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Flood flow attenuation diminishes cottonwood colonization sites: an experimental test along the Boise River, USA

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ABSTRACT

The Boise River in southwest Idaho, USA, flows from forested mountain headwaters to the sagebrush steppe where the river was first regulated in 1909 for irrigated agriculture. Large upstream dams constructed in 1915, 1950, and 1955 are now operated to manage water for both irrigation and the attenuation of flood flows. This, in combination with bank armoring and channelization, has produced a narrowed river channel with simplified morphology. After damming, the native black cottonwood forest, *Populus trichocarpa*, expanded onto positions previously within the active channel. Since then, sexual reproduction of these cottonwoods appears to have become limited, apparently because of the lack of colonization sites devoid of competing vegetation. We investigated this hypothesis by constructing a channel that simulated recruitment sites previously formed by flood flow events. We observed extensive black cottonwood seedling recruitment along this channel in contrast to nearby reference sites where there were no seedlings, only saplings that originated as clonal root suckers. We conclude that the attenuation of flood flows has removed the geomorphic disturbance that previously created sites for colonization. As a consequence, the forest currently propagates primarily by clonal suckering that fails to introduce genetic diversity essential for adapting to change in the environment. To compensate for this loss, we recommend selective clearing and regrading of the floodplain according to an engineered design as one method to create cottonwood colonization sites.

KEY WORDS black cottonwood; *Populus trichocarpa*; riparian restoration; dams; hydrology; Intermountain West; wetlands; rivers; seedlings; clonal reproduction

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INTRODUCTION

Growing on the river floodplains of the North American Intermountain West, black cottonwood, *Populus trichocarpa* (syn. *Populus balsamifera* ssp. *trichocarpa*) is the dominant tree and a keystone species in the plant community. Although limited in spatial distribution, these riparian forests are ecologically rich. In Idaho, USA, for example, the black cottonwood forest occupies only 0·2% of the land area but is ranked by the US Fish and Wildlife Service as the fourth most important habitat type (Boccard, 1980). Their determination is based on the presence of threatened, endangered, and endemic wildlife; ecosystem services and habitat values; wildlife abundance and diversity; and the degree of risk to these natural qualities. It is also ranked as the fourth most inadequately protected habitat type within the state (Boccard, 1980).

In other regions of western North America, riparian cottonwood forests composed of various *Populus* species have been weakened in health downstream from dams (Fenner *et al*., 1985; Bradley and Smith, 1986; Friedman *et al*., 1998; Williams and Cooper, 2005). This has resulted, in part, from drought stress because of deficient in-stream flows, abrupt declines in river stage and corresponding alluvial groundwater levels, and reductions in the quantity of transported sediments (Scott *et al*., 1999; Amlin and Rood, 2002; Rood *et al*., 2013).

While drought stress and declines in river stage have been shown to lead to the collapse of cottonwood forests, we believe a more gradual deterioration in woodland health results from other changes in flow regulation, particularly that from the attenuation of flood flows (Wilding *et al*., 2014). Flood flows provide the geomorphic disturbance that causes erosion of earth, and the transport and deposition of sediments responsible for creating barren sites suitable for cottonwood colonization (Auble and Scott, 1998; Polzin and Rood, 2006). Floods are therefore essential for the periodic recruitment of seedlings of riparian cottonwoods and willows (Scott *et al*., 1997;

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Samuelson and Rood, 2004). In addition, high flows recharge the alluvial groundwater table and provide patterns of river stage that locate seedlings at elevations high enough to avoid scour by movement of ice or flood flows in following years (Kalischuk *et al*., 2001; Dixon, 2003). Further, periodic high flows discourage the encroachment of flood intolerant upland vegetation that competes with cottonwood and willow seedlings in the intermittently inundated, parafluvial zone (Polzin and Rood, 2000).

We recognized a unique opportunity along the lower Boise River to investigate the influence of river regulation on the recruitment of black cottonwood and designed a manipulative study to test the hypothesis that with flood flow attenuation the scarcity of colonization sites due to a lack of geomorphic disturbance limits seedling recruitment.

The Boise River in southwest Idaho (Figure 1) is typical of many in the intermountain region of western North America that have been dammed and their flows regulated. The North, Middle and South Forks of the Boise River originate in high elevation, mountainous terrain where winter ends in most years with a deep snow pack. Melting of this snow contributes much greater volumes of water to the lower reaches of the river in spring and summer than that from local precipitation in the semi-arid, lower elevation valley. Here, a broad alluvial floodplain supports an extensive riparian cottonwood forest, which by legend led early French fur trappers to proclaim as they arrived ‘les boisé, les boisé’, translated to ‘the trees, the trees’. This is said to be the origin of both the name of the river and the City of Boise.

The Boise River is now controlled by three major dams that were constructed and originally operated to irrigate what once were large tracts of the high desert sagebrush steppe. However, with downstream population growth and urban development, flood control has become increasingly important (Figure 2). Diversion dam was placed into operation in 1909. It enables irrigation diversions into the large (68 m^3/s) New York Canal, but provides minimal water storage. In contrast, the large upstream reservoirs impounded by Arrowrock (1915), Anderson Ranch (1950), and Lucky Peak (1955) dams together store approximately 120 000 ha m of water (US Bureau of Reclamation, 2014), which approximates the average annual snow pack in the watershed.

Below the diversion dam, the river emerges from the mountains to form a broad floodplain that has been altered over the past century by forest clearing for agriculture and ranching, the construction of dikes and levees to restrict overbank flows, channelization to straighten the bed of the river and reduce friction along its banks, and more recently by urbanization (Stacey, 1993). In spite of this, biodiverse remnants of the black cottonwood gallery forests persist along the lower Boise River corridor.

Using cadastral survey notes and interpretations of historic aerial photographs, MacCoy and Blew (2005) compared the channel morphology of the lower Boise River before and after damming. They observed that prior to damming, the natural channel was a complex sequence of meanders and braids with numerous, elongated midchannel islands. Within the active channel, an abundance of parafluvial surfaces, unvegetated bands composed primarily of river cobbles and sands, were inundated for only parts of most years.

