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Vegetation cover dynamics along two Himalayan rivers: Drivers and implications of change

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HIGHLIGHTS

- This study investigated vegetation changes along the Sutlej and Beas Rivers, India, over 30 years.
- Vegetation and land cover were classified from remotely sensed data and trends calculated for three geomorphic zones.
- Vegetation increased in all zones, with trends greatest in the active river channel related to dam-related planform change.
- Vegetation succession and farms were observed, which reinforce the planform and expose people and infrastructure to new risks.

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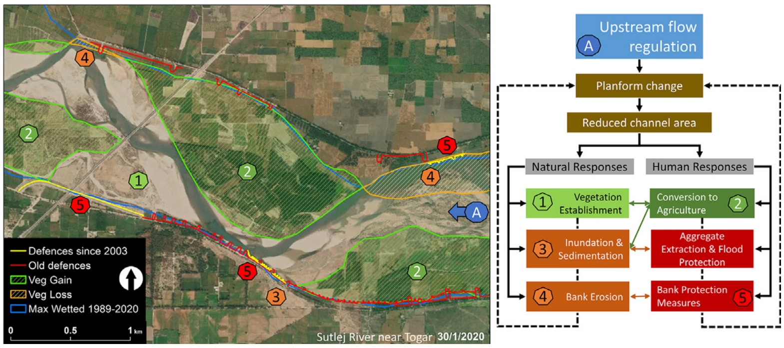
GRAPHICAL ABSTRACT



ABSTRACT

Rivers are dynamic landscape features that change in response to natural and anthropogenic factors through hydrological, geomorphic and ecological processes. The severity and magnitude of human impacts on river system and riparian vegetation has dramatically increased over the last century with the proliferation of valley-spanning dams, intensification of agriculture, urbanization, and more widespread channel engineering. This study aims to determine how changes in geomorphic form and dynamics caused by these human alterations relate to changes in channels and riparian vegetation in the lower Beas and Sutlej Rivers. These rivers are tributaries of the Indus that drain the Western Himalayas but differ in the type and magnitude of geomorphic change in recent decades. Winter season vegetation was analysed over 30 years, revealing increasing trends in vegetated land cover in the valleys of both rivers, consistent with large-scale drivers of change. Greater trends within the active channels indicate upstream drivers are influencing river flow and geomorphology, vegetation growth and human exploitation. The spatial patterns of vegetation change differ between the rivers, emphasizing how upstream human activities (dams and abstraction) control geomorphic and vegetation community response within the landscape context of the river. The increasing area of vegetated land is reinforcing the local evolutionary trajectory of the river planform from wide-braided wandering to single thread meandering. Narrowing of the active channels is altering the balance of resource provision and risk exposure to people. New areas being exploited for agriculture are exposed to greater risk from river erosion, inundation, and sediment deposition. Moreover, the change from braided to meandering planform has concentrated erosion on riverbanks, placing communities and infrastructure at risk. By quantifying and evaluating the spatial variations in vegetation cover around these rivers, we can better understand the interaction of vegetation and geomorphology alongside the impacts of human activity and climate change in these, and many similar, large systems, which can inform sustainable development.

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1. Introduction

River systems are critical for ecological diversity (Tockner and Stanford, 2002), supporting many ecosystem services (Bai et al., 2011) and are key to meeting several of the United Nations' sustainable development goals (SDGs) (Momblanch et al., 2019; United Nations, 2021) that provide a future global development framework towards a sustainable future for all. However, they respond to multiple natural and anthropomorphic pressures that influence discharge rates, drive hydro-geomorphological processes and affect riparian and aquatic ecosystems, river channels and valleys. The drivers of change may be global (e.g. climate change), upstream (dam discharges and management) or caused by local factors such as economic incentives, population growth, industrial development, new technology and competition for resources (Grabowski et al., 2022). A key challenge for sustainable management is to determine how these drivers control the rate of geomorphic change and influence riparian vegetation communities, which in combination affect the physical habitat complexity, resource provision and risk exposure.

Riparian vegetation (the plants, shrubs and trees growing within and along rivers) plays an important role in and near the active channel, locally providing important habitat to support biodiversity (Bai et al., 2011; Friedman et al., 1996; Tockner and Stanford, 2002) and inducing geomorphic change to have wider effect by constraining lateral erosion. Downstream effects may include a reduction in peak flows (Dadson et al., 2017) leading to lower fluvial flooding risk, and a reduction in the transport of sediment downstream (Gurnell et al., 2012). The distribution of woody vegetation within river channels and the erodible corridor of geomorphically active rivers is strongly affected by channel hydraulics, sediment erosion and sediment deposition (Camporeale and Ridolfi, 2010, 2006; Gurnell and Grabowski, 2016). This leads to a greater variety of habitats for plants and other organisms (Grabowski et al., 2022). If high discharge events decline in frequency and magnitude, due to natural (e.g. climate change) or human influences (e.g. dams), the vegetation will respond through the growth and development of woody species, and the lateral expansion and succession of communities (Johnson et al., 2016). These ecological changes, especially the establishment and growth of shrubs and trees leads to greater geomorphic stability that contributes to planform change, such as channel simplification, straightening, or narrowing (Friedman et al., 1996). The response of natural vegetation communities and their local and downstream effects on river hydrology and geomorphology is complicated by human activity in riparian areas, which affect community composition and cover, such as agriculture or development. Whilst these feedbacks between plants and hydrology and geomorphology have been well-studied in recent decades (Grams et al., 2020; Gurnell and Grabowski, 2016; Tockner and Stanford, 2002) the effects of multiple pressures on these feedbacks within the landscape context needs further research focus (Best, 2019).

These issues are particularly relevant for Himalayan rivers, which have seen rapid changes in recent decades. These changes include the construction of dams for irrigation, water supply and hydropower, land use change, channel engineering, aggregate extraction and the effects of global climate change (Kumar and Katoch, 2017). The Himalayan glaciers that feed these rivers have lost at least 40 % of their Little Ice Age area (Lee et al., 2021) and have seen a doubling of the average loss rate when the periods 1975–2000 and 2000–2016 are compared (Maurer et al., 2019). Average rainfall rates are also changing in the region, with significant decreases in some areas of the upper Beas River but increases elsewhere. Overall, the streamflow is predicted to increase by 1.9 % to 16.5 % on average between 2015 and 2050 compared to the period 1974–2010 (Rani and Sreekesh, 2019). These changes have pointed to a pressing need for a structured analysis of geomorphological and vegetation over space and time in a Himalayan River system. The Sutlej and Beas catchments are good examples where significant geomorphic planform change was observed over the recent three decades, including channel narrowing, straightening and loss of side channels (Vercruysse and Grabowski, 2021),

The aim of this study is to determine how human alterations to river flows and riparian land management cause changes in vegetation communities and the significance of those changes on geomorphic form, dynamics, resource availability, and hazard to humans. The study quantified channel and riparian vegetation extent over time in the and evaluated timing and directions of change in consideration of anthropogenic uses (farming and infrastructure) and pressures (dam operations). The specific objectives were to: (1) Determine temporal trends in riparian and channel vegetation cover, (2) evaluate the role of global, upstream and local drivers on vegetation patterns and trends (dam operations, valley setting, local anthropogenic activity), and (3) discuss how vegetation has changed how humans use the landscape and the risks they pose. The Beas and Sutlej Rivers share many characteristics with other river systems in areas of rapid economic and population growth, where human pressures are adding to global impacts of climate change. The understanding gained through this study is transferable to many similar systems and inform future policy in order to address the sustainable development goals.

2. Material and methods

A multi-step process was used to quantify spatial-temporal vegetation cover and relate it to the anthropogenic drivers. First, trends in vegetation dynamics were identified by temporal and spatial analysis of remote sensing data, using normalised difference vegetation index (NDVI) as an indicator of vegetation cover. These trends were then compared to trends in geomorphic change identified in the same rivers by previous work (Vercruysse and Grabowski, 2021) and a flood frequency analysis of the discharges from the Pong and Bhakra Dams. Next, a supervised classification approach was used to determine seasonal and annual changes in land cover within the active channel zone to separate trends caused by vegetation vigour from those related to fractional land cover. Finally, several sites were selected for more detailed analysis to determine causal relationships between geomorphic change and vegetation in both rivers and to identify risks to resource provision and exposure. The study period of 1989 to 2020 was driven by the availability of Landsat data.

