Riparian Vegetation as a Primary Control on Channel Characteristics in Multi-thread Rivers

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While many previous studies have explored the effects of vegetation on single-thread rivers, systematic studies on multi-thread rivers are scarce. Our approach is to synthesize data and ideas from a field-based study of the Waitaki River in New Zealand with results from laboratory flume experiments and a cellular numerical model for which variables can be controlled. The combination of the results from the three approaches suggests that vegetation affects channel planform mainly through reductions in the total channel width, braiding index, and relative mobility of channels. A major driver is the effect of vegetation on flow dynamics and the apparent cohesion of channel bed and banks. By choking off weaker channels, vegetation corrals the flow into fewer, stronger channels with more uniform higher velocities; by strengthening the banks and exposed bars, vegetation reduces channel migration rates and limits bed-material exchange with islands and bars. At present there is no indication that the maximum shear stress is increased by vegetation, only that the low-stress tail of the total stress distribution is cut off. Thus total flow width appears to be relatively sensitive to changes in vegetation intensity while maximum velocity and width of the region of active sediment transport are less so. In natural channel systems, vegetation reduces the total channel width by occupying freshly exposed areas of bare sediment. Though this happens naturally, it is often enhanced by changes in the flow regime that may be due, for example, to climate change or damming. Colonization by vegetation is not easily reversible, and therefore typically has long-term effects on the system. We investigate historical channel changes on the Platte River in central Nebraska to separate out the effects of discharge reduction and vegetation expansion on channel width, and find that discharge reduction alone cannot account for the current reduced width on the Platte today.

1. INTRODUCTION

Vegetation has been recognized as a primary control on river planform, particularly as a determinant of whether a river will adopt a braided or single-thread pattern (e.g. Millar [2000]). Studies have shown that overall behavior of the system correlates with vegetation type or density, shifting between a single-thread channel and a multi-thread system as vegetation changes [Mackin, 1956; Brice, 1964; Nevins, 1969; Goodwin, 1996; Ward and Tockner, 2000]. Murray and Paola [1994] concluded that braiding is the main mode of instability for unconstrained flow over a noncohesive bed. In other words, in the absence of cohesion to stabilize the banks and/or discourage formation of new channels, the flow tends to create new channels until a braided system develops. There-
fore, braiding represents the “default” type of channel instability for rivers in non-cohesive sediment without vegetation. In natural systems the cohesion necessary to stabilize banks can be derived either from finegrained sediment (silt, clay) or from vegetation. Seeds are transported and dispersed readily by wind and water, and opportunistically colonize areas of the channel abandoned or exposed at low flows [Johnson, 1994, 1997, 2000]. Vegetation increases bank stability through root binding of the sediment and increases the threshold shear stress needed to erode the sediment. In addition, vegetation offers local resistance to flow by increasing drag and reducing velocity, thus decreasing the shear stress available for erosion and transport [Thorne, 1990; Carollo, 2002]. Vegetation that is not removed while young, when the plants can be uprooted or buried by even minor flows, becomes stronger and increasingly resistant to erosion and removal by the flow. Thus, at least initially, both bank strength and flow resistance increase with time, though this may be reversed for mature plant systems [Johnson, 1994, 2000].

The physical details of vegetation effects on river channels are complex. Increased vegetation density is typically linked to a decrease in bank erosion and lateral migration rates [Smith, 1976; Beeson and Doyle, 1995]. Roots add strength by physically binding particles to roots. Soil without roots has high compressional strength, but little tensile strength. Roots add tensile strength and elasticity, which helps to distribute stresses, thus enhancing the bulk shear strength of the soil [Vidal, 1969; Thorne, 1990; Simon and Collison, 2002]. Roots thus function like the bars in reinforced concrete or the fibers in a carbon-fiber composite material. Several experiments and field studies have documented the connection between increased density of roots and increased soil strength (for example Ziemer [1981], Gray and MacDonald [1989], and Simon and Collison [2002]). Vegetation can also contribute to bank stability through canopy interception and evapotranspiration. These effects lead to drier, better drained banks with reduced bulk unit weight, as well as lower positive pore pressures [Simon and Collison, 2002].

Vegetation along banks affects flow dynamics as well. A number of studies have linked physical properties such as width, depth, and velocity to vegetation density in the riparian zone (e.g. Hadley [1961], Brice [1964], Zimmerman et al. [1967], Charlton et al. [1978], Andrews [1984], Hey and Thorne [1986], Huang and Nanson [1997], and Rowntree and Dollar [1999]). Vegetation along the banks usually increases roughness, decreasing local velocity and inducing deposition of fines [Thorne, 1990; Hupp and Simon, 1991; Shimizu and Tsujimoto, 1994; Stone and Shen, 2002]. The addition of fine materials to the banks due to baffling by plants may increase bank cohesion. Increased roughness can reduce conveyance over parts of the channel and force the flow into a smaller area [Johnson, 1994]. The resulting higher flow depths can lead to greater flood potential as well as increased bed degradation [Tsujimoto and Kitamura, 1996].

