera, E. Lopez, and J. Cabello. 2011. Social preferences regarding the delivery of ecosystem services in a semiarid Mediterranean region. *Journal of Arid Environments* 75:1201–08.

Central Bureau of Statistics (CBS). 2012. National population and housing census 2011. Kathmandu, Nepal: CBS, Government of Nepal. Accessed March 6, 2021. https://data.humdata.org/dataset/nepal-census-2011-district-profiles-demography.

Chen, N. S., G. S. Hu, W. Deng, N. Khanal, Y. H. Zhu, and D. Han. 2013. On the water hazards in the trans-boundary Kosi River basin. *Natural Hazards and Earth System Science* 13:795–808.

Chettri, N., B. Shakya, R. Thapa, and E. Sharma. 2008. Status of a protected area system in the Hindu Kush-Himalayas: An analysis of PA coverage. *International Journal of Biodiversity Science and Management* 4 (3):164–78. https://doi.org/10.3843/Biodiv.4.3:4.

Collins, S. E., J. A. Thoms, and Flotemersch, M. C. 2014. Hydrogeomorphic zones characterize riverbed sediment patterns within a river network? *River Systems* 21:203–15.

Costanza, R. 2020. Valuing natural capital and ecosystem services toward the goals of efficiency, fairness, and sustainability. *Ecosystem Services* 43:101096.

Costanza, R., R. D'Arge, R. De Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neill, J. Paruelo, et al. 1998. The value of ecosystem services: Putting the issues in perspective. *Ecological Economics* 25 (1):67–72. doi: 10.1016/S0921-8009(98)00019-6.

Costanza, R., R. de Groot, P. Sutton, S. van der Ploeg, S. J. Anderson, I. Kubiszewski, S. Farber, and R. K. Turner. 2014. Changes in the global value of ecosystem services. *Global Environmental Change* 26:152–58. doi: 10.1016/j.gloenvcha.2014.04.002.

Costanza, R., and S. Farber. 2002. Introduction to the special issue on the dynamics and value of ecosystem services: Integrating economic and ecological perspectives. *Ecological Economics* 41 (3):367–73. doi: 10.1016/S0921-8009(02)00087-3.

Crossman, N. D., B. Burkhard, S. Nedkov, L. Willemen, K. Petz, I. Palomo, E. G. Drakou, B. Martín-Lopez, T. McPhearson, K. Boyanova, et al. 2013. A blueprint for mapping and modelling ecosystem services. *Ecosystem Services* 4:4–14. doi: 10.1016/j.ecoser.2013.02.001.

Cumming, G. S., A. Buerkert, E. M. Hoffmann, E. Schlecht, S. von Cramon-Taubadel, and T. Tscharntke. 2014. Implications of agricultural transitions and urbanization for ecosystem services. *Nature* 515 (7525):50–57. doi: 10.1038/nature13945.

Daily, G. C. 1997. *Nature's services*. Washington, DC: Island.

Danish, M., P. Gupta, J. Alam, and P. M. Muzammil. 2013. River Kosi, sorrow of India: An overview. In *Proceedings of 2nd International Conference on Emerging Trends in Engineering & Technology*, vol. 12, p. 13. India: TMU.

De Groot, R., L. Brander, S. van der Ploeg, R. Costanza, F. Bernard, L. Braat, M. Christie, N. Crossman, A. Ghermandi, L. Hein, et al. 2012. Global estimates of the value of ecosystems and their services in monetary units. *Ecosystem Services* 1 (1):50–61. doi: 10.1016/j.ecoser.2012.07.005.

Dhital, M. R. 2015. *Geology of the Nepal Himalaya: Regional perspective of the classic collided orogen*. New York: Springer. https://doi.org/10.1007/978-3-319-02496-7.

Dixit, A., M. Upadhya, K. Dixit, A. Pokhrel, and D. R. Rai. 2009. *Living with water stress in the hills of the Koshi Basin, Nepal*. Kathmandu, Nepal: ICIMOD.