With damming, the morphology of the channel was altered and is now largely a sequence of runs, riffles, and

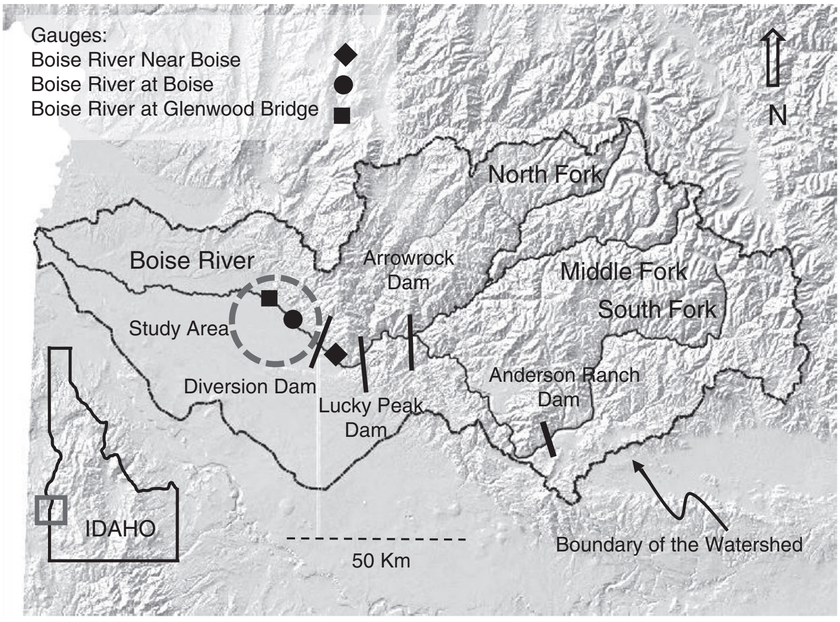

Figure 1. Locations of the Boise River watershed, study area, and dams. Hydrometric gauges are shown in accordance with Table I.

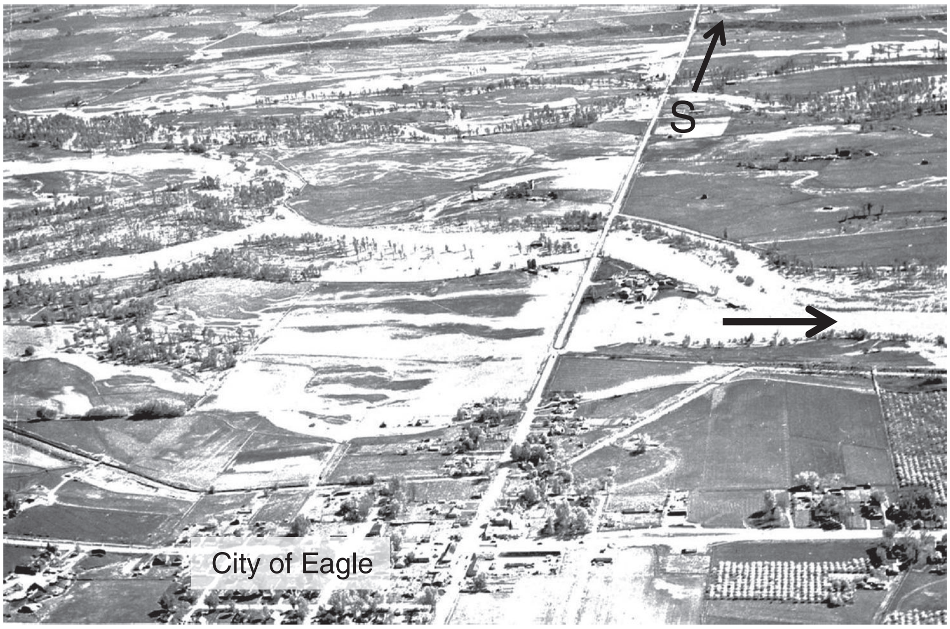

Figure 2. Oblique aerial photograph of the lower Boise River (river mile 43·8), 20 April 1943, below the City of Boise near Eagle, Idaho (at the lower, left edge of the photograph). This was the last flood flow prior to attenuation by Arrowrock, Anderson Ranch, and Lucky Peak dams combined. Source: USDI Bureau of Reclamation.

pools; with few islands and sloughs; and limited braiding. Because the upriver dams have prevented the downstream transport of alluvial sediment, the bed of the river has become armoured with rock cobble. Areas of gravel appropriate for salmonid spawning are either absent or embedded with fine sediment (Asbridge and Bjornn, 1988). Initial stabilization of the channel resulted in groves of black cottonwood expanding onto the channel in what were formerly dynamic, parafluvial surfaces (MacCoy and Blew, 2005). In recent time, that expansion has ceased because available colonization sites that were protected from scour by river regulation are now fully occupied by riparian vegetation. MacCoy and Blew (2005) attribute the present lack of parafluvial surfaces along the lower Boise River to the control of extreme river flow events. They estimate that the present average bank full width of the channel (43 m) is less than one quarter of its historic width prior to regulation (~275 m) and attribute this solely to flow attenuation and woodland expansion.

The US Bureau of Reclamation operates Arrowrock and Anderson Ranch dams, and the US Army Corps of Engineers operate Lucky Peak Dam in coordination, with a goal of limiting peak flow to 184 m^3/s at the Glenwood Bridge gauge below the City of Boise (Department of the Army and Department of the Interior, 1956). This approximates the current bank full condition or Q_2 event, the event likely to occur once every 2 years. They have successfully controlled flood flows to such extent that it is unlikely that the lower Boise River can now provide the geomorphic disturbance required to produce the barren areas required for cottonwood seedling recruitment. In its absence, seeds instead fall on areas unsuitable for their germination, growth, and survival. While asexual reproduction by suckering – sprouting from the roots and base of stems – may continue (Kaltenecker *et al*., 1994; Gom and Rood, 1999), trees grown by asexual reproduction, or cloning, may lack the vigour of those grown from seed and do not contribute to the genetic diversity essential for the long-term fitness of the population (Reed and Frankham, 2003).

Various methods have been proposed for restoring riparian forests along regulated rivers (Malanson, 1993) including the following: (1) deliberate re-regulation of downstream flows to enable seedling recruitment (Hughes and Rood, 2003; Rood *et al*., 2003, 2005; Bhattacharjee *et al*., 2006; Hall *et al*., 2011); (2) localized inundation of the floodplain to simulate river flooding (Molles *et al*., 1998); (3) planting cottonwood seedlings, saplings and clonal stem cuttings (Briggs and Cornelius, 1998; Stanturf *et al*., 2009); and (4) the physical manipulation of the floodplain surface to provide barren colonization sites (Friedman *et al*., 1995; Taylor *et al*., 1999, 2006; Sprenger *et al*., 2002). However, each method has its limitations.