1.1. Combined human-vegetation effects

Human development of rivers often alters the natural flow regime and diminishes the threshold flows that would otherwise flush out vegetation in its early stages [Eschner et al., 1983; Johnson, 2000]. As a result, vegetation colonizes large areas of the bed and plays an active role in determining the channel morphology. The case is similar for periods of drought. In many river systems new plant species were artificially introduced to stabilize the banks to support agriculture in the river valley. These new species often have characteristics adapted to highly variable environments: abundant seeds during a short dispersal period characterized by rapid germination and root and shoot growth [Graf, 1978; Johnson, 1994; Pettit et al., 2001]. Thus they are often more aggressive colonizers than native equivalents. With the addition of river development (e.g. dams, irrigation) the combination of introduced species and altered flow regime can lead to dramatic changes in river planform. Islands and banks become stabilized and the native species are eliminated.

Studies thus far suggest that the cumulative effects of riparian vegetation on river morphology can be either beneficial or detrimental to the system. In addition to its natural and aesthetic appeal, its effectiveness at offering bank stability makes vegetation an attractive method for restoring degraded streams. For instance, vegetation is being used to alter the stream flow direction and induce meandering in straight degraded stream channels Nevins, 1969; Rowntree and Dollar, 1999; Bennet et al., 2002]. The vegetation around a bend effectively reduces erosion and induces bank accretion and lateral migration [Beeson and Doyle, 1995]. One of the most striking changes that occur with increasing vegetation is a substantial reduction in the channel width which can reduce the channel capacity and increases the risk of flooding [Eschner et al., 1983]. The channel and near-channel areas of unvegetated systems are typically characterized by unstable sediment deposits that are mobilized during periods of high discharge. With the onset of vegetation the potential for flooding increases due to bars that are immobile and inflexible [Graf, 1978]. The reduction in the near-bank velocities from increased resistance greatly promotes sediment deposition and bank and bar accretion. The vegetation is also effective in trapping fine suspended material. Over time these processes decrease the median grain size in the system, which can substantially affect the adequacy for spawning by, for example, salmon and trout [Kondolf and Wolman, 1993]. The altered systems are characterized by a decrease in the number of active channels, a decrease in the total wetted width, and a decrease in channel mobility; the riverbed has
been “pinned” into a well defined fairway that is substantially narrower than the original width. An important biological effect of the planform changes is that critical resting grounds for migratory birds (e.g. sand hill and whooping cranes) are reduced or eliminated [Eschner, 1983; Currier et al, 1985]. This effect has motivated programs to remove vegetation (e.g. on the Platte River in central Nebraska). Unfortunately we still lack a physically-based understanding of what might be termed “river biophysics” that could aid in developing optimal strategies for adding and removing vegetation.

Much of the research thus far on the interactions between vegetation and channel flow dynamics has been focused on single-thread channels. Research on vegetation effects in multi-thread channels is sparse in comparison. Johnson [1994] suggested that the combined effects of flow alterations and vegetation differ considerably between braided and meandering rivers. In meandering rivers floods are needed to overtop the normal bars and produce high elevation point bars through sedimentation in order to enable recruitment. Relative to a braided river, in a meandering river depth is more sensitive and width less sensitive to changes in discharge. In meandering rivers a decrease in flood peaks reduces meandering rates, leading to a reduction in production of new colonizable area. The opposite is true for braided rivers. The area of active channel exposed is very sensitive to small changes in the flow so that discharge reduction increases the colonizable area.

In this paper our goal is to synthesize what is known about vegetation effects on multi-thread channels in non-cohesive sediments, i.e. rivers where vegetation is the primary source of cohesion in the system. We focus on rivers in humid-temperate climates with well-defined channels and perennial flows. Thus we will consider mainly bank vegetation and not channel-bottom vegetation. We begin with a field-based case study of the Waitaki River in New Zealand. The work is based largely on analysis of aerial photos. As has occurred in many rivers, a change in the natural flow regime due to dam control and irrigation brought about a change in the vegetation cover in the river. While such cases offer us opportunities to use the field as a natural laboratory, it is often difficult to separate the effects of vegetation on the river from the effects of other parameters with which vegetation co-varies (e.g. a change in climate, discharge, sediment type or supply). To isolate individual parameters we turn to laboratory flume experiments and a cellular numerical model as ways of observing the whole channel system under different vegetation conditions with other parameters held constant. Unfortunately, because these studies have not been coordinated, they use different means of measuring vegetation, which complicates comparing them. Thus our approach here is to seek common vegetation effects that are consistent across all three approaches and strong enough to be clearly visible despite the measurement differences. Finally, we use two additional field studies, the Platte River in Nebraska and an alluvial fan at a tailings mine in northern Minnesota, to consider the implications of a long-term change in discharge in a field situation.