2.1. Study areas

The Sutlej and Beas Rivers drain the Western Himalayas and are tributaries of the Indus, stretching from the Tibetan Autonomous Region in China, through the Indian states of Himachal Pradesh and Punjab, and into Pakistan. The study was conducted in the lower parts of the catchments downstream of the major dams on both rivers to their confluence (220 km long and 11,992 km^2 in Sutlej and 160 km long and 2951 km^2 in Beas). For the first third of this distance the river valleys are wide with a defined hillslope boundary; for the Beas Valley the elevation range is 251–600 m with the river falling 0.0018 m m^{-1}, for the Sutlej Valley the elevation range is 270–940 m with the river falling 0.0022 m m^{-1}. Elsewhere, the majority of the study area is in the Punjab plains consisting of mainly Quaternary deposits (Bindal, 2007), where the elevation is between 210 m and 270 m, the rivers fall very gently by only 0.0003 m m^{-1}, and the valley sides are not well defined in part because of tectonic activity (Bhatt et al., 2008). These plains are primarily covered in rain-fed and irrigated cropland with scattered patches of urban areas and grassland (Momblanch et al., 2019).

The most significant direct human impact on the river systems are inline dams that control water and sediment fluxes downstream. The Bhakra Dam on the Sutlej was completed in 1963 and the Pong Dam on the Beas in 1974, these being the earliest significant dam constructions on these rivers upstream of the study area. Both are used to store and supply water for hydro-power generation and irrigation: regulating high flows during the monsoon season (July to September) (Momblanch et al., 2019). The water flow in both rivers is dominated by controlled discharges from these dams and is less variable than prior to dam construction. For example, below the Pong dam the minimum average monthly flow increased from 120 to 300 m^3/s (Vercruysse and Grabowski, 2021); increases in base flow of this nature are typically associated with decreases in peak and geomorphically relevant flows (Kondolf, 1997). Despite this, their hydrology remains seasonally driven, with the peak discharges of geomorphic relevance occurring because of monsoon season rains regularly exceeding the dam capacity resulting in the overspill or release of large volumes of water into the rivers.

As adjacent catchments the Sutlej and Beas Rivers share similar characteristics and have experienced significant geomorphic changes over the last 150 years. However, the contrasts in the type and magnitude of geomorphic change in recent decades are attributable to different sources of water and variable anthropomorphic influences. For example, upstream of these major dams the Sutlej River receives 56 % of its water from glacier and snow melt whereas the Beas receives only 18 % from these sources (Momblanch et al., 2019). There are consequential differences in the range and levels of peak discharges from these dams, and the nature of downstream geomorphic change, as observed in earlier work (Vercruysse and Grabowski, 2021).

The study area was divided into longitudinal sections to permit analysis of vegetation cover and geomorphic change longitudinally through the river network (Vercruysse and Grabowski, 2021). The upper section (S0) of each river is downstream of the dam which begin with relatively steep valley slopes, narrow valley bottoms and narrow river channels that are often highly branched. The planform is rather different in the upper sections (bar and island braided gravel/cobble reaches) than the lower ones (S1–S4/5), which are currently single thread meandering. These lower sections are delineated in approximately 30 km lengths.

The landscape was delineated into geomorphic zones; Active Channel, Valley Bottom, and Valley Slopes (Fig. 1), so that the impact on the river could be better studied. The Active Channel Zone is defined by the maximum wetted area of the channel between 1989 and 2018. This includes any area that was under water or surrounded by water during the post-monsoon season (October to December) in at least one of those intervening years. The land cover in this zone would normally be expected to be a mixture of water, sand and gravel bars, rocks and stones, and riparian vegetation (Kujanová et al., 2018). This zone experiences significant geomorphic change during some monsoon seasons caused by erosion and deposition. It may also be subject to anthropomorphic change such as sand and aggregate extraction (United Nations Environment Programme (UNEP) Global Alert Service, 2014), the construction of flood defences (India Central Water Commission, 2012) and transport infrastructure (Roy, 2021). The Valley Bottom Zone is the relatively flat land that lies between the Active Channel Zone and the Valley Slopes Zone. This zone includes the floodplain and low-lying terraces and is predominantly associated with agricultural and urban land cover. The Valley Slopes Zone comprises the valley sides and is least likely to be influenced directly by river and its geomorphic changes. This zone was included in the analysis to serve as an indicator or large-scale changes in vegetation caused by climatic and socio-economic drivers.

Several sites were selected (Fig. 1) to help understand how and where vegetation cover has changed within and around the river (objective 2) and how humans take advantage of the change (objective 3) within sections of river where geomorphic changes had previously been identified (Vercruysse and Grabowski, 2021). The Goindwal-Sahib site is a stretch of the Beas River near the town of the same name, located in section S4, it showed evidence of channel simplification (reduction in anabranching index) and channel straightening (reduction in channel area without significant change in width). The Zindanpur site is part of S1 of the Sutlej River identified as an area of significant channel narrowing, located on a long right-hand bend in the river a few kilometres downstream of the Ropar Headworks and the city of Rupnagar. The Mau site in S3 of the Sutlej River is about 12 km northwest of the large industrial city of Ludhiana, with evidence of gravel and sand bars becoming vegetated. One further site near Togar on the Sutlej River has been used to visualize vegetation and human responses to geomorphic change, and changes in fluvial risk, relating to the second and third objectives. This site demonstrates the establishment of agriculture in the Active Channel Zone during the last decade, and the creation of new flood defences to protect the banks from further erosion.

2.2. Definition of geomorphic zones

The delineation of the river and surrounding land into geomorphic zones included two steps: (i) identification of the active channel area using multispectral satellite data and (ii) a terrain analysis using a digital surface model (DSM). The boundary between the Active Channel Zone and the Valley Bottom Zone was delineated by the maximum wetted area between 1989 and 2018 as defined by a previous study (Vercruysse and Grabowski, 2021). The latter was calculated by combining the areas of water detected during the post-monsoon season (October–December) in each year. Areas of water were detected by cloud-free remote sensing data from the Landsat 5, 7, or 8 (U.S. Geological Survey, 2021)

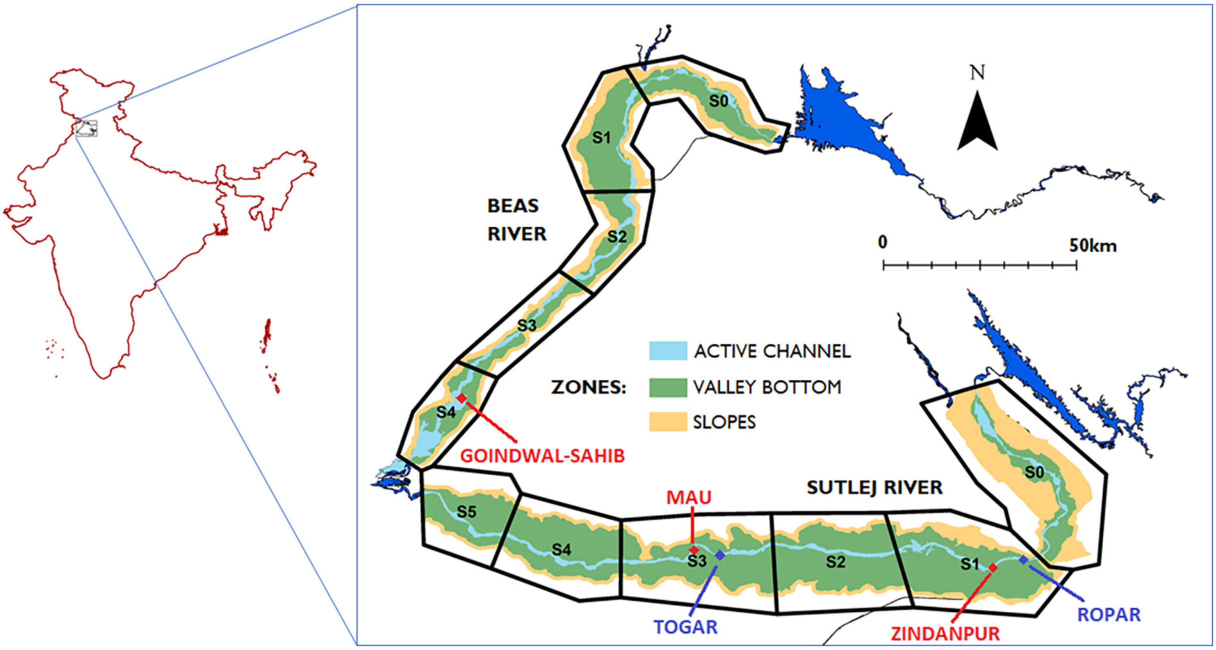

Fig. 1. Study site location in India, including Beas and Sutlej River sections and zones. The names and locations of the sites used for analysis of land cover change are shown in red and those of sites used for illustration only are shown in purple.

multispectral satellites. The modified normalised difference water index (mNDWI), as defined by Eq. (1) (Xu, 2006), was calculated using the green and Short Wave Infra-Red (SWIR) bands B2 and B5 (Landsat 5 and 7) or B3 and B6 (Landsat 8), to derive a season average raster image. A threshold of 0.15 was applied (Vercruysse and Grabowski, 2021), above which the pixels were classified as having a water surface.

$$mNDWI = \frac{(Green - SWIR)}{(Green + SWIR)} \tag{1}$$

The areas classified as water in each year were converted to vector format and manually edited to include all areas of apparent islands and any stray pixels that might represent temporary or permanent bodies of water away from the river (Vercruysse and Grabowski, 2021). The extents of the annual shapefiles were then combined (as a union) to provide a 1989–2018 summary of the maximum extent of the wetted area.

