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Creating a catchment perspective for river restoration

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Abstract

One of the major challenges in river restoration is to identify the natural fluvial landscape in catchments with a long history of river control. Intensive land use on valley floors often predates the earliest remote sensing: levees, dikes, dams, and other structures alter valley-floor morphology, river channels and flow regimes. Consequently, morphological patterns indicative of the fluvial landscape including multiple channels, extensive floodplains, wetlands, and fluvial-riparian and tributary-confluence dynamics can be obscured, and information to develop appropriate and cost effective river restoration strategies can be unavailable. This is the case in the Pas River catchment in northern Spain (650 km^2), in which land use and development have obscured the natural fluvial landscape in many parts of the basin. To address this issue we coupled general principles of hydro-geomorphic processes with computer tools to characterize the fluvial landscape. Using a 5-m digital elevation model, valley-floor surfaces were mapped according to elevation above the channel and proximity to key geomorphic processes. The predicted fluvial landscape is patchily distributed according to topography, valley morphology, river network structure, and fan and terrace landforms. The vast majority of the fluvial landscape in the main segments of the Pas River catchment is presently masked by human infrastructure, with only 15% not impacted by river control structures and development. The reconstructed fluvial landscape provides a catchment scale context to support restoration planning, in which areas of potential ecological productivity and diversity could be targeted for in-channel, floodplain and riparian restoration projects.

1 Introduction

There is a growing consensus that a catchment scale perspective that encompasses the complete fluvial landscape is critical for successful river restoration (Logan and Furze, 2002; Bannister et al., 2005; Kondolf et al., 2006; Nilsson et al., 2007). The fluvial landscape includes the physical and biological features created by interacting fluvial, terrestrial, and ecological processes. It includes all the surface landforms and biologic communities that affect and are affected by the flow of water, sediment and organic materials through the network of river corridors including active and former river and side channels, off-channel water bodies, wetlands, floodplains, terraces, and riparian vegetation (Fausch et al., 2002; Ward et al., 2002' Nakamura, 2006, Benda et al., 2004a) and subsurface patterns of hyporheic flow and associated organisms (Poole et al., 2006).

River restoration planning, design and implementation (levee removal, channel engineering, placement of in stream structures, planting riparian vegetation, etc.) necessarily and typically occur at the scale of individual channel reaches (100–1000 m) (Rosgen, 1996; Wohl et al., 2005). However, local restoration projects can be more effective if they are designed using a catchment (fluvial landscape) context to strategically place them for the greatest ecological benefit (Gilvear and Casas, 2005). A catchment scale context also provides a larger frame of reference for smaller scale projects, such as how valley topography, river network structure and sediment supply influence the distribution of habitats and how those landscape factors affect restoration projects (positively or negatively). Restoration activities within the framework of a catchment perspective can target meso-scale habitats such as large floodplains and islands (Jahnig et al., 2010) and can include measures such as levee pullback, re-meandering, flood embankment removal, buffer strip creation, reconnection of side channels, and wetland development (Gilvear and Casas, 2008).

Developing a catchment scale perspective for river restoration requires a "guiding ecological image" (Palmer et al., 2005): a spatially explicit quantitative and qualitative description of the fluvial landscape. Variation in river discharge in combination with variable river morphology is the primary driver that creates the fluvial landscape. Aquatic and riparian communities have evolved to capitalize on both seasonal variations in flow and on the landforms and habitat features created by periodic large floods (Poff et al., 1997). The processes and landforms that form the fluvial landscape vary with location in a catchment governed by valley topography, river network structure, and the area inundated by flood flows (Frissel and Nawa, 1992; Reeves et al., 1995; Naiman et al., 1992; Benda et al., 2004). The fluvial landscape is thus a dynamic entity, formed and altered over time by the storms and floods that bring water, sediment and organic material downslope and downstream from all points in a watershed.

Recognizing and characterizing the features and processes that form the fluvial landscape is a critical step in creating a catchment scale perspective and in forming a guiding ecological image of a river system. Regulation of discharge with dams and weirs, hardening of channel banks with revetments, construction of dikes and levees, dredging of channels, and draining of wetlands have individually, and in concert, acted to eliminate or obscure evidence of the fluvial landscape (Sedell and Luchessa, 1981; Logan and Furze, 2002; Ward et al., 2002). These activities have reduced in-channel and off-channel habitats important to many aquatic species, reduced the renewal of sediment reservoirs important to riparian species, and altered the riparian groundwater and hyporheic flow systems.

Thus, design of a river-restoration strategy requires two important steps: (1) recognizing the spatial and temporal characteristics of the fluvial landscape, unique to some degree for every river system, that govern geomorphic and ecosystem interactions, and (2) recognizing human alterations to the fluvial system and the consequences for geomorphic and ecological processes. Although information from satellite imagery, aerial photography, field surveys, and data on land use and local biology can inform descriptions of fluvial landscapes, information on a reference condition may not be available in catchments with extensive and long-term human development.

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Our goal is to show how hydro-geomorphic principles coupled with available computer analysis tools can characterize fluvial landscapes in catchments where they have been mostly obscured by extensive land use. We apply our approach to the Pas River basin (650 km^2), located in the Cantabria Region of Northern Spain, that has a long history of land development extending back to the 17th century; river control structures include 50 bridges, 24 weirs and minor dams (<10 m), and more than 120 engineered works (levees and dikes) for flood protection and urban development (GESHA, 2005a).

For our analysis we used available topographic data with the analysis toolset "NetMap" (www.netmaptools.org) to examine relationships among valley geometry, river-network structure, landforms, and the potential for channel-floodplain and confluence interactions. We used 2010 satellite imagery to map the current extent of the fluvial landscape in the Pas River catchment and to estimate the degree to which riverine processes are presently constrained by human land use.

Thus, our objectives include: (1) reconstructing the natural fluvial landscape in the Pas River catchment; (2) evaluating how the fluvial landscape is created and influenced by topography, valley morphology, river network structure and other geomorphic processes; (3) contrasting the current, regulated fluvial landscape with the natural fluvial landscape that we infer from our analysis; and (4) describe how our analysis can provide a catchment scale context for restoration planning, including identifying a provisional set of fluvial landscape "hotspots".

2 Study area

The Pas River catchment (650 km^2) is located in the province of Cantabria, northern Spain, and drains northwards to the Atlantic Ocean (Fig. 1). The Pas River is flanked by the Escudo Mountain Range (1328 m) on the west, the Castro Valnera Massif (1718 m) on the south and the Sopeña Mountain Range and Las Enguinzas Massif on the east (1240 m and 964 m, respectively). The La Dehesa and Fuentellano Mountain Range (1238 m) divides the main Pas and Pisueña tributaries (West and East Forks), while

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the Escudo de Cabuérniga Mountain Range constrains both West and East Forks at about 20 km from the river mouth (Fig. 1). Sandstones, conglomerates and shales dominate within the Escudo the Escudo de Cabuérniga Mountain Range. Lower cretaceous limestone mixed with sandstone is also present in the Castro Valnera Massif, and dominates in the Las Enguinzas Massif (IGME, 1989).

The Pas River catchment has a humid temperate climate with an average annual temperature and precipitation ranging from 14 °C to 8 °C and from 1200 mm to 2500 mm from the coast to mountains. Snow is common from late autumn to early spring above 1000 m. Rainfall is regularly distributed throughout the year with maximums in winter and spring. Mean annual flow in the Pas River basin is 15.4 $m^3 s^{-1}$, with the largest spates concentrated between November and April (mean annual maximum flow is 215 $m^3 s^{-1}$) and dry periods from August to November (mean annual maximum flow is 1.6 $m^3 s^{-1}$; GESHA, 2005b).

The coastal forest, below 400 m, is mainly composed of ashes (*Fraxinus excelsior*), limes (*Tilia* sp.), hazelnuts (*Corylus avellana*), maples (*Acer* sp.), oaks (*Quercus* sp.), poplars (*Populus* sp.) and holm oaks (*Quercus ilex*). Currently, eucalyptus plantations (*Eucalyptus globulus*) and pastures dominate the coastal area. Vegetation between 400 to 1100 m includes oaks (*Quercus robur* and *Q. petrae*) dominating on the southern slopes and beeches (*Fagus sylvatica*) and holly trees (*Ilex aquifolium*) on the northern slopes. This vegetation belt has also been highly modified by pasture land. Higher in the catchment (1100 to 1800 m) vegetation is dominated by birches (*Betula* sp.), shrubs (*Genista* sp., *Erica* sp. and *Ulex* sp.) and mountain grasslands.

The riparian vegetation is dominated by oceanic alder groves (*Alnus glutinosa*) from sea level up to 700 m (Lara et al., 2004). Willow groves (*Salix atrocinerea*) replace alder groves when they deteriorate, or where soils are not deep enough or there are large flow fluctuations. Higher in altitude, alder groves are replaced by *F. excelsior* or by Hazelnuts (*C. avellana*). In controlled river environments or in areas impacted by human activities, riparian vegetation is usually dominated by *Rubus* sp., *Rosa* sp., *Crataegus monogyna*, *Prunus spinosa* or even pasture.