The periodic release of large volumes of water to inundate the floodplain and the ramping of high flows is not practicable on many rivers due to conflicting demands for amount and time of delivery of stored water. While high flow events on regulated rivers may occasionally offer opportunities for functional flows and restoration of the riparian environment (Rood *et al*., 1998; Bovee and Scott, 2002), it is seldom permissible to deliberately allow their delivery because of the potential damage to infrastructure and development in the floodplain. And, supplemental irrigation water that is often required for nursery grown container plants and stem cuttings may be unavailable or difficult to deliver.

With this study, we investigate the fourth method of restoration, physical manipulation of the floodplain to create ground surfaces suitable for seedling colonization. Our observations of the black cottonwood forest over the past two decades and our examination of historic river flows have led us to believe there is presently a lack of seedling recruitment, and we hypothesize this is attributable to a scarcity of barren areas free of competing vegetation normally produced by geomorphic disturbance. We tested this hypothesis by experiment, with the excavation of an engineered channel adjacent to the lower Boise River that, in part, mimicked the effect of flood disturbance. We sought to determine whether the black cottonwood forest retained the ability for sexual reproduction and developed two overlapping hypotheses: H_1: Sexual reproduction of black cottonwood has been diminished because of the attenuation of flood flows resulting in a static river channel and floodplain with limited sites for colonization and, subsequently, H_2: The excavation of a channel with barren, moderately sloping banks could provide colonization sites and enable local recruitment of black cottonwood seedlings.

METHODS

Historic hydrology

The lower Boise River – regulated river flows. We compiled a 100-year historic record of river discharge for the lower Boise River below the City of Boise by coordinating composite records from three US Geological Survey hydrometric gauges (Table I). Our analysis is somewhat confounded by a lack of complete data accounting for diversions into irrigation canals. However, this is a minor inaccuracy because floods typically occurred during late spring when irrigation diversions were minimal. Water masters commonly closed gates at these times to avoid damage to canals and to prevent the introduction of suspended sediments into the irrigation system. We assessed peak flows within this composite, as measured by maximum annual mean daily discharge, and compared the recurrence of these flows for intervals of time both before and after 1955, when Lucky Peak Dam was placed into operation and river managers considered the river to be under their control (Figure 3).

We then compared daily hydrographs over the past century, both prior to and after damming, and display two examples covering 4-year intervals (Figure 4). The hydrograph for the free flowing river is represented by the interval from 1901 to 1904, which preceded the three major upstream dams. The hydrograph for the interval from 1991 to 1994, typical of the postregulation condition, coincides with construction and operation of the constructed channel and the gathering of data for our study.

The upper Boise River – a reference system. We also analyzed Boise River discharge near Twin Springs, upstream of Arrowrock Reservoir (Table I, Figure 5) to determine if factors other than river regulation have influenced recent

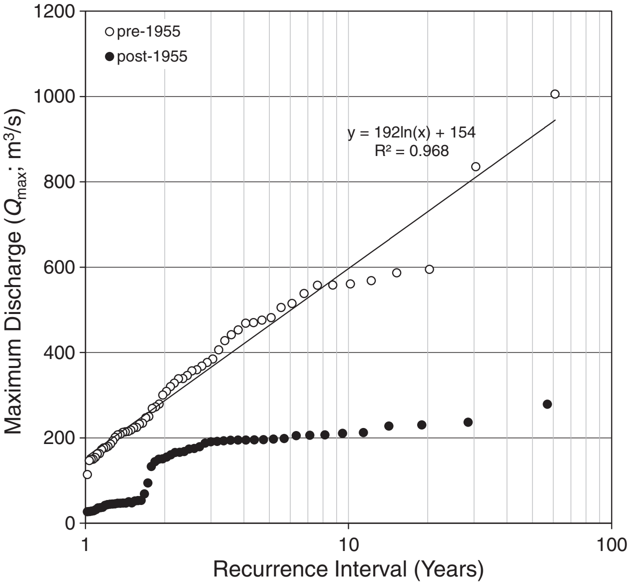

Figure 3. Recurrence interval for annual peak discharge for the lower Boise River for the interval from 1895 to 1954 (o) versus 1955 to 2013 (●), after Lucky Peak Dam was placed into operation.

Table I. US Geological Survey hydrometric gauges investigated, sequenced from upstream to downstream along the Boise River.

Number	Name	Interval	Comment
13185000	Boise R nr Twin Springs	1911–2013	Upstream of study area, unregulated and above inflow from South Fork
13202000	Boise R nr Boise	1895–1916; 1950–2013	Downstream of dams and above diversion canals
13205500	Boise R at Boise	1940–1982	Below major diversion canals
13206000	Boise R at Glenwood Bridge	1938–1940; 1982–2013	

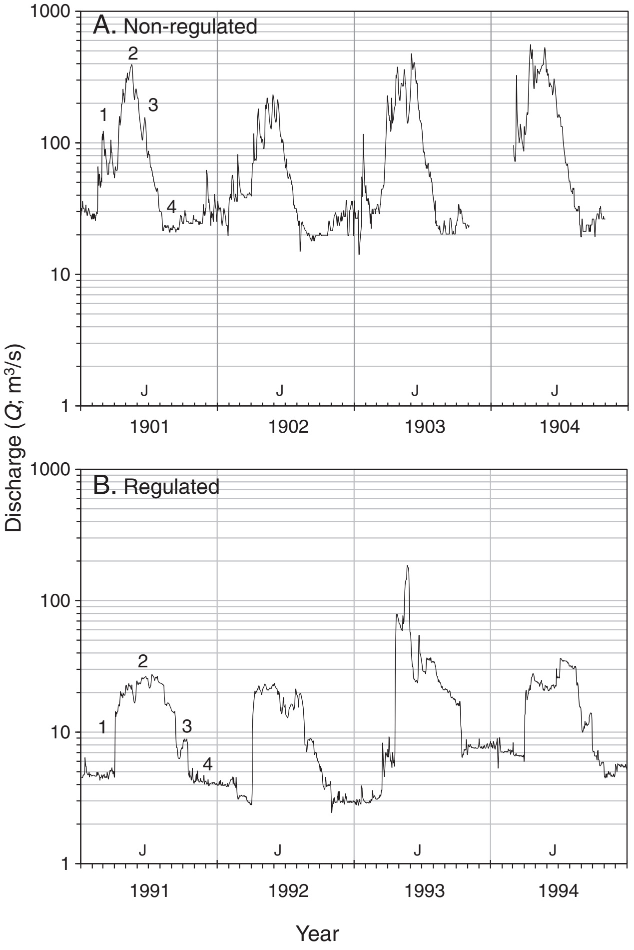

Figure 4. Hydrographs displaying 4 years of daily discharge for the lower Boise River near Boise, from 1901 to 1904, prior to operation of the three major dams (top, with incomplete winter data), and for 1991 to 1994, during and after construction of the experimental channel (bottom). For the first year of each plot the numbers shown indicate the components of the hydrograph including the following: (1) rising limb, (2) peak, (3) falling limb, and (4) low autumn flow (J=June).