The Valley Bottom Zone was defined as the area between the Active Channel Zone boundary and the inner boundary of the Valley Slopes Zone. In the plains, the valley bottom is very wide in places and the edges are difficult to delineate based on topographical form because of the flat landscape altered by tectonic activity (Bhatt et al., 2008). The delineation was enabled by geomorphon classification (Jasiewicz and Stepinski, 2013) in GRASS GIS (GRASS Development Team, 2020). The method is described and illustrated in detail in the Supplementary information, Section S1 and Fig. S1.

2.3. Inter-annual vegetation trends

Temporal trends and spatial patterns in vegetation cover within and surrounding the river channels (objective 1) were quantified first based on satellite multispectral data using the normalised difference vegetation index (NDVI). This optical remote sensing index provides a measure of the density of photosynthetically active vegetation. It is calculated from the reflectance in wavebands that lie either side of the chlorophyll or 'red' edge (Horler et al., 1983), as shown in Eq. (2). For Landsat these are the Near Infra-Red (NIR) and red channels; B4 and B3 (Landsat 5 and 7) or B5 and B4 (Landsat 8), respectively.

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \tag{2}$$

Winter season Landsat 5, 7 and 8 top of atmosphere (TOA) images between 1989 and 2020 were selected in the Google Earth Engine (GEE) (Gorelick et al., 2017) data catalogue. Data from the winter season (January to March) were selected for the NDVI analysis for two reasons: (i) this period has a high number of cloud-free images, and (ii) the results would not be affected by the early onset or late end of the monsoon season. Landsat 7 images acquired after 2003 suffer from lines of missing data caused by a sensor defect (Kovalskyy and Roy, 2013), Landsat 5 or 8 data were used, when available. TOA data was used after initial analysis found that there was a level shift in the atmosphere-corrected Landsat data between Landsat 5/7 and Landsat 8, which would contribute a false component to the trend analysis. Cloudy pixels were masked by a cloud-likelihood score <40 %, which was calculated by a function provided in GEE (Google Earth Engine, 2021) specifically for the analysis of Landsat data, using a combination of brightness, temperature, and normalised difference snow index (NDSI). NDVI and mNDWI were calculated at each pixel, then averaged across all images to produce an image of winter season mean values. Those pixels with mean mNDWI > 0.15 (water surface) were excluded from the NDVI analysis. For each combination of section and zone, a spatially averaged, mean winter season NDVI was calculated for each year using GEE zonal statistics functions. The resulting NDVI time series were analysed in R (R Core Team, 2019), using the Mann-Kendall test (Kendall, 1975; Mann, 1945) to determine if any trends are statistically significant ($p < 0.05$), and Sen's slope to quantify and compare the strength of the trends (Sen, 1968).

The Valley Slopes Zone was used as a control to isolate trends in NDVI caused by geomorphic change in the river systems from those driven by other factors, such as climate and economic factors. Visual assessment of this zone from high resolution imagery suggested that geomorphic change caused by direct river action was minimal during the 30+ years of study and that any trends in NDVI would be mainly caused by other factors. Prior to trend analysis, the NDVI values in the Active Channel and Valley Bottom Zones were expressed relative to the NDVI in the Valley Slopes Zone, as illustrated in Fig. 2.

2.4. Inter-annual and seasonal land cover trends

The trend analysis conducted with NDVI was replicated using an alternative approach based on supervised classification of land cover. This step was necessary (for objectives 1 and 2) because (i) changes of NDVI can be caused by changes in leaf cover, vegetation density, type or vigour within a pixel (Xue and Su, 2017), (ii) NDVI and mNDWI are not intended to be able to distinguish between sand bars and other types of bare soils and urban landscapes, bridges and infrastructure, and (iii) NDVI-based thresholds for vegetation classification are impacted by drought or heavy rainfall (Rousta et al., 2020).

Using the same Landsat images as the NDVI analysis, land cover classification was performed in GEE using the Gradient Tree Boost (Friedman, 2002) classifier with 10 decision trees. The raw data comprised the blue, green, red, NIR, SWIR1 and SWIR2 channels (bands 1–5 and 7 of Landsat 5/7 and bands 2–7 of Landsat 8). Supervised classification, being less affected by atmospheric conditions than NDVI, could be repeated for all seasons; winter (January to March), pre-monsoon (April to June), monsoon (July to September) and post-monsoon (October to December). As before, the data was averaged over each season using all the available cloud-free images.

The training dataset was created by manual inspection of the visible band colour images for each year of the 32-year record, identifying locations that were invariant in land cover. Five classes were identified: water, sand, other non-vegetated land, vegetated, and densely vegetated (see Supplementary Table S1). Training locations for water and sand were found behind dams and adjacent to bridges. Because of the difficulty in distinguishing bare soil from other sparsely or unvegetated sites, a single class was created for soil, rocks, roads and urban fabric. Vegetation was split across two classes; densely vegetated included areas of established tree plantations, whilst farmed land and permanent grassland was classed as vegetated. There were not enough unambiguous locations to define training points for grassland as a separate class.

The output of the supervised classification process was a stack of 128 raster images of land cover (32 years by 4 seasons), with each pixel assigned to one of the five classes. The accuracy of the classification was assessed using a set of validation locations chosen by the same criteria as, but excluded from, the training set. The results of the accuracy assessment are presented in the Supplementary information, showing that the overall accuracy is in the range of 66 to 76 % with the best performance in the winter and post-monsoon seasons, and for the water (98 % User's Accuracy) and vegetation classes (78–80 % User's Accuracy). Taking each land cover image in turn, the number of pixels within each section and zone were counted by land cover class. These counts were divided by the total pixel count in each area to obtain a fractional land cover for each class, by section and zone.

For comparison with the earlier NDVI trend analysis, cover fractions of vegetated and densely vegetated land (classes 4 and 5) were summed, and winter season results selected. The annual time series was analysed (i) for trend using the Mann-Kendall test and Sen's slope and (ii) for land cover correlation with NDVI. Spearman's rank correlation coefficient, ρ (Spearman, 1904), was selected to assess the degree of correlation, as this makes no assumption that the potential relationship is linear. The *p*-value was calculated for statistical significance at the 95 % confidence interval to reject the null hypothesis that $\rho = 0$.

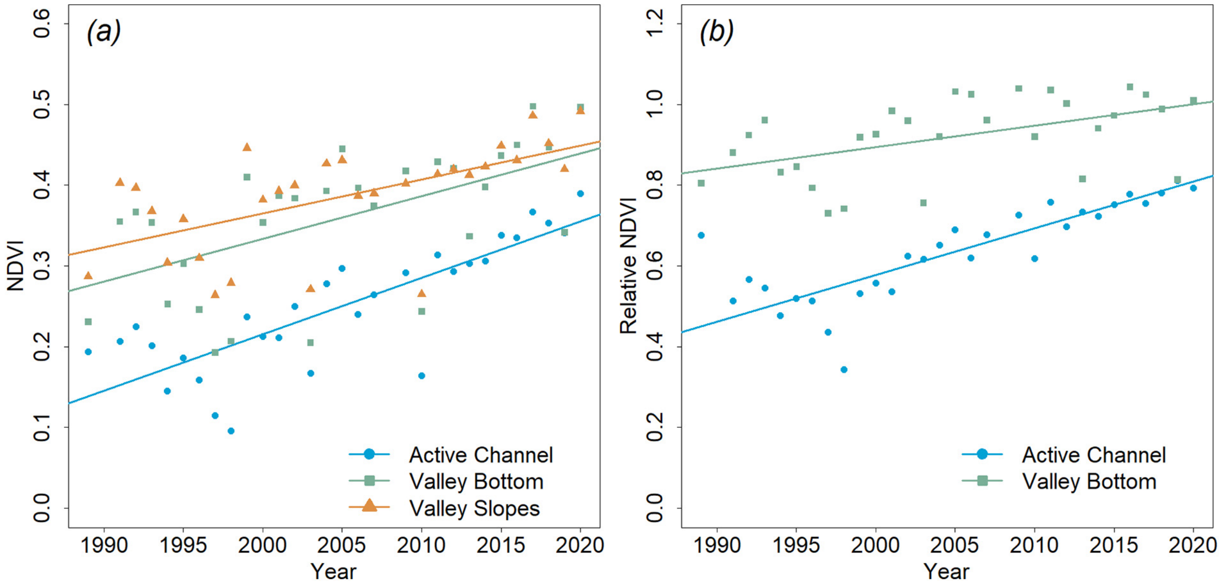

Fig. 2. (a) Time series from 1989 to 2020 of average winter season NDVI, aggregated within the three analysis zones within S0 of the Beas River (immediately below the Pong Dam) and (b) the same data with the NDVI expressed as a proportion of the NDVI in the Valley Slopes Zone, to isolate river influences from climate change and economic drivers. The solid lines are the trends as measured by Sen's slope.

2.5. Land cover transition

To address objective 2 (the river as a key local driver of change) it was necessary to analyse the nature of land cover changes in the active channel zone between two seasons (inter- or intra-annually) and compare to river discharge data. A transition matrix was used to reclassify pixels into transition classes, aggregating them to focus on changes that would have been related to geomorphic change. The new classes were unchanged, erosion (anything changing to water), deposition (water changing to sand of non-vegetated), vegetation destruction (vegetation and dense vegetation to sand or non-vegetated) and greening (water, sand or non-vegetated to vegetated or densely vegetated) (see Supplementary Table S2). The land cover transition analysis was focused on three of the test sites introduced in Section 2.1 where specific examples of geomorphic change had been identified in earlier work (Vercruysse and Grabowski, 2021). Because of the paucity of good, cloud free Landsat images between 1989 and 1993, the analysis starts in 1992 (Goindwal-Sahib and Mau sites) and 1994 (Zindanpur site). The land cover classification maps in 1992/4, 2000, 2010 and 2010 were and overlaid with the change matrix image (within the active channel zone only) for 1992/4 to 2000, 2000 to 2010 and 2010 to 2020 (Fig. 6). The inter-annual increases or decreases in vegetated land cover were calculated (Fig. 8).

2.6. River discharge analysis

Discharges from the Pong and Bhakra dams drive the flow rates in the first section (SO) of both rivers despite some water being used to supply irrigation canals and hydropower. To determine whether the magnitude and type of landcover transition caused by geomorphic change is linked to streamflow and flood events in the rivers, flood frequency analysis (Bedient et al., 2013) was applied to dam release rates between 1985 and 2021. Data pre-2013 were supplied by the Bhakra Beas Management Board (BBMB) for a previous study (Momblanch et al., 2019; Vercruysse and Grabowski, 2021) and BBMB reports and websites were used to obtain more recent data (post 2013) (Bhakra Beas Management Board, 2022, 2021). The range and variability of the discharges were analysed in bar and whisker plots. To identify years of unusually high peak river flows that may cause geomorphic change, each calendar year was classified according to the return period of its peak discharge (1, 2, 5, 10, 25, 50 and 100 years).

3. Results

3.1. Inter-annual vegetation trends

Significant trends in NDVI were detected within the Active Channel Zone from 1989 to 2020, but they differ in magnitude within and between the rivers, as determined by Sen's slope and the Mann-Kendall test (Fig. 3). In the Beas River the NDVI trend becomes weaker with distance from the Pong Dam, whereas in the Sutlej River it becomes strongest further away from the Bhakra Dam. The NDVI increases are almost exclusively within the Active Channel Zone, where subsequent analyses were focused.

Results of the supervised classification of Landsat images confirmed that increasing NDVI in both rivers was caused by increasing vegetation cover. Significant increasing trends in vegetated land cover and decreasing trends in areas of bare sediment were found, though there were differences within and between rivers. In most sections of the Beas River, the increasing vegetation cover was classified as lightly vegetated (e.g., Fig. 4(e)), but in the uppermost section (S0) the trend is towards heavily vegetated cover. Channel area (i.e., water cover fraction) was either stable (S0 and S4) or decreasing in area (S1-S3). Similar trends are seen for the Sutlej River, but the rates of change towards increased vegetation area are greater, and there is a much stronger decreasing trend in channel area, especially in S0-S4 (Fig. 5). Except for two sections, Beas S1 and S3, all others show a significant decreasing trend in the area of sand and other non-vegetated land cover. The concomitant increase in vegetation cover suggests the colonisation of exposed bars by vegetation.

The correlation between NDVI and total vegetated land cover (Spearman's Rank correlation coefficient, ρ, between 0.43 and 0.75) (see Supplementary Fig. S2) indicates that the increase in NDVI is mostly driven by the increase in area vegetated land cover.

3.2. Land cover change analysis

The land cover change analysis for the three targeted sites provides greater insight into the fluvial processes and anthropogenic drivers and responses. Decadal changes aligned with the land cover trends for their

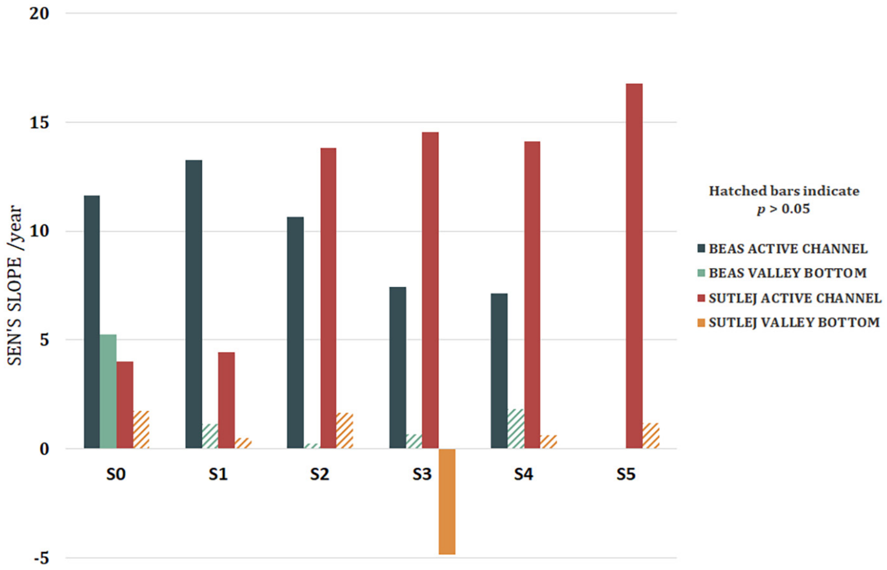

Fig. 3. Magnitude of trends in mean winter season active channel NDVI (relative to slopes zone) in the Beas and Sutlej Rivers from 1989 to 2020, as measured by Sen's slope. The solid bars show that $p \leq 0.05$ by the two-sided Mann-Kendall trend test the trend is statistically significant at the 95 % confidence interval.

respective sections capture the spatial dimension to the land cover changes (Figs. 6 and 7).

The trends are consistent with the NDVI trends previously identified for the rivers and sections containing the sites and in most years there was a greater increase in vegetated land cover than a decrease. There are greater land cover changes overall between 1994 and 1997, at Zindanpur between 2000 and 2003 and at Mau in 2015. Across all three sites, from 2000 to 2017, vegetated area increases consistently exceed the losses. There were some notable exceptions - 1995 (Mau) and 1996 (Goindwal Sahib). At Mau, the period of consistent vegetation increases began earlier, in 1996. In years where there is a significant imbalance in vegetation area increase and loss, this was followed by the opposite imbalance the next year. In particularly where large losses were followed by gains, seen at Goindwal Sahib in 1996/7 and Mau in 1994/5/6. This suggests that there are areas where vegetation could rapidly re-establish within a year following destruction in high discharge conditions.

3.2.1. Goindwal Sahib

At Goindwal-Sahib, which was selected for its evidence of channel simplification and channel straightening (Vercruysse and Grabowski, 2021), there was a statistically significant decrease in sand and water areas, balanced by a large increase in lightly vegetated land cover.

The transition maps (Fig. 6, top) show that between 1992 and 2000 there was dramatic geomorphic change taking place with the creation of a new, shorter channel, though this is still quite meandering. Parts of the old channel have silted up and become vegetated, but the channel still exists. This is consistent with a reduction of vegetation area seen in 1996 (probably the creation of a new channel) followed by an increase in 1997 (parts of old channel being vegetated). A flood frequency analysis of the dam discharges from 1989 to 2018 (see Supplementary information) showed that there was a 1 in 25-year dam release in 1995 followed by a 1 in 10 year in 1996 that are likely agents of this change. The following decade (2000 to 2010) is more geomorphically stable with evidence of vegetation establishment in former channel and sandy areas. Being light vegetation, this is likely to be sparse natural succession or establishment of agriculture or grazing, In the third decade (2010–2020) the main channel has broadened and is less meandering. The relatively high dam discharges in 2011, 2013 and 2015 may have caused this. Further areas of the original channels and the meander loops have become fully vegetated.

3.2.2. Zindanpur

At Zindanpur, which was selected because channel narrowing was detected in a previous study, there were reductions in the areas of water and sand areas balanced with increases in vegetated area, but this time including dense vegetation.

In the first decade (1992–2000) Fig. 6 (middle) shows that there is significant change in land cover in the active channel in this period, but the pattern is complicated. There are significant areas of vegetation loss, probably caused by flooding and erosion, but vegetation has established elsewhere. This period is highly dynamic, geomorphically, and coincided with the very high discharges from the Bhakra Dam. Between 2002 and 2011, by contrast, a more well-defined channel has been eroded and more of the active channel has become vegetated. This process continues in the following decade with the channel showing signs of becoming even narrower and relatively stable in position.

3.2.3. Mau

At Mau, which was selected for its evidence of the establishment of vegetation on areas sand and gravel bars (Vercruysse and Grabowski, 2021), there were, as expected, strong decreasing trends in sand and non-vegetated cover, matched by an increasing trend in light vegetation. The land cover maps show that the active channel featured a large area of sand that may have been deposited by earlier flood events, there having been several very high discharges from the Bhakra Dam before and during this period. The transition maps (Fig. 6) show that, from 1992 to 2010, much of this sand area has become vegetated, with year-on-year gradual increases. This trend seems to have reduced since 2016.

3.3. River discharges

The flood frequency analysis (Supplementary information, Section S5, Table S3 and Fig. S3) shows that, whilst the normal level of peak discharge is similar into the two rivers (800 and 969 m^3/s), the higher discharge events that occur less frequently are at a much higher discharge level in the Beas River than the Sutlej River. The period 1988 to 1998 and the years 2015 and 2019 have high peak discharges in both rivers, but since 1999 there has been a period characterised by few significant flooding events. The Beas River has seen some higher discharges between 2009 and 2015 and the Sutlej in 2015 and 2018, as exceptions to this pattern.

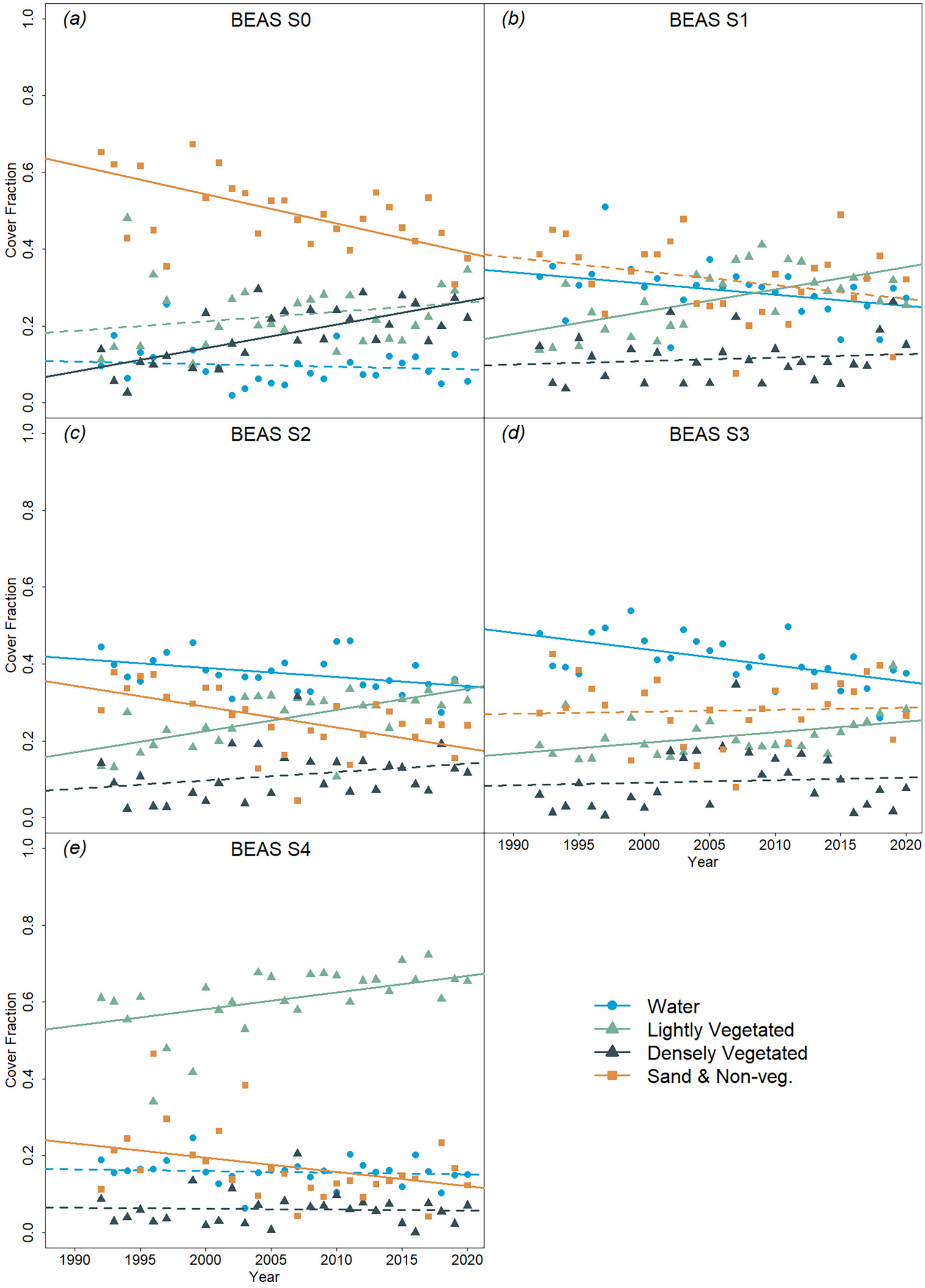

Fig. 4. Beas River, Active Channel Zone land cover fraction trends by section. Each plot shows the data point for each winter season and a trend line based on best fit to the Sen's slope. Solid lines indicate $p \leq 0.05$ and dashed $p > 0.05$.

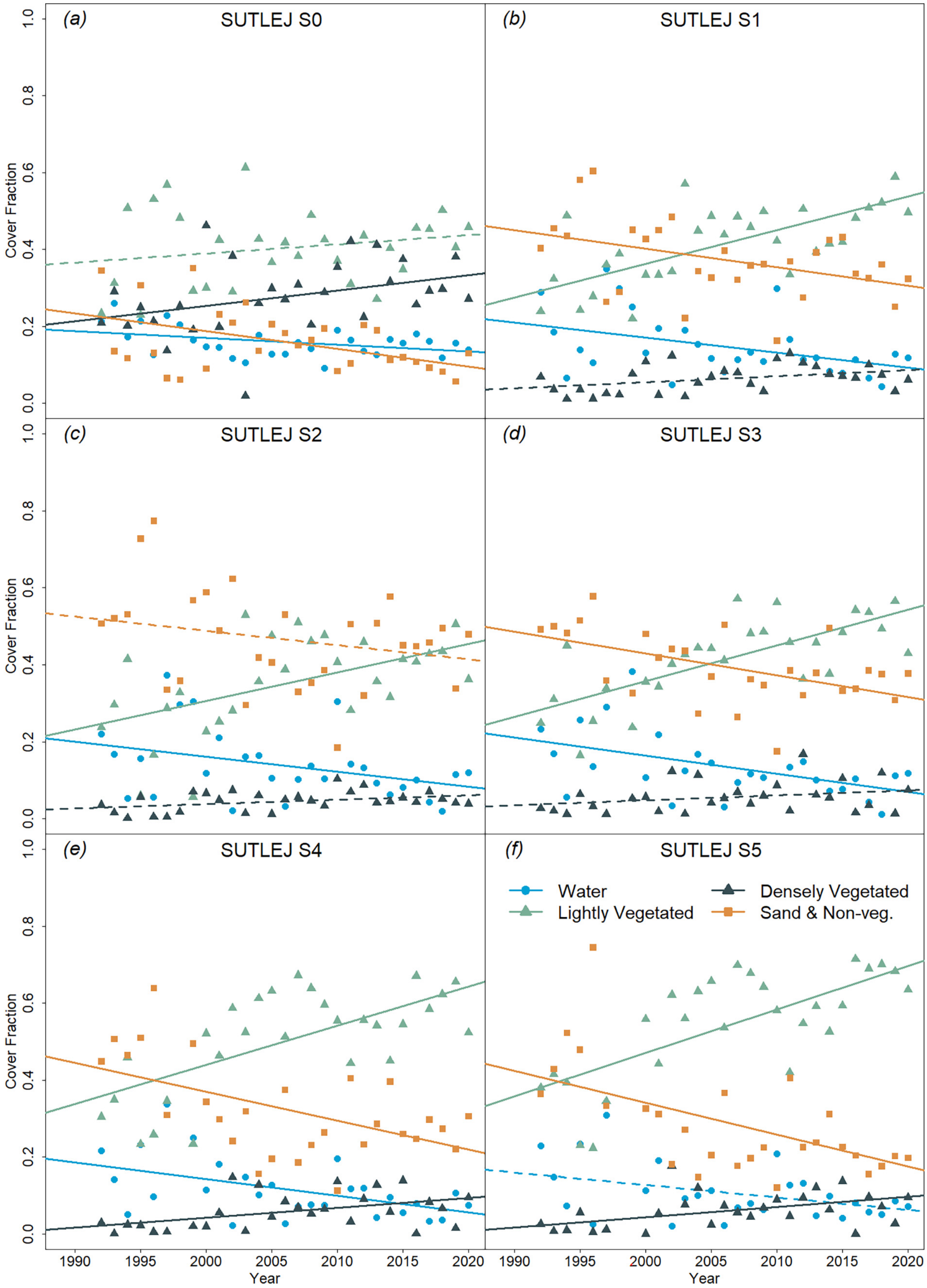

Fig. 5. Sutlej River, Active Channel Zone land cover fraction trends by section. Each plot shows the data point for each winter season and a trend line based on best fit to the Sen's slope. Solid lines indicate $p \leq 0.05$ and dashed $p > 0.05$.

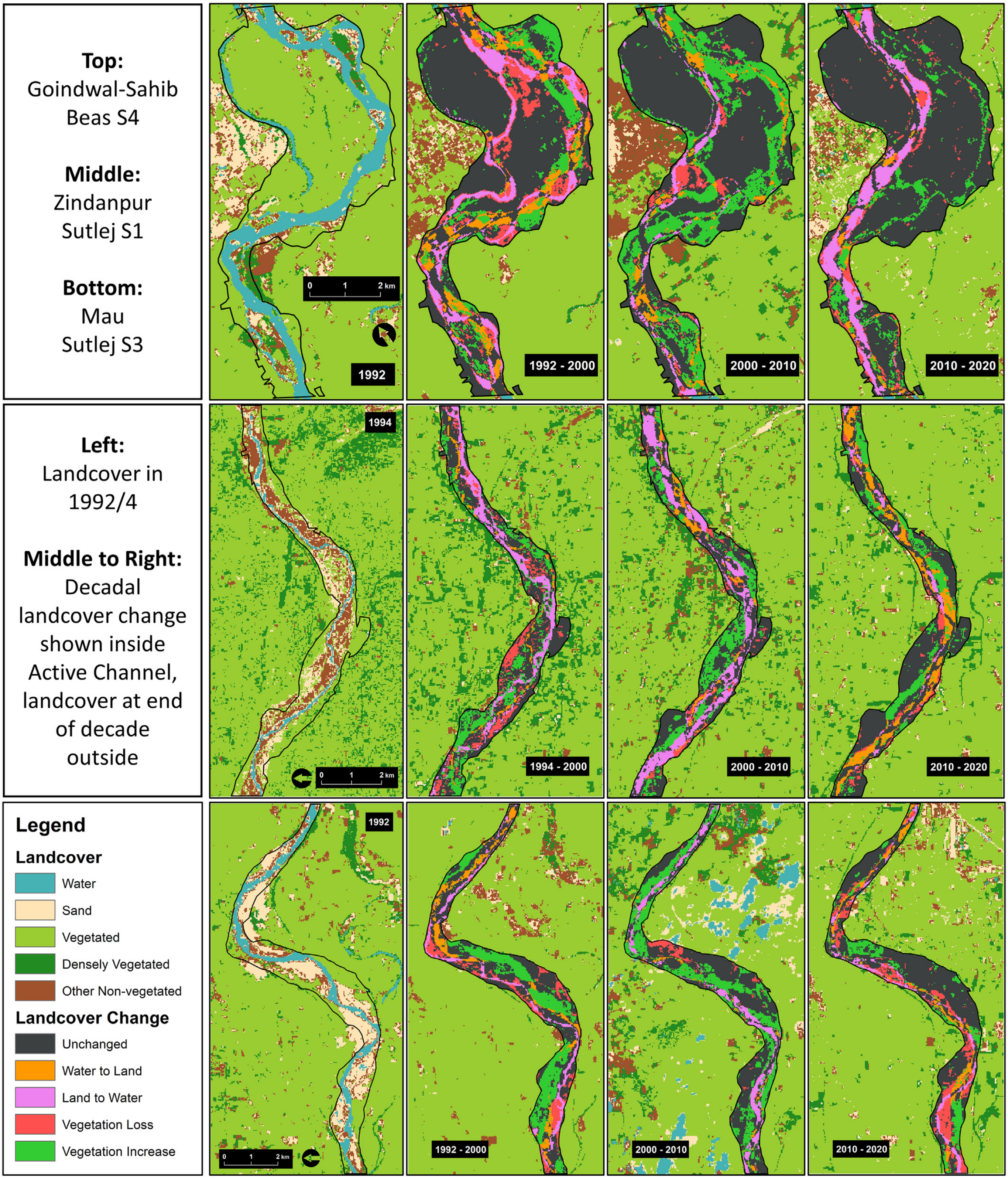

Fig. 6. Land cover transition maps for the three example sites Goindwal-Sahib (top), Zindanpur (middle) and Mau (bottom). Each group shows, first, the land cover map in 1992 or 1994 followed by the land cover transition maps over (approximately) three decades up to 2020. The transition map is shown only inside the active channel zone (outlined in black) overlaid on the land cover map for 2000, 2010 or 2020.

4. Discussion

This study aimed to determine how river-associated vegetation communities respond to human alterations to river flows and riparian land management to affect geomorphic form, dynamics, and risks to humans in the lower reaches of the Himalayan Sutlej and Beas Rivers. This aim was addressed by a temporal and spatial analysis of NDVI and supervised classification of land cover from remote sensing satellite data over a period

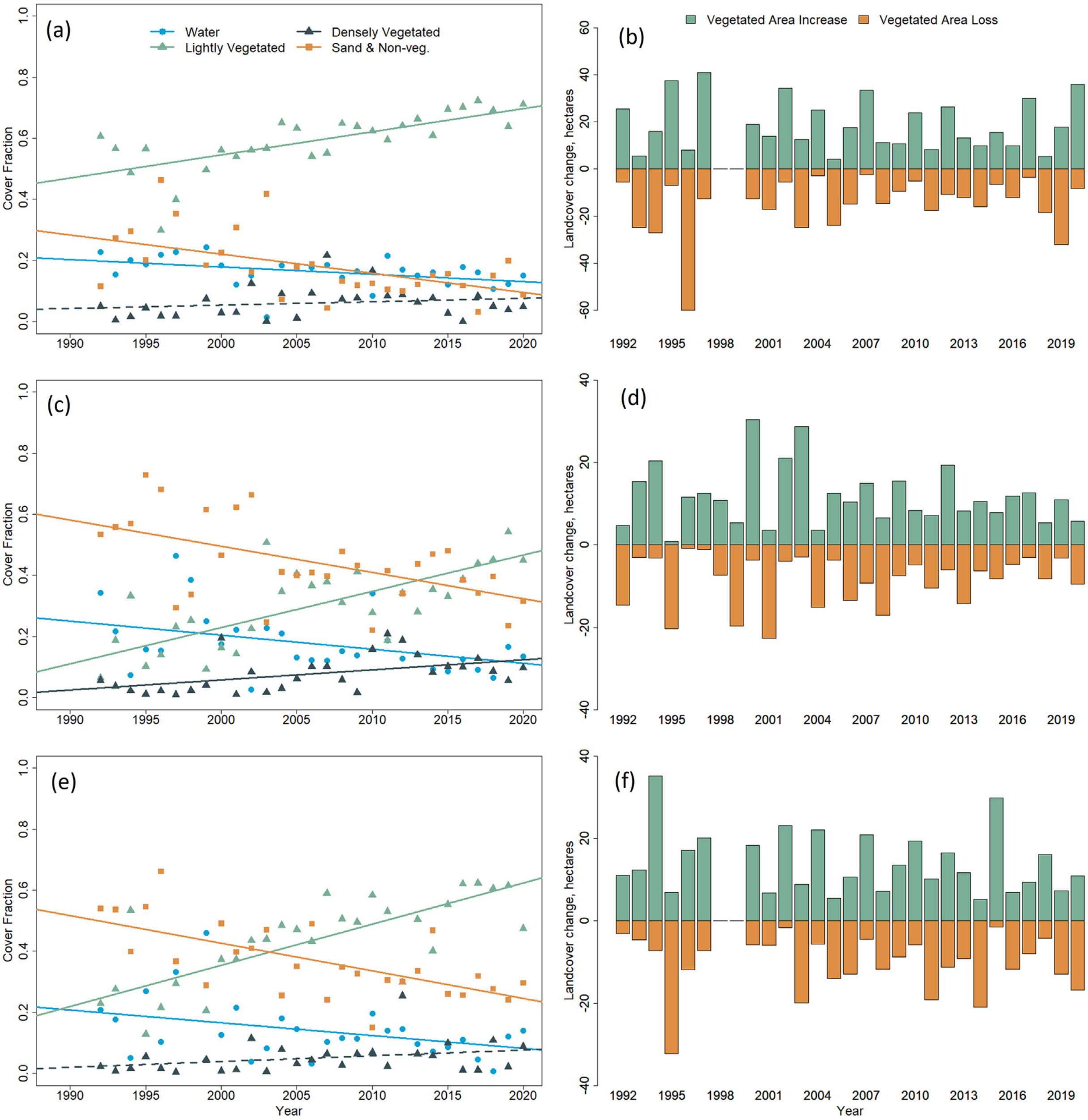

Fig. 7. Land cover transition trends for the three example sites Goindwal-Sahib (a, b), Zindanpur (c, d) and Mau (e, f). For each site: (a, c, e) land cover fraction trends in winter season (trend lines based on best fit to the Sen's slope, solid lines indicate $p \leq 0.05$ and dashed $p > 0.05$) and (b, d, f) changes to vegetation area in hectares to next winter season.

of over 30 years, which identified significant long-term trends, periods of geomorphic activity and inactivity, and spatial patterns in vegetation cover that relate to land cover upstream, local, and global anthropocentric factors as drivers and risks.

The first main finding is that there are significant increasing trends in in NDVI linked to changes in vegetation land cover within all geomorphic zones in both rivers (Fig. 2), albeit with different spatial patterns (Fig. 3). Previous studies have reported that, in the Beas floodplain, from 1989 to 2015, there was a 5 % increase in agricultural land area and a 49 % increase in plantation area (Brar et al., 2020). In the Sutlej floodplain, between 1975 and 2011, 85 % of barren and wetland areas were replaced by agriculture and 77 % of water areas were transformed to agriculture or other vegetation (Kaur and Brar, 2013). Regional and global factors may explain why the trend towards agricultural and plantation land use is observed across the hillslopes, valley bottoms and river channels. The factors are likely to include economics, for example, the high demand and availability of markets for crops (Zhu et al., 2016) because of population growth, and improvements and greater efficiency in crop cultivation (Dutta, 2012). Climate change could also be having a positive effect in creating favourable growth conditions through the availability of water from rainfall or melting of ice, changes in temperature or the fertilisation effect of higher levels of CO_2 in the atmosphere (Kelly and Goulden, 2008; Momblanch et al., 2020; Zhu et al., 2016).

The strength of the NDVI and vegetation cover trends are much greater in the Active Channel and Valley Bottom geomorphic zones compared to the Valley Slopes Zone (Figs. 3, 4 & 5), consistent with the reductions in water area and wetlands found in earlier studies (Brar et al., 2020; Kaur and Brar, 2013). This is evidence for changes in the river influenced by upstream factors, the most obvious of which are the large, valley-spanning Pong and Bhakra Dams. These dams differ in their discharge statistics, which may explain the substantial differences seen between the two rivers in the spatial dimensions of the vegetation community dynamics. The impacts of the dams would include reduced sediment transport, diversion of water for irrigation or hydropower (Poff et al., 2007), frequency and timing of inundation, water table depth, mean water levels, erosion, and deposition, all of which would affect the condition and spatial distribution of vegetation biomass in the active channel or floodplain vegetation through hydrological and geomorphic processes (Fryirs, 2017; Mertes et al., 1995; Micheli and Kirchner, 2002; Tockner and Stanford, 2002). The river sections immediately downstream of the Pong and Bhakra Dams (Sections S0) and the Ropar Headworks (Sutlej S1) show a significant decreasing trend in sand and gravel area - this was an especially strong observation in S0 of the Beas River (Figs. 4 & 5). Sediment is captured by dams and barrages such that the water downstream has a significantly lower sediment load than elsewhere, reducing the rate of deposition processes (Brandt, 2000; Grabowski et al., 2022; Grant et al., 2013; Kondolf, 1997).

Increasing NDVI trends in the active channel are correlated with increases in vegetated land cover (Supplementary Fig. S2), within former areas of water, sand and gravel (Caponi et al., 2019; Friedman et al., 1998). Previous work supports this by highlighting the simplification of river planform - width reduction and incision, reduced anabranching (fewer channels), channel straightening and channel migration - caused by a decrease in the annual maximum daily discharge (Vercruysse and Grabowski, 2021). The simplification (i) reduces the river channel area, leading to (ii) areas of sand and gravel becoming more geomorphically stable, enabling (iii) establishment of riparian vegetation on these areas and later (iv) some of the land being adopted for farming. This is illustrated in Fig. 8 for a part of Sutlej River S1, where large areas of former active channel have become farmed between 2003 and 2020, with only very small losses.

The magnitude of the increasing NDVI trend has a different spatial pattern in the two rivers; in the Beas River, the trends decrease from a high magnitude towards a greater fraction of lightly vegetated land (probably agriculture) in S1 to smaller trends further downstream (Fig. 3). By contrast, in the Sutlej River, the trends start relatively weak but increase significantly downstream. Furthermore, in S4 and S5 there are statistically significant increasing trends in the proportion of densely vegetated land (Fig. 4), which contrasts with the similar sections of the Beas (Fig. 5). A possible explanation would be the increasing importance of local factors, perhaps leading to the establishment of tree plantations, crops that have a high cover fraction or high vigour, or areas of grazing. This longitudinal variance between rivers suggests a difference in the timing of impact of upstream drivers (Alldredge and Moore, 2014; Nilsson and Jansson, 1995). Recent changes in dam releases seem to have affected the upstream section of the Beas more than the Sutlej, consistent with earlier work that suggested that the Sutlej had already responded geomorphically to the construction of the Bhakra Dam (Vercruysse and Grabowski, 2021). Relatively high magnitude releases from the Pong Dam on the Beas River (Supplementary Table S3) have kept this river system more dynamic, but vegetation has encroached greatly during the period where peak discharges were relatively low. By contrast, the Sutlej experienced greatest NDVI increases in its section furthest downstream, which may reflect the reduction in influence of the Bhakra Dam with distance and impacts on water level from the proximity of the confluence with the Beas River (Leite Ribeiro et al., 2012). The existence of historic flood defences that are now some distance from the main channels (as seen in Fig. 8) confirms that there has been a consistent trend towards channel narrowing in the Sutlej.

The sections immediately below the dams (S0) are less typical of the overall NDVI trends because of their topography, being slightly above the flat plains of Punjab and in a less agricultural area (Fig. 3). In both rivers, there is a statistically significant trend ($p < 0.05$) from sand and non-vegetated cover to densely vegetated (Figs. 4(a) and 5(a)). This is consistent with findings of an earlier study (Vercruysse and Grabowski, 2021) that identified a reduction in the area of gravel bars, and the probable natural succession of herbaceous plans and shrubs to trees in a less dynamic gravel/cobble bed braided river (Gurnell et al., 2012).

The high-resolution mapping of land cover transitions at three sites on the rivers provides a greater detail on the processes driving local vegetation change. In all three sites, large tracts of land have converted to vegetation, corresponding to former side channels or courses of the main channel (Fig. 6). The simplification of river planform and narrowing of the geomorphic-active zone is driven by the upstream drivers but materializes in the spatial context of the reach. Lower sections of the Beas (S1 to S3) show trends from water to lightly vegetated cover, probably caused by the establishment of agricultural crops (Fig. 7). In the rabi season (November to May) the main crop in the plains is wheat and barley, and in the kharif crop season (May to December) maize, pulses (kidney gram), sugar cane (Das, 2017), but in the Active Channel Zone some seasonal crops may be grown such as vegetables (Kumari et al., 2018), mustard, wheat and fodder crops. Vegetation establishment, the construction of new bank defences alongside new farmland and settlements, and the building of roads, bridges and other infrastructure, together resist a switch back to the original braided or wandering planform. This is also likely to lead to channel incision, but we have no direct evidence for that in this study.

Finally, at a local level geomorphic changes in the river channel will directly impact the proportion of land that is vegetated, bare or under water. Sand and aggregate extraction (Hackney et al., 2020; Koehnken et al., 2020; Koehnken and Rintoul, 2018) is a significant anthropomorphic agent of change. There continues to be significant activity in the Sutlej River (Supplementary Fig. S4), Though this is no longer licensed in the Beas River to protect the native dolphin, there are reports that illegal activities still take place (Kalota et al., 2019). The extraction process often involves constraining and diverting the active channel with levees, the consequence of which may be incision and lateral movement of the channel. The channel may not return to its original planform. The continual removal of sand will reduce the rivers sediment load and create more erosion, and less deposition downstream. Sand mining can lead to geomorphic change by these mechanisms.

The significant increasing trends in vegetation cover in the Sutlej and Beas Rivers are driven by global and upstream drivers (climate change, dam operations, water abstraction), which has created new terrestrial habitats and resources for human exploitation. High resolution imagery clearly shows where people have taken advantage of new land for agricultural purposes (Fig. 8). However, the vegetation encroachment into the former active channels has two significant implications for people and infrastructure.

First, whilst the Sutlej and Beas Rivers are predominantly single thread meandering rivers over most of the study area currently, early Landsat imagery show the existence of wide active channels. These wide channels with exposed gravel suggest that the rivers were previously gravel-bar braided or meandering. This observation is supported by visual evidence of flood embankments over 1 km wide along much of the length of the Sutlej (Fig. 8). Planform change has made new land available for farming inside the historical flood embankments. Agriculture has established in former channel areas, rather than the expected natural colonisation by plant species, perhaps indicating economic pressures to increase the area of farmed land and take advantage of newly available, fertile areas, with good ground water supply. Changes to the flow regime have impacted natural vegetation communities and the resources they provide (e.g., timber, fuel, food) and traditional agricultural practices, like flood-recession farming (Richter et al., 2010). Whilst new opportunities for resource exploitation have been created there are new risks to infrastructure. The substantial increase in observations of aggregate mining could be related to these geomorphic changes or reflect increased demand locally.

Secondly, the trapping of sediment by the dam results in sediment starvation and reduction in peak flows, leading typically to the observed narrowing of the river channel (Nelson et al., 2013; Vercruysse and Grabowski, 2021), with risk of incision and lateral erosion, putting at risk some of the newly farmed areas. Aggregate mining can also lead to channel incision, not only at the site of the extraction but propagating upstream many kilometres as knickpoint retreat (Kondolf, 1997; Rinaldi et al., 2005). This study has identified the consequences in the form of changes in the main sites of erosion and deposition from the gravel bed of the previously braided system, to the outside of meander bends (Brandt, 2000;

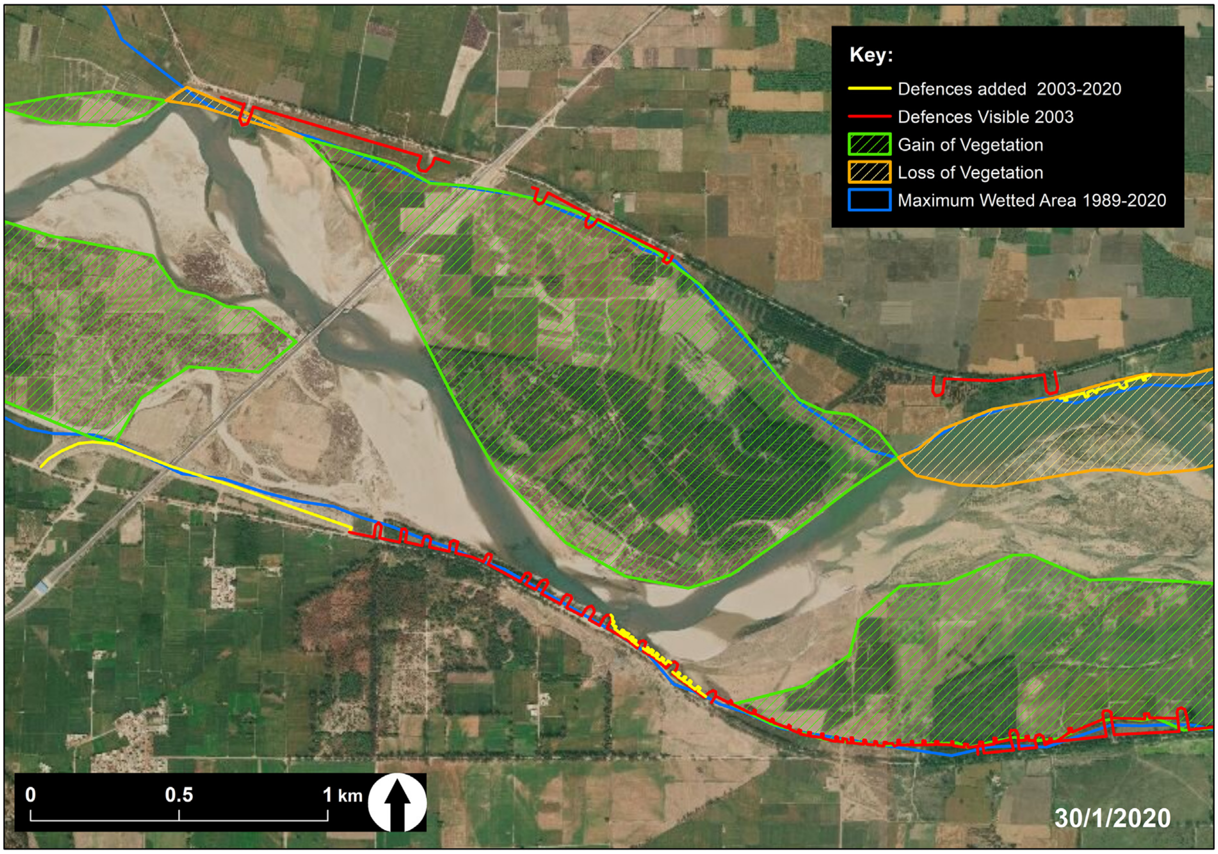

Fig. 8. Illustration of channel narrowing at a site on the Sutlej River in S1 near Togar. The satellite image is from 2020, on which are marked the marked the changes in areas of vegetation when compared to the earliest available high resolution satellite image, taken in 2003. Gains in vegetated area are shown in green hatching, which are much greater in areas than those lost (in orange hatching). Flood defences of some age are visible alongside roads, these are shown in red, but additional defences were added between 2003 and 2020 as shown in yellow. The bridge and associated earthworks were constructed between the dates of the two images. Image is copyright Maxar Corporation.

Grant et al., 2013; Sundborg, 1956). New flood defences continue to be deployed in such areas of rapid erosion, as seen in Fig. 8, some of which are to protect farmland that is relatively recently established within the Active Channel Zone.

5. Conclusions

This study highlights that vegetation in river corridors responding to a combination of natural and anthropogenic drivers operating locally, globally and upstream can create new resources and risks for communities and infrastructure. The last 30+ years has seen a significant increase in vegetated landcover across the lower Beas and Sutlej catchments, indicative of global drivers of change. Greater increases seen in the active channels are in response to geomorphic change caused by upstream and local drivers. The vegetation establishment and succession are facilitated by channel narrowing, and simplification in the lower Beas and Sutlej Rivers, though the location and scale of those changes relate to differences in the operations of the two valley-spanning dams that control discharge in these systems. These changes are reinforced by local river management, vegetation recruitment and succession, and conversion to agriculture, which contributes to changing geomorphic dynamics, the river-related resources they provide and the risks they pose.

The study created a novel dataset on vegetation cover along two main rivers draining the Western Himalayas, which was analysed within a geomorphic framework to interpret the impact of different drivers. The findings confirm previously-reported observations on vegetation change on rivers in other regions, but highlight the pronounced response in the active channel related to hydrological alterations and local land use in the Himalayan region. A key contribution from the research is the robust evidence for local trade-offs caused by interactions between the established vegetation and river processes. Both rivers changed in planform from braided to single thread meandering, which has allowed new areas to be colonised by vegetation and exploited for farming. However, the vegetation is stabilizing the former river bed and reinforcing the new meandering planform, which places historically-protected communities and infrastructure at risk from bank erosion.

The shifts in vegetation cover provide insights into the social and geomorphic response of these Himalayan rivers to regulation and development. The understanding gained through this study is transferable to many similar systems. The Beas and Sutlej Rivers share many characteristics with other regulated river systems in areas of rapid economic and population growth, where human pressures are adding to global impacts of climate change. These results will help inform future policy to address the sustainable development goals.

CRediT authorship contribution statement

John Beale: Methodology, Software, Validation, Formal analysis, Visualization, Writing - Original draft preparation. **Robert Grabowski:** Conceptualization, Writing - Review & editing, Supervision, Project Administration, Funding acquisition. **Pauline Long'or Lokidor:** Investigation, Methodology, Writing - Review & editing. **Kim Vercyusse:** Methodology, Conceptualization, Supervision, Data curation, Writing - Review & editing. **Daniel Simms:** Supervision, Writing - Review & editing.

Data availability

Data access and a link for processed outputs are explained in the acknowledgements section.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.157826.

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