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Human settlements in the Pas River catchment began during the upper Paleolithic (40 000–10 000 BP), evidenced by cave paintings from Monte Castillo. Beginning in the 16th century, population densities increased along with numerous land use modifications (Delgado, 2003). Human population density rapidly increased during the 17th and 18th centuries in the main villages of the catchment with a concurrent increase in pasture land for cattle (Delgado, 2003). During this period deforestation was used to create pasture land but also to supply fire wood to the iron industry (Alcala-Zamora, 2006). More recently, Eucalyptus and pine forestry, urban developments, flood protection and the need for water supply have modified the fluvial landscape of the Pas River, involving more than 55 bridges, 24 weirs and low-dams (<10 m), 124 engineered works (e.g., levees) and 20 water intakes within the catchment (GESHA, 2005a).

The Pas River maintains a small population of Atlantic salmon (*Salmo salar*) in the southern most extent of that species range, although the fish has a threatened status (Garcia de Jalon, 1997). Other species include Brown Trout (*Salmo trutta*), minnow (*Phoxinus bigerri,*) with Allis shad (*Alosa Alosa*), Barbo di Graells (*Luciobarbus graellsii*), Parachondostroma (*Parachondrostoma miegii*) found in the lower parts of the catchment (Doadrio, 2001). Other estuarine fish species that also enter the fluvial freshwater habitat in the Pas River are European flounder (*Platichthys flesus*) and Thicklip grey mullet (*Chelon labrosus*).

3 The fluvial landscape and general principles of hydro-geomorphic processes

We define the fluvial landscape as that part of the valley floor that is periodically inundated and it can include channels (single and multiple), floodplains, wetlands, and low terraces. The fluvial landscape is characterized by channel floodplain, fluvial-riparian and tributary to tributary (via confluence) interactions. General principles of hydro-geomorphic processes, universal in catchments, can inform the analysis of the fluvial landscape in controlled riverine environments where dikes, levees, and in-channel structures have altered or obscured it. We focus on network-scale processes and

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landforms, those most likely to be detected using computer tools in conjunction with remotely sensed information (e.g., digital elevation models, aerial photography, and satellite imagery). The general principles of hydro-geomorphic processes relevant to the Pas River cover five domains including: (1) valley geometry; (2) river network structure, including spatially variable sediment supply; (3) hillslope and fan/terrace forcing; (4) river longitudinal profile and fluvial morphology; and (5) riverine-estuarine fluvial environments. A brief description of each of these is provided in turn.

3.1 Valley geometry

Geologic controls and major slope movements can create variations in valley width and shape. Constrained (narrow) valleys typically lack sediment storage while unconstrained (wide) valley segments act as storage reservoirs of alluvial sediment, often creating wide, more complex floodplains within the fluvial landscape (Grant and Swanson, 1995; McDowell, 2001). At the upstream transition from unconstrained to constrained valley segments, a bottleneck in the transfer of sediment can occur, often enhanced by logjams. Increased sediment storage at the transition promotes heightened connectivity between channels and adjacent valley floors. The transition from unconstrained to constrained segments also enhances hyporheic downwelling (Edwards, 1998). At the downstream transition from constrained to unconstrained valley segments, increased sediment deposition, flow divergence, and hyporheic upwelling can occur (Edwards, 1998). Thus, there is typically greater channel-valley connectivity and hence larger fluvial landscapes immediately above and below valley constrictions, with increased occurrence of floodplains, side channels, and riverine wetlands (Baxter, 2001). Alternating constrained and unconstrained river segments promote patchy heterogeneity in fluvial processes and riparian environments, a pattern often referred to as a “string of pearls” (Standford and Ward, 1988).

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3.2 River network structure, confluences and sediment supply

Channel confluences juxtapose two separate flow and sediment supply regimes, with effects on channel and valley-floor morphology, water temperature, and water chemistry. Input of sediment from a tributary channel can result in locally heightened sediment storage near the confluence resulting in reduced elevation differences between channels and adjacent valley floors, leading to development of large floodplains, side channels, wetlands, and increased hyporheic flow and therefore an enlarged fluvial landscape (Grant and Swanson, 1995; Benda et al., 2004a). Other morphological changes observed at channel junctions include finer channel substrate, higher width-depth ratios, pool formation, and increased meandering and braiding (Best, 1988; Church, 1983). Attendant changes in aquatic biota include increased animal and plant productivity and diversity (Rice et al., 2001; Kiffney et al., 2006). Alluvial and debris-flow deposition at confluences is highly episodic, and the morphological (and ecological) imprints on valleys (e.g., floodplains, side channels, low terraces higher biotic diversity), wax and wane over time due to the stochastic interactions of storms, floods, fires, and other perturbations (Benda et al., 2004a).

A large river system contains hundreds of channel confluences, involving a wide range of tributary and receiving channel sizes and inter-tributary spacing. Factors that are important when examining the role of tributaries, via confluences, on rivers include the basin shape and geometric structure of the river network that govern the size of the tributary relative to the size of the receiving channel, inter-confluence distances and the spatial frequency of confluences along channels, planform morphology of intersecting streams (tributaries running parallel or intersecting at right angles), erosion regime of the tributary channel, and stochastic aspects of erosion and sediment supply (Benda et al., 2004a; Rice et al., 2008). Spatial patterns of confluences strongly influence the upstream and downstream transfer of abiotic and biotic materials and they are an important determinant to the migration of organisms (Eros et al., 2011).

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The spatial pattern of erosion in a catchment is drive by topography, lithology, and soils. The resultant supply of sediment to a channel system is punctuated at confluences and it is organized by the spatial structure of a river network (Benda and Dunne, 1997a,b).

3.3 Hillslope-fan/terrace forcing

Debris cones and fans created by rockfalls and landslides can form in numerous locations in a watershed displacing channels and creating alternating constrained and unconstrained valley segments (Ouimet et al., 2008) and thus variation in the fluvial landscape. Other fan landforms created by fluvial and debris flow processes at confluences can create spatially punctuated but repetitive channel morphology (e.g., boulder deposits). Terraces can form in conjunction with landslide, alluvial, and debris deposits and they can also influence valley width, further promoting formation of alternating constrained and unconstrained fluvial landscapes. Terrace formation may reflect different erosion and sedimentation regimes during past climates or different river base levels due to past sea levels.

3.4 Longitudinal profile – fluvial morphology

River channels have a range of distinct morphologies (and habitat types) that are directly related to the valley elevation profile (e.g., gradients) (Schumm, 1977) as well as sediment supply (Montgomery and Buffington, 1997), confluence zones (Bigelow et al., 2007) and disturbance regimes (Benda and Dunne, 1997a,b). Distinct channel types include braided, meandering pool-riffle, step pool, and cascade.

Large streams and rivers with sediment availability in low-gradient valley settings typically meander and form extensive floodplains (Schumm, 1977). Floodplain environments often include multiple channels, wetlands and diverse riparian vegetation and thus they constitute an important component of the fluvial landscape. Where valleys are wide with actively meandering channels, hillslope-fan/terrace forcing and tributary

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confluences may have little effect. Meandering river and floodplain environments are often highly fertile and are usually associated with widespread human resource use, including development of agriculture, urban centers, and transportation systems. Typically river control occurs most aggressively in wide valley floors, including the building of dikes, levees, and in-channel flow weirs. From a river restoration perspective, a favored target and one that responds to many restoration techniques is the meandering pool-riffle morphology with its attendant floodplains.

3.5 Mixed riverine-estuarine environments

Near the mouth of mid to large rivers as they enter oceans, a mixed fluvial-estuarine environment typically forms and it may extend for several kilometers upstream (from the ocean) depending on river size, local valley morphology, and tide ranges. The meandering-braided river environment with its extensive floodplain can overlap with the brackish, low-gradient and fine-sediment estuarine area leading to highly diverse and productive fluvial landscapes. In mixed riverine-estuarine environments, the elevation differences between channels and adjacent lands may be low due to frequent inundation of combined flood-tidal surges. In this environment, the effects of confluences, hillslope-fan/terrace forcing, and variable valley morphology will be minimal to non-existent. Mixed riverine-estuarine environments are often selected for human occupation and development. In addition to dikes and levees, engineering controls can include estuarine and channel dredging to reduce flooding and to allow for navigation.

4 Methods

Using the "NetMap" system of digital watersheds and shared analysis tools (Benda et al., 2007, 2009) we analyzed the channel network and valley attributes of the Pas River basin in the context of the hydro-geomorphic principles outlined above. The steps in the analysis included: (1) developing a synthetic, attributed and routed stream layer

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using 5-m digital elevation data, (2) estimating the area of flood inundation adjacent to the channel at specified elevations above the channel in units of bankfull depths (bankfull depth refers to the depth of water in a channel of an elevation similar to the uppermost eroded banks and/or it refers to the depth of flow associated with a flood of an approximate two-year recurrence interval), (3) predicting the potential for tributaries to geomorphically and ecologically influence channels, (4) characterizing valley morphology in terms of degree of confinement, (5) predicting spatially variable sediment yields throughout the river network using a topographic index of erosion, (6) mapping across-valley profiles to determine valley-hillslope topography and identify constraints on channel-valley connectivity, and (7) mapping the current extent of the active channel and floodplain surface area along the largest channels in the Pas River basin using satellite imagery (Google Earth).

A synthetic channel network was delineated using flow directions inferred from a 5-m digital elevation model (DEM); algorithms for flow direction and channel delineation are described by Clarke et al. (2008). GIS data on channel locations were used for drainage enforcement in low-relief areas. The channel network was divided into a linked set of channel segments (scale 10–100 m). Contributing area and channel length were calculated from the DEM for each segment; segment endpoints were located to minimize attribute variability. Bankfull channel width and depth were estimated using regional regressions of drainage area and mean annual precipitation to field-measured widths and depths over a range of channel sizes (bankfull width $= 1.683 \times \text{area}^{0.4365} \times \text{precipitation}^{0.4408}$; bankfull depth $= 0.63 \times \text{area}^{0.1731} \times \text{precipitation}^{0.1516}$).

To characterize valley-floor surfaces DEM cells were classified according to elevation above the channel. Each cell within a specified radius (1500 m) of a channel is associated to the closest channel cell, with distance to the channel weighted by intervening relief. Valley-floor DEM cells are associated with channels that are closest in Euclidean distance and have the fewest and smallest intervening high points. The elevation difference between each valley floor cell and the associated channel location

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is normalized by bankfull depth and valley floors are characterized in terms of number of bankfull depths above the channel. This procedure is repeated for every channel segment.

Floodplains typically lie at, or somewhat above, bankfull stage (Dunne and Leopold, 1978). In practice, zones of frequent inundation are defined by an elevation above the channel equivalent to two bankfull depths (Rosgen, 1996; Castro, 1977). To illustrate a wide range of flow inundation-valley topography relations in the Pas River, we delineated surfaces above the DEM-inferred channel using elevation equivalents of one, two, and three bankfull depths.

The probability of observing confluence related changes in the morphology of mainstem channels (confluence effects) depends on the size of the tributary relative to the mainstem (Benda et al., 2004b). In the Pas River, logistic regression equations were used to predict the probability of confluence effects as:

$$P_\mathrm{e} = \exp\left(g(x)\right)/1\ \left(1 + \exp\left(g(s)\right)\right) \tag{1}$$

Where P_e is the probability of a confluence effect and $g(x)$ is fitted to regional data in the western United States on confluence effects (in Benda et al., 2004b). Confluence effects are defined as wider fluvial landscapes, side channels, mid channel bars, meanders, terraces, log jams, deeper pools and changes in substrate. Based on Eq. (1) there is an 85% probability that a tributary with a drainage area one tenth that of the mainstem will create a confluence effect. The probability decreases to less than 10% for tributary basins that have a drainage area less than about 1/1000 of the mainstem.

The spatial frequency of tributary intersections along the mainstem rivers was calculated over a moving window equivalent to four channel segments, ranging between approximately 0.5 to 2 km (average 0.9 km).

In the Pas River average annual sediment yields were estimated using a topographic index of erosion. Erosion in the form of shallow landslides, gullies and surface erosion is often driven by slope steepness and slope convergence (Dietrich and Dunne, 1978; Sidle, 1987). To estimate a measure of erosion potential in the Pas River catchment,

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a dimensionless index that employs slope gradient and local topographic convergence was used (Miller and Burnett, 2007):

$$\mathrm{GEP} = (A_\mathrm{L} \cdot S)/b \tag{2}$$

where GEP is the generic erosion potential, b is a measure of local topographic convergence (the length of an elevation contour crossed by flow out of a pixel, values less than one pixel indicate convergent topography), A_L is a measure of local contributing area (within one pixel length) and S is slope gradient (Miller and Burnett, 2007).

GEP was converted into average annual sediment yield by specifying a catchment average erosion or sediment yield rate, and then distributing that rate linearly according to the GEP index. High values of GEP yield average annual erosion rates in excess of the catchment mean value and low values of GEP erosion rates yield less than the catchment mean value. In the model, the cumulative sum (area weighted) of downstream routed GEP-based average sediment yields must equal the assigned catchment average at the mouth of the river. Because we are concerned with relative rather than absolute values of average sediment yield, we employed an approximated average erosion rate of $100\,\mathrm{t\,km^{-2}\,yr^{-1}}$.

The Pas River system was divided into three sections for our analysis: (1) the East Fork (Yera River), which is 35 km long, (2) the West Fork (Pisuena River), 60 km long, and (3) the Mainstem, extending downstream of the West Fork-East Fork confluence for about 20 km to where it enters the Liencres estuary.

We compared the extent of the topographically inferred fluvial landscape to the current extent of active channel surfaces mapped from 2010 satellite imagery available from Google Earth. The present day fluvial landscape (e.g., active channel and floodplain – unvegetated or lightly vegetated fluvial surfaces located adjacent to the channel) was mapped in four areas of the Pas catchment. Mapping was done only in the larger rivers where valley walls and riparian vegetation did not obscure the existing channel and gravel bars and where the fluvial landscape is bounded by human infrastructure including roads, agricultural fields and urban centers.

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5 Results

5.1 Characterizing fluvial landscapes in the Pas River

Each of the three river sections presents a distinct downstream sequence of geomorphic attributes. Hence, even though the East and West Fork study sections contain a similar range of channel sizes and gradients, the fluvial landscapes differ between them. We describe results for each river section below. The predicted fluvial landscapes for all three bankfull depths are shown on the accompanying maps. For simplicity in our graphical analysis of the fluvial landscape, we used valley topography inferred from one and two bankfull depths elevations only.

5.1.1 Mainstem

Extending downstream of the confluence of the East and West Forks, the Mainstem study section has a drainage area of 560 to 640 km^2. Predicted bankfull widths range from 21 to 34 m and depths from 1.7 to 2 m along its 20 km length. Predicted channel gradients in the Mainstem section range between 0.5 and 0.1%. In the Mainstem segment, the widest zone of inundation at one bankfull depth (600–1200 m) and the least difference between the surface areas of the two fluvial landscapes occurs near the estuary between RK 0 to RK 4 (Fig. 2; A in Figs. 3 and 4). This likely reflects the mixed riverine-estuarine environment where the elevation of channel-adjacent land surface is subtle (XS-1, 2, Fig. 5). Wide fluvial landscapes (20–800 m) are also predicted throughout the rest of the Mainstem segment (B in Figs. 3 and 4), but particularly between RK 10 and 18. Variation in the spatial extent of the fluvial landscape (one and two bankfull depths) indicates variation in valley floor elevations, likely reflecting the existence of terraces formed by historical river meandering. The presence of levees, or roads located on engineered elevated surfaces above the channel (that function as levees) can be detected on the 5-m DEM (XS-3, XS-4, Fig. 5). Channel constraining dikes can limit the extent of the predicted fluvial landscape, particularly at one bankfull depth.

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The dikes become mostly irrelevant to the predicted extent of the fluvial landscape at an elevation equivalent to two and three bankfull depths.

Due to the very narrow basin width (<5 km) of the Mainstem segment, the confluence effects are predicted to be negligible (Fig. 3). Moreover, because of the lack of large tributaries the downstream gradient of average sediment yields is predicted to be flat, at about 100 t km^{-2} yr^{-1} (the catchment average). There is a high frequency of tributaries (4–8 km) in the middle portion of the Mainstem between approximately RK 8 and 14. Even though the tributaries are small in size, a high spatial frequency of tributary confluences may enhance the ecological productivity and diversity of that portion of the mainstem segment.

5.1.2 West Fork

The West Fork drains 360 km^2 and has predicted bankfull widths up to 35 m and depths up to 2.1 m. Estimated channel gradients range from greater than 10% in the headwaters to 0.6% through broad-valley segments downstream. Very narrow fluvial corridors are predicted in two, several kilometer segments of the West Fork, one bounded by a high terrace (RK 16–22) and the other in a canyon at RK 22-26 (C, D Figs. 3 and 4; XS-3 in Fig. 5). The high terrace is mapped as a Holocene fluvial landform (IGME, 1989) and the canyon segment is formed within the mechanically strong Dolomite rock of the Escudo de Cabuérniga Mountain Range.

Moving upstream, wide fluvial landscapes (200–1200 m) are predicted to occur within the broad valley of the West Fork at RK 25 to 40, although with considerable differences in surface area between one and two bankfull depths (E in Figs. 3 and 4; XS-4 and 5, Fig. 5). The differences between predicted fluvial corridors indicate variable valley floor elevations, likely reflecting the presence of low terraces. The probability of confluence effects in the wide river valleys of the West Fork are less than 0.02 given the small size of the tributaries in relation to the drainage area of the mainstem channels (tributary area/mainstem area <0.08) (Fig. 3). Overall, the geomorphic effects of tributaries on the West Fork appear to be minimal. However, at least one high energy

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tributary intersects the West Fork directly (near the western valley wall) and it is associated with local widening of the fluvial landscape (Fig. 6). In addition, tributaries that flow parallel to the mainstem include their own fluvial landscapes that merge with the fluvial landscape of the West Fork.

Upstream in the West Fork there is a large meander (length = 1.5 km) at RK 40 with an associated large fluvial landscape (200–500 m) at both one and two bankfull depths (Figs. 3 and 4 F). The wide fluvial landscape there may be driven, in part, by the close proximity of the large tributary (and an increase in sediment supply) that enters from the south at RK 42.

Another large fluvial landscape occurs in association with the confluence created by the intersecting tributary from the south at RK 42 (G in Figs. 3 and 4). A 300 m to 400 m wide fluvial landscape is predicted to occur both upstream and downstream on the confluence (confluence probability = 0.25), in association also with the predicted increase in average sediment yield of 125 t km^{-2} yr^{-1} to 140 t km^{-2} yr^{-1}.

Moving upstream in the West Fork along the narrower east-west trending valley, hillslopes, high terraces and alluvial fans bound both sides of the channel, thereby reducing the width of the fluvial landscape to less than 200 m (H in Figs. 3 and 4). The potential importance of tributaries, via confluences, is more apparent along this segment. For example, there are numerous tributaries that are predicted to have the potential to create confluence effects along the 15 km-long valley, including the building of fans and terraces between RK 50 and 60 (Fig. 3). In addition, tributaries along this portion of the West Fork are predicted to have average annual sediment yields in excess of 150 t km^{-2} yr^{-1} (Fig. 3). Unconstrained valley segments occur intermittently where elevation differences between channels and fan/terraces are less than about 4 m and constrained segments are typically bounded by fan/terraces of about 4 to 9 m in height (Fig. 7).

Upstream of RK 60, the West Fork valley narrows further and the fluvial landscape diminishes to less than 50 m wide, although the pattern of alternating wide and constrained reaches continues (I in Figs. 3 and 4).

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Although relatively large tributaries may be needed to create large geomorphic effects in receiving rivers (tributary area/mainstem area >0.3; Benda et al., 2004b), even small tributary confluences can serve as important ecological nodes because they can act as migration corridors, micro habitats, thermal refugia, and sources of nutrients (Rice et al., 2008; Eros et al., 2011). The frequency of confluences along the West Fork study segment varies between 2 and 20 per kilometer and the higher frequencies may identify areas of higher ecological potential. There are high confluence frequencies in the wide valley between RK 8 and 15, in the canyon segment (RK 22 to 28) and in the upper basin upstream of RK 40, and in particular between RK 42 and 52 (Fig. 3).

An additional factor that is relevant to how network structure potentially influences the fluvial landscape is found in the longitudinal patterns of tributaries as they intersect mainstem channels. For example, the position of the West Fork within its valley between RK 25 and 40 alternates between the middle and one side or the other. Consequently, tributaries that intersect the West Fork have different energy gradients. Tributaries that intersect the West Fork near the western valley wall have higher-energy gradients and thus are more effective in transferring water, sediment, organic materials and nutrients directly to the mainstem (#1 and #6 in Fig. 6), all other things being equal such as tributary basin size and erosion potential. In contrast, tributaries that intersect the West Fork after traveling over the valley floor, including paralleling the main channel, have lower energy gradients and thus may be less effective at routing materials to the mainstem, e.g., more storage along the valley floor (Fig. 6). For example, tributary #6 (Fig. 6) that directly intersects the West Fork at the western valley wall is associated with an enlarged fluvial landscape.

5.1.3 East Fork

The East Fork drains about 200 km^2 and predicted channel width and depth ranges up to 22 m and 1.8 m respectively. Estimated channel gradients range from greater than 10% in the headwaters to 0.4% through broad-valley segments downstream.

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The East Fork of the Pas River contains a different pattern of fluvial corridors compared to the West Fork. At the downstream end of the East Fork (RK 0 to 4), there is an extension of the very narrow fluvial landscape (channel bounded by a high terrace, e.g., XS-3, Fig. 5, J in Figs. 4 and 8). Upstream of that area, a broad valley (1–1.5 km at RK 5–12) is predicted to have considerably wider fluvial landscapes (200–800 m), with pronounced differences between the two bankfull depth elevation bands (K in Figs. 4 and 8). The East Fork then enters a narrow canyon to the south (the channel cross cuts through the same east-west trending Dolomite ridge that creates the gorge in the West Fork) with the resultant diminution of the fluvial landscape (<50 m) (M in Figs. 4 and 8). At the upstream end of the 5-km long canyon, an abrupt increase in the width of the fluvial corridor (200–1200 m) occurs in conjunction with an intersecting tributary and a valley transition from constrained to unconstrained (N in Figs. 4 and 8). Upstream of that area and heading south, the East Fork resides within a broad valley (1 km wide) creating an environment for a wide fluvial corridor (200–400 m) with no significant tributary confluence influences (O in Figs. 4 and 8). However, smaller tributaries coincide within the wider fluvial landscape in this area (and run parallel to the main channel) indicating where interaction between tributaries and main channels within the fluvial landscape could occur (Q, Fig. 4). The upper most East Fork then trends east-west into a narrow valley where hillslope-fan/terrace forcing limits the width of the fluvial landscape to between 30 and 60 m.

Geomorphically effective tributary confluences are predicted to be limited in the larger East Fork channels (drainage areas > 100 km^2). Exceptions occur at RK 10 and RK 20–22 where larger tributaries are spatially associated with wider fluvial landscapes (K, N in Figs. 4 and 8). Although more geomorphically effective tributaries are predicted to occur in the upper East Fork catchment (>RK 25), narrow valley floors limit development of the fluvial landscape, although alternating areas of constrained and unconstrained reaches occur due to hillslope-fan/terrace forcing, similar to the upper West Fork.

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There is also considerable spatial variability in the frequency of intersecting tributaries in the East Fork. The spatial frequency of confluences varies from about 2 to over ten per kilometer (Fig. 8). There are several spikes in the confluence frequency that arise due to topographic and network controls at RK 4 to 6, 15 to 18 and upstream of RK 28 (within the narrow east west trending valley). Higher concentrations of tributaries may indicate areas that have a higher potential to be ecologically diverse and productive, particularly if the mainstem channel was not controlled and or the wider fluvial landscape was not constrained by development.

The East Fork is located within its valley at variable positions with respect to the intersecting tributaries originating from the valley walls. The position of the East Fork alternates between the east and west side of the valleys and thus the energy gradients of the tributaries as they intersect the mainstem vary, similar to the East Fork (e.g., Fig. 6).

5.2 Current extent of the fluvial landscape

Surface areas of four mapped segments of the currently active channel and floodplain surface in the catchment were measured (Fig. 2) and compared to the topographically inferred fluvial landscape (Fig. 9). In all four areas, the currently active fluvial landscape is considerably narrower than the potential fluvial landscape inferred from DEM topography (Table 1). Mapped fluvial landscapes occupy 44% to 78% (average 55%) of the fluvial landscape delineated at an elevation of one bankfull depth above the channel, 11% to 25% (average 17%) of the fluvial landscape delineated at two bankfull depths above the channel, and 6% to 19% (average 10%) of the fluvial landscape at three bankfull depths above the channel (Table 1). Empirically, floodplains tend to lie within two to three bankfull depths above the channel (Dunne and Leopold, 1978; Rosgen, 1996) suggesting that the current fluvial landscape has been diminished by a factor of 6 to 10, leaving only 10% to 17% remaining (Table 1).

The causes of the diminution of the present fluvial landscape include flood control dikes and levees that isolate the channel from its potentially larger fluvial landscape

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(e.g., Fig. 5, XS-3 and 4). In low-lying areas protected from flooding, urban developments, farms and road networks have been built (Fig. 5 photos). Reductions in the present day fluvial landscape are less in narrow valleys because of less intensive development in the form of urban centers, roads and river control structures (dikes, levees and weirs). For example, both the east-west trending valleys of the West and East Forks appear to have less of a reduction in the fluvial landscape but that inference could not be verified using satellite imagery because of dense forest cover in those areas.

6 Discussion

6.1 Creating a catchment scale context for restoration planning

In North America and Europe River restoration has been evolving from the scale of individual stream reaches (100–1000 m) to a more expansive scale of entire catchments (Palmer et al., 2005; Bannister et al., 2005). Although restoration at the reach scale can be successful, it can also pose limitations on understanding and on project design that can lead to unsuccessful outcomes (Frissel and Nawa, 1992; Wohl et al., 2005). In Europe, the EU Water Framework Directive (EU 2000) and EU Habitat Directive (Jahnig et al., 2010) specifically recommends creating a catchment scale context for river restoration projects. This perspective stems from an interest in returning rivers to a more natural form with improved biological productivity and diversity in those areas where it is most beneficial and feasible, even with the recognition that it will be impractical to do so in many areas because of the constraints imposed by extensive land use development, including urban centers, agriculture, and transportation systems.

The key to creating a catchment scale context for river restoration will be establishing a guiding ecological image (Palmer et al., 2005) also referred to as a geomorphic template (Brierly et al., 2008). This is challenging because it will require an explicit analysis of the entire catchment of interest, highlighting the spatial and temporal characteristics

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of the fluvial landscape that govern geomorphic and ecosystem interactions (Kondolf, 2000). However, more often than not, morphological patterns indicative of a well functioning fluvial landscape have been obscured or eliminated (including by flow regulation by dams and weirs, construction of flood control levees and dikes, hardening of banks, filling in of side channels and wetlands, and building on floodplain).

Reconstructing the fluvial landscape in catchments where past land uses have obscured it has been successful, particularly in areas where historical aerial photographs support mapping of pre-development floodplains, side channels, beaver dams and log jams (Collins et al., 2003). However, reconstructing the natural fluvial landscape in catchments with a multi-century history of land use can be more difficult, particularly in areas where historical photos and other evidence are not readily available.

In large catchments, such as the Pas River (650 km^2) where extensive land use has eliminated or partly obscured the natural fluvial landscape, efficient approaches will be needed to create the types of maps and databases necessary to underpin catchment scale planning in river restoration. In this paper, our approach takes advantage of recent advances in the science of fluvial landscapes and computer based analysis tools. However, because of its reliance on remote sensing, field surveys would be required to verify many of the inferences that are drawn and to create the necessary context for smaller scale restoration projects.

A guiding ecological image or geomorphic template for river restoration at the catchment scale can be considered at different levels of detail. In a geographic context, one can consider the natural history and patterns of the fluvial landscape with the aim of better understanding landform development. On a more applied level, a catchment scale perspective can be used to identify fluvial landscape "hotspots", those areas that stand out because of potential for fluvial-floodplain, fluvial-riparian, and confluence interactions driven by catchment topography, valley morphology, river network structure, and channel morphology.

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6.2 The geographic context of the Pas River fluvial landscape

The spatial patterns inferred from DEM analysis in the Pas River system reflect unique geological and geomorphological catchment controls on the fluvial landscape. At a broad scale, the width of the fluvial landscape generally increases downstream as channels, and the valleys they flow through, become larger (Figs. 3 and 8), but there is considerable spatial variability in the width and geometry of the fluvial landscape due to topographic and river network controls.

The widest and potentially the most complex fluvial landscape may be related to the geologic structure of the Pas River catchment. For example, the N-S trending valley on the West Fork parallels the strike of an anticline (IGME, 1989), which may have contributed to its broad geometry. A similar broad valley in the East Fork at the same latitude suggests an analogous geological control. The broad east-west trending valley in the lower East Fork coincides with several major faults, suggesting a structural origin for this valley as well. Both the West and East Forks follow narrow canyons cut through an east-west trending Dolomite ridge. The fluvial landscape through these canyon reaches is very constrained, with the exception of one small area at the downstream end of the East Fork canyon.

The various shapes of the catchment subbasins and the associated river network structure dictate the potential role of confluences in influencing the dimensions and function of the fluvial landscapes. Overall, within the larger fluvial landscape of the Pas River catchment, tributary effects are predicted to be modest; each of the sub-basins are relatively narrow and tributary channels have small drainage areas relative to the trunk streams. However, within the larger channels of the West and East Forks, there are several locations where confluences may be associated with wider fluvial landscapes (F, G in Figs. 3 and 4; K, N in Figs. 4 and 8).

In contrast to wider valleys, the east-west trending West Fork is asymmetrically located within its basin with numerous large tributaries intersecting the valley from the south (Fig. 2). This factor, in addition to predicted high sediment yields and a narrow valley floor, promotes hillslope-fan/terrace forcing of the fluvial landscape. The terrace-fan landforms bound the active channel and the resultant fluvial corridor ranges in width between 50 and 200 m on one or both sides of the channel throughout the 15-km-long segment. Through this reach, unconstrained valley segments occur where elevation differences between channels and terraces are less than 4 m and constrained segments are bounded by landforms 4 to 9 m high (Fig. 7). These alternating constrained and unconstrained reaches could be considered a "string of pearls" (Ward et al., 2002) that likely contributes to physical heterogeneity through this portion of the river corridor.

Although the broad N-S trending valleys in the West and East fork contain relatively minor tributaries, several of them run parallel to the mainstem. This can increase the potential for ecological complexity, because the floodplains of the two fluvial systems can overlap and there is greater opportunity for hyporheic exchange. In addition, the spatial frequency of confluences (of tributaries of any size) is highly variable along all of the study segments, ranging from 2 to 20 per kilometer (Figs. 3 and 8). The zones of highest confluence frequency tend to be clumped and areas of higher numbers of tributary intersections could be considered to have high ecological potential in the context of restoration. The patterns of confluences and tributaries that occur away from the mainstream also have important ecological implications (Eros et al., 2010).

6.3 Identifying provisional fluvial landscape hotspots

Comparing the current extent of active channels and floodplains with the topographically delineated fluvial landscape reveals that perhaps only 10% to 15% of the original fluvial landscape remains active in the Pas River catchment. Nevertheless, even in controlled riverine environments, it is feasible to reestablish a functioning channel-floodplain ecosystem, at least incrementally in certain areas (Logan and Furze, 2002; Gilvear and Casas, 2005). The catchment-scale perspective of the natural fluvial landscape can provide an important context from which to plan, design, and carry out restoration projects.

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Restoration planning could focus on geomorphic and ecological "hotspots" in the Pas River catchment, local areas (0.5 to 5 km long, 0.1 to 1 or more km^2) that have the combination of processes and landforms (or their potential) to create favorable riverine environments characterized by extensive channel-floodplain, fluvial-riparian and confluence interactions. Four types of fluvial landscape hotspots in the Pas River are considered in the context of potential restoration activities, specifically involving the reconnection of channels with a more extensive fluvial ecosystem. The sites described briefly below are necessarily at the "meso-scale" due to the remote sensing dependence of this study. However, in practical terms, restoration planning and project design will likely be carried out at smaller reach scales.

1. Narrow valleys – string of pearls: in both the upper West and East Forks, hillslope-fan/terrace forcing has created a sequence of alternating wide and narrow fluvial landscapes (Fig. 7). In the upper basins, human encroachment on the channel-floodplain complex appears to be limited due to the lower densities of roads and dwellings, although a few urban centers exist. Restoration here could target the wide-corridor segments – the fluvial landscape "pearls" G through H in Figs. 4, 10 and 11). For example, field surveys could be used to examine the degree to which bank protection (dikes), roads, and other structures restrict channel-floodplain interactions through the wide sections, and identify those sites where restoration activities could enhance the coupling between aquatic and riparian systems. Restoring areas in close proximity to one another could be an effective restoration strategy to restore ecological connectivity.

2. Broad valleys – complex floodplains: the widest inferred fluvial corridors in the Pas catchment lie in broad valleys between RK 25–40 in the West Fork, between RK 4–12 and RK 18–25 in the East Fork, and between RK 2–15 in the Mainstem (A, B, E, K, N O in Figs. 3, 4 and 8). In the absence of human alterations, these areas likely exhibited extensive lateral connectivity among channels, floodplains, and riparian areas. Major tributary confluences do not exist within most

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of the broad valleys (an exception being Site N in the East Fork at RK 18–20). However, the frequency of intersection of tributaries of all sizes is highly variable (2–20 km, Figs. 3 and 8), and zones of high frequencies could be viewed in the context of the wider fluvial landscapes in the broad valleys to locate provisional fluvial hotspots (Figs. 10 and 11). Individual, high energy tributaries may also drive locally wider fluvial landscapes at confluence intersections (Fig. 6). Moreover, tributary channels that run parallel to mainstem channels can contribute to floodplains, wetlands, and hyporheic flow. In such broad-valley environments, tributary spacing and orientation is important, because tributary intersections function as key dispersal corridors for aquatic and riparian plant and animal species (Eros et al., 2011).

Because of the multiple processes active in broad, low-gradient fluvial zones, these fluvial landscapes probably constituted the most diverse riverine environments in the Pas catchment prior to pervasive human development, and therefore pose the highest potential for restoring diversity in the riverine ecosystem. Areas within these zones with the least human development (e.g., E and O in Fig. 4 and see XS-4 photo, Fig. 5) can therefore pose exceptional targets for restoration of combined mainstem-tributary environments (Figs. 10 and 11). Throughout most of these areas, the diminution of the fluvial landscape has been generally universal and to a similar extent. However, field studies would be required to validate the provisional findings presented here and to provide additional smaller scale, site-specific information on restoration opportunities.

Similar geomorphic settings in other broad valleys (B, K, Fig. 4 and see XS-2 photos, Fig. 5) have more extensive urban development that would be less conducive to restoration activities.

3. Individual Fluvial Landforms, Confluence Areas, and Valley Transitions: there are numerous unique and individual fluvial landscape zones that could be highlighted for restoration because of their potential for creating ecologically diverse

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and productive areas. Three are listed below and analysts could find numerous others by examining the maps and graphical data in this paper. Site F in the West Fork at RK 40 (Fig. 4) is located in a wide fluvial landscape located downstream and in close proximity to a large sediment-producing tributary (see XS-5 photo, Figs. 5, 10). Another area is site Q in the East Fork at RK 22 (Fig. 4) where several small tributaries that originate from the eastern valley merge onto the fluvial landscape and run parallel to the mainstem channel (Figs. 10 and 11). Other areas could be identified that focus on the spatial frequency of tributary confluence intersections (e.g., Figs. 3 and 8, lower panel).

Individual large tributaries can have a significant local impact on the development of fluvial landscapes. One is located where the West Fork turns from north-south to east-west (RK 42, Fig. 3). The large intersecting tributary there is associated with a local increase in the width of the fluvial corridor (G, Figs. 4 and 10). Another site is located in the East Fork at RK 18–20 where a large tributary intersects the truck stream at the upstream transition from an unconstrained to a constrained valley segment (N, Figs. 4 ,8, 10 and 11). Areas where tributaries intersect valley transitions could present very unique geomorphological and hence ecological settings, and could be highlighted in a catchment scale context for restoration.

4. Lower Riverine-Estuarine Environments: the interaction of fluvial and tidal processes creates a unique, diverse, and highly productive environment that includes fluvial, near shore, subtidal, and estuarine habitats. In the Pas River system, this zone occupies the widest, lowest relief fluvial corridor (A in Figs. 3 and 4). The mixed fluvial-estuarine environment may represent the most valuable ecosystem to restore, but also the most challenging, given the typical presence of urban centers and transportation systems (XS-1 photo, Fig. 5).

Whether or not the provisional types and locations of fluvial landscapes described above present restoration opportunities will require a clear planning process that links on the ground projects with desired ecological outcomes as well as field

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evaluation of relevant geomorphic and ecological criteria (Mika et al., 2010). There are undoubtedly other types and locations of restoration opportunities based on the landscape interpretation presented in this paper, limited only by imagination, training, experience and field work.

7 Conclusions

There is an emerging consensus in the science of river restoration in Europe and North America that a catchment scale perspective is prerequisite to support planning and project design. This mandate, however, presents a challenge in catchments with a long history of land use that has either eliminated or obscured the fluvial landscape. There are various approaches and methods that could be used to reconstruct the fluvial landscape at the scale of entire catchments and in this paper we have illustrated one of them that combines general principles of hydro-geomorphic processes with available computer tools.

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Table 1. Surface area (m^2) of the present day fluvial landscape in the Pas River at four locations (Fig. 2) is compared to the predicted fluvial landscape based on one, two and three bankfull depths. The values in ( ) indicate the percent remaining based on the present day Google Map images and the percentage reduction in surface area, respectively.

	Active channel surface (m^2) (2010)	Inundated area at one bankfull (m^2)	Inundated area at two bankfull (m^2)	Inundated area at three bankfull (m^2)
Northern west fork (#1)	1 781 034	3 727 575 (47%, −210%)	6 897 882 (25%, −385%)	9 399 339 (19%, −525%)
Upper East Fork (#4)	424 341	541 8171 (78%, −125%)	2 154 313 (19%, −500%)	5 148 263 (8%, −1200%)
Lower East Fork (#3)	200 288	449 829 (44%, −225%)	1 846 184 (11%, −900%)	3 278 370 (6%, −1600%)
West Fork (#2)	707 464	1 297 463 (54%, −180%)	5 285 891 (13%, −750%)	7 546 984 (9%, −1000%)
Average		(55%, −185%)	(17%, −630%)	(10%, −1100%)

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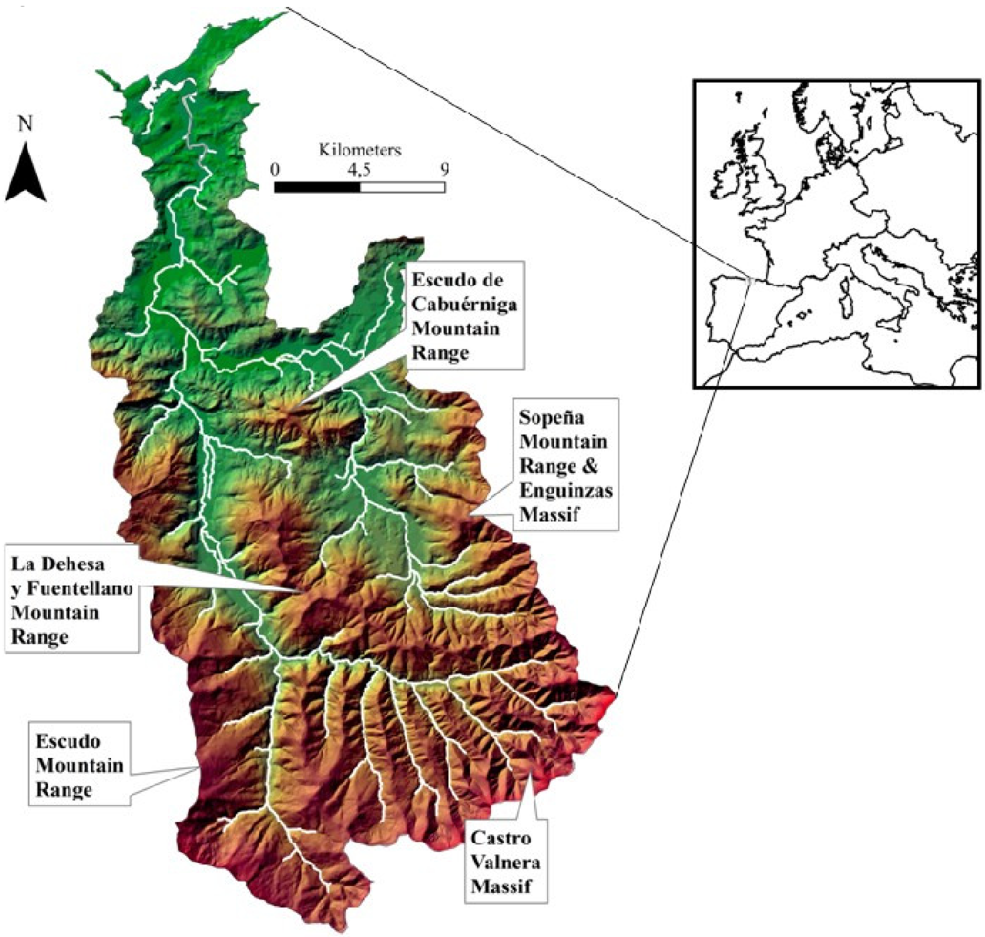

Fig. 1. The study area is the Pas River basin (650 km^2) located the northern part of Spain in the Cantabria region.

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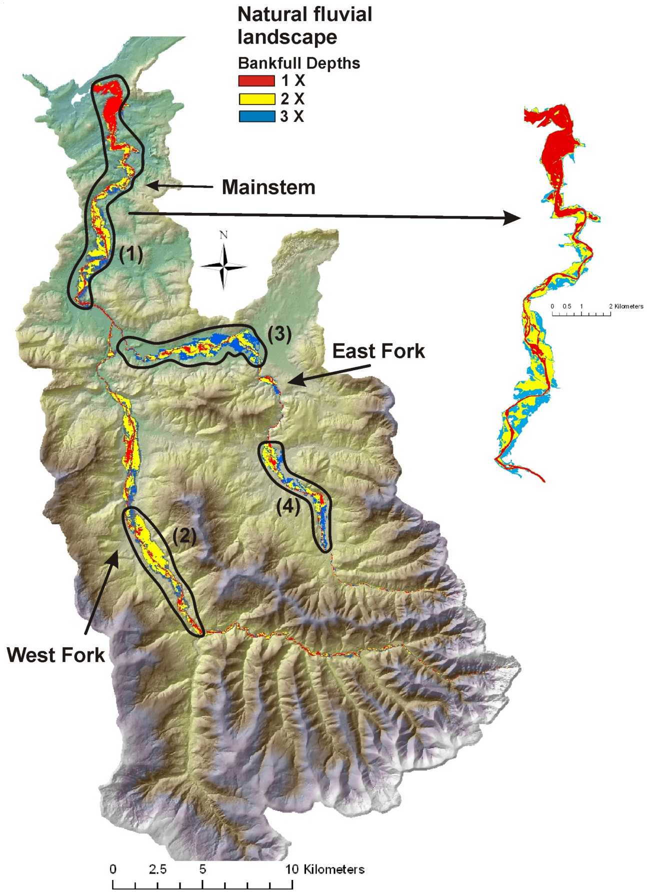

Fig. 2. The natural fluvial landscape is characterized using three elevation bands above the channel, in units of one, two and three bankfull depths. The study segments of "Mainstem", "West Fork" and "East Fork" are shown. The present day extent of the fluvial landscape measured from satellite imagery (Google Earth 2010) was mapped in four areas, outlined as #1–#4.

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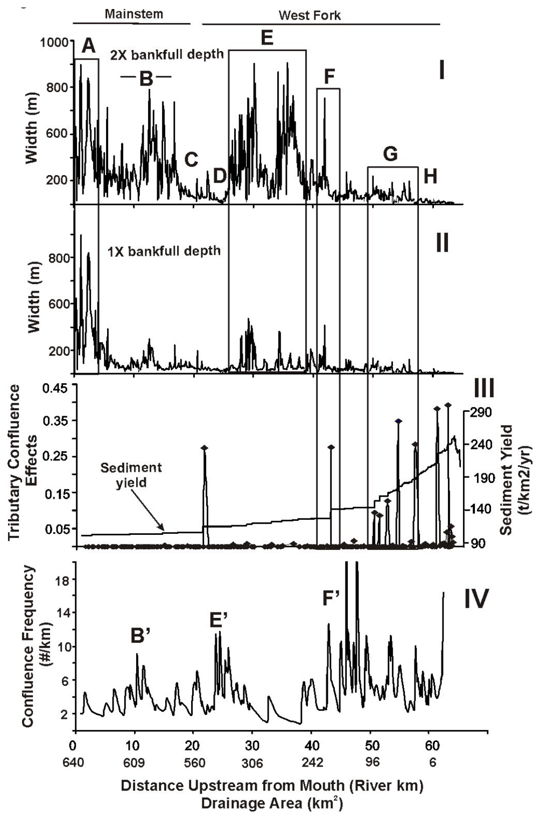

Fig. 3. The predicted fluvial landscape in the West Fork of the Pas River at an elevation above the channel equivalent to one and two bankfull depths is highly variable (I, II). The predicted tributary confluence effects and average sediment yields (using an illustrative basin wide average of 100 t km^{-2} yr^{-1}) are shown in III. The spatial frequency of tributary intersections along the Mainstem and West Fork study segments shows a clumped pattern (IV). Site locations A–I are mapped in Fig. 4.

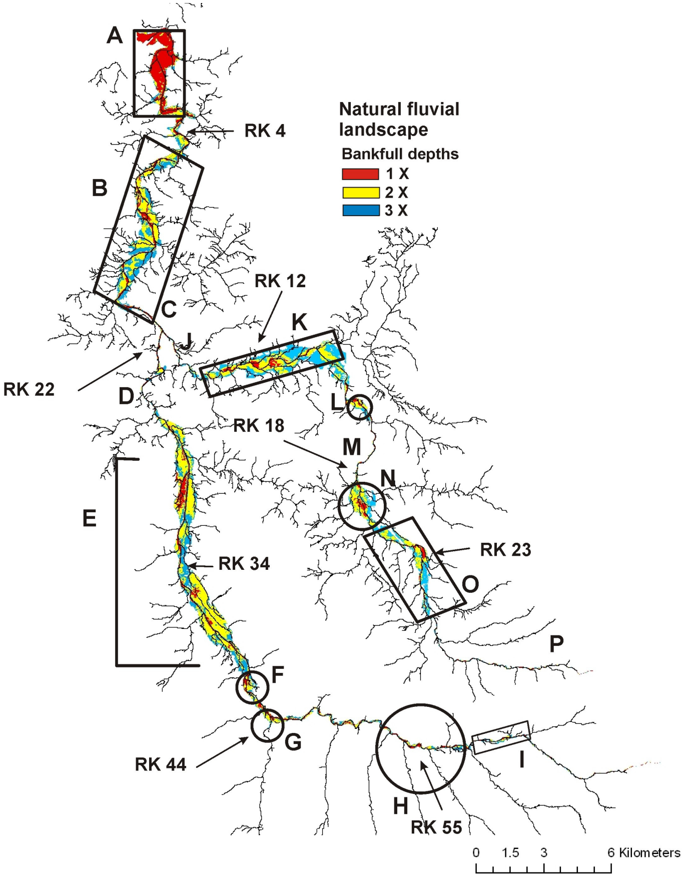

Fig. 4. The stream network (channels with gradients less than 10%) and the predicted fluvial landscape are shown for the Pas River basin in association with elevations above the channel equivalent to one, two and three bankfull depths. Sites A–I correspond to locations indicated in Fig. 3 and sites J through P are shown in Fig. 8.

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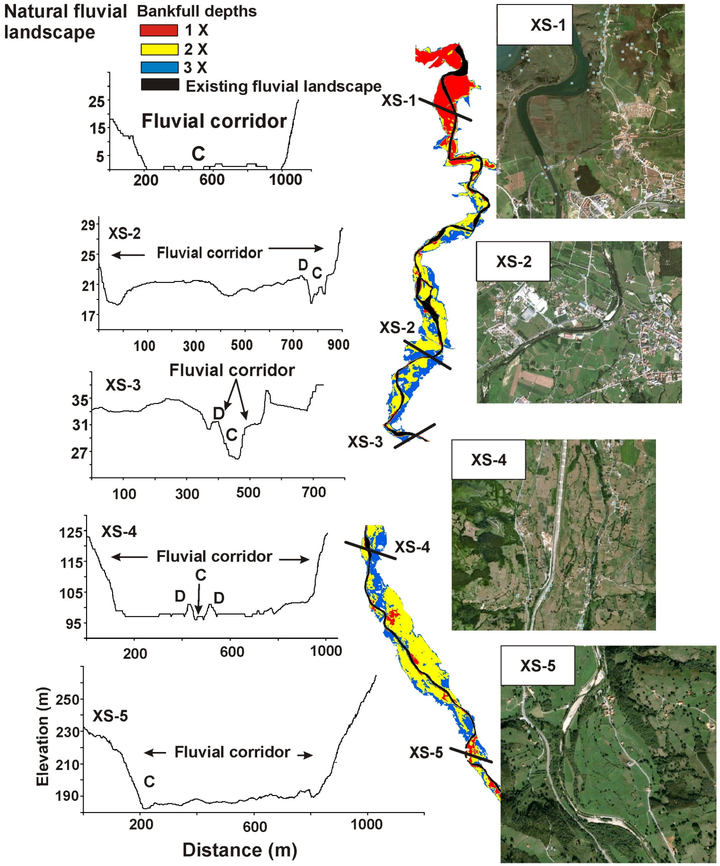

Fig. 5. Across-valley elevation profiles show the location of the predicted fluvial landscape with associated satellite images (Google Earth). The narrow present day extent of the fluvial landscape (e.g., channel and floodplain) is denoted by "C". Elevated surfaces that are considered to be levees are denoted by "D". The fluvial landscapes depicted in the cross sections correspond to elevations associated with two bankfull depths.

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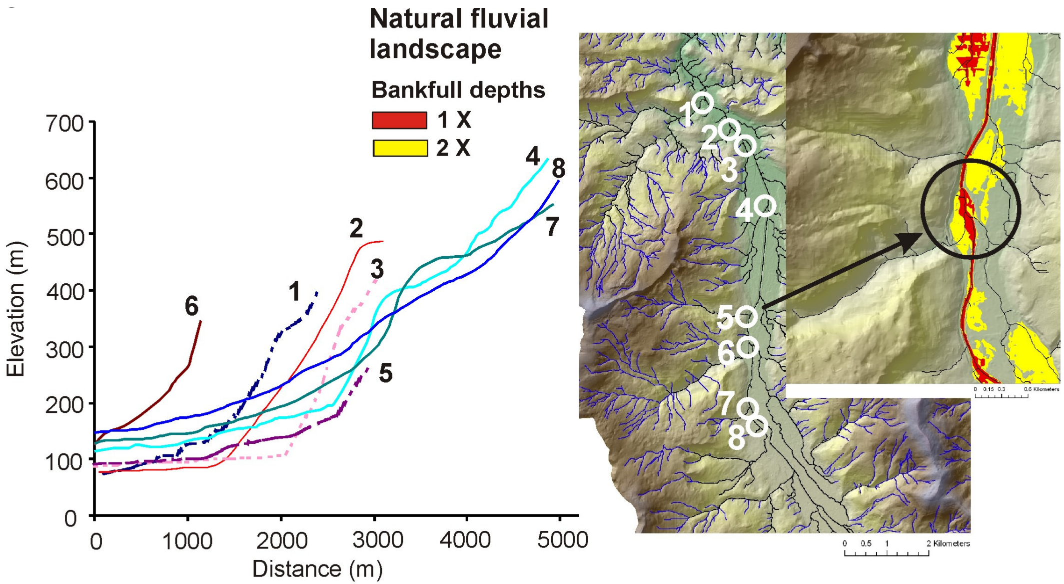

Fig. 6. Elevation (energy) gradients are shown for a select number of tributaries entering the West Fork in the wide valley (location E in Fig. 4). Tributaries 1 and 6 directly enter the mainstem and have high-energy gradients. Tributaries 2, 3, and 5 flow across the low gradient valley floor and have lower energy gradients where they intersect the West Fork. Tributaries 4, 7, and 8 are intermediate. Tributary #6 is associated with a locally wider fluvial landscape, as depicted in the image.

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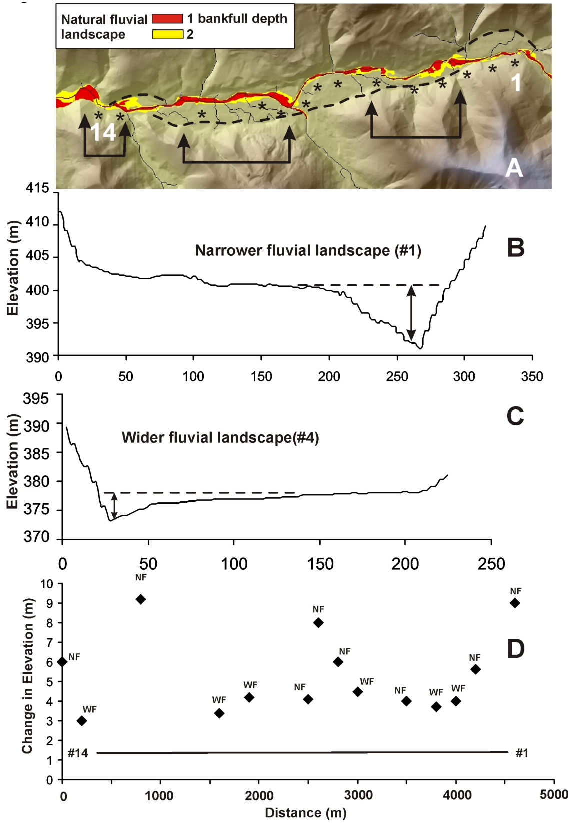

Fig. 7. The narrow east-west trending valley in the upper West Fork contains terrace and fan deposits that create alternating wide and narrow fluvial landscapes **(A)**. In the lower panel **(D)**, the change in elevation corresponds to the elevation difference between the channel and bounding landforms, as illustrated in **(B)** and **(C)**; NF and WF indicates "narrow fluvial landscape" and "wider fluvial landscape, respectively". "*" on the upper panel denotes locations of the cross sections 1 through 14, from right to left.

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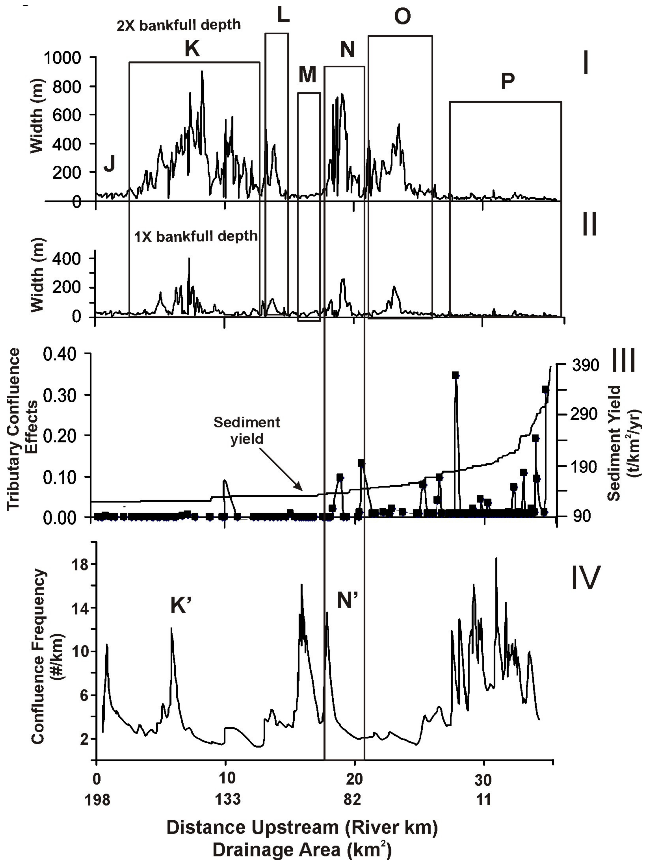

Fig. 8. The predicted fluvial landscape in the East Fork of the Pas River at an elevation above the channel equivalent to one and two bankfull depths is highly variable (I, II). The predicted tributary confluence effects and average sediment yields (using an illustrative basin wide average of $100\,\mathrm{t\,km^{-2}\,yr^{-1}}$) are shown in III. The spatial frequency of tributary intersections along the East Fork reveals a clumped pattern (IV). Site locations J–P are mapped in Fig. 4.

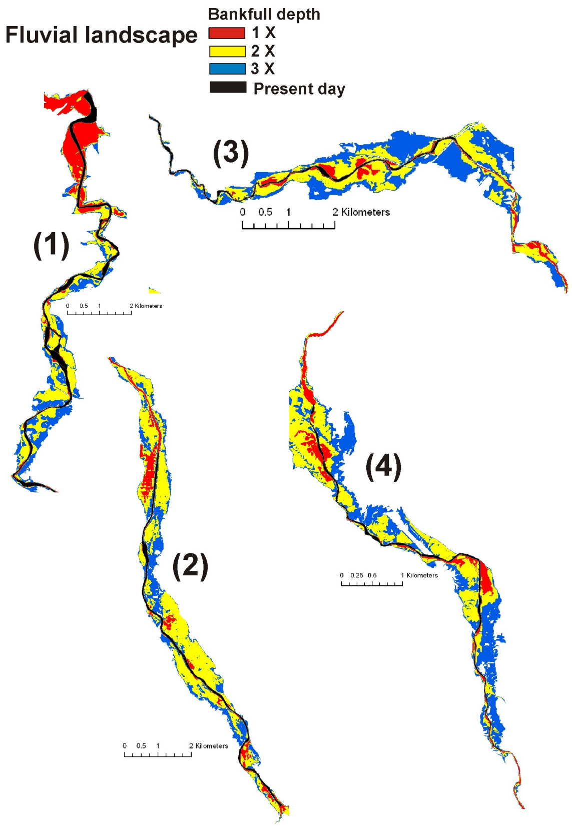

Fig. 9. The present day extent of the fluvial landscape along four segments of the Pas River (Fig. 2) was mapped using satellite imagery (Google Earth 2010). The predicted fluvial landscape using one, two and three bankfull depths above the channel are shown for comparison. The present day fluvial landscape is approximately 10% to 17% of the predicted fluvial landscape using two and three bankfull depths (Table 1).

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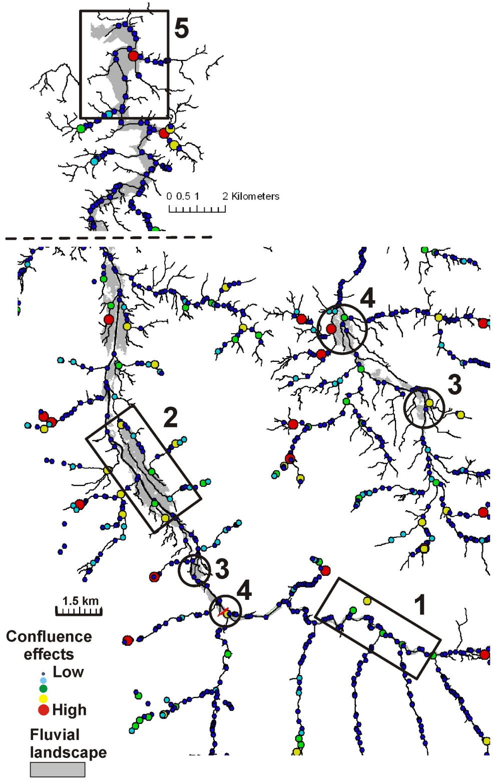

Fig. 10. The analysis of fluvial landscapes in the Pas River network provides a catchment scale context for restoration planning. Four types of fluvial landscapes are identified: (1) narrow valleys-string of pearls, (2) broad valleys-complex floodplains, (3 and 4) individual fluvial landforms, confluences and valley transitions, and (5) lower riverine-estuarine environments. Not all sites that fall into these categories are shown. The shaded reconstructed riverine landscape denotes areas located within one and two bankfull depths (Fig. 2).

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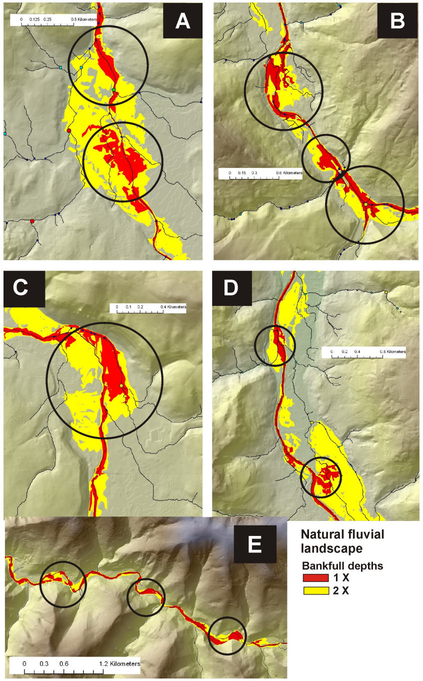

Fig. 11. A sample of close up images is shown of the predicted fluvial landscape at potential restoration "hotspots": **(A)** an enlarged fluvial landscape located at the transition from an unconfined to a confined valley in combination with a large tributary confluence (N in Figs. 4 and 8); **(B)** individual fluvial landscapes that have high potential for lateral connectivity are located at the site of a large meander and at a significant tributary confluence (F, G) – Figs. 3 and 4; **(C)** an area within the East Fork basin where a channel interacting with hillslope forcing, in combination with a high density of parallel running tributaries, denote a potentially productive and complex fluvial landscape (Q, Fig. 4); **(D)** areas within the wide valley of the West Fork, one of which may be influenced by a confluence (E) – Figs. 3 and 4; and (E) the upper West Fork segment where hillslope/fan forcing has created alternating wide and narrow fluvial landscapes.

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