2. BACKGROUND AND METHODS

2.1. Waitaki River: Description

The Waitaki River is located on the South Island of New Zealand. It is the country’s largest braided river by discharge (mean discharge ~ 358 m³/s) and a major source for hydroelectric power. Hydropower works include three dams along the middle, gorged section of the Waitaki Valley and a network of canals, control structures, and power stations that utilize the storage from three natural lakes in the upper basin. The Lower Waitaki River is the portion of the Waitaki that flows ~ 70 km from the furthest downstream dam (Waitaki Dam) to the sea (Figure 1). It is braided for all but the first few km downstream of the dam and has a sandy gravel bed-material with a median size of approximately 30 mm.

Since the completion of the Waitaki Dam in 1937, the discharges to the Lower Waitaki have been controlled, resulting in a damped flood regime and generally steadier river flow, and there has been no bed-material input from the upper catchment. By comparing the measured discharge record with a simulation of the natural, unregulated record, the mean annual flood discharge of the lower river is estimated to have been reduced from 1434 m³/s to 1171 m³/s. Tributary sediment budget estimates plus reservoir surveys indicate that the dams have reduced the bed-material supply to the Lower Waitaki River.

Figure 1. The Waitaki River basin, South Island, New Zealand.
by approximately 50% [Hicks et al., 2002]. The remaining bed-material supply is sourced from tributaries and reworking of the Pleistocene valley-fill. While some of the supply deficit appears to have been compensated by degradation within a few km downstream of the Waitaki Dam, degradation along the braided reach is not obvious; indeed, it is likely that the effect of reduced sediment supply has been moderated by the reduced transport capacity of the flow regime.

The pre-dam riverbed, almost 2 km wide, was characterized by sparse willow trees, temporary islands vegetated mainly by native tussock and scrub, and shifting gravel bars and channels (Figure 2a). The appearance was described as “bare and windswept” [Thompson et al., 1997]. The onset of flow regulation was followed by an invasion of the riverbed by exotic vegetation (notably willow, broom, and gorse) (Figure 2b). This was able to establish because the new flow regime lacked the extreme seasonal variations necessary to flush seedlings and saplings out of the bed or allow grazing of riverbed sites during prolonged spells of lower winter flows [Hall, 1984]. In consequence, the less resilient native vegetation was displaced and islands and bars became choked with exotic vegetation and tended to stabilize, while flood break-outs along the riverbed margins became a hazard. Although a policy of devegetating a central “fairway” or braidplain (i.e., area of non- or sparsely vegetated, active riverbed) with spraying and machinery has been implemented since the 1960s, a net increase in vegetation cover remains traceable from aerial photographs. By 2001, the river’s braidplain had been reduced to an average width of about 0.5 km (Figure 2b). The total area of riverbed (vegetated and braidplain) has also decreased by conversion of marginal riverbed to pastureland.

2.2. Waitaki River: Methods

Studies of aerial photographs (e.g. Hall [1984]) have noted qualitatively that this narrowing of the braidplain has been accompanied by a reduction in braiding activity and a tendency for flows to congregate in one or two principal braids. Clear time-trends of braiding intensity change are difficult to distinguish owing to a dependence of the number of flowing channels on discharge and the varying discharge at times of aerial photography. Here we minimize this complication by analyzing results at a reference discharge. To utilize the only aerial photograph of the river taken prior to regulation, we set this reference discharge at 152 m$^3$/s to match the mean daily discharge on the day of the 1936 photograph, which covered an 11 km reach adjacent to the coast (Figure 2a). A near identical discharge was photographed during a low-flow trial in 2001, when the flow was kept steady at 150 m$^3$/s for 24 hours (Figure 2b).