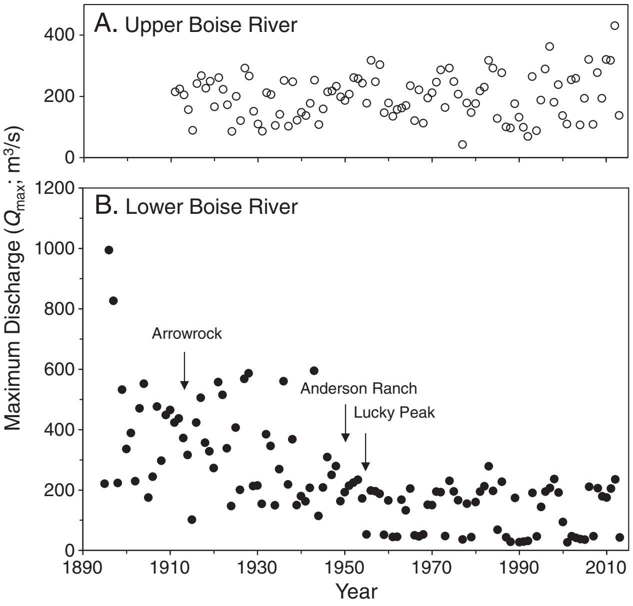

Figure 5. Annual peak discharge (maximum mean daily Q) for the periods of record for the upper Boise River upstream from the three major dams (top) and the lower Boise River near Boise. The years each of the dams was placed into operation are shown.

flows. Measurements at this gauge represent the combined flows of the North Fork and Middle Fork, but not the South Fork of the Boise River. A continuous, 100-year historic record exists (1911–2012) for river flows at this location that is unaltered by dams or diversions. The watershed upstream from the gauge is in Federal ownership and administered by the US Forest Service. It is located in mountainous terrain and fairly remote, but has been impacted by logging, fire, and catastrophic debris flows from tributaries. We thought this historic record of discharge had the potential to reveal hydrologic patterns due to natural oscillations in climate or more directional climate change (Rood *et al*., 2008).

Opportunities for functional flows and restoration of the riparian environment. We analysed river stage and discharge data for the lower Boise River at Glenwood Bridge, the US Geological Survey hydrometric gauge closest to the experiment, to explore the effects of river management both during and after the duration of the constructed channel experiment. Hydrographs of river stage were compared with the hydrologic requirements for recruitment of cottonwood seedlings as described by the recruitment box model (Amlin and Rood, 2002; Braatne *et al*., 2007; Stella *et al*., 2010). Because the channel of the lower Boise River is composed mainly of coarse alluvia, has moderate gradient, and presently supports stands of black cottonwood we judged an elevation range from 0·6 to 2·0 m above the base stage as a reasonable estimate of the likely band for seedling recruitment (Polzin and Rood, 2006). We assumed base stage of the river to be the same as typical annual low flow – a measured gauge height of approximately 1 m – and therefore subtracted 1·0 m from measured gauge height to estimate river stage above this base. We observed cottonwood and willow seed release over numerous years to thoughtfully consider the role of phenology in our study (Amlin and Rood, 2002).

Construction of the experimental channel and assessment of colonization by black cottonwood

With the assistance of others, and as part of compensation required by §404 of the Clean Water Act for the loss of wetlands, we together designed and constructed an experimental channel in the late winter and spring of 1991. The channel was located at river mile (RM) 38·2 (river miles are historically mapped for this system: 1 mile = 1·6 km) immediately downstream from Linder Road in Ada County, Idaho. The constructed channel was 975 m long, approximately 15 m wide and varied in depth from approximately 1–2 m. It was aligned parallel to the lower Boise River and approximately 10 m, measured horizontally, distant from the ordinary high waterline (OHWL) of the river as shown by scour lines, drift marks, sediment deposits, and water marks on tree trunks (Environmental Laboratory, 1987). The OHWL represents the recent high flow stage and for this river approximates the Q_2 event.

The constructed channel was designed to replicate the physical characteristics of a meandering river with bends spaced apart from one another by five to seven times the width of the channel. Along the convex flank of each bend, the bank was constructed at a 10:1 slope. Along the corresponding concave flank of the same bend, the bank was constructed at a 3:1 slope. Its final appearance in cross section, perpendicular to flow was that of a trapezoidal channel with a moderate side slope mimicking a site of deposition of sediment. Located directly across from this was a steeper bank replicating a site of scour and erosion of earth. The native subsoil mixed with river cobble was excavated and reshaped to form the experiment. The thin veneer of topsoil at the site was stripped and stockpiled. The exposed substrate of native alluvia composed of sands, gravels, and river cobbles with some finer silts and clays was used as the potential recruitment surface.

To minimize the potential for stream capture, no inlet to the channel from the river was constructed. However, the channel was excavated to the depth of the shallow alluvial groundwater table, which allowed exposed groundwater to infiltrate, and subsequently flow down the trough of the channel along an elevation gradient that matched the slope of the river. A constructed outlet allowed for two-way movement, outflow to and backwater from the river, to occupy the bottom one third of the channel at typical summer flows. After construction, surface water elevations in the channel were observed to rise and fall in close association with the surface water elevations of the river, indicating high hydraulic permeability of the alluvia.

Hydraulic analysis of the regulated flow regime was conducted as part of planning for the project and predicted that river flows between the Q_5 and Q_{10} events, likely to occur every 5–10 years, would overtop the banks of the adjacent river and enter the constructed channel. In the spring of 1993, flows reached 191 m^3/s, a Q_8 event (Figure 3; Burgess and Kunz, 1994). This caused a breach in the south bank of the river that resulted in the channel capturing a portion of its flow. It produced two distinct hydraulic environments within the channel, both during and after the breach. Above the breach, we observed little scour and no deposition of river sediment. Below the breach, both the bed and banks of the channel were scoured, and sediment was deposited as a series of point bars. During subsequent field inspections, standing water with intermittent flow was observed above the breach, where it was impounded by one of the point bars. Between the breach and the outlet of the channel, flowing water was commonly observed.

Cottonwood seedlings and saplings were sampled from 20 October to 1 November 1994. For the two treatments (i.e. above the breach and below the breach) within the experiment – identified in the statistical analysis as *location* – replicate quadrats were randomly located along a transect that followed the length of the constructed channel where cottonwoods grew in a continuous band at and near the waterline.