Elgueta, A., E. M. Habit, M. C. Thoms, K. Górski, and G. Díaz. 2019. Functional process zones and their fish communities in temperate Andean river networks. *River Research and Applications* 35 (10):1702–11. doi: 10.1002/rra.3557.

Ezenwaka, J., and A. Grave. 2014. Ecosystem services of the Niger Delta. *Journal of Agriculture and Social Research* 14:37–56.

Flotemersch, J. E., S. M. Shattuck, K. B. Aho, C. E. Cox, and M. R. Cairns. 2019. Factors influencing social demands of aquatic ecosystems. *Ecology and Society* 24 (4):9–18. doi: 10.5751/ES-11165-240409.

Francesconi, W., R. Srinivasan, E. Pérez-Miñana, S. P. Willcock, and M. Quintero. 2016. Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: A systematic review. *Journal of Hydrology* 535:625–36. doi: 10.1016/j.jhydrol.2016.01.034.

Gerlitz, J.-Y., S. Banerjee, B. Hoermann, K. Hunzai, M. Macchi, and S. Tuladhar. 2014. *Poverty and vulnerability assessment—A survey instrument for the Hindu Kush Himalayas*. Accessed March 3, 2022. http://lib.icimod.org/record/29972.

Gilvear, D. A., M. W. Greenwood, M. C. Thoms, and P. A. Wood, eds. 2016. *River science, management and policy for 21st century*. Chichester, UK: Wiley.

Grêt-Regamey, A., S. E. Rabe, R. Crespo, S. Lautenbach, A. Ryffel, and B. Schlup. 2014. On the importance of non-linear relationships between landscape patterns and the sustainable provision of ecosystem services. *Landscape Ecology* 29 (2):201–12. doi: 10.1007/s10980-013-9957-y.

Grimm, N. B., S. T. A. Pickett, R. L. Hale, and M. L. Cadenasso. 2017. Does the ecological concept of disturbance have utility in urban social-ecological-technological systems? *Ecosystem Health and Sustainability* 3 (1):e01255. doi: 10.1002/ehs2.1255.

Haase, D., N. Frantzeskaki, and T. Elmqvist. 2014. Ecosystem services in urban landscapes: Practical applications and governance implications. *AMBIO* 43 (4):407–12. doi: 10.1007/s13280-014-0503-1.

Haines-Young, R., M. Potschin, and F. Kienast. 2012. Indicators of ecosystem service potential at European scales: Mapping marginal changes and trade-offs. *Ecological Indicators* 21:39–53. doi: 10.1016/j.ecolind.2011.09.004.

Hamann, M., R. Biggs, and B. Reyers. 2015. Mapping social-ecological systems: Identifying "green-loop" and "red-loop" dynamics based on characteristic bundles of ecosystem service use. *Global Environmental Change* 34:218–26. doi: 10.1016/j.gloenvcha.2015.07.008.

Hanna, D. E. L., D. J. Roux, B. Currie, and E. M. Bennett. 2020. Identifying pathways to reduce discrepancies between desired and provided ecosystem services. *Ecosystem Services* 43:101119. doi: 10.1016/j.ecoser.2020.101119.

Hanna, D. E. L., S. A. Tomscha, C. Ouellet Dallaire, and E. M. Bennett. 2018. A review of riverine ecosystem service quantification: Research gaps and recommendations. *Journal of Applied Ecology* 55 (3):1299–1311. doi: 10.1111/1365-2664.13045.

Hornung, L. K., S. A. Podschun, and M. Pusch. 2019. Linking ecosystem services and measures in river and floodplain management. *Ecosystems and People* 15 (1):214–31. doi: 10.1080/26395916.2019.1656287.

Hussain, A., G. Rasul, B. Mahapatra, S. Wahid, and S. Tuladhar. 2018. Climate change-induced hazards and local adaptations in agriculture: A study from Koshi River Basin, Nepal. *Natural Hazards* 91 (3):1365–83. doi: 10.1007/s11069-018-3187-1.

Kafle, K. R., S. N. Khanal, and R. K. Dahal. 2015. Dynamics of the Koshi River on the perspective of morphology and sedimentation with emphasis on post disaster impact of the 2008 Koshi flood. *Journal of Science, Engineering and Technology* 11:71–92.

Kamlun, K., and U. R. B. Arndt. 2019. Expert-based approach on mapping ecosystem services potential supply in circling a protected areas by integrating matrix model assessment. *Journal of Physics* 1358:012032.

Kastens, J. H. 2008. Some new developments on two separate topics: Statistical cross validation and floodplain mapping. PhD diss., University of Kansas, Lawrence.

Khadka, D. B. 2021. Performance evaluation of hydropower plants of Nepal using multi criteria decision analysis: Review study. *Journal of Fundamentals of Renewable Energy and Applications* 11 (2):e292. doi: 10.4172/2090-4541.1000292.

Kreiling, R. M., M. C. Thoms, L. A. Bartsch, J. H. Larson, and V. G. Christensen. 2020. Modelling land use effects on sediment nutrient processes in a modified watershed using structural equation models. *Water Resources Research* 56 (7):e2019WR026655. doi: 10.1029/2019WR026655.

Kumar, P., and J. Martinez-Alier. 2011. The economics of ecosystem services and biodiversity: An international assessment. *Economic and Political Weekly* 46:76–80.

Large, A. R. G., and D. J. Gilvear. 2015. Using Google Earth, a virtual-globe imaging platform, for ecosystem services-based river assessment. *River Research and Applications* 31 (4):406–21. doi: 10.1002/rra.2798.

Likens, G. E., K. F. Walker, P. E. Davies, J. Brookes, J. Olley, W. J. Young, M. C. Thoms, P. S. Lake, B. Gawne, J. Davis, et al. 2009. Ecosystem science: Toward a new paradigm for managing Australia's inland aquatic ecosystems. *Marine and Freshwater Research* 60 (3):271–79. doi: 10.1071/MF08188.

Lovett, G. M., C. G. Jones, M. G. Turner, and K. C. Weathers. 2005. Ecosystem function in heterogeneous landscapes. In *Ecosystem function in heterogeneous landscapes*, ed. G. M. Lovett, C. G. Jones, M. G. Turner, and K. C. Weathers, 1–4. New York: Springer.

Maasri, A., M. Pyron, E. R. Arsenault, J. H. Thorp, B. Mendsaikhan, F. Tromboni, M. Minder, S. J. Kenner, J. Costello, S. Chandra, et al. 2021. Valley-scale hydrogeomorphology drives river fish assemblage variation in Mongolia. *Ecology and Evolution* 11 (11):6527–35. doi: 10.1002/ece3.7505.

Mahato, R. K., and K. S. Shukla. 2013. Geomorphological landforms of Sapt Kosi River. *International Journal of Lakes and Rivers* 6:85–101.

Martín-López, B., I. Iniesta-Arandia, M. García-Llorente, I. Palomo, I. Casado-Arzuaga, D. G. D. Amo, E. Gómez-Baggethun, E. Oteros-Rozas, I. Palacios-Agundez, B. Willaarts, et al. 2012. Uncovering ecosystem service bundles through social preferences. *PLoS ONE* 7 (6):e38970. doi: 10.1371/journal.pone.0038970.

Millenium Ecosystem Assessment (MEA). 2005. *Ecosystems and human well-being: Synthesis*. Washington, DC: Island.

Mishra, K., R. Sinha, V. Jain, S. Nepal, and K. Uddin. 2019. Towards the assessment of sediment connectivity in a large Himalayan river basin. *Science of the Total Environment* 661:251–65. doi: 10.1016/j.scitotenv.2019.01.118.

Mitchell, M. G. E., E. M. Bennett, and A. Gonzalez. 2015. Strong and nonlinear effects of fragmentation on ecosystem service provision at multiple scales. *Environmental Research Letters* 10 (9):094014. doi: 10.1088/1748-9326/10/9/094014.

Mitchell, M. G., A. F. Suarez-Castro, M. Martinez-Harms, M. Maron, C. McAlpine, K. J. Gaston, K. Johansen, and J. R. Rhodes. 2015. Reframing landscape fragmentation's effects on ecosystem services. *Trends in Ecology & Evolution* 30 (4):190–98. doi: 10.1016/j.tree.2015.01.011.

Mitsch, W. J., and J. G. Gosselink. 2015. *Wetlands*. 5th ed. Hoboken, NJ: Wiley.

Mittermeier, R. A., P. R. Gil, M. Hoffmann, J. Pilgrim, T. Brooks, C. G. Mittermeier, J. Lamoreux, and G. A. B. Fonseca, eds. 2004. *Hotspots revisited—Earth's biologically richest and most endangered terrestrial ecoregions*. Mexico City, Mexico: Cemex/Agrupacion Sierra Madre.

Phillips, J. D. 2018. Place formation and axioms for reading the natural landscape. *Progress in Physical Geography: Earth and Environment* 42 (6):697–720. doi: 10.1177/0309133318788971.

Pingram, M., J. Price, and M. C. Thoms. 2019. Integrating multiple aquatic values: Historical perspectives and a collaborative future for river science. *River Research and Applications* 35 (10):1607–14. doi: 10.1002/rra.3562.

Potschin, M., R. Haines-Young, R. Fish, and R. K. Turner. 2016. *Routledge handbook of ecosystem services*. London and New York: Routledge.

Qiu, J., S. R. Carpenter, E. G. Booth, M. Motew, and C. J. Kucharik. 2020. Spatial and temporal variability of future ecosystem services in an agricultural landscape. *Landscape Ecology* 35 (11):2569–86. doi: 10.1007/s10980-020-01045-1.

Qiu, J., and M. G. Turner. 2015. Importance of landscape heterogeneity in sustaining hydrologic ecosystem services in an agricultural watershed. *Ecosphere* 6 (11):art229. doi: 10.1890/ES15-00312.1.

Qiu, J., C. B. Wardropper, A. R. Rissman, and M. G. Turner. 2017. Spatial fit between water quality policies and hydrologic ecosystem services in an urbanizing agricultural landscape. *Landscape Ecology* 32 (1):59–75. doi: 10.1007/s10980-016-0428-0.

Rieb, J. T., and E. M. Bennett. 2020. Landscape structure as a mediator of ecosystem service interactions. *Landscape Ecology* 35 (12):2863–80. doi: 10.1007/s10980-020-01117-2.

Ruiz, N. N., M. L. S. Alonso, and M. R. Vidal-Abarca. 2021. Contributions of dry rivers to human well-being: A global review for future research. *Ecosystem Services* 50:0307.

Schröter, M., A. Bonn, S. Klotz, R. Seppelt, and C. Baessler, eds. 2019. *Atlas of ecosystem services*. Berlin: Spinger.

Schumm, S. A. 1985. Patterns of alluvial rivers. *Annual Review of Earth and Planetary Sciences* 13:5–27.

Shrestha, A. B., S. R. Bajracharya, A. R. Sharma, C. Duo, and A. Kulkarni. 2017. Observed trends and changes in daily temperature and precipitation extremes over the Koshi River basin 1975–2010. *International Journal of Climatology* 37 (2):1066–83. doi: 10.1002/joc.4761.

Sinha, R., A. Gupta, K. Mishra, S. Tripathi, S. Nepal, S. M. Wahid, and S. Swarnkar. 2019. Basin-scale hydrology and sediment dynamics of the Kosi River in the Himalayan foreland. *Journal of Hydrology* 570:156–66. doi: 10.1016/j.jhydrol.2018.12.051.

Tamy, T., K. N. Liss, A. Gonzalez, and E. B. Bennet. 2016. Landscape structure affects the provision of multiple ecosystem services. *Environmental Research Letters* 11:124017.