We used these 1936 and 2001 photographs to measure the number and total width of flowing channels and also the ground cover along 21 valley-normal cross-section lines spaced at 500 m intervals along the coastal reach. Because of a lack of information on channel depth and discharge, all the flowing channels that connected into the braiding network were counted (with backwaters and groundwater-fed channels ignored). The analysis was undertaken using GIS. The 2001 photographs were color digital ortho-images with 0.5 m pixel resolution, georeferenced to the New Zealand Map Grid with a horizontal accuracy of 1 m. The 1936 photographs (black and white) were scanned at 1 m pixel resolution, then rectified and georeferenced using a polynomial fit to approximately 12 control points per frame that were common to both the 2001 and 1936 imagery. While this resulted in absolute positioning errors of up to 5 m on the 1936 imagery, there was negligible distortion of the scaling (i.e., channel widths were accurately measured to within 1-2 m, even if their absolute location was uncertain to ~ 5 m). Ground cover type was classified by eye and digitized. The classes included fenced-off pasture, tall vegetation (mainly willow trees), low vegetation (bushes, typically willow and broom), berm or island grass/tussock, sparse vegetation (isolated bushes on gravel bars), bare gravel, flowing water, and standing water. Total width of riverbed (braidplain width) spans the space of “wildland” between pasture borders. We defined vegetation density as the percentage of riverbed area covered in continuous tall and low vegetation (i.e., trees and bushes). We excluded the native grasses established on transient islands from this definition since they are relatively easily scoured and provide little flow resistance compared with the exotic trees and bushes. In plotting the data, we denoted 1936 as a vegetation density cover of zero, and other years represent the change (positive or negative) from 1936. Changes between 1936 and 2001 over part of this study reach may be compared in Figure 2.

While no intervening historical photographs were available at or near this discharge, we used reach-averaged hydraulic geometry-type relationships determined by MWD [1982] to estimate number of channels and total width of flowing channel at 150 m$^3$/s, matching these with ground-cover measurements made from air-photographs taken in 1985. These relations are $N = 1.17 Q^{0.28}$ and $W = 24 Q^{0.50}$, where $N$ is number of flowing channels, $W$ is total width of flowing channels normal to the valley slope (m), and $Q$ is the total discharge (m$^3$/s). We note that for the width relation, we have increased the coefficient by a factor of 1.14 to account for the MWD (1982) widths being measured normal to individual channels, not the valley axis. The 1.14 value is the average channel sinuosity. The 1985 photographs (color) were processed and analyzed in the same fashion as the 1936 photographs. The
A.

B.

Figure 2. The Lower Waitaki River ~ 5 km upstream from the coast, photographed in 1936 (a) and 2001 (b) when the river discharge was ~ 150 m³/s. Flow is left to right. Frame bases span 3.7 km; scales are identical.

ground-cover analysis was also repeated for other photography epochs for the same reach.

2.3. Flume Experiments: Methods

A series of flume experiments was run at the St. Anthony Falls Laboratory to investigate the effects of vegetation density on channel geometry and flow dynamics in multi-thread channels formed in non-cohesive sediment. The details of the flume experiments are described in Gran and Paola [2001].

Here we offer a brief description of the experimental procedures pertaining to the results used in this paper. Experiments were conducted in a 2 m by 9 m flume with a slope of 0.014. The experiments consisted of five different runs, four of which are presented here: one with no vegetation and three with varying densities (stems per unit area) of alfalfa (Medicago sativa), used for vegetation in the flume [Ziemer, 1981; Gray and MacDonald, 1989]. Water entered the upstream end of the flume at a constant discharge, and sediment (well sorted quartz sand, $D_{50} = 0.5$ mm) was fed at a constant rate. An initial
straight channel widened, and a braided channel system was allowed to develop fully before any vegetation was added (Figure 3a). After the braided channel system developed, the discharge was reduced to half the original discharge, and the sediment feed was shut off during seed dispersal. Seeds were dispersed manually over the entire area of the flume. Some seeds were deposited directly, and some were removed and reworked through the channel and along bars and banks by the flow, thus simulating natural dispersion of seeds by wind and water. The water was shut off for 10–14 days while the plants grew. Once the vegetation was fully established (Figure 3b), the discharge was returned to its original value, and the run continued. Vegetation density was the only variable that changed between runs, varying from 0-9.2 stems/cm². Data from four different runs are presented in this paper, with each run representing a different density.

Width, depth, and number of active channels were measured at 5 equally spaced transects along the study reach every 2 hours for the duration of each run [Gran and Paola, 2001]. Measurements were taken at the same place for the unvegetated and vegetated beds. Depths were mapped using an image-based dye density technique. Active channels were defined as those that had a minimum depth of 0.002 m, which corresponds to the threshold shear stress for bedload transport. Summary statistics were compiled on the average number of active channels, or braiding intensity (BI), and the average total width (w) of active channels [Gran and Paola, 2001]. Summary statistics represent compilations of all cross-sections taken at each time slice for the run (after reaching steady state). Bed topography was measured along all of the same 5 cross-sections every 5–7 hours using a point gauge. This time scale allowed for measurable changes in the bed topography to occur, without sacrificing continuity between sequential profiles.

Gran and Paola [2001] used bed topography data to quantify channel mobility rates by treating the cross-section data as a form of time series data and computing a correlation coefficient ($r_0$) at each cross-section between sequential profiles ($\eta_1$ and $\eta_2$)

$$r_0 = \frac{\text{cov}(\eta_1, \eta_2)}{\sqrt{\text{var}(\eta_1) \cdot \text{var}(\eta_2)}}$$

Here cov and var refer to the standard statistical definitions of covariance and variance. This correlation coefficient is similar to an auto-correlation coefficient, and in this context gives an index of the coherence of the section geometry with time. The same analysis was done with bed topography data from the cellular model.

Figure 3. Photographs of the experimental flume at St. Anthony Falls Laboratory during the unvegetated fully braided stage (a) and after the vegetation has been established and only two main channels exist (b).
2.4. Cellular Model: Methods

The goal of the original cellular model [Murray and Paola, 1994] was to include only a small number of processes, represented via simple, abstracted rules, to determine what aspects of the interactions and resulting feedbacks that we see in the field and in the laboratory are sufficient to produce an ongoing, dynamic, multiple-channel pattern. It was found that a nonlinear relationship between sediment flux and local flow strength robustly leads to a braided pattern, but that the gravity-driven component of sediment transport on lateral slopes is necessary to maintain the dynamics indefinitely [Murray and Paola, 1994, 1997]. In a similar spirit, Murray and Paola [2003] added simplified representations of some of the main effects vegetation has on sediment transport, to investigate what plant effects might be responsible for producing single-thread patterns in bedload-dominated rivers. We stress that, in the cellular approach, some processes are omitted and others represented in simplified form. The goal is thus not to pursue detailed matches with natural examples, but rather to identify model behaviors that are robust and insensitive to specific parameterizations [Murray and Paola, 2003]. For example, trends that persist despite changes in parameter values should reflect the basic interactions included in the model. The algorithms of the basic model and the treatment of plant effects are described in detail by Murray and Paola [1994, 1997, 2003]. Here we briefly recap the main points, and describe the changes to the algorithm used in experiments reported in this paper.

2.4.1 Basic algorithm. A lattice of cells represents the braid plain, with average elevations decreasing longitudinally, creating an overall slope. In the model runs reported in this paper, the lattice was 500 cells long in the downstream direction. The initial elevations decreased linearly in the longitudinal direction, with small-amplitude, white noise perturbations added independently in each cell. Low terraces (three cells wide) along the sides minimized interaction between the flow and the inerodible high sidewalls that confined the flow. Except where noted, the discharge was introduced into the middle 36 cells wider than the discharge introduction in the first row.

Discharge is expressed in arbitrary units. One of the experiments reported below involves changing the total discharge from one run to another. Changes in total discharge are represented by altering the number of first-row cells that receive discharge, which is analogous to changing the width of flow entering a stream while holding the discharge per width constant. In these variable-discharge runs, the braid plain was always 12 cells wider than the discharge introduction in the first row.

The amount of sediment transported from cell to cell is related nonlinearly to the stream power (discharge times slope). Runs reported in this paper used $Q_s$, rule 6 from Murray and Paola [1997], in which the stream power immediately upstream of a cell, weighted by a factor $d$, is added to the local stream power. In runs reported here, $d = 0.25$, and the coefficient relating the adjusted stream power to sediment transport, $K_s = 5 \times 10^{-23}$. We have performed experiments using different parameter values and different sediment-transport rules [Murray and Paola, 1997], and have found that the results reported here do not depend sensitively on the exact form of the rule used.

With noncohesive material, wherever the flow is causing sediment movement, gravity causes a downslope component of sediment transport. Near a channel bank, this component of the transport will be in a direction lateral to the flow direction. This lateral transport moves bank material toward the lower parts of a channel, tending to widen the flow. In the model, if a lateral neighbor cell has a higher elevation than the cell in question, a sediment discharge, $Q_{sl}$, is transported down the lateral slope, $S_l$, according to:

$$Q_{sl} = K_s S_l Q_{s0}$$

where $K_s$ is a constant, adjusted so that $Q_{sl}$ is a few percent of the sediment transport in the cell in question, $Q_{s0}$, roughly consistent with Parker [1984].

The water routing and sediment transport rules are applied row by row until the water reaches the downslope end of the lattice. Then the elevation in each cell is adjusted according to the difference between the amounts of sediment entering and leaving that cell, conserving sediment mass. The elevation of the cells at the upstream and downstream ends of the lattice remained fixed during each run.

Nothing in the model constrains what scale of stream is simulated; the length represented by a cell, and the time represented by an iteration, are not determined [Murray and Paola, 1997]. Using the parameter values above, it takes approximately 100,000 iterations for the discharge pattern to change sufficiently that the correlation coefficient of the elevation pattern at the two times, as defined in the experimental section above, falls below 0.75. This provides a characteristic pattern-change time scale, $T_{ch}$, for the model.
2.4.2 Simulation of vegetation. The rules that have been added to simulate plant growth and plant effects are designed to be the simplest representations of what we hypothesize to be the main effects in the context of plant/stream interactions [Murray and Paola, 2003]. Murray and Paola [2003] found that the most important of the plant effects included is an increase in bank strength (a decrease in lateral sediment transport, \( Q_{sl} \)), representing the development of root networks. The plant effects increase in any cell, as described below, as long as conditions are conducive to plant growth, up to a limiting time after which the vegetation is assumed to be fully developed. This plant-development time scale, \( T_{pd} \), is equal to \( T_{ch} \) (100,000 iterations) in the runs reported here. Any plants in a cell are assumed to be destroyed if either of two conditions is met: 1) the rate of deposition of sediment rises above a cutoff value (either continuously or with interruptions lasting less than a specified plant-resurrection time) for more than a threshold time, effectively burying the plants under too much sediment for recovery; or 2) the rate of erosion rises above a cutoff value (either continuously or with interruptions lasting less than the plant-resurrection time) for longer than a threshold time. When deposition and erosion rates in a cell both fall below the cutoff for longer than the plant-resurrection time, plant growth begins again. The values used here for \( T_{pd} \) and the cutoffs and thresholds are consistent with those used previously [Murray and Paola, 2003]. Additional experiments in which these values were changed by an order of magnitude produced qualitatively the same results as those presented in Murray and Paola [2003].

The effect of plant roots on bank erosion is simulated by decreasing the magnitude of the lateral sediment transport (\( Q_{sl} \)) out of a vegetated cell. In this way, if plants are growing in a cell next to a channel (on top of a bank), a steeper slope can develop and be maintained longer between the vegetated cell and the adjacent channel cell. The coefficient in the lateral transport rule, \( K_p \), decreases linearly from a value appropriate for noncohesive sediment [Murray and Paola, 1997] to a minimum value over the plant growth time scale. We treat the minimum value, \( K_{pmin} \), which is inversely related to plant-enhanced bank strength, as an independent variable in some of the experiments reported below. We vary \( K_{pmin} \) by two orders of magnitude; thus, for fully developed vegetation in runs with the “strongest” plants, the bank erosion rate is reduced by two orders of magnitude. This magnitude is conservatively consistent with field experiments that have shown that banks protected by roots can have erosion resistances several orders of magnitude greater than those without protective vegetation [Smith, 1976].

The number and total width of active channels, as well as bed topography, were measured along 250 cross-sections every 100,000 iterations for the duration of the run after a statistically steady state was achieved (after approximately 1,000,000 iterations). A discharge threshold of approximately 10% of the typical discharge for a cell in a channel during a run without vegetation was used to delineate the active channels.

3. RESULTS

3.1. Vegetation Parameters

Each of the three approaches described above measures the relative importance of vegetation to the stream system in a different way. We stress that the three parameters used are significantly different from one another, and do not wish to imply that in any sense they are interchangeable.

In the Waitaki River study the vegetation parameter is the fractional areal cover of vegetation over the braid plain, referenced to the vegetation cover in 1936 (defined as a vegetation intensity of zero). For the flume experiments the vegetation parameter is the density of alfalfa stems, from zero to a den-

| Table 1. Average number of flowing channels and total width of flowing channels at ~ 150 m³/s, plus average widths of riverbed ground cover for the 11 km reach of the Waitaki River adjacent to the coast, as measured in 1936, 1985, and 2001. |
|-------------------------------------------------|--------|--------|--------|
| Number of channels                             | 11.6   | 4.9    | 6.8    |
| Total flowing width (m)                        | 416    | 294    | 243    |
| Width of tall vegetation (m)                   | 27     | 272    | 352    |
| Width of low vegetation (m)                    | 85     | 181    | 328    |
| Width of grassed island/berm (m)               | 298    | 42     | 1      |
| Braidplain width (m)                           | 1223   | 758    | 549    |
| Total width of riverbed (m)                    | 1632   | 1254   | 1229   |
| Vegetation density (% of total width)          | 6.9    | 36     | 55     |
| Normalized braiding index                      | 1      | 0.42   | 0.59   |
| Normalized total flowing width                 | 1      | 0.71   | 0.58   |
sity of 9.2 stems/cm² [Gran and Paola, 2001]. Finally, vegetation in the cellular model was varied by changing the plant-effect ratio, which is the vegetation strength measure for that model [Murray and Paola, 2003]. The plant-effect ratio is a ratio between the erodibility of a bank with no vegetation and a bank with fully grown vegetation. A plant-effect ratio of 0.1 means that a bank with fully developed vegetation is 1/10 as erodible as one without any vegetation. The vegetation parameter in the model is thus the plant-effect ratio.

3.2. Waitaki River

Results from the Waitaki River (Table 1 and Figure 4) show an increase in riverbed cover by trees and bushes (i.e., tall and low vegetation) from 7 to 55% of riverbed area between 1936 and 2001. This occurred at the expense of the braidplain, while the original areas of grassy berm were effectively reclaimed to pastureland. This overall trend occurred despite the substantial phase of vegetation removal by machinery in the early 1960s, ongoing spraying since then, and scour during a 100-year return period flood in December 1995 (Figure 4). Both braiding index and total flowing channel width (at ~150 m³/s) decreased by ~ 40% between 1936 and 2001. The low braiding index in 1985 suggests that the reduction in braiding occurred in the earlier decades. While this result is estimated rather than measured, it confirms previous qualitative reports.

The Lower Waitaki is a typical field situation in that the role of vegetation in driving geomorphic change cannot be isolated from the effects of other controls, such as flow regime change and reduced bed-material supply. Indeed, it appears to have been flow regulation that catalyzed the invasion of the riverbed by the exotic trees and bushes. However, it is clear from our present understanding of the influence of these types of plants on flow dynamics, sedimentation processes, and effective bank strength that, once established, they play a significant role in effecting the morphological evolution toward a less braided state. The role of the reduced upstream supply of bed-material to the Lower Waitaki by entrapment in the hydro-lakes is less certain. While abundant bed-material supply is a driver of the braiding process (e.g. Carson [1984]), it is not clear how much of the Lower Waitaki River’s supply deficit has been recovered from storage in its own braidplain. Certainly, any upstream supply deficit effect would be delayed while dispersing to the coastal reach, so we consider it unlikely that this was a dominant driver of the morphological changes that we have measured there.

3.3. Comparison of Results from the Waitaki River, Experimental Flume, and Cellular Model

Despite different approaches to investigating the effects of vegetation on multi-thread channels in the field, experimental, and cellular-model studies, we found similar trends relating riparian vegetation and braiding intensity, channel geometry, and the mobility of channels (Figure 5a,b,c). Increasing vegetation decreases the size and number of active channels (braiding intensity) in all three study systems (Figure 5a,b). Channel width is the sum of the widths of all active (as defined for each study) channels along a cross section. Channel statistics represent compilations of all cross-sections over the study reach for the Waitaki River, and all cross sections through time in each run for the experimental flume and the cellular model. As the riparian vegetation cover increased in the Waitaki River, channels became narrower, with fewer active channels along each cross-section. These trends mirror those found in the experimental flume and the cellular model. Channel widths and braiding intensity in both decreased with an increase in the plant density (experimental flume) and plant-effect ratio (cellular model), both proxies for the stabilizing effect of plant roots.

The field and experimental results reflect the effect of vegetation at a fixed discharge. One advantage of the cellular model is that the discharge can be easily varied without the problem of discharge affecting the vegetation parameter. To test the effect of initial discharge, we carried out a series of runs with constant discharge, but different vegetation strength as measured by the plant-effect parameter. This was repeated five times, for five different discharge values. In all cases, the width decreased with increasing vegetation (Figure 6). Although the fractional width decrease varied between a plant effect ratio of 1 and 0.1 for the different runs, all runs began to converge on the same decreased normalized width value (approximately 0.25) for a plant effect ratio of 0.05.

Because the measures of vegetative influence differ for the three approaches, and because the flume and the cellular model are highly simplified systems, we do not expect quantitative agreement between the results. However, we can compare general behaviors. All the approaches we have compared in this paper show that the effect of vegetation on channel pattern and
dynamics is quite strong. In the flume and the cellular model the braiding intensity was reduced by half as the vegetation influence was increased from minimum to maximum (Figure 5a). The channel width was reduced by approximately 80% for the same increase. The Waitaki River had a decrease of approximately 40% in both parameters (Figure 5a,b). The channel mobility as measured by \( r_0 \) for the flume and the cellular model decreased by approximately 25% (Figure 5c).

In both the flume and the cellular model we measured channel mobility indirectly by computing correlation coefficients \( (r_0) \) on topographic cross-sections between adjacent time steps. The \( r_0 \) values for the experimental flume runs with varying vegetation densities and the cellular model runs with varying plant effect ratios are shown in Figure 5c. An \( r_0 = 1 \) represents perfect correlation between sequential profiles, with lower \( r_0 \) indicating higher channel mobility rates. In both cases, \( r_0 \) increased with increasing plant density or strength, indicating lower mobility rates with increasing vegetation intensity. The results of the cellular model from data collected every 100,000 iterations showed similar trends to those collected every 200,000 iterations, showing that the results are not sensitive to a factor of two change in the sampling interval. For simplicity, we have plotted only the results from the 100,000 iteration interval in Figure 5c.

Another common aspect of the effect of vegetation for all three approaches we studied is that the changes in channel characteristics were strongly nonlinear for all measures of vegetation influence. The channel system is most sensitive to initial changes in vegetation and becomes less sensitive as the vegetation continues to increase. For the cellular model, for instance, the changes in channel width, braiding intensity, and channel mobility were strong initially and then weakened, stabilizing around a minimum value (Figure 5a,b,c and Figure 6). The strongest decreases in braiding intensity and channel width corresponded to an initial 30% increase in vegetation; for the channel mobility, the rapid increase in bed

![Figure 5](image-url)
topography correlation corresponded to an initial 8% change in vegetation. Because we did not continue increasing the vegetation in the flume past a certain density, it is not possible to see the diminishing effect of the vegetation clearly. The same is true for the Waitaki River, due to the small number of data points. We believe however, that given more data, the nonlinearity would hold true in both studies as well, making it independent of how vegetation is measured.

The vegetation caused a reduction in braiding intensity in all three studies (Figure 5a). The systems were transformed from multiple channels to one or two dominant channels. This reduction in the number of active channels corresponds to a transition in planform from a multi-thread system (braided) toward a single-thread one (Figure 3a,b). A true meandering river as defined by Leopold and Wolman [1957] is characterized by curves with consistent wavelengths. This was not true for the dominant channels that developed in our studies, although they did follow sinuous paths. Therefore the systems that emerged as a result of an increase in vegetation should be considered wandering or irregularly sinuous streams [Church and Rood, 1983].

4. DISCUSSION

Vegetation on river channel banks and bars constrains the flow of the river by stabilizing banks through root reinforcement and by offering resistance to flow. It also induces deposition of fine-grained, cohesive sediments, increasing the overall bank strength. Work done to date in multichannel rivers has established that increasing vegetation density decreases braiding intensity, channel mobility, and total channel width. However, because vegetation in natural rivers often changes along with other parameters such as discharge regime, it is difficult to tease out the effects of these various interactions from field observations alone. The cellular model is especially useful in clarifying the effect of increased bank strength due to vegetation, since increased bank strength is the main way in which vegetation effects are represented in the model. The inhibition of lateral transport due to increased bank strength leads to deeper, narrower channels [Murray and Paola, 2003], and a decrease in lateral mobility (Figure 5b,c and Figure 6). These trends are also clearly seen in field and experimental data (Figure 5b,c). The consistency in these trends suggests that the simplified treatment of vegetation in the cellular model does indeed capture a major element of vegetation effects on channel dynamics and that bank strength alone is sufficient to produce many of the changes seen in natural channels.

The trends in decreasing lateral mobility and channel widths as vegetation intensity increases for the multi-thread rivers considered here are consistent with those observed for natural single-thread channels [Hadley, 1961; Charlton et al., 1978; Andrews, 1984; Hey and Thorne, 1986; Beeson and Doyle, 1995; Huang and Nanson, 1997; Rowntree and Dollar, 1999]. Furthermore, the runs with highest vegetation density in the model and in the flume produced channels with characteristics that were more similar to those of single-thread rivers (i.e. lower width to depth ratios and lower mobility rates), suggesting that vegetation does indeed play a dominant role in determining whether a river will be single or multi-thread.

So far we have analyzed the effect of plants on river channels in terms of local effects such as increasing bank strength and flow resistance. The common trends in channel behavior we have identified across the three approaches considered here suggest two more global vegetation effects on channel systems: (1) selective colonization, and (2) the vegetation “ratchet” effect. Selective colonization refers to the tendency of plants to selectively occupy channels with relatively low discharge, in effect “corraling” the flow into a few larger channels. In this way even modest amounts of plant growth can quickly reduce total channel width (as noted in all three study approaches) without dramatically affecting flow in the dominant channels. In this view, the effect of the vegetation is mainly to organize the flow rather than to strengthen it. It is noteworthy that, at least according to the laboratory experiments of Gran and Paola [2001] the open channels remaining after vegetation
establishment do not exhibit larger maximum velocities than the equivalent unvegetated systems; they are simply able to maintain more consistently high velocities. We will return to this point below. The “ratchet” effect refers simply to the observation that once vegetation has colonized a location on the bed, it is relatively difficult to remove. In an unvegetated channel network, a channel may be abandoned and then readily reoccupied due to a slight change in flow conditions elsewhere; with vegetation, colonization of an abandoned channel can quickly make it very hard for the flow to reoccupy. Channel abandonment in a system with active vegetation is much less reversible than in a system without. In the following section, we explore these two ideas in more detail using additional field examples.

4.1. Field Studies: Platte River, Nebraska and Alluvial Fan, Northern Minnesota Tailings Mine

The effects of the trends we have discussed thus far are nicely illustrated in the post-colonial history of the Platte River (central Nebraska, USA) (Figure 7), as presented in Eschner [1983], Eschner et al. [1983], Kