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MORTALITY OF RIPARIAN BOX ELDER FROM SEDIMENT MOBILIZATION AND EXTENDED INUNDATION

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ABSTRACT

To explore how high flows limit the streamward extent of riparian vegetation we quantified the effects of sediment mobilization and extended inundation on box elder (*Acer negundo*) saplings along the cobble-bed Gunnison River in Black Canyon of the Gunnison National Monument, Colorado, USA. We counted and aged box elders in 144 plots of 37.2 m^2, and combined a hydraulic model with the hydrologic record to determine the maximum shear stress and number of growing-season days inundated for each plot in each year of the record. We quantified the effects of the two mortality factors by calculating the extreme values survived during the lifetime of trees sampled in 1994 and by recounting box elders in the plots following a high flow in 1995. Both mortality factors can be modeled as threshold functions; box elders are killed either by inundation for more than 85 days during the growing season or by shear stress that exceeds the critical value for mobilization of the underlying sediment particles. Construction of upstream reservoirs in the 1960s and 1970s reduced the proportion of the canyon bottom annually cleared of box elders by high flows. Furthermore, because the dams decreased the magnitude of high flows more than their duration, flow regulation has decreased the importance of sediment mobilization relative to extended inundation. We use the threshold functions and cross-section data to develop a response surface predicting the proportion of the canyon bottom cleared at any combination of flow magnitude and duration. This response surface allows vegetation removal to be incorporated into quantitative multi-objective water management decisions. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: *Acer negundo*; critical shear stress; flood; riparian vegetation; sediment

INTRODUCTION

Riparian forests are often a focus of water management because of their importance as an animal habitat (Brinson *et al*., 1981) and their influence on transport of water and sediment (Burkham, 1976; Smith, 1976). Flow regulation can influence the population of a forest species by altering processes controlling establishment, growth, or mortality. Several recent studies have investigated the relationship between flow and tree establishment (Bradley and Smith, 1986; Johnson, 1994; Auble *et al*., 1997; Friedman *et al*., 1997; Scott *et al*., 1997). Specific flow regimes have been prescribed to promote establishment of riparian trees (Scott *et al*., 1997), to prevent tree establishment (Johnson, 1994), or to promote tree growth (Stromberg and Patten, 1990). The processes leading to mortality of existing trees, however, are less well quantified (Scott *et al*., 1999).

High flow can kill riparian trees in at least two ways. First, floods can kill a tree by physically damaging or removing it. Debris or ice piled against the tree may abrade enough bark to kill it (Sigafoos, 1964; Yanosky, 1982). Debris piles on the upstream side of a tree increase the fluid drag exerted against the trunk, and may cause the tree to be toppled or the trunk to be broken (Osterkamp and Costa, 1987; Oplatka and Sutherland, 1995); many riparian species are able to sprout a new stem following such damage (Sigafoos, 1964; Stromberg *et al*., 1993; Friedman *et al*., 1996). If shear stresses are sufficient to mobilize the sediment in which the tree is rooted, it can be washed away (Stevens and Waring, 1985; Osterkamp and Costa, 1987). A tree may also be killed by sediment deposited by floods (Hupp, 1988).

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Floodplain trees can be removed by bank failure following fluvial erosion of sediment at the base of the bank (Thorne, 1990).

Second, extended inundation can kill a tree without physically damaging the tree or changing the underlying sediment. Mortality from prolonged inundation is typically associated with oxygen depletion in the root zone or exhaustion of energy reserves. The number of days of flooding a tree can survive depends upon the species, age, size, and gender of the tree; the depth, temperature, and clarity of the water; and the timing of inundation relative to the growing season (Gill, 1970; Whitlow and Harris, 1979; Stevens and Waring, 1985; Dawson and Ehleringer, 1993).

Water management typically decreases magnitude and frequency of floods. Proposals for ecological restoration of regulated rivers often recommend restoration of flooding (Junk *et al*., 1989; Stanford *et al*., 1996) to reduce populations of susceptible exotic fish species (Meffe, 1984), to flush fine sediments from gravels used by spawning fish and hyporheic invertebrates (Milhous *et al*., 1989; Stanford and Ward, 1993; Kondolf and Wilcock, 1996), to facilitate exchange of organisms and nutrients between channel and flood plain (Junk *et al*., 1989; Power *et al*., 1995; Stanford *et al*., 1996), to create and maintain fluvial landforms used by aquatic organisms (Milhous, 1982), and to prepare a bare, moist seedbed for early successional riparian plants (Nilsson *et al*., 1991; Friedman *et al*., 1997; Scott *et al*., 1997).

Prescribed floods may also be useful for removing riparian trees that have encroached on the stream channel as a result of a reduction in peak flows (Johnson, 1994; Kondolf and Wilcock, 1996). These new forests may be undesirable because they reduce channel conveyance or because they replace the open habitats necessary for some stream and riparian animals. Alternatively, flooding may threaten survival of a valued existing population of trees. In order for removal of riparian vegetation to be considered in water management decisions, methods must be developed to quantify the relation between flow and tree mortality (Oplatka and Sutherland, 1995; Kondolf and Wilcock, 1996; Toner and Keddy, 1997). In this study we related survival of riparian trees along the Gunnison River, Colorado, to two aspects of flooding: shear stress, a function of flood intensity; and number of days inundated, a measure of flood duration.

