The effect of vegetation and beaver dams on geomorphic recovery rates of incised streams in the semi-arid regions of the Columbia River basin, USA

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Channel incision, evolution and potential recovery in the Walla Walla and Tucannon River basins, northwestern USA†

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Abstract

We evaluated controls on locations of channel incision, variation in channel evolution pathways and the time required to reconnect incised channels to their historical floodplains in the Walla Walla and Tucannon River basins, northwestern USA. Controls on incision locations are hierarchically nested. A first-order geological control defines locations of channels prone to incision, and a second-order control determines which of these channels are incised. Channels prone to incision are reaches with silt-dominated valley fills, which have sediment source areas dominated by loess deposits and channel slopes less than $0{\cdot}1(\text{area})^{-0{\cdot}45}$. Among channels prone to incision, channels below a second slope–area threshold (slope = $0{\cdot}15(\text{area})^{-0{\cdot}8}$) did not incise. Once incised, channels follow two different evolution models. Small, deeply incised channels follow Model I, which is characterized by the absence of a significant widening phase following incision. Widening is limited by accumulation of bank failure deposits at the base of banks, which reduces lateral channel migration. Larger channels follow Model II, in which widening is followed by development of an inset floodplain and aggradation. In contrast to patterns observed elsewhere, we found the widest incised channels upstream of narrower reaches, which reflects a downstream decrease in bed load supply. Based on literature values of floodplain aggradation rates, we estimate recovery times for incised channels (the time required to reconnect to the historical floodplain) between 60 and 275 years. Restoration actions such as allowing modest beaver recolonization can decrease recovery time by 17–33 per cent. Published in 2007 by John Wiley & Sons, Ltd.

Keywords: channel incision; channel evolution; aggradation; stream restoration

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Introduction

Incised channels range from small rills and gullies to large, entrenched river channels (Harvey and Watson, 1986; Schumm, 1999). Gullying into unchanneled valleys or swales is commonly initiated when land use changes cause increased runoff or decreased vegetative cover (Montgomery, 1994; Prosser and Slade, 1994; Prosser and Soufi, 1998; Croke and Mockler, 2001), whereas stream channel entrenchment often results from base level lowering, climate or land use changes that increase stream flows, or loss of riparian vegetation (Balling and Wells, 1990; Booth, 1990; Magner and Steffen, 2000; Waters and Haynes, 2001; Croke and Mockler, 2001; Doyle *et al.*, 2003). In all of these cases, incision occurs when erosive forces of the stream overcome the strength of underlying materials (Harvey and Watson, 1986), often starting low in the drainage and progressing upvalley as a migrating vertical headcut (Leopold *et al.*, 1964). Both gullying and channel entrenchment are common throughout the world (Bravard *et al.*, 1997; Wasson *et al.*, 1998; Scott *et al.*, 2000), causing declines in both stream and riparian ecosystem functions (Shields *et al.*, 1995; Bravard *et al.*, 1997).

Although many studies have related the occurrence of incision to changes in climate or land use impacts (Cooke and Reeves, 1976; Schumm, 1999), few have sought to explain why some channels in a river basin are entrenched while others are not. Moreover, characteristics of entrenched channels (e.g. incision depth, cross-section shape) vary longitudinally as well as among tributaries (Patton and Schumm, 1975; Schumm *et al.*, 1984; Simon and Hupp, 1987; Thorne, 1999), and mechanisms underlying such patterns have received limited attention. In this paper our first aim is to explain these patterns in a semi-arid river basin by identifying geological and fluvial controls on the occurrence and nature of channel entrenchment. Our approach to this problem relies on a hierarchical framework that first identifies which channels are prone to incision, and second identifies a slope–area incision threshold within the population of channels prone to incision. Channels that are prone to incision typically flow through silty valley fills, whereas channels in coarse-grained alluvium generally resist incision (Cooke and Reeves, 1976; Schumm, 1999). Therefore, we hypothesize that channel incision is limited to reaches in which the caliber of source sediment and low transport capacity caused accumulation of fine-grained valley fills. Among channels prone to incision, channels with greater flow strength are more likely to incise (Prosser and Abernethy, 1996; Montgomery, 1999), so we also hypothesize that – within the population of channels prone to incision – channels with steeper slope and larger drainage areas are more likely to be incised. Thus, we assess the degree to which channel slope, drainage area and the geology of sediment source areas are related to locations and depths of channel incision, and we identify both first- and second-order thresholds for channel incision.

Once incision begins, channels are commonly described as evolving through four stages: incision of a narrow channel, channel widening, development of an inset floodplain and aggradation (see, e.g., Schumm *et al.*, 1984; Simon and Hupp, 1987; Thorne, 1999). Region-specific channel evolution models vary in the number and details of these stages, but all encompass these four general phases. Incision typically occurs rapidly once it begins, but rates of subsequent widening and aggradation vary widely (Simon *et al.*, 1999; Elliott *et al.*, 1999). The length of each stage and the timing of transitions between stages are a function of bank height and material, erosive forces at the toe of the bank, the capacity of the stream to export failed materials and sediment retention mechanisms (Simon *et al.*, 1999; Elliott *et al.*, 1999). However, there has been little research describing variation in evolution pathways or rates, and little focus on restoration strategies that seek to aggrade channels to the level of their historical floodplains (Pollock *et al.*, 2007). Our second objective, therefore, is to describe basin-scale variation in channel evolution and potential recovery rates. Specifically, we show that published channel evolution models do not adequately describe the observed variation in channel form and evolution. Therefore, we propose a second evolution model to describe channels that do not fit traditional models, and show how channel size and incision depth determine which of two channel evolution models a reach is likely to follow. Finally, we estimate the time required for a channel to aggrade to the elevation of its former floodplain based on published aggradation rates, and examine the potential for decreasing recovery time through restoration actions.

Study Area

We selected a geologically simple study area comprised of two main lithologies, erosion resistant basalt (Mackin, 1961; Lasmanis, 1991) and fine-grained surficial deposits comprised of mainly of silt (Bretz, 1929) (Figure 1). These lithologies produce distinctly different size classes of sediments: mainly silt and finer sediments from the surficial deposits, and mainly gravel and coarser sediments from the basalts. The Walla Walla and Tucannon River basins have their headwaters in the Blue Mountains of southeastern Washington State, USA, which are comprised of Miocene Grande Ronde Basalt (Lasmanis, 1991). The middle and lower portions of the basins are dominated by loess hills and terraces of silt-dominated deposits of the Lake Missoula floods (Bretz, 1929). The glacial Lake Missoula repeatedly formed east of the Rocky Mountains between 15 300 and 12 700 years before present (ybp), when the continental ice sheet dammed what is today the Clark Fork River in northern Idaho (Pardee, 1910; Waitt, 1985). Each failure of the ice dam released a catastrophic flood through the Columbia basin (Bretz, 1923; Baker, 1978; Waitt, 1985), and left deep silt deposits in the backwater of flood flows near the mouth of the Walla Walla River (Bretz, 1923, 1925). Subsequent aeolian erosion of these deposits carried silts eastward to form the loess hills of the Palouse region (Busacca and McDonald, 1994), which cover the majority of the study area. Silt terraces in the lower Walla Walla River are remnants of the Lake Missoula flood deposits (Bretz, 1929).

The Walla Walla and Tucannon Rivers flow from the Blue Mountains into the Columbia and Snake Rivers (Figure 1). Peaks in the Blue Mountains typically exceed 1500 m in elevation, and the Palouse Hills to the west range in elevation from approximately 150 to 650 m. Mean annual precipitation ranges from less than 25 cm yr^{-1} at low elevations in the western portion of the basin to more than 150 cm yr^{-1} at higher elevations in the Blue Mountains (NRCS, 1998). Much of the winter precipitation falls as snow and melts later in the spring. Headwater channels in the study area are generally steep (slope > 0·10), and slopes of the major tributaries in narrow valleys of the Blue Mountains are typically 0·02–0·04. Our study focused on lower elevation streams with wide valley floors and channel slopes typically less than 0·02.