Thoms, M. C., M. D. Delong, J. E. Flotemersch, and S. E. Collins. 2017. Physical heterogeneity and aquatic community function in river networks: A case study from the Kanawha River Basin, USA. *Geomorphology* 290:277–87. doi: 10.1016/j.geomorph.2017.02.027.

Thoms, M. C., M. Scown, and J. Flotemersch. 2018. Characterization of river networks: A GIS approach and its applications. *JAWRA: Journal of the American Water Resources Association* 54 (4):899–913. doi: 10.1111/1752-1688.12649.

Thoms, M. C., and F. Sheldon. 2019. Large rivers and complex adaptive systems. *River Research and Applications* 35 (5):451–58. doi: 10.1002/rra.3448.

Thorp, J. H., J. E. Flotemersch, M. D. Delong, A. F. Casper, M. C. Thoms, F. Ballantyne, B. S. Williams, B. J. O'Neill, and C. S. Haase. 2010. Linking ecosystem services, rehabilitation, and river hydrogeomorphology. *BioScience* 60 (1):67–74. doi: 10.1525/bio.2010.60.1.11.

Thorp, J. H., M. C. Thoms, and M. D. Delong. 2006. The riverine ecosystem synthesis: Biocomplexity in river networks across space and time. *River Research and Applications* 22 (2):123–47. doi: 10.1002/rra.901.

Tockner, K., and J. A. Stanford. 2002. Riverine flood plains: Present state and future trends. *Environmental Conservation* 29 (3):308–30. doi: 10.1017/S037689290200022X.

Tomscha, S. A., S. E. Gergel, and M. J. Tomlinson. 2017. The spatial organization of ecosystem services in river-floodplains. *Ecosphere* 8 (3):e01728. doi: 10.1002/ecs2.1728.

Turner, M. G., and R. H. Gardner, eds. 2015. *Landscape ecology in theory and practice*. New York: Springer.

Uddin, K., S. M. Wahid, and M. S. R. Murthy. 2015. Mapping of Koshi Basin wetlands using remote sensing. In *Proceedings of the 5th International Conference on Water & Flood Management* (ICWFM-2015), 461–68. Dhaka, Bangladesh: Institute of Water and Flood Management (IWFM), BUET.

Van Looy, K., T. Tormos, Y. Souchon, and D. Gilvear. 2017. Analyzing riparian zone ecosystem services bundles to instruct river management. *International Journal of Biodiversity Science, Ecosystem Services and Management* 13 (1):330–41. doi: 10.1080/21513732.2017.1365773.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37 (1):130–37. doi: 10.1139/f80-017.

Wahid, S. M., G. Kilroy, A. B. Shrestha, S. R. Bajracharya, and K. Hunzai. 2017. Opportunities and challenges in the trans-boundary Koshi River Basin. In *River system analysis and management*, ed. N. Sharma, 341–52. Singapore: Springer.

Weigelhofer, G., M. Brauns, D. Gilvear, G. Haidvogl, and T. Hein. 2021. Riverine landscapes: Challenges and future trends in research and management. *River Research and Applications* 37 (2):119–22. doi: 10.1002/rra.3769.

White, E. P., and J. H. Brown. 2005. The template: Patterns and processes of spatial variation. In *Ecosystem function in heterogeneous landscapes*, ed. G. M. Lovett, C. Jones, M. G. Turner, and K. C. Weathers, 31–47. Berlin: Springer.

Yarnell, S. M., and M. C. Thoms. 2022. Enhancing the functionality of environmental flows through an understanding of biophysical processes in the riverine landscape. *Frontiers in Environmental Science* 10:787216. doi: 10.3389/fenvs.2022.787216.

Yeakley, J. A., D. Ervin, H. Chang, E. F. Granek, V. Dujon, V. Shandas, and D. Brown. 2016. Ecosystems, their properties, goods and services. In *River science, management and policy for the 21st century*, ed. D. A. Gilvear, M. W. Greenwood, M. C. Thoms, and P. A. Wood, 335–52. Chichester, UK: Wiley.

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