Study area

Black Canyon of the Gunnison National Monument is located along the Gunnison River on the western slope of the Rocky Mountains in Montrose County, Colorado, at latitude 107°45′ west and longitude 38°34′30″ north (Figure 1). The river flows through a steep-walled canyon cut into pre-Cambrian gneiss. Peak flow occurs in May or June as a result of snowmelt. Prior to flow regulation there was little vegetation in the canyon bottom (Warner and Walker, 1972) probably because of the effects of frequent scouring floods. Between 1966 and 1976 Crystal, Morrow Point, and Blue Mesa dams were constructed on the Gunnison River upstream of the Monument for power generation and water storage (Figure 1; US Department of the Interior, 1990). Dam operation has reduced peak flows, apparently allowing development of vegetation on the canyon bottom. Flows are further modified by diversion of water into the Gunnison Tunnel at East Portal (Figure 1); this diversion decreases mean annual discharge, but has little effect on peak flows (Diaz *et al*., 1994). A minimum flow of 8.5 m^3/s is imposed by an instream flow right owned by the state of Colorado (Diaz *et al*., 1994).

The National Park Service chose a 1-km reach for intensive study (Figure 1; Auble *et al*., 1994; Elliott and Hammack, 1999). The width of the canyon bottom within this reach varies from 40 to 90 m and the elevation is approximately 1707 m. The watershed is 10000 km^2 (Hansen, 1987), and average annual precipitation is 370 mm (Colorado Climate Center, 1984). Because of the precipitous canyon walls, the study reach is relatively inaccessible and has probably never been grazed by livestock. Discharge is measured at East Portal, approximately 14.5 river km upstream of the study reach at US Geological Survey Gauge 09128000. This gauge has been in operation since 1906; the highest recorded instantaneous discharge was 538 m^3/s in 1921. There are no dams, diversions, or important tributaries between the gauge and the study reach. The closest dam and reservoir upstream of the Monument are operated to eliminate the large daily fluctuations in discharge commonly associated with power-peaking at hydroelectric dams

(Stanford *et al.*, 1996). The physicochemistry of this portion of the river is described by Stanford and Ward (1984). The response of the herbaceous vegetation to alternative flow regimes is explored by Auble *et al.* (1994).

We examined hydrologic factors associated with mortality of the dominant woody species, box elder (*Acer negundo* L.); less frequent species include saltcedar (*Tamarix ramosissima* Ledeb.) and sandbar willow (*Salix exigua* Nutt.). Size of box elders is strongly related to their position. Mature trees apparently predating upstream dams occur only at the edge of the canyon bottom in positions high above the channel. The only box elders at lower levels are immature individuals less than 5 m tall and apparently postdating dam construction.

Hypotheses

Our preliminary observations at this site indicated that high flows kill box elders by extended inundation during the growing season or by erosion of the sediment in which the trees are rooted. We hypothesized that:

1. patterns of survival of box elder in a given year are strongly related to the number of days of inundation during the growing season, and

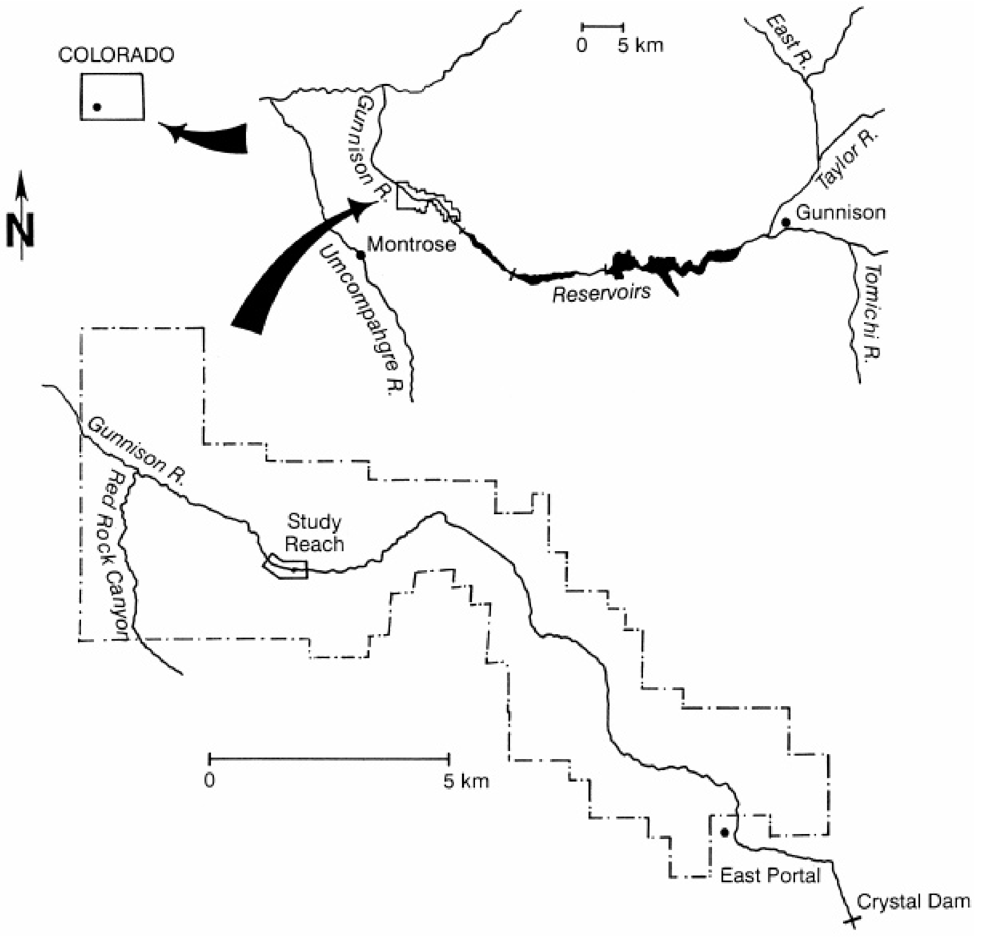

Figure 1. Location of the study site along the Gunnison River in Black Canyon of the Gunnison National Monument, Montrose County, Colorado, USA. The Gunnison River flows west and north. The dashed line is the Monument boundary

2. box elders are killed when the shear stress during a high flow exceeds the critical shear stress necessary to mobilize the underlying sediment.

METHODS

In 1994 the National Park Service surveyed 12 cross-sections within the study reach, seven located at hydraulic control points and five located for analysis of vegetation within the relatively flat sections between rapids. The Park Service used a step-backwater hydraulic model, HEC-2, (Hoggan, 1989; Hydrologic Engineering Center, 1990) to determine water surface elevation and energy gradient for all 12 cross-sections at flows up to 566.4 m^3/s. The model was calibrated by measurements of stage at discharges of 9.5, 21.7, 44.9, 49.0, 97.7, 146.4, 192.6, and 266.2 m^3/s.

Along the five vegetation cross-sections we established belt transects 12.19 m wide, and divided the transects into plots of 3.05×12.19 m (144 total). Between 29 July and 3 August, 1994, we counted all box elders in each plot, characterizing individuals as small (<30.5 cm tall) or large (>30.5 cm tall). Although it is a diffuse-porous species (Phipps, 1985), box elder produces discernible annual rings (Reily and Johnson, 1982). In each plot we determined the height and year of establishment of two large and two small box elders, where present. For trees larger than 15 cm diameter at ground surface we determined establishment years by collecting cores as close to the ground as possible (<30 cm above-ground). For smaller individuals in both size classes we cut transverse sections at the ground surface; in order to explore the difference between age at the ground surface and age at the establishment surface, we also cut transverse sections at the buried root collar (Scott *et al*., 1997). We sanded cores and sections using progressively finer sandpaper down to a particle size of 15 μm (600 grit) and counted annual rings under a microscope (Phipps, 1985). Between 21 and 23 September, 1995, we again counted all box elders in the plots to determine survival of those individuals that had not been sacrificed for age determination in 1994. In addition we counted all box elders in a set of new plots located in 6.10 m extensions on both sides of the original belt transects. We estimated box elder densities in 1990 by combining data from a vegetation sample done on a different set of plots at the same site (Auble *et al*., 1994) with a 1990 census of all box elders on bars intersected by three of the five cross-sections.

The elevation of each plot was defined as the average of the elevations at the two plot boundaries along the cross-section. We compared plot elevations to the stage–discharge relation for each cross-section to determine the minimum discharge necessary to inundate each plot (inundating discharge). For each plot in each year we counted the number of days during the growing season (1 May–1 October) in which the mean daily flow exceeded the inundating discharge. Because high flows at the study site generally occur at the beginning of the growing season, box elders are unlikely to experience the highest flow in the year they are established, therefore, we assumed that the first year of flow experienced by an individual was the year after establishment. Because the relationship between inundation and survival demonstrated a threshold relationship we modeled it with a step-function: 100% survival below a threshold number of days inundated, and 0% survival above the threshold. We calculated the value of the threshold that minimized the number of mis-classified plots. In this calculation, if a plot was predicted by the threshold to have 0% survival but instead had 100% survival, then a misclassification of 1 was counted; if the same plot had 40% survival, then a misclassification of 0.4 was counted.

If flow is not accelerating, then the force of gravity in the downstream direction must be counterbalanced by friction between the water and the channel boundary. The shear stress, τ (force per unit area applied by the water along the boundary surface), is, therefore, equal to the downstream component of the weight of the water column:

$$\tau = \rho g R S \tag{1}$$

where ρ is the density of water (1000 kg/m^3), g is the acceleration of gravity (9.807 m/s^2) R is the hydraulic radius (here approximated by water depth), and S is the energy gradient at the cross-section. Most studies of shear stress, which focus on mobilization of sediment on the channel bed, calculate the average shear stress for a cross-section using the hydraulic radius or average depth for R in Equation (1). In this study, we did not use a cross-sectional average because we were interested in the differences in shear stress between points high and low on the bank. Therefore, we used the local depth at each plot in Equation (1) (Milhous *et al.*, 1989; Kondolf and Wilcock, 1996). To calculate the highest shear stress that occurred in a plot in a given year we iteratively applied Equation (1) to find the maximum value for τ over the range of instantaneous discharge for that year.

The critical shear stress necessary to mobilize sediment (τ_{cr}) is proportional to the sediment particle size:

$$\tau_{cr} = \tau^*_{cr} g(\rho_s - \rho) d_{50} \tag{2}$$

where τ^*_{cr} is the critical dimensionless shear stress, a constant at the large Reynolds numbers in this application; ρ_s is the density of sediment (2650 kg/m^3); and d_{50} is the median sediment particle size on the sediment surface in the plot (Shields, 1936). We determined sediment particle size in a total of 27 pebble counts (Wolman, 1954) on all distinct fluvial surfaces encountered along the cross-sections; all plots on a fluvial surface were assigned the d_{50} determined in the pebble count for that surface. For τ^*_{cr} we used 0.031, the average dimensionless shear stress necessary to mobilize the median particle size on the bed surface in a study of 24 gravel-bed rivers in Colorado (Andrews, 1984).

RESULTS

The median particle diameter for plots (d_{50}) ranged from 0.9 to 27 cm. For discharges between 8.5 and 566.4 m^3/s, maximum water depth over a plot was 4.66 m, energy gradients at cross-sections ranged from 0.0011 to 0.0079, and maximum shear stress was 208.9 Pa.

Density of box elders was greatest at moderate inundating discharges (Figure 2). In 1990, following 4 years of consistently low flow (Figure 3), the population of box elders on the canyon bottom was dominated by individuals less than 30.5 cm tall concentrated on surfaces inundated by discharges of 10–60 m^3/s (Figure 2). High flows in 1993 and 1995 were associated with reduced density of box elders less than 30.5 cm tall and a shift of the distribution to higher inundating discharges (Figure 2). Following the high flow of 1995 the box elder population was dominated by individuals taller than 30.5 cm on surfaces inundated by discharges higher than 40 m^3/s (Figure 2).

In 1994 we determined the ages of 73 large and 51 small box elders. Eleven of the largest individuals were cored; the rest of the large individuals and all of the small individuals were sampled by transverse section at ground-level and at the excavated root collar. The median height in the large size class was 0.99 m (range = 0.33–11.4 m). Some individuals had resprouted from a point above-ground following cutting by beaver in the late 1980s. We found no recent flood scars and little flood debris on sampled stems. Individuals knocked over by the high flow of 1993 occasionally resprouted from the base of the stem, but not from the formerly above-ground portions of the stem.

The maximum and minimum of three independent age determinations on ten ground-level samples and cores from the large size class differed by an average of 1.7 years (S.D. = 1.82, range = 0–6). Sections taken below ground were generally more difficult to interpret. For the 15 large individuals whose age at the root collar could be clearly determined, mean depth of burial of the root collar was 3.8 cm (range = 0–15.2 cm), and age at the root collar averaged 2.1 years older than age at ground surface. This small difference in age between sections taken at ground-level and sections taken at the root collar was not important in this study; for all but one box elder the largest discharge during the life of the stem (aged at ground surface) was the same as the largest discharge during the life of the root collar. We used section data from the ground surface in all analyses relating survival to flow.

Box elders have become established in many different years and over a wide range of inundating discharges (Figure 3). The absence of older individuals on surfaces with low inundating discharges, however, is consistent with the hypothesis that low-lying individuals are removed by large flows. In 1994, box elders established prior to 1970 had survived only on surfaces with inundating discharges greater than 133 m^3/s (Figure 3). Individuals established between the high flows of 1970 and 1983 had survived down

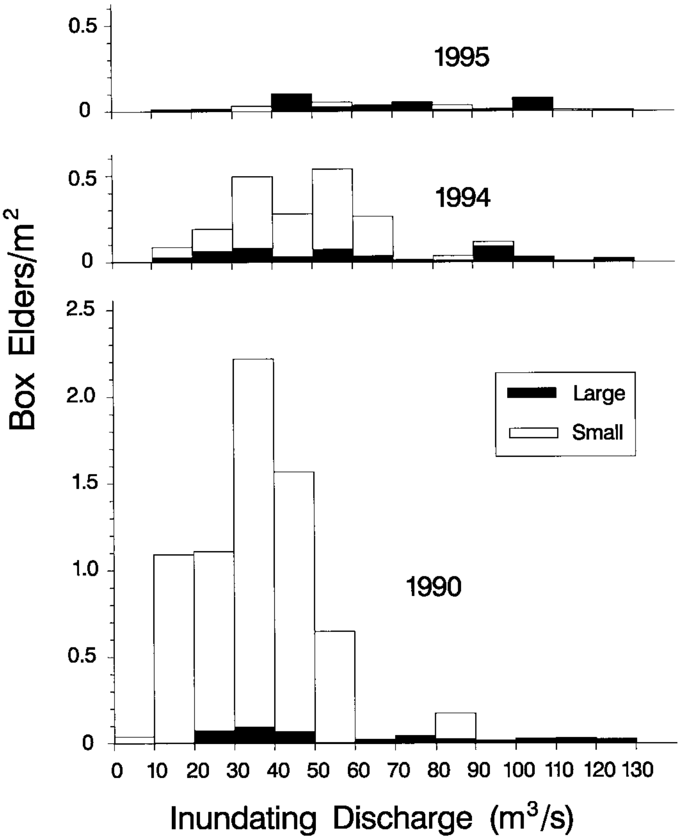

Figure 2. Densities of large ($\geq$ 30.5 cm tall) and small (< 30.5 cm tall) box elders within classes of inundating discharge, Black Canyon of the Gunnison National Monument, Colorado, USA. Inundating discharge is the minimum discharge necessary to inundate a plot

to inundating discharges of 38 m^3/s. Box elders established after the high flow of 1984 had survived in abundance down to the stage of the minimum discharge, 8.5 m^3/s.

Survival of box elders from 1994 to 1995 was strongly related to the number of days during the growing season that a plot was inundated (Figure 4). This relationship is well described by a threshold function at a value of 85 days; 9% of trees survived inundation for more than 85 days, while 92% of trees survived inundation for less than 85 days. Peak instantaneous discharge during this period (1995) was 268 m^3/s; the discharge exceeded for 85 days was 114 m^3/s.

Sediment mobilization apparently killed fewer trees than extended inundation during the high flow of 1995 (Figure 4). Of the 38 plots that contained trees following sampling in 1994, 12 experienced a shear stress exceeding the critical shear stress necessary to mobilize the sediment (1995 shear–critical shear > 0, Figure 4). Eight percent of the trees in these plots survived between 1994 and 1995. This low survival in plots experiencing high shear stress is consistent with the hypothesis that box elders are killed by exceeding the critical shear stress for mobilization of the underlying sediment. However, sediment mobilization does not explain the relatively low survival (19% of trees) in the many plots where the critical shear stress was not exceeded (Figure 4). This mortality was apparently because of extended inundation.

To investigate survival by box elders of high flows prior to 1995 we determined the highest shear stress and longest growing-season inundation experienced by the sampled box elders throughout their lives (Figure 5). In comparison to the data on survival from 1994 to 1995 this historical data set has the advantage of integrating the effects of multiple events, but the disadvantage of including information only on individuals that lived; we have no information from these plots about box elders that died prior to

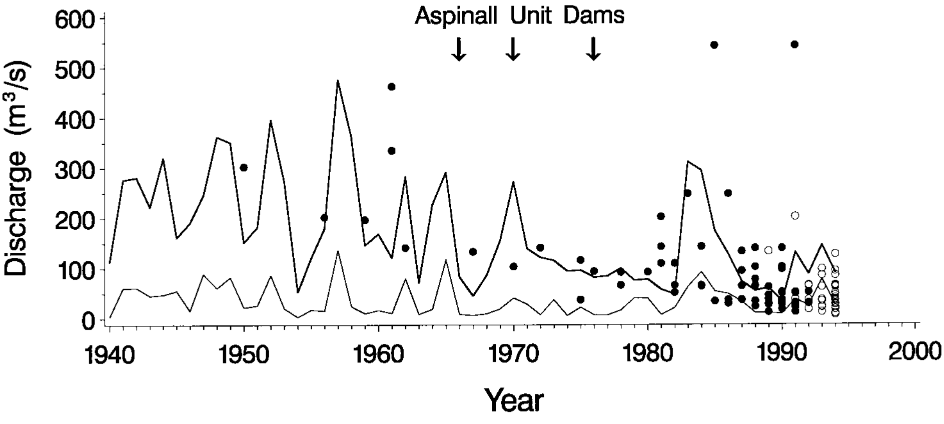

Figure 3. Inundating discharge and establishment year of box elders aged in 1994, and high flow history at Black Canyon of the Gunnison National Monument. Open and closed circles are trees less than and greater than 30.5 cm tall. Two trees established before 1940 are not depicted; these trees were established in 1921 and 1923 and occurred at inundating discharges of 202 and 825 m^3/s. The thick line is the annual peak instantaneous discharge, and the thin line is the discharge exceeded for 85 growing-season days. Arrows indicate completion dates of the three Aspinall Unit dams

1994. This historical analysis provides clear evidence of the importance of sediment mobilization as a mortality factor. Only 11% of the 95 box elders sampled had survived a shear stress greater than the critical shear stress, and no box elders had survived a shear stress that exceeded the critical shear stress by more than 24 Pa (Figure 5). An alternative explanation for this pattern is that box elders rarely survive shear stresses above critical simply because such high shear stresses are rare. This alternative must be rejected because shear stresses above critical are in fact common. For example, critical shear stress was exceeded in 1983 in 44% of the plots above the minimum flow line (inundating discharge of 8.5 m^3/s). The inability of box elders to survive shear stresses much greater than critical explains why individuals more than a few years old are restricted to the highest plots (Figures 2 and 3). The median age of sampled box elders in the large size class was only 7 years.

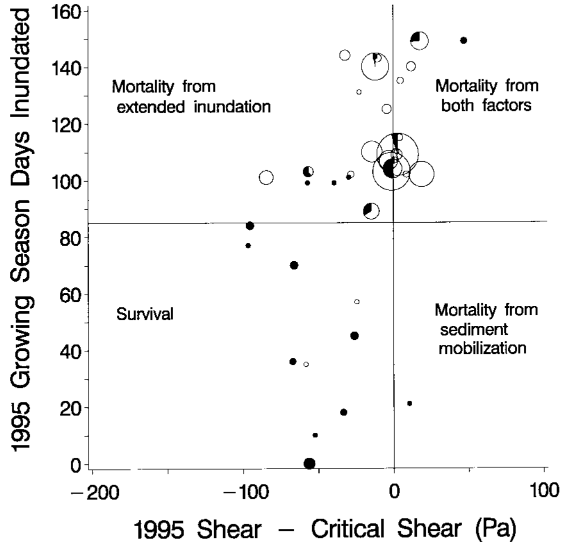

Figure 4. Survival of box elders from 1994 to 1995 as a function of growing-season days inundated in 1995 and the difference between shear stress experienced in 1995 and the critical shear stress of the sediment in the plot. Each circle represents a plot. The filled fraction of the circle indicates the proportion of box elders that survived. The area of the circle is proportional to the density of box elders present on the plot in 1994, ranging from 0.027 to 2.2 individuals per m^2. Reference lines indicate mortality thresholds. The quadrants of the graph are labeled to indicate the expected mortality pattern

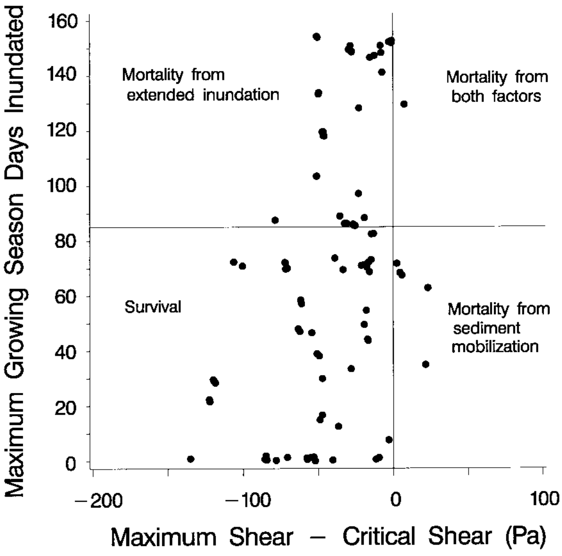

Figure 5. Extreme historical conditions survived by box elders aged in 1994. On the vertical axis is the maximum duration of inundation survived by the plant during a single growing season; on the horizontal axis is the difference between maximum shear stress ever experienced by the plant and the critical shear stress of the sediment in the underlying plot. Each point represents one box elder. Reference lines indicate mortality thresholds. The quadrants of the graph are labeled to indicate the expected mortality pattern. Establishment years of sampled box elders are shown in Figure 3

Whereas the number of days inundated during the growing season was strongly related to survival of box elders from 1994 to 1995 (threshold of 85 days inundated in Figure 4), the influence of inundation is less clear in the historical analysis of survival prior to 1994 (Figure 5). Thirty-four percent of 95 harvested box elders had survived 85 days of inundation during a growing season, and 15% had survived more than 140 days of inundation. This apparent discrepancy is largely a result of the distribution of box elders prior to the high flow of 1993 (Figure 2). In 1990 the density of box elders was much higher at inundating discharges of 10–60 m^3/s than at inundating discharges greater than 60 m^3/s (Figure 2), apparently because relatively high moisture availability promoted establishment at lower positions. In 1993 the discharge exceeded for 85 days was 78 m^3/s. Between 1990 and 1994 area–weighted densities decreased by 78% at inundating discharges below 80 m^3/s but only decreased by 10% at inundating discharges above 80 m^3/s. Thus proportional survival of box elders was low on surfaces inundated for more than 85 days in 1993, but many individuals remained (Figure 5) because initial densities were very high.

Flow regulation by reservoirs on the Gunnison River has decreased both the frequency and magnitude of peak flows (Figure 3). Annual peak flows exceeding 200 m^3/s occurred in 68% of the years before reservoir construction (1910–1965), but in only 15% of the years since reservoir completion (1976–1995).

PREDICTING BOX ELDER REMOVAL BY SPECIFIC FLOW SEQUENCES

Assuming that box elder saplings can be killed by inundation for 85 days or by exceeding the critical shear stress for mobilization of underlying sediment, we can use the peak instantaneous discharge and the sequence of daily flows in any year to predict which plots along the cross-sections should be cleared. For example, 67% of cross-section 2 was inundated for more than 85 days in 1995, while only 17% of the cross-section experienced a shear stress greater than critical (Figure 6). All plots expected to be cleared by sediment mobilization were also inundated for more than 85 days (Figure 6), therefore, extended inundation was a more important cause of mortality than sediment mobilization along this cross-section in 1995, a conclusion that is supported by the pooled results from all cross-sections for this year (Figure 4).

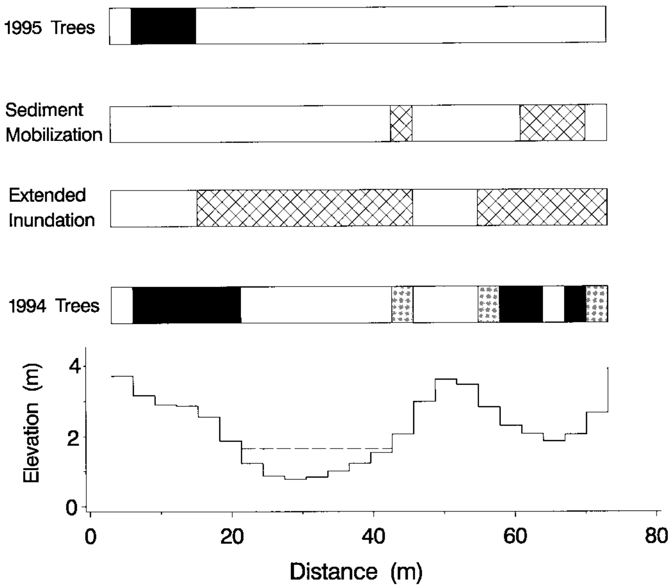

Figure 6. Box elder distribution and mortality along cross-section 2, 1994 to 1995. Elevations along the cross-section are relative to an arbitrary datum. The elevation of each plot is depicted as it was represented in the analysis. The dashed line is the stage at a discharge of 8.5 m^3/s, the currently imposed minimum streamflow. In the lowest of the four horizontal bars, solid blocks indicate plots containing box elders after destructive sampling in 1994, and shaded blocks indicate plots from which all box elders were removed by destructive sampling. In the middle two horizontal bars, cross hatched blocks indicate plots predicted to be cleared by the mortality functions for sediment mobilization and extended inundation in early 1995. The solid block in the top horizontal bar indicates plots containing box elders that survived the high flow of early 1995

Expanding this analysis to all cross-sections and all years in the flow record at East Portal provides an estimate of the proportion of the canyon bottom cleared by inundation and sediment mobilization each year since 1911 (Figure 7). We exclude from this analysis the permanently flooded plots with inundating discharges below 8.5 m^3/s, the minimum flow determined by an instream flow right owned by the state of Colorado (Diaz *et al.*, 1994). The relative importance of sediment mobilization and extended inundation in removing box elder saplings at Warner Point has been altered by reservoir construction (1966–1976; Figure 7). Before reservoir construction, sediment mobilization predominated; since reservoir

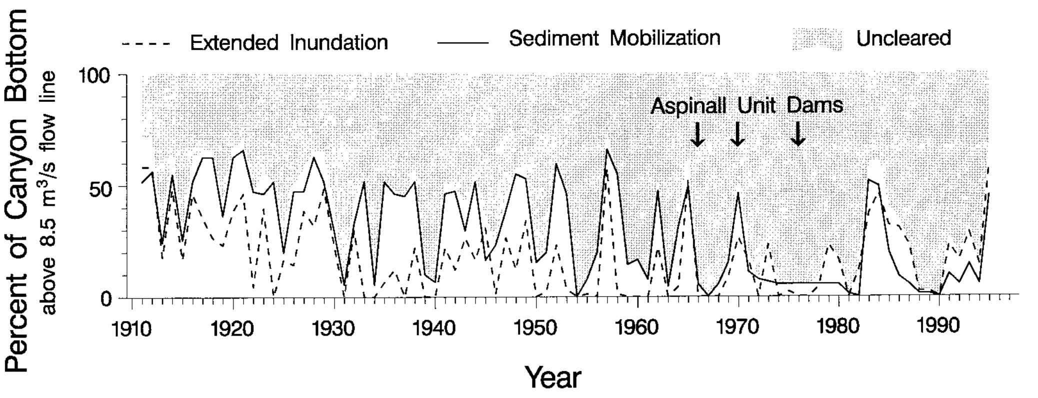

Figure 7. Percent of the canyon bottom cleared each year by sediment mobilization and extended inundation as simulated by application of threshold mortality functions to the historical hydrologic record. Excluded are permanently flooded areas with inundating discharges below 8.5 m^3/s, the imposed minimum discharge. Because a plot can be cleared by both extended inundation and sediment mobilization, the total area cleared in a year may be less than the sum of the areas cleared by the two factors. Arrows indicate completion dates of the three Aspinall Unit dams

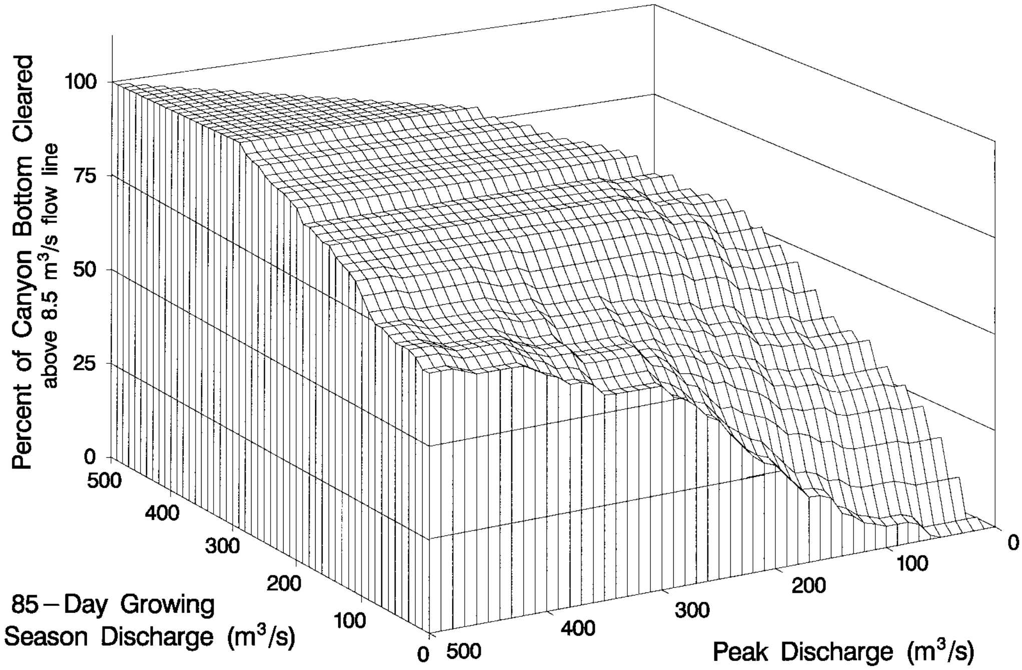

Figure 8. Percent of canyon bottom cleared as a function of annual peak discharge and discharge exceeded for 85 growing-season days. Excluded are permanently flooded areas with inundating discharges below 8.5 m^3/s, the imposed minimum discharge. Response is based on threshold mortality functions for extended inundation and sediment mobilization. Because the discharge exceeded for 85 growing-season days cannot be greater than the peak annual discharge, such combinations are not plotted

construction, extended inundation has predominated because water storage and diversion have decreased the magnitude of high flows more than their duration (Figure 7). On a shorter time scale, the relative roles of sediment mobilization and extended inundation vary among years. For example, sediment mobilization was more important in 1983 and 1984 than in 1995, when peak flow had lower magnitude and longer duration (Figure 7). This is one reason why survival from 1994 to 1995 (Figure 4) shows a weaker effect of sediment mobilization than the conditions survived by box elders excavated in 1994 (Figure 5).

The equations underlying Figure 7 can be used to develop a response surface showing the percent of the canyon bottom that is cleared of box elder at any combination of flood peak and duration (Figure 8). This response surface can be used to design a flood hydrograph that achieves a given level of box elder removal within constraints resulting from limited availability of water or concerns about downstream flooding. From the point of view of water conservation, sediment mobilization is a more efficient method than extended inundation for removal of box elder. However, sediment mobilization requires higher instantaneous flows, which may cause unacceptable damage to other resources. In addition, 34% of the canyon bottom above the 8.5 m^3/s flow line cannot be cleared by sediment mobilization at flows up to 566.4 m^3/s (Figure 8) because sediment particle size is too large, water is too shallow, or energy gradient is too low. On the other hand, a strategy relying heavily on extended inundation for removal of box elder will require large volumes of water, and may lead to establishment of new box elders on high surfaces that were formerly too dry for seedling establishment. Such new individuals would be difficult to remove by sediment mobilization or extended inundation.

This study has examined the importance of flow magnitude and duration in controlling removal of box elder along the Gunnison River. Two additional important factors are return interval and timing relative to the growing season. As the number of years between high flows increases, the size of box elders increases and their susceptibility to removal declines. Whereas the mostly immature box elders in this study were generally removed by 85 days of inundation during the growing season, tree-sized box elders may not be removed even by an entire growing season of inundation (Bell and Johnson, 1974; Harris, 1975; Whitlow and Harris, 1979), and the tree roots may stabilize the sediment to the point that the critical shear stress is greatly increased (Smith, 1976; Prosser *et al.*, 1995). Therefore, uninterrupted low-flow periods longer than 10–15 years may result in irreversible streamward encroachment of woody vegetation.

Extended inundation in the dormant season will be much less likely to kill trees than similar inundation in the growing season (Gill, 1970). On the other hand, high flows during the growing season are more likely to promote establishment of new seedlings above the zone of removal. Such an effect is less likely if the declining limb of the hydrograph is rapid enough to cause death by desiccation of the young seedlings.

GENERALITY OF RESULTS

The approach developed in this study should be applicable to a wide range of situations where removal or protection of woody riparian vegetation is a management concern. However, care should be exercised in applying the specific thresholds developed in this study (reference lines in Figures 4 and 5) to other sites. Although box elder is generally considered to be flood-tolerant (Hall *et al.*, 1946; Whitlow and Harris, 1979; Hook, 1984), the number of days necessary to kill a box elder is strongly age-dependent. Adults can typically survive an entire growing season or more of inundation (Hall *et al.*, 1946; Yeager, 1949; Bell and Johnson, 1974; Harris, 1975; Whitlow and Harris, 1979), while first-year seedlings can survive growing-season inundation of 25 to more than 60 days (Hosner, 1958; Hosner 1960; Hosner and Boyce, 1962; Loucks and Keen, 1973). A study of flood tolerance of box elder saplings less than 2 m tall reported elimination of all individuals from six of 16 plots following inundation for 105 days (Noble and Murphy, 1975). The 85-day survival threshold observed for inundation of box elder saplings in this study is consistent with the literature on flood tolerance for box elder even though almost all of the studies cited above were carried out in relatively humid parts of southeastern North America, on different varieties of box elder from that native to Colorado (var. *interior*; Sargent, 1961), and involved finer-textured soils flooded by standing water that may have been warmer than the hypolimnial (bottom) reservoir releases into the Gunnison River (Stanford and Ward, 1984). Our threshold for inundation is also similar to the value of 80 days determined by Toner and Keddy (1997) for prevention of encroachment by other woody species along the Ottawa River, Ontario. However, because of the many factors that can influence this threshold, predictions of inundation mortality at other sites should be calibrated using local measurements of survival of floods of known duration. If box elders at the study site are allowed to grow to tree stature, then inundation for 85 days will no longer be sufficient to kill them.

Care must also be taken in applying the Shields Criterion (Equation (2)) to model removal of riparian vegetation. In this study the τ^*_{cr} was treated as a constant, however, this assumption is not valid for particle diameters less than about 2 mm (Shields, 1936). More important, as particle size decreases, the relative contribution of plant roots to sediment stability increases greatly (Smith, 1976; Prosser *et al.*, 1995), therefore, the Shields Criterion is likely to underestimate the shear stress necessary to mobilize densely vegetated particles finer than gravels. In this study the two box elders that survived shear stresses more than 20 Pa greater than the critical value (Figure 5) were both rooted in relatively fine sediments ($d_{50} < 2.5$ cm).

Calculations of critical shear stress are sensitive to the value chosen for τ^*_{cr}, which may vary by an order of magnitude depending on the assumptions and conditions of analysis (Wilcock, 1993; Buffington and Montgomery, 1997). In this study, we assumed that sediment is mobilized when the dimensionless shear stress for the median surface particle exceeds 0.031, a typical value for gravel stream beds when sediment particle size is measured at the surface (Andrews, 1983; Komar, 1987, p. 207; Wilcock, 1993; Wilcock *et al.*, 1996). This value is corroborated by observations of sediment moved by known discharges at the study site in 1995 (Elliott and Hammack, 1999) and by our successful prediction of the greatest shear stress box elders can survive (Figure 5). In other studies, however, different values for τ^*_{cr} may be needed. Critical shear stress is influenced by the degree of bed armoring (Andrews, 1983; Komar, 1987); the smaller the particles underlying the bed surface, the more easily the surface particles roll and slide and the lower their τ^*_{cr}. When the subsurface particles are included in sediment particle size measurements, d_{50} tends to be lower and τ^*_{cr} tends to be higher. Although sediment mobilization is typically modeled as a threshold function, there is a small amount of sediment transport at shear stresses below critical (Milhous, 1973; Lavelle and Mofjeld, 1987), and if such flows have a long duration they could remove riparian plants.

In our consideration of sediment mobilization, we have assumed that the contribution of bank slope to sediment stability is negligible. Steep banks, however, can decrease the discharge necessary for mobilization of sediment or removal of trees. For example, erosion at the base of high banks may remove plants on top of those banks by bank failure (Thorne, 1990; Johnson, 1997). Where riparian trees are removed by toppling or stem breakage as a result of force applied by water against debris piled upstream of the stem (Friedman *et al.*, 1996), then analysis of drag forces on the tree may predict tree removal more successfully then analysis of shear stress along the bed.

SUMMARY

Along the Gunnison River, high flows limit the streamward extent of box elder saplings through extended inundation and sediment mobilization. Both mortality factors can be modeled as threshold functions; box elders can be removed either by inundation for more than 85 days during the growing season or by shear stress that exceeds the critical shear stress for the underlying sediment. Applying these threshold functions to the hydrologic record indicates that construction of upstream reservoirs in the 1960s and 1970s reduced the proportion of the canyon bottom annually cleared by high flows. Furthermore, because the dams decreased the magnitude of high flows more than their duration, flow regulation has increased the relative importance of extended inundation as a mortality factor. The threshold functions and cross-section data can also be used to develop a response surface predicting the proportion of the canyon bottom cleared at any combination of flow magnitude and duration. This response surface allows vegetation removal to be incorporated into quantitative multi-objective water management decisions.

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