Two naturally occurring black cottonwood stands growing immediately down river from Lucky Peak Dam, both large in area, were selected as reference sites. At these sites, an irregular distribution of young cottonwoods grew in a patchy pattern where there were openings in the tree canopy. We recognized these openings from aerial photographs and randomly selected two locations for sampling: (1) along the south bank of the Wood Duck Island slough (RM 57·0) within 3 m horizontal distance of the OHWL and (2) along the south bank of the Barber Pool high flow channel (RM 60·0) at the OHWL.

For each sample site, five 0·5 × 0·5 m square quadrats were positioned to provide a total of 20 samples from the four locations. Because our experiment was opportunistic – taking advantage of both the regulatory requirement for the constructed channel and the sudden, large-in-size breach between the river and the channel – our funding and therefore our level of effort dedicated to sampling was limited. Although the samples are sparsely replicated, we believe the data we have is sufficient. We acknowledge, however, our interpretation of results could be strengthened by both a greater numbers of samples at the experiment and additional reference sites for comparisons to them.

The quadrats were repeatedly observed and photographed to document site conditions with time. At the time of harvest and destructive sampling, all of the black cottonwood seedlings and saplings within each quadrat were removed from their substrate. They were identified by their morphology as either seedlings or adventitious root suckers (Gom and Rood, 1999). Seedlings displayed tapering tap roots, while suckers were connected to larger horizontal roots from adjacent, parent trees. The harvested seedlings and saplings were grouped by quadrat and photographed to document their growth form. The age of seedlings was determined by the number of apical bud scars along their stems. The age of suckers was estimated by observing the branching of stems and their diameters, and by annual growth rings displayed in cross sections. Numbers of seedlings and suckers were counted for each quadrat, and their shoot lengths were measured. Statistical analyses using JMP (SAS Institute Inc., Cary, NC, USA) employed nonparametric comparisons for each pair of locations (i.e. above and below the breach, and two reference sites) using the Wilcoxon each pair method and for all four locations using the Steel–Dwass all pairs method. We compared median values of two response variables, the first *number of seedlings and sucker*s and the second *shoot length*, by the factor *location*.

After completion of the experiment, the constructed channel was filled with earth to reestablish its original elevations and contours as required by the Idaho Department of Water Resources. This was done to prevent the further capture of river flow by the constructed channel and the possible bypass of that flow around an adjacent irrigation diversion that is protected by historic water rights.

RESULTS

Historic hydrology

The lower Boise River – regulated river flows. River regulation has caused major changes in the flow regime of the lower Boise River (Figures 3 and 4). The hydrograph for the period prior to the operation of the three major upriver dams displays a natural nival or snow melt-dominated pattern of river discharge showing the following: (1) a gradual increase in early spring, (2) one or more abrupt peaks in late spring during the interval of greatest mountain snow melt and spring rains, (3) gradual recession throughout the summer, and (4) minimal flows in late fall and winter (Figure 4).

Following regulation of flows by these dams, the hydrograph displays river discharge as a step function showing the following: (1) an abrupt increase in flow in spring to evacuate the three upriver reservoirs to accommodate spring run-off, (2) a period of fluctuating and moderate flow release throughout the summer to provide water for irrigation, (3) an abrupt decrease in flow in the fall to store water for the following water year to meet contractual commitments to irrigators, and (4) low flow through the late fall and winter (Figure 4). Flows for all seasons have been altered, but low flows especially have been reduced as shown by an average, regulated low flow in late fall and winter of 8 m^3/s as compared with a natural low flow of 37 m^3/s.

The spring peak component of the hydrograph (Figure 4, ‘2’) is especially important to the fluvial geomorphic processes responsible for the removal of vegetation, erosion of earth, and transport and deposition of sediment. While the record prior to damming is limited, it shows annual peak discharge approaching 1000 m^3/s (Figure 4) for the free flowing river. After the first of the three major dams was placed into operation, annual peaks were substantially reduced.

More severe attenuation of flood flows followed after the last dam was completed in 1955. This is shown by average annual peak discharge prior to the operation of Lucky Peak Dam (1955), which was 342 m^3/s, while after it declined to 128 m^3/s. There is no indication of a similar decline for the unregulated upper Boise River, above the dams (Figure 5), and we, therefore, reason that this change is not the result of a regional pattern in climate. Indeed, the highest peak flow of record for the upstream reach occurred in 2012 and approximated a flow likely to occur once in 100 years, or having a 1% chance of occurring in any single year, also known as the Q_{100} event.

Recurrence intervals of annual peak flows further demonstrate the extent of flood flow attenuation on the lower Boise River. While the Q_{100} event is important for regional planning and the protection of public health and safety, more common floods with recurrences between 5 and 10 years (Q_5 to Q_{10}) are likely more influential on channel form and process, and the development of floodplain forests (Scott *et al*., 1997; Samuelson and Rood, 2004). These flows approximated 450–600 m^3/s given the natural regime, but were reduced to approximately 200 m^3/s following river damming (Figure 3).

Our analysis shows that along with the attenuation of high flows, their duration too has been extended by the operation of dams (Figure 4). Prior to regulation, approximately two thirds of the annual discharge of the lower Boise River occurred in the months of May and June. Now, water stored in the three reservoirs is released over a longer period during the irrigation season, generally from 15 April to 15 October (Figure 4).

Finally, the magnitude and duration of low flows have also been altered by regulation of the lower Boise River. Prior to the operation of the three major upriver dams, minimum river discharge was 12 m^3/s in the winter of 1915. With regulation, river discharge declined to 0 m^3/s on at least one occasion annually for 15 years of the 35-year period of record from 1954 to 1989 when the gates of Lucky Peak Dam were closed to conserve stored irrigation water. This practice has since ended in recognition of the ecological importance of in-stream flows, and a winter minimum flow of 4 m^3/s is now protected by a water right held by the Bureau of Reclamation (1996).

The upper Boise River – free flowing hydrology. Our analysis of the record of discharge over the past century for the free flowing, upper Boise River at Twin Springs indicated only a slight influence of climate change on the flows of the river. There was no linear trend in peak discharge (Figure 5; $r = 0{\cdot}12$, n.s.) or mean annual discharge ($r = 0{\cdot}04$, n.s.) over the past century. The only significant pattern in seasonality was an increase in flow occurring in March (1912–2012:

$Q_{\mathrm{Mar}} = (0{\cdot}116 \times \mathrm{year}) - 203$; $r = 0{\cdot}30$, $p < 0{\cdot}01$). This is consistent with increased spring flows observed for other Rocky Mountain rivers, which has been attributed to early spring snow melt because of a warming climate (Mote *et al*., 2005; Stewart *et al*., 2005; Rood *et al*., 2008). We reason from this analysis that the major hydrologic changes observed for the lower Boise River reflect the influence of river damming and flow regulation, and have not been produced by climate change.