Natural upland vegetation is predominantly sage brush (*Artemisia* spp.) in the western lowlands, grasslands (*Agropyron* spp., *Festuca* spp.) in the Palouse hills and mixed grassland and ponderosa pine (*Pinus ponderosa*) forest in the Blue

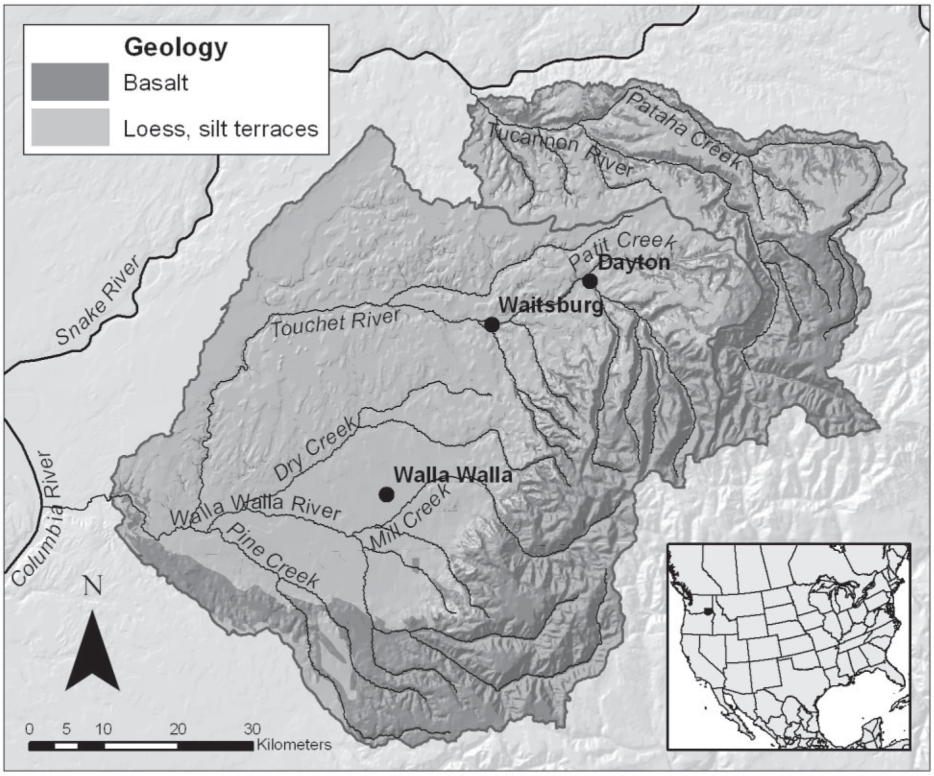

Figure 1. Study area locations and geologic map of the Walla Walla and Tucannon River basins in northwestern USA.

Mountains (Franklin and Dyrness, 1973). Natural riparian vegetation in the lower reaches is dominated by shrubs and small trees, including willow (*Salix* spp.) and red osier dogwood (*Cornus stolonifera*). Sedges (*Carex* spp.) are also common on inset floodplains in the lower reaches. Middle reaches are dominated by hardwood species including white alder (*Alnus rhombifolia*), black cottonwood (*Populus trichocarpa*) and quaking aspen (*Populus tremuloides*). The upper floodplain reaches are dominated by cottonwood, aspen and ponderosa pine.

The historical record indicates that channel incision in the Walla Walla and Tucannon River basins occurred later than 1863, as there was no mention of gullies or incised channels in prior surveys (General Land Office survey notes, 1860–1863). The presence and depth of channel incision varies among tributaries and reaches, with incised channels located predominantly in silt-dominated valley fills and non-incised channels in gravel or coarser valley fills (Figure 2). Erosion of loess soils has been substantial in the past century (Pimental *et al.*, 1995), with as much as 1 m of soil loss in some locations (Figure 3). Upland erosion rates estimated from sediment yields in the 1960s were 146 tonnes $km^{-2} yr^{-1}$ in the Blue Mountains to over 1400 tonnes $km^{-2} yr^{-1}$ in cultivated areas of the Palouse Hills (Mapes, 1969). Most sediment exported from the Walla Walla basin originated in the loess-dominated Dry Creek and Touchet River basins, with the highest sediment concentration (maximum 316 000 mg l^{-1}) recorded in Dry Creek (Mapes, 1969). Suspended load comprised 88–95 per cent of the total sediment load in the mountains, and 92–98 per cent of the load in the lowlands (Mapes, 1969). The suspended load was predominantly silt (60–75 per cent of the suspended load). Erosion control practices implemented since the 1970s are estimated to have reduced sediment yields by approximately 10 per cent from 1970s levels (Ebbert and Roe, 1998). Valley bottom soils are layered, silt-dominated deposits with bulk density of about 1·3 g cm^{-3} (Harris *et al.*, 1964).

Methods

In this study we first focused on determining why some relatively low-gradient (slope < 0·02 m m^{-1}) stream channels in the Walla Walla and Tucannon River basins had incised while others had not. We considered a channel to be incised ('entrenched' in the terminology of Schumm, 1999) when its former floodplain had become a terrace (Pickup and

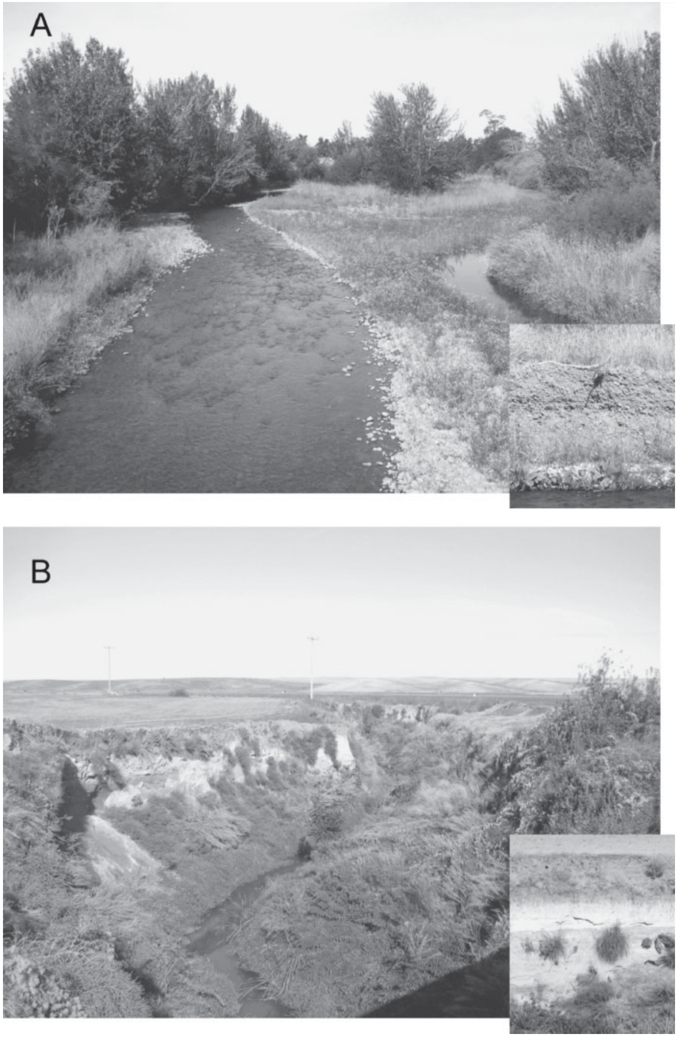

Figure 2. Typical incised and non-incised channels in the study area. (A) Non-incised channel with gravel floodplain (Walla Walla River). Active channel width is approximately 19 m; the inset shows a closer view of gravelly floodplain deposits. (B) Channel incised into cohesive silt deposits (Dry Creek). Active channel width is approximately 2·5 m, incision depth is ~7 m and the top width of the incised channel is ~24 m; the inset shows a closer view of silt-dominated terrace deposits (terrace height is ~5 m).

Warner, 1976), and we could identify a bankfull channel cross-section inset within a larger incised-channel cross-section (Montgomery and MacDonald, 2002). We defined the floodplain as the depositional surface adjacent to a stream that is flooded at least every few years (Dunne and Leopold, 1978), whereas a terrace is a former floodplain that is no longer inundated (Wolman and Leopold, 1957). Our second aim was to determine whether recovery pathways or rates vary among channels, and to explain the utility of using more than one channel evolution model in planning and implementing incised channel rehabilitation efforts. Finally, we estimated recovery time (the time required to refill the incised channel and reconnect it to its historical floodplain), and evaluated whether restoration actions can significantly decrease recovery time.

Channel mapping and measurement

We visited 63 sites in the two mainstem rivers and 10 of their tributaries, and measured key channel dimensions at 45 of these sites with a laser rangefinder (Impulse Laser 200 LR, Laser Technology). At the remaining 18 sites, we noted whether channels were incised or not to aid in mapping the extent of channel incision in the basin. We mapped the spatial extent of incision of 501 km of channel based on cross-section measurements and continuous visual surveys

Figure 3. Deflation of a loess soil surface by as much as 1 m around a cemetery at least 135 years old in the Dry Creek basin (cemetery established ca. 1869). The scarp at the lower right edge of the cemetery is approximately 1 m high, and the scarp near the post is approximately 50 cm high. Maximum erosion rate at this site over the past 135 years averages 0·07 cm yr^{-1}.

between cross-section locations. Where access was difficult and we could not conduct visual surveys between cross-sections (less than 10 per cent of the mapped channels), we inferred incision based on upstream and downstream conditions, and similarity of channel slope and valley floor width in the unobserved reach to slope and valley floor width of upstream and downstream reaches. Channel slopes and valley floor widths were measured from a 10 m resolution digital elevation model. At each of the 45 field sites we measured top width of the incised channel (width at the level of the historical floodplain) and incision depth (depth from historical floodplain to current channel bed) (Figure 4). Where bankfull channel dimensions could be reliably identified (39 of 45 sites), we also measured bankfull width (channel width at elevation of the inset floodplain) and bankfull depth (depth from inset floodplain to current channel bed). We classified the dominant bed, bank and terrace material as silt or finer (<0·063 mm), sand (0·063–2 mm), gravel (2–64 mm), cobble (64–256 mm) or boulder (>256 mm), and described bank and floodplain vegetation. Site locations were recorded with a handheld global positioning system (GPS), and we later used a geographic information system (GIS) to calculate drainage area upstream of each site (A), the proportion of the drainage area mapped as basalt (B) and channel slope at the site (S) from a 10 m resolution digital elevation model.

Relating incision to drainage basin and channel characteristics

We examined the occurrence of channel incision in relation to drainage basin or channel characteristics in two ways. First, we assessed whether mean values of channel slope (S), drainage area (A) or percent basalt (B) differed

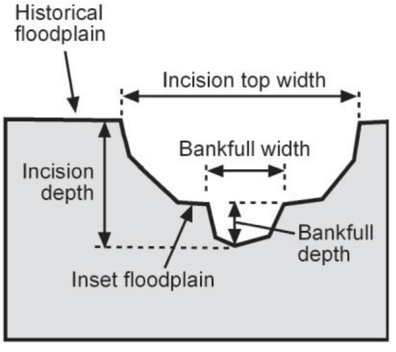

Figure 4. Schematic diagram of incised channel with inset floodplain and bankfull channel, illustrating measurements and terminology used in this paper.

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significantly between incised and non-incised channels. Second, we identified slope–area domains of fine-grained and coarse-grained floodplains to document a potential threshold between the two (similar to slope–discharge thresholds in previous studies, Leopold and Wolman, 1957; Patton and Schumm, 1975; Church, 2002). We expected that channels with lower channel slope and smaller drainage areas would be more likely to accumulate fine sediments on their floodplains historically, and therefore were more likely locations for channel incision.

We examined whether incision depth was related to slope, discharge and percent basalt using regression analysis (Neter *et al.*, 1989). Incision depth was equivalent to depth of fine sediment accumulation, as incised channels cut through the entire fine sediment deposit until reaching a resistant layer (bedrock or paleo-river bed). We regressed sediment depth against individual variables, multiple variables and interaction terms among variables (Neter *et al.*, 1989). We hypothesized negative relationships between depth of accumulated sediment (d_{total}) and channel slope or percent basalt because lower slope reaches should retain more fine sediments and reaches with less of their drainage basin in basalt should have a higher supply of fine sediments (i.e., more of the total sediment load is from loess deposits). We also hypothesized a negative relationship between d_{total} and drainage area because reaches with smaller drainage areas have smaller discharge and should therefore aggrade more rapidly. Finally, we hypothesized that the relationship between d_{total} and the slope–area index (*SA*, channel slope multiplied by drainage area) would be negative because reaches with low stream power (a correlate of *SA*) should retain more fine sediment. Reaches with low percent basalt combined with either low channel slope or low stream power should have the deepest accumulations of fine sediment.

Results

We observed channel incision in over half of the stream length surveyed (259 km out of 501 km), with incision rarely occurring in the mountain valleys (Figure 5). Most channel incision was in the lower portions of rivers and tributaries, where only a small proportion of the drainage basin lithology was basalt (median percentage = 34 per cent basalt), and

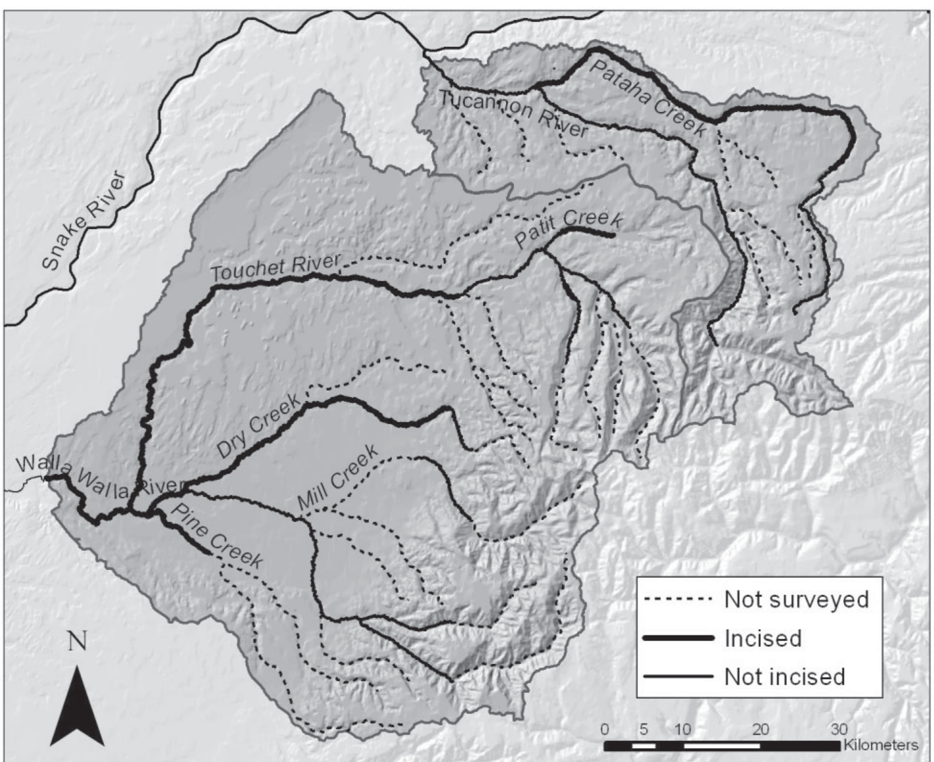

Figure 5. Location and extent of incised and non-incised channels in the Walla Walla and Tucannon River basins. Only the major tributaries were surveyed in this study.

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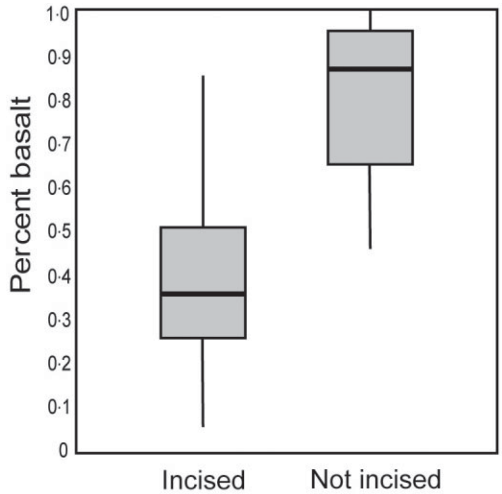

Figure 6. Proportion of drainage basin upstream of incised and non-incised cross-section sites mapped as basalt. Heavy line indicates median value, box indicates inter-quartile range and whiskers indicate range.

sediment source area was dominated by loess deposits. Drainage basins of almost all non-incised channels were dominated by basalt (median = 87 per cent basalt) (Figure 6).

Slope and drainage area clearly distinguished three groups of channels. Channels with slope steeper than about $0{\cdot}1(A)^{-0{\cdot}45}$ had floodplains of gravel and coarser particles, and none of these channels were entrenched (Figure 7). Channels with slope less than $0{\cdot}1(A)^{-0{\cdot}45}$ accumulated thick, valley-filling silt deposits prior to the late 1800s. Of these, only six reaches (on two streams) with slope less than $0{\cdot}15(A)^{-0{\cdot}8}$ were not entrenched, whereas the remaining channels had incised through relatively uniform silt-dominated deposits until reaching either bedrock or the gravel-cobble armor layer of a paleo-channel. We found no gravel or coarser deposits in the silt-dominated strata overlying the paleo-channel bed material, suggesting that channels were not armored with gravel or coarser material during the period of silt accumulation. However, 93 per cent (26/28) of entrenched channels have gravel or coarser beds today, indicating that present-day channels easily transport silt.

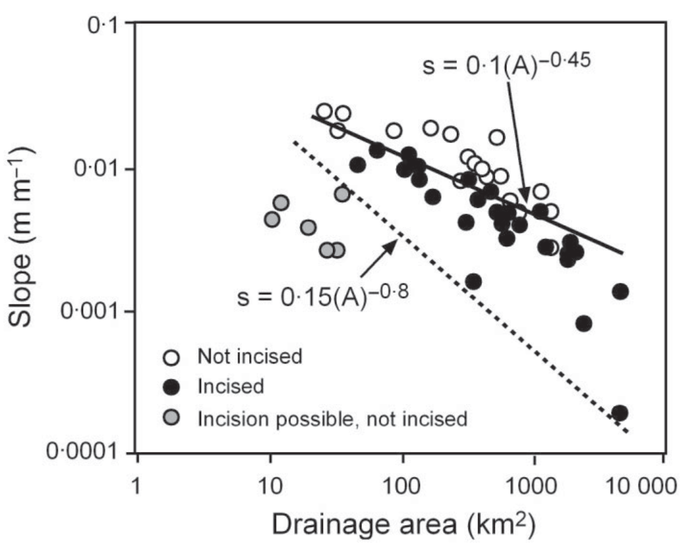

Figure 7. Drainage area and slope plot, illustrating that channels with slope exceeding $0{\cdot}1(A)^{-0{\cdot}45}$ are generally not incised, whereas incised channels tend to have slope less than $0{\cdot}1(A)^{-0{\cdot}45}$. Very small, low slope streams (gray filled circles) are prone to incision (i.e., they have slopes considerably less than $0{\cdot}1(A)^{-0{\cdot}45}$), but are not incised.

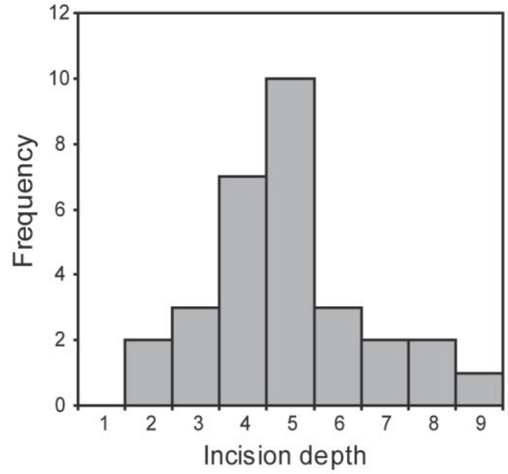

Figure 8. Histogram of incision depths measured at 30 locations in the Walla Walla and Tucannon River basins.

Channel incision depth ranged from 1·8 to 8·3 m, and more than 50 per cent of measured incision depths were between 4 and 6 m (Figure 8). Incision depth was negatively related to both slope ($P = 0{\cdot}02$, $r^2 = 0{\cdot}18$) and percentage of drainage basin in basalt ($P = 0{\cdot}01$, $r^2 = 0{\cdot}22$), but was more strongly related to the interaction term slope multiplied by percent basalt ($d_{\text{total}} = 0{\cdot}93(SB)^{-0{\cdot}21}$, $P = 0{\cdot}0006$, $r^2 = 0{\cdot}36$). This interaction term indicates that reaches with low slope and low percent basalt are most deeply incised, and also that incision depth decreases more rapidly with increasing channel slope where percent basalt is low. Incision depth was not significantly related to either drainage area or the slope–area index, either separately or in combination with other variables (i.e. where either variable was included in interaction terms or a multi-variable model).

Total cross-section areas of incised channels ranged from 18 to 327 m^2, and were on average about one order of magnitude larger than cross-section areas of non-incised channels (Figure 9(A)). Bankfull cross-section areas of incised channels were similar to those of non-incised channels on average, but were more variable (Figure 9(B)). Bankfull width–depth ratios of incised channels were consistently lower than those of non-incised channels (Figure 9(C)), and did not increase with increasing drainage area. By contrast, bankfull width–depth ratios of non-incised channels increased with increasing drainage area.

Channel form varied with drainage area and incision depth, but did not consistently follow idealized channel evolution models (Figure 10). Small channels that were deeply incised had sloped failure deposits buttressing the base of vertical silt banks, and apparently cannot widen and develop significant inset floodplains. These reaches had top width to incision depth ratios less than 6. The mainstem Walla Walla and Touchet Rivers are considerably wider, but the reaches with widest top width to incision depth ratios between 17 and 45) were upstream of reaches that have not yet widened and developed inset floodplains (width–depth ratios between 4 and 12).

Discussion

Our results highlight several new aspects of channel incision and evolution, each of which has important implications for understanding controls on locations of channel incision or for understanding rates and pathways of incised channel recovery. We examine these results and their implications in three parts. First, we discuss how regional patterns of relatively continuous channel entrenchment are controlled predominantly by geomorphic propensity for incision, rather than by the spatial pattern of land uses or channel modifications. To our knowledge, no prior studies have systematically examined a geological control on locations of channel entrenchment, although several studies have examined slope-discharge thresholds for discontinuous gullying (e.g. Patton and Schumm, 1975) or variation in land uses as a control on incision locations (e.g., Thorne, 1999). Second, we describe how rates and pathways of channel evolution vary as a function of channel size and incision depth, and propose a second channel evolution model for channels that do not evolve in a sequence consistent with traditional evolution models. The two models can be used to help identify where channel rehabilitation efforts are most likely to be successful (Shields *et al.*, 1998). Finally, we address the concept of 'recovery time' (Beechie *et al.*, 2000; Beechie, 2001), and estimate how long it may take for channels to reconnect to their historical floodplains both with and without restoration actions.

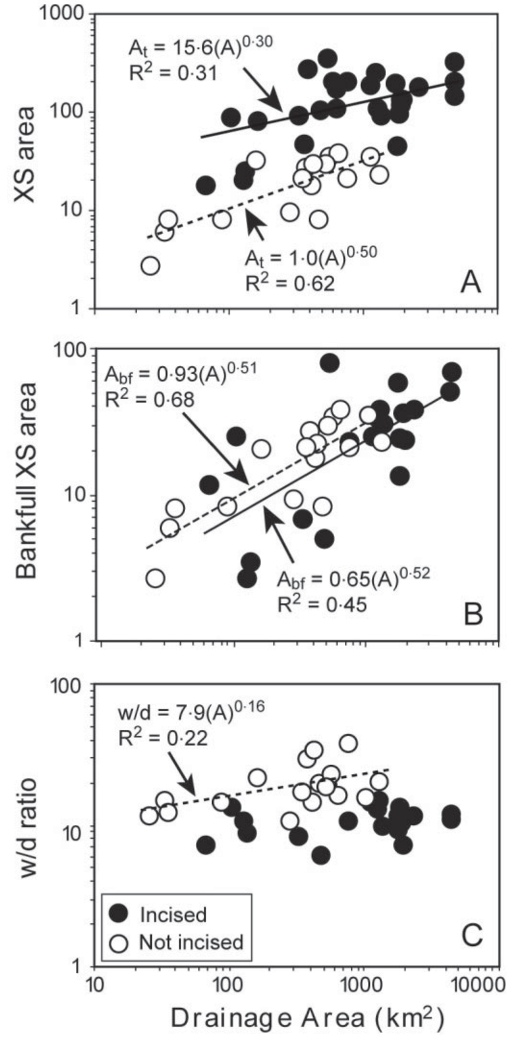

Figure 9. Channel dimensions of incised and non-incised channels: (A) incised channel cross-section area (for non-incised channels, bankfull channel cross-section areas are plotted), (B) bankfull cross-section areas and (C) width–depth ratio of the bankfull channel. Regression equations and R^2 values are shown for significant regressions ($p < 0{\cdot}05$). Variables in equations are total cross-section area of incised channel (A_t), bankfull cross-section area (A_{bf}), width to depth ratio (w/d) and drainage area (A).

Hierarchical controls on channel incision locations and depth

We hypothesized that the spatial pattern of channel entrenchment in the Walla Walla and Tucannon River basins was largely controlled by location of silt-dominated valley fills, which in turn was determined by the availability of fine-grained source sediments and the capacity of reaches to retain fine sediment. Indeed, we found that reaches were prone to incision when their drainage basins were dominated by either loess or silt-dominated deposits of the Pleistocene Lake Missoula floods and had channel slopes less than $0{\cdot}1(A)^{-0{\cdot}45}$. We also observed that the smallest and lowest slope channels had not incised, indicating that some channels prone to incision did not have sufficient flow strength to initiate incision (i.e. those with slope less than $0{\cdot}15(A)^{-0{\cdot}8}$). These results are consistent with our hypotheses that incised channels are found only in silt-dominated-valley fills, that a supply of fine-grained sediment was prerequisite for deep accumulation of silts and that lower energy channels favoured retention of silt and finer sediments on the valley floor.

These results differ from previous studies in that (1) channels prone to incision are below a slope threshold for incision rather than above the threshold and (2) controls on channel incision locations are hierarchical. Previous studies of channel entrenchment and gullying into unchanneled valleys have shown that propensity for incision

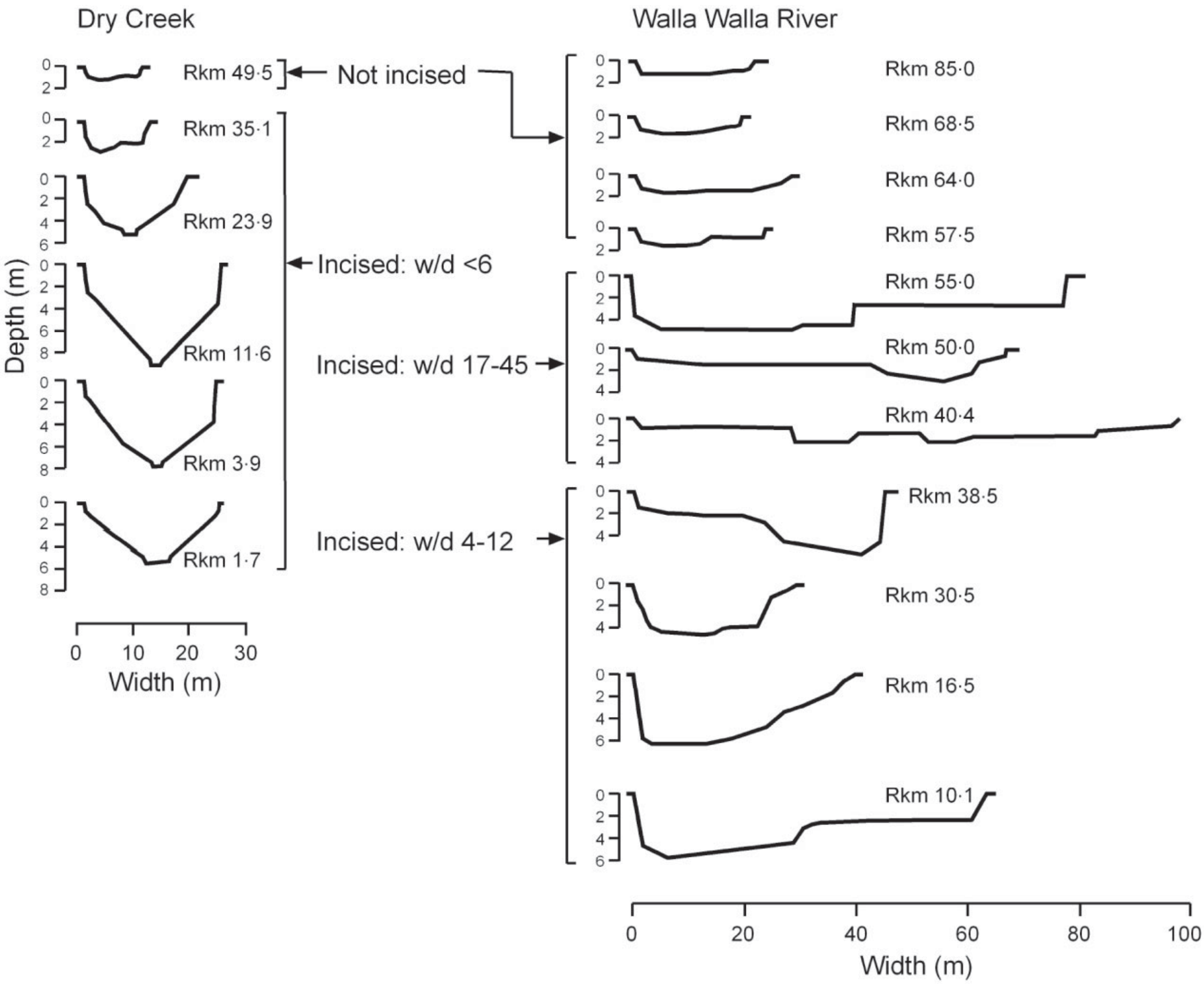

Figure 10. Cross-sections of Dry Creek and Walla Walla River indicate deviations from an idealized channel evolution model. Dry Creek cross-sections illustrate very low top width to incision depth ratios (*w/d*), apparently because small channels cannot export sediment delivered from failing banks and widening is limited. Walla Walla River cross-sections illustrate extreme widening and inset floodplain development in mid-basin, apparently because high gravel bed load supply from upstream reaches forces bank erosion and the large channel easily exports fine sediment from failing banks. Lower Walla Walla reaches have intermediate widening because bed load supply is low, bank erosion is relatively slow and the channel is large enough to export fine sediment from failing banks.

increases with increasing slope or drainage area (e.g. Patton and Schumm, 1975; Prosser and Abernethy, 1996; Montgomery, 1999), whereas we found the opposite. These results suggest differing mechanisms underlying incision thresholds, which in part reflect a lack of clarity regarding the hierarchical nature of controls on channel incision, and in part reflect fundamentally different physical controls on incision locations.

Controls on locations of channel entrenchment are hierarchical in that (1) some reaches are prone to incision whereas others are not (e.g., some of the network cannot be incised because there are no fine sediments through which the channel can erode) and (2) some reaches prone to incision may incise while others do not (e.g., some reaches with fine sediment accumulations will not incise because an incision threshold is not reached). Both types of threshold have been examined in previous studies, although the lack of a hierarchical framework for incision thresholds has made it difficult to ascertain which type of threshold each study addressed. The first-order control has been demonstrated by Patton and Schumm (1975), who noted that locations of oversteepened reaches were controlled by fine sediment accumulation at cross-valley alluvial fans, and that incision tended to occur on the steeper down-valley slope of the fan. Our result is similar in that fine sediment accumulation controlled incision location, but we found continuous incision in long low-slope reaches, which are controlled by relative supply of fine sediment and the ability of channels to retain it. While both results reflect the first-order control of geologic propensity for incision, they differ in geomorphic setting and in processes that control incision locations. Among channels prone to incision, the second-order threshold is essentially one of flow strength. We found that, of the channels that were prone to incision, channels with steeper slope and greater drainage area were incised. This result is similar to those of other studies that have examined this second-order threshold (e.g., Prosser and Abernethy, 1996; Montgomery, 1999), indicating that not all channels prone to incision have sufficient flow strength to initiate incision.

Viewing channel incision thresholds in a hierarchical framework that asks (1) which channels are geologically prone to incision and (2) which of these channels actually incise helps achieve a more comprehensive explanation of patterns of channel incision within drainage basins. This hierarchy also puts previous studies into a broader conceptual context that helps explain relationships among seemingly contradictory results. Comparison of our results with those of other studies illustrates that the first-order geological control on locations prone to incision can produce differences in incision patterns (continuous or discontinuous), as well as differences in apparent incision thresholds (steep or low-slope channels). While these differences in geological controls at first appear contradictory, in both cases channels prone to incision flow through fine-grained valley fills. Hence, propensity for incision is indeed a function of valley fill texture (Cooke and Reeves, 1976; Schumm, 1999), but the spatial distribution of fine-grained valley fills varies with geologic and geomorphic setting (e.g., compare this study with Patton and Schumm, 1975). In examining the second-order control on channel incision, we found that, of channels prone to incision, our slope–area threshold parallels those of other studies. That is, ours and other studies have shown that the second-order control is a flow strength threshold, in which steeper channels are more likely to incise. While the specific slope and discharge values of second-order thresholds will vary among regions and basins, it is clear that this threshold reflects drivers of flow strength (slope and drainage area) (see, e.g., Prosser and Abernethy, 1996; Montgomery, 1999).

All of the incised channels had downcut to either bedrock or paleo-sediments coarse enough to prevent further incision. Because channels incised through the entire fine-grained alluvial fill, the depth of incision was roughly equivalent to the depth of silt deposits accumulated prior to incision. Depth of incision increased with decreasing channel slope and decreasing proportion of the drainage basin mapped as basalt, consistent with our hypotheses of negative relationships between incision depth and channel slope or per cent basalt. However, we did not find significant relationships between incision depth and drainage area or the slope–area index as we had expected, most likely because drainage area was negatively related to both channel slope and percent basalt. Thus, the expected increase in sediment retention at lower discharges was countered by the effects of steeper slope (reduced retention) and higher percent basalt (lower silt supply). Overall, the interaction of slope and percent basalt was the best predictor of incision depth, indicating that the deepest incision was in reaches with both a low channel slope and a sediment source area dominated by erodible, fine-grained materials (i.e. loess and Lake Missoula flood deposits). Thus, first-order geological controls on incision location (high silt loads and relatively low sediment transport capacity) also strongly influenced depths of incision.

Variation in channel evolution pathways

Cross-sections of incised channels in the study area indicate that channels follow at least two different evolutionary trajectories. Small, deeply incised channels tend to retain sediment from collapsed banks, apparently because they are too small to export sediment as rapidly as it is delivered (notably Dry and Pataha Creeks). Thus, these channels tend to resist widening, and develop a distinctive cross-section form with high vertical banks buttressed by failure deposits (Figure 10). These channels have bankfull widths roughly equal to or less than incision depth (Figure 11) and are likely to evolve slowly and begin aggrading prior to substantial widening. In other words, these channels follow an evolution model that differs from typical models in that there is no significant widening after incision (Figure 11). An alternative model for these channels (referred to here as Model I) includes (a) pre-incision, (b) degrading, (c) degrading and limited widening and (d) aggradation controlled by dense vegetation anchoring failure deposits at the base of the banks. While this model bears some similarity to the model for small and medium sized arroyos illustrated by Elliot *et al.* (1999), it differs in its lack of a distinct widening phase prior to the onset of aggradation.

In channels with bankfull width larger than incision depth, flow strength is sufficient to export fine-grained sediment entering the channel from bank failures (e.g. Touchet River and lower reaches of the Walla Walla River) and channels exhibit a characteristic widening phase after incision (Model II in Figure 11). Hence, Model II is described by (a) pre-incision, (b) degrading, (c) degrading and widening, (d) aggrading and widening and (e) quasi-equilibrium. Reaches following Model II in our study have widened to varying degrees, but the widest reaches tend to be upstream of narrower reaches – the opposite of patterns observed elsewhere (see, e.g., Schumm *et al.*, 1984; Elliott *et al.*, 1999). The upstream reaches have top width to incision depth ratios between 17 and 45, whereas the narrower downstream reaches have top width to incision depth ratios of 6–12. Nevertheless, both upstream and downstream reaches exhibit

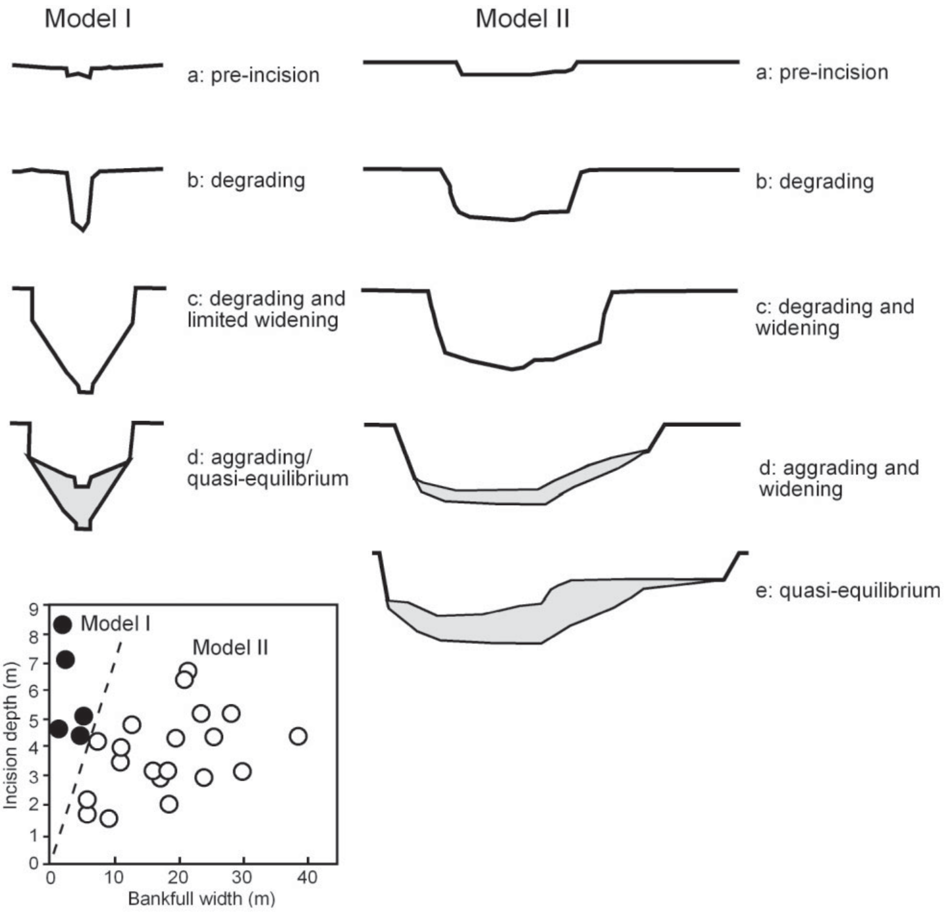

Figure 11. Alternative channel evolution models for entrenched channels in the Walla Walla and Tucannon River basins. Model I differs from published channel evolution models in its lack of a significant widening phase. Model II is similar to those of Simon and Hupp (1987) and Schumm *et al.* (1984). Model I applies to small, deeply incised channels (filled circles in graph, lower left), whereas Model II applies to larger channels (open circles).

a widening phase after incision, so we consider both to follow Model II, albeit at different rates. Both trajectories are similar to previous evolution models (see, e.g., Schumm *et al.*, 1984; Simon and Hupp, 1987), and differences between the two reaches resemble differences between channel evolution models for large and small arroyos (Elliott *et al.*, 1999).

A common explanation for differences in the degree of widening of incised channels is that channels incised into relatively cohesive materials tend to deepen more and widen less than channels incised into less cohesive materials (Schumm, 1999). However, all channels in our study have incised into similar silt-dominated fills. Hence, variation in valley fill texture does not explain variation in width–depth ratios of incised channels. Rather, this variation is largely explained by relative supply of non-cohesive bed load from upstream. The wide, upstream reaches have large gravel bars and relatively weak armoring of the bed, indicating a substantial supply of bed load from upstream (Dietrich *et al.*, 1989; Montgomery and MacDonald, 2002). In these reaches, the inset bankfull channel is formed in non-cohesive gravels, which favors a wide, shallow form and high lateral migration rates (Schumm, 1985; Thorne and Osman, 1988; Eaton *et al.*, 2004; Beechie *et al.*, 2006). Both factors force more rapid bank erosion and contribute to rapid widening of the incised channel. Bed load supply decreases in the downstream direction due to particle attrition and decreasing gravel sediment sources, so narrower downstream reaches exhibit none of the indicators of high bed load supply and have narrower width-to-depth ratios. These reaches still exhibit a widening phase, but widen more slowly than the upstream reaches. Hence, the downstream sequence from (1) non-incised channel to (2) wide incised channel to (3) narrow incised channel (see Figure 10) reflects a gradual transition from gravel-dominated to silt-dominated valley fills, which in turn reflects a decreasing supply of bed load to the channel.

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Our identification of two channel evolution models implies that planning incised channel rehabilitation based on stage of evolution (Shields *et al.*, 1998; Watson *et al.*, 2002) should consider potential errors introduced by reliance on a single evolution model. Some planning approaches assert that stream rehabilitation should not begin until after a channel has reached the widened and aggrading stage (Stage D in our Model II), which helps to avoid failure of in-stream wood or boulder structures by undercutting or rapid widening (see, e.g., Shields *et al.*, 1998). This approach is based largely on traditional channel evolution models characterized by a distinct widening phase after incision, and on the assumption that widened channels have achieved a new equilibrium (Schumm *et al.*, 1984; Harvey and Watson, 1986; Bledsoe *et al.*, 2002; Brooks *et al.*, 2003). While this approach can be readily applied to our Model II channels, we also identified a second channel evolution pathway that does not include the commonly cited widening phase. Hence, application of this criterion in our study area would mean that channels evolving along the Model I pathway might never be targeted for rehabilitation because they appear to be at an early stage of evolution. In fact, incision and widening appear to have ceased in our Model I channels (i.e., they are at Stage C in Figure 11), and rehabilitation efforts may be no more likely to fail than rehabilitation structures installed in Model II channels that are at Stage D. Therefore, it is important to recognize which evolution model a channel follows and to adjust rehabilitation planning criteria accordingly.

Recovery time and potential restoration of incised channels

Efforts to rehabilitate incised channels have commonly focused on improving conditions within the incised channel (Shields *et al.*, 1995, 1998, 2004; Watson *et al.*, 2002), rather than considering reconnecting the channel to its historical floodplain. Perhaps because of this focus, there has been little effort towards estimating how long it will take for incised channels to aggrade to the level of their former floodplains (Elliot *et al.*, 1999), or how one might enhance sediment retention to achieve such an objective (Pollock *et al.*, 2007). Both are critical questions in planning stream rehabilitation efforts, as recovery time and restoration techniques both influence cost-effectiveness of restoration efforts (Beechie *et al.*, 1996). Here we examine recovery time of incised channels in the study area, focusing on how such calculations might influence restoration decisions.

The concept of recovery time is important in restoration planning, both for assessing feasibility of specific types of restoration effort and for setting appropriate expectations for restoration outcomes (Beechie *et al.*, 2000; Beechie, 2001). Recovery time can be generally defined as the time required to transition from a 'degraded' state to a state resembling a 'reference' condition. This reference condition is not necessarily static. Rather, it implies a state of natural geomorphological and ecological function similar to that expected when human impacts are absent (Beechie *et al.*, 1996). Here we estimate recovery time for incised channels, defining recovery time as the time required to reconnect incised channels to their historical floodplains.

Complete filling of entrenched channels and reconnection of the historical floodplain has historically occurred on timescales of hundreds to thousands of years (Elliott *et al.*, 1999), and published long-term aggradation rates (1000 years or more) are on the order of 10^{-2} cm yr^{-1} (Table I). Such aggradation rates are too slow to aggrade most incised channels in our study area in less than 10 000 years. However, published aggradation rates measured over the last

Table I. Published long-term (>1000 years) and recent (<200 years) average aggradation rates of channels and floodplains

Location	Aggradation rate (cm yr^{-1})	Citation
Long-term rates (>1000 years)		
Cann River, Australia	0·01	Brooks *et al.*, 2003
Upper Mississippi Valley, USA	0·02	Knox, 1987
Bega River, Australia	0·08	Brooks and Brierly, 1997
Short-term rates (<200 years)		
Cache River, AR, USA	1·0	Kleiss, 1996
Bega River, Australia	1·3	Brooks and Brierly, 1997
Rio Puerco, NM, USA	1·6–5·2	Elliott *et al.*, 1999
River Garrone, France	0·5–2·5	Steiger *et al.*, 2000
Upper Mississippi Valley, USA	0·3–5·0	Knox, 1987
Coon Creek, WI, USA	0·5–15	Trimble, 1999
Bridge Creek, OR, USA	4–48*	Pollock *et al.*, 2007

* Rate of channel and floodplain aggradation upstream of beaver dams in incised channels.

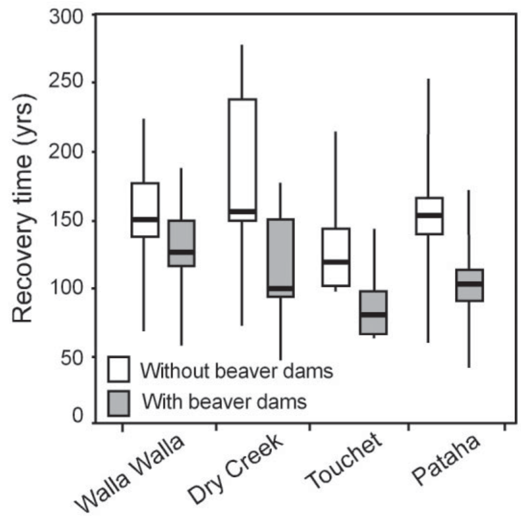

Figure 12. Box and whiskers plot of estimated recovery time (time required for the channel to aggrade to the level of its historical floodplain) for all sites in each of the four main river channels, both with and without restoring modest beaver populations. Heavy line indicates median value, box indicates inter-quartile range and whiskers indicate range. See text for explanation of recovery time calculations.

several decades are 10^{-1}–10^{1} cm yr^{-1} (Table I), one to three orders of magnitude higher than long-term aggradation rates. At these aggradation rates, channels may aggrade to their historical floodplains within decades to centuries (Elliott *et al.*, 1999). A simple assessment of which channels are likely to have relatively short recovery times (t_r) can be made assuming a modest aggradation rate based on literature values (Δd, in m yr^{-1}) and using a simple equation that relates incision depth (d_{total}, in m) to recovery time:

$$t_r = \frac{d_{total}}{\Delta d} \tag{1}$$

Assuming a relatively low aggradation rate in incised channels of the Walla Walla and Tucannon basins (~0·03 m yr^{-1}), recovery time could be as short as 40 years where incision is modest (<2 m deep) or more than 200 years in deeper channels (>7 m deep) (Figure 12). Such recovery periods are comparable to those of riparian forests and channel morphology in humid landscapes (Murphy and Koski, 1989; Beechie *et al.*, 2000), as well as to those of aggraded channels where sediment supply has significantly increased (Pitlick and Thorne, 1987; Harvey, 1987; Madej and Ozaki, 1996; Beechie, 2001). Hence, projected recovery times are within typical management time frames, suggesting that restoring entrenched channels may be a feasible restoration goal.

Recovery time of incised channels may be reduced by increasing retention of suspended sediment through restoration actions, or by simply allowing natural recovery processes to occur (Pollock *et al.*, 2007). For example, beaver recolonization and construction of beaver dams in the incised channel of Bridge Creek, OR, has led to local aggradation rates as high as 0·45 m yr^{-1} and average retention rates of approximately 0·10 m yr^{-1} (Pollock *et al.*, 2007). These rates are roughly one order of magnitude higher than most published aggradation rates. To illustrate the effects that restoring beaver populations could have on recovery time of incised channels in our study area, we estimated recovery time with and without beaver dams for each reach in the four largest incised channels. Using the relatively low aggradation rate of 0·03 m yr^{-1} as above, we estimated that recovery time without beaver dams ranges from 60 to 270 years across all sites (Figure 12). However, allowing even low densities of beaver dams (two dams per kilometer of stream on average, Pollock *et al.*, 2004) – each of which traps an average of 171 m^3 of sediment per year (Pollock *et al.*, 2007) – would decrease recovery time to 40–186 years (a decrease of 17–33 per cent).

These calculations are obviously oversimplified, and do not consider whether sufficient sediment is supplied to these channels to achieve the estimated aggradation rates. Estimates of annual storage volume required to sustain an aggradation rate of 0·03 m yr^{-1} (without beaver dams) ranged from 28 500 to 82 400 m^3 yr^{-1} (Table II), and adding beaver-dam storage increases the range of estimates to 44 900–113 900 m^3 yr^{-1}. These values are a relatively small proportion of annual sediment yields, ranging from 3·0 per cent to 11·8 per cent of annual yield without beaver dams,

Table II. Annual storage volumes and percentages of annual sediment yield required to sustain an aggradation rate of 0·03 m yr^{-1} (without beaver dams), and the same aggradation rate plus beaver-dam storage of 171 m^3 yr^{-1} at a frequency of 2 dams km^{-1}. Sediment yields are based on mid-range values for each basin from Mapes (1969), with downward adjustments of 10 per cent to account for recent land use changes (Ebbert and Roe, 1998)

	Incised channel volume (m^3)	Annual sediment yield (m^3)	Annual storage without beaver dams (m^3) (per cent of annual yield)	Annual storage with beaver dams (m^3) (per cent of annual yield)
Walla Walla River	8 897 000	2 145 000	65 200 (3·0%)	78 600 (3·7%)
Dry Creek	5 559 000	633 000	28 500 (4·5%)	44 900 (7·1%)
Touchet River	11 262 000	1 519 000	82 400 (5·4%)	113 900 (7·5%)
Pataha Creek	6 765 000	320 000	37 600 (11·8%)	56 500 (17·7%)

and from 3·7 per cent to 17·7 per cent with beaver dams. These percentages are consistent with sediment retention rates measured elsewhere (14 per cent; Kleiss, 1996), indicating that our recovery time estimates are plausible given current sediment yields and typical aggradation rates. Hence, it appears reasonable to consider a restoration option that seeks to aggrade incised channels to the level of their historical floodplains, at least for channels with relatively shallow incision depths and high sediment yields.

Conclusions

Our study makes three novel contributions to the study of incised channels. First, we have shown that controls on the spatial pattern of incision in river basins are hierarchical, with a first-order geological control on location of channels prone to incision, and second-order control representing flow strength and the ability of channels to incise into cohesive materials. Channels prone to incision in our study area are below a slope–area threshold (in contrast to other studies, in which channels prone to incision are above a slope threshold), and channels prone to incision have incised only where they exceeded a second slope–area threshold. Second, we have shown that some incised channels do not follow the common channel evolution model characterized by a distinct widening phase after downcutting has ceased. These channels do not have sufficient flow strength to export sediments entering the channel from bank failures, which results in accumulation of failure deposits at the base of banks and prevention of channel widening. Thus, a second channel evolution model is required to adequately describe their recovery pathway, and this second model lacks a distinct widening phase. Recognition of which channel evolution model a particular reach is likely to follow is important in determining when a channel has reached an evolutionary stage at which rehabilitation efforts are appropriate. Finally, we apply the concept of ‘recovery time’ to incised channel restoration, illustrating that the time required to reconnect incised channels to their historical floodplains ranges from 60 to 270 years with modest sediment retention rates. Moreover, simple restoration actions such as allowing or encouraging recolonization by beaver can reduce recovery time by up to 33 per cent.

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