Assessment of colonization by black cottonwood in the constructed channel

We observed substantial seedling recruitment immediately after the bank breach event. Deposition of cottonwood seeds and the growth of seedlings were most often on 10:1 slopes, where water velocities and rate of decline in water elevation were least severe (Figure 6f). While herbaceous, native vegetation grew among cottonwood seedlings above the breach (Figure 6c), it grew below the breach only in small, isolated areas. Herbaceous species we observed included fringed willowherb (*Epilobium ciliatum*), common spikerush (*Eleocharis palustris*), and jointleaf rush (*Juncus articulatus*). We know from casual observations that their habits of growth are compatible with one another and with other species of hydrophytic vegetation, allowing for a fairly diverse community. They are common in lentic waterways along the lower Boise River where there is an absence of competition by non-native grasses.

Below the breach, the ground surface appeared as a mosaic of dense concentrations of black cottonwood

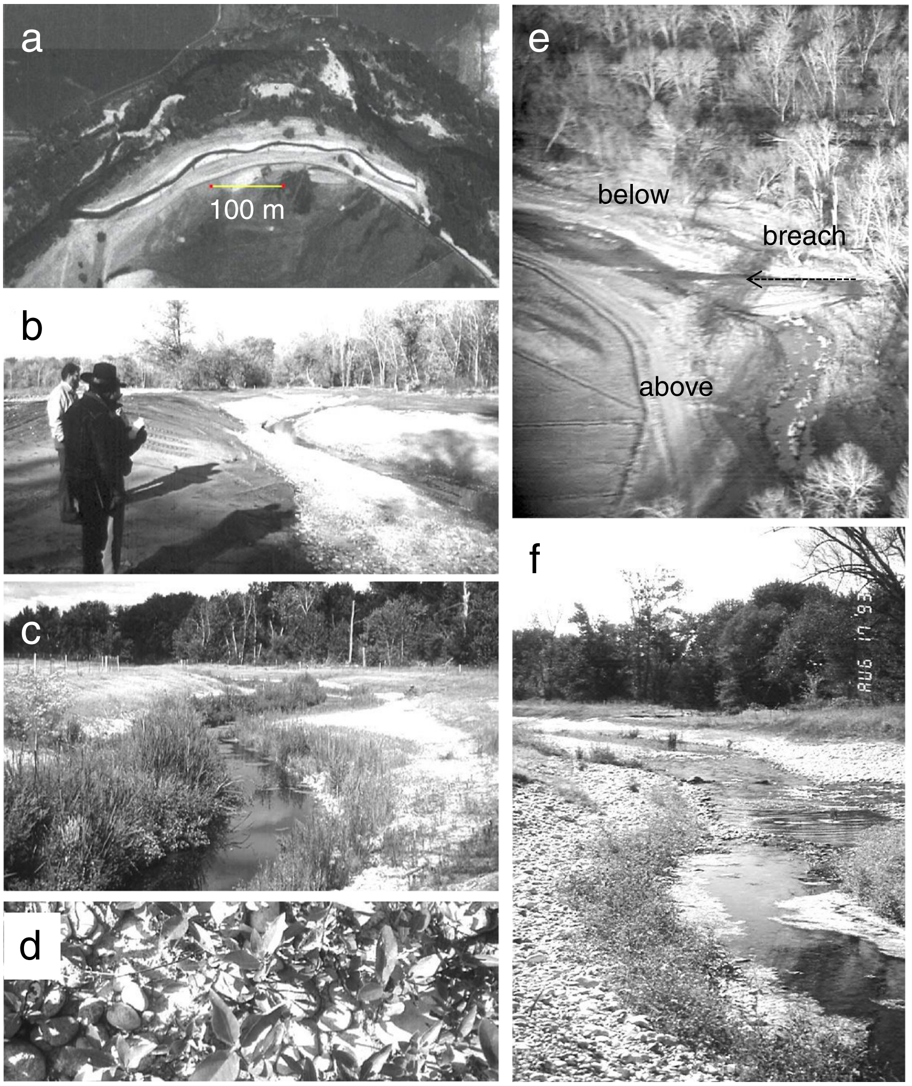

Figure 6. Aerial and ground level photographs (facing downstream) of the channel during and after construction (1992) and after the breach (1993). (a) Aerial photograph of the constructed channel. (b–d) Above the breach: (b) channel during construction, (c) channel after construction and (d) cottonwood seedlings. (e–f) After the breach, looking downstream: (e) aerial view and (f) ground level. (b–f photographs by R. Tiedemann).

seedlings and large patches of bare ground. Scour marks and drift lines were present below the breach, but not above it. And, river cobble was exposed among coarse sands below the breach, while absent above the breach where finer textured soils dominated.

The density of seedlings along the constructed channel was significantly ($p < 0{\cdot}05$) greater above the breach (308 ± 92 (SE)/m^2) than below the breach (74 ± 7/m^2) (Wilcoxon $Z = -2{\cdot}5$, $p = 0{\cdot}01$). We speculate this may be due to the removal of many of the smaller seedlings by scouring flows below the breach. Seedlings below the breach were also significantly taller than those above the breach (36·1 ± 2·3 cm vs 7·3 ± 0·3 cm) (Wilcoxon $Z = 13{\cdot}1$, $p < 0{\cdot}01$), supporting our interpretation that smaller seedlings had been selectively removed from the zone below (Figure 7). Further support of this is offered by a comparison of the range of lengths of seedlings within the 10% and 90% quantiles of the distribution, which are distinctively different from one another (above the breach = 2·9–12·3 cm, below the breach = 8·3–65·1 cm). We continue to consider alternative explanations however, including the greater growth rate of seedlings below the breach due to less intraspecific competition, or the presence of a more favourable moisture regime.

In contrast to the abundant seedlings along the excavated channel, we observed suckers but no seedlings at the two naturally occurring black cottonwood stands at the Wood Duck Island slough and Barber Pool channel. The density of seedlings below the breach was similar to the density of saplings growing as suckers at the two naturally occurring stands of trees (Wood Duck Island 34 ± 7/m^2; Barber Pool 15 ± 6/m^2). In addition, the mean height of suckers was not significantly different between the Wood Duck Island slough and the Barber Pool channel (61·3 ± 7·1 vs 42·4 ± 5·9) (Wilcoxon $Z = 1{\cdot}5$, $p = 0{\cdot}13$) (Figure 7). We estimated the growth rate for the 2-year-old seedlings below the breach at approximately 18 cm/year and found it to be similar to the 15 cm/year (mean height 51·9 cm/3·5 years) rate for the 3- and 4-year-old suckers.

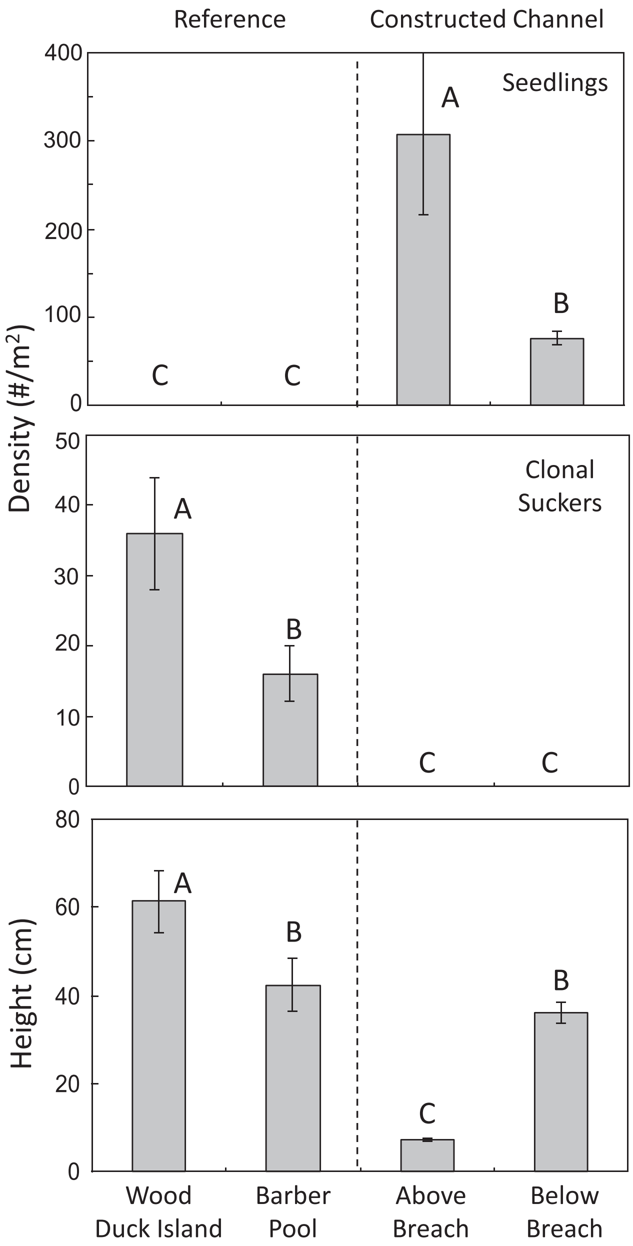

Figure 7. Characteristics of juvenile black cottonwoods within sample quadrats at two reference sites along the lower Boise River (left) and at two locations along the constructed channel (right). The origin of saplings was determined through excavation. Mean (±SE) densities of seedlings (top) and clonal root suckers (middle) are displayed, along with corresponding lengths (bottom). Note the eightfold difference in y-axis scales for the two densities. Within each plot, values with different letters differ significantly ($p < 0{\cdot}05$).

DISCUSSION

Previous studies have shown that perturbations of the floodplain by avulsive flood flows can alter the topography of the ground surface and the texture of its substrate (Florsheim and Mount, 2002), and therefore influence both temporal and spatial patterns of riparian vegetation. Other researchers have shown that clearing the floodplain of competing vegetation; providing temporary irrigation water; and coordinating the rate of rise and fall of river stage with time of seed dispersal, rate of elongation of the roots of seedlings, and the risk of scour or burial in subsequent years can influence the survival of cottonwood seedlings (Friedman *et al.*, 1995; Roelle and Gladwin, 1999; Taylor *et al.*, 1999; Florsheim and Mount, 2002; Dixon, 2003; Polzin and Rood, 2006).

Our experiment differs from these in that it was carried out in an engineered channel with regular meanders and side slopes, and at the larger scale of a portion of a river reach nearly 1 km in length. It therefore replicates the physical characteristics of a river while maintaining some level of control of the experiment.

Our study differs also in that it emphasizes the importance of sexual reproduction of the black cottonwood forest and the need for periodic recruitment of seedlings to compensate for the progressive aging of the woodland population. Like the other section Tacamahaca cottonwoods – the narrowleaf cottonwood, *P. angustifolia*, and the very closely related balsam poplar, *P. balsamifera* – black cottonwoods are capable of extensive clonal expansion through root suckers (Gom and Rood, 1999). However, asexual reproduction does not provide for diversity through genetic recombination, which is essential for adapting to a changing environment and evolution of a species.

The three primary requirements for seedling recruitment of black cottonwood and other riparian plants are availability of the following: (1) viable seed; (2) suitable establishment sites; and (3) water for imbibition, germination, and growth. Both rate of development and time of release of seed are temperature related (Stella *et al.*, 2006) and when in synch with the flow regime of a river can produce large areas of same age cohorts of trees. Following release, the small seeds of black cottonwood are dispersed by wind, and depending on where they land may be transported large distances by running water. They remain viable for approximately 2 weeks during which time they must find a moist soil surface to germinate and grow.

We have observed prolific seed production along the lower Boise River each year during the past 20 years and do not consider the availability of seed a limiting factor to black cottonwood reproduction. Instead, we reason the processes of erosion of substrate, and the transport and deposition of sediment have been greatly diminished by river regulation. As a result, the availability of suitable establishment sites is instead the principal factor limiting sexual reproduction.

Prior to damming, a dynamic Boise River frequently avulsed beyond its banks causing disturbance to the surface of the floodplain that contributed to its ecological functions and services. Flood flows once removed competing vegetation and exposed river cobbles, gravels, and moist sands which together are a proper seedbed for pioneering plant species (Findorff and Reichmuth, 1991) including black cottonwood and the three species of willows native to the area, namely, sandbar willow (*Salix exigua*), yellow willow (*Salix lutea*), and Pacific willow (*Salix lucida* ssp. *lasiandra*).

Our analysis of historic hydrology for the lower Boise River provides an explanation for its change in morphology and character that is consistent with the interpretations of MacCoy and Blew (2005). Because of the attenuation of flood flows – especially after the completion of Lucky Peak Dam in 1955 – the river is no longer able to create large areas of barren substrate. The fact they are now rare, in combination with a scarcity of seedlings throughout the river corridor supports our first hypothesis that the lack of barren colonization sites limits woodland recruitment along the lower Boise River. Contributing further to the problem of diminished geomorphic disturbance from flood events, the physical presence of constructed dikes and the armoring of banks have also altered the floodplain and reduced the area of suitable surfaces for cottonwood colonization.

The results of the constructed channel experiment support our second hypothesis, that the artificial creation of barren surfaces – composed of alluvial substrate common in the river corridor and at elevations where moist soils are present – can still enable germination and growth of substantial numbers of black cottonwood seedlings.

Our analysis of historic hydrology and results of the constructed channel experiment together suggest to us that the recruitment of native riparian vegetation can be improved by the adjustment of river flows. Although flows above full bank stage are aggressively avoided by river managers, we observe there remains even with river regulation a 2 m change in river stage that corresponds to a suitable elevation band for colonization by black cottonwood and willow seedlings and likely other native species (Amlin and Rood, 2002). Fortunately, the timing of regulated high flows is also suitably coordinated with the period of seed dispersal by these species.

Within these limits, favourable river hydraulics at a local scale continue to erode earth, and transport and deposit sediment at select locations. They include slumping banks that deliver material later deposited as point bars and islands within the channel, and areas of accumulation of woody debris that promote localized scour both within the channel and across the floodplain. We have observed both within the more urbanized reaches of the river from RM 53 to 55. Although discouraged, fire also could be used as a restoration tool because of its ability to efficiently produce both barren surfaces and openings in the forest canopy. Finally, the work of beaver may be of some benefit, although beaver cutting is often followed by clonal coppice shoot regrowth (Gom and Rood, 1999).

However, each of these approaches to restoration is likely to occur only at the scale of a small portion of a river reach and therefore would have limited efficacy for revival of the larger population. Restoration at the scale of the black cottonwood gallery forest will require more extensive methods. These include regrading the flood fringe of the floodplain to establish barren surfaces at elevations at or below the Q_2 event, or applying irrigation water at elevations at or near the Q_2 event to produce a moist substrate for the germination of seed when it is impractical to remove earth (Friedman *et al.*, 1995).

Regardless of the scale of restoration, other problems remain to be resolved. Seedlings established in low elevation positions in the channel are known to be vulnerable to scour by energetic river flows, shearing by moving ice, and burial by the deposition of sediment. Each can be lethal to large swaths of otherwise healthy seedlings. This was suggested in the constructed channel where seedling densities were significantly greater above the breach as compared to below the breach where scour due to river flow was observed. Given the current operation of the three upriver dams, infrequent recruitment of black cottonwood seedlings along the lower Boise River will continue to be constrained by their locations in other than survivable 'seedling safe sites', as characterized by Polzin and Rood (2006).

Because it is often irregular, the recession limb of the hydrograph after the spring peak also remains inhospitable to the recruitment of black cottonwood. Adjustments to the flow regime of the river to provide a more gradual decline in stage would benefit seedling survival if and when recruitment sites are created by methods other than flood flows (Figure 8). To accomplish this, we recommend the 'tapered ramping' of the rate of decline of river stage at and near the elevation of the flood fringe. This would encourage the recruitment of willow seedlings common to lower topographic positions along the channel and increase the survival of both willows and black cottonwood seedlings that require a more gradual decline of river stage as they mature (Amlin and Rood, 2002). Until then, periodic application of temporary establishment water by flood irrigation could promote the growth and survival of seedlings or transplanted saplings by encouraging extension of their roots to reach the fluctuating phreatic surface of the shallow groundwater table.

In years when there is carry over of stored water from the previous year, our proposed pattern of functional flows could achieve the release of similar volumes of water as were delivered during the 2012 water year, but with high flows extended into the late spring and early summer. The extensive water storage capacity provided by the three large upstream reservoirs suggests this may be feasible, especially in wetter years when river flows are more abundant and irrigation demand is typically reduced. However, better forecasting of the accumulation of snow pack and the rate of its melt are required to balance this with the need to protect public health and safety from flood flow events.

Regardless of chosen method, continued human intervention will likely be required to sustain genetic recombination and species diversity along the lower Boise River and other black cottonwood forests in the Intermountain West where river discharge has been altered by dams and irrigation diversions. The required level of effort to accomplish this is determined by, among other factors, the degree of success and number of sites required to promote the ecological functions and services desired by the public, the size of populations required to preserve their genetic integrity, and the ability of a population to adapt to uncertain future changes in the environment.

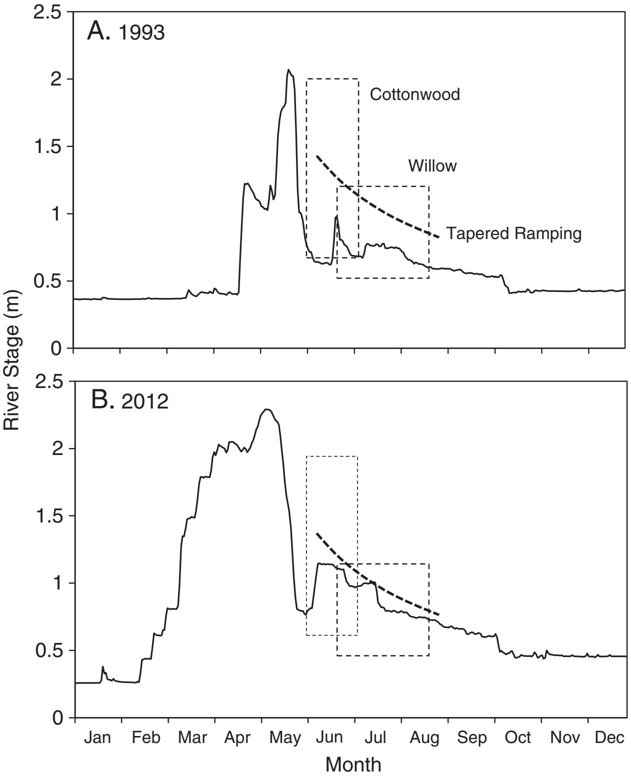

Figure 8. Hydrographs of river stage for the lower Boise River for 1993, during operation of the experimental channel, and in 2012. The cottonwood and willow 'recruitment boxes' are plotted (Amlin and Rood, 2002) within a range of elevations likely to result in seedling recruitment from the local release of black cottonwood and sandbar willow seed. The tapered, dashed lines suggest a favourable ramping pattern that could promote colonization by black cottonwood and willow seedlings, with the latter at lower elevations and requiring a more gradual rate of decline in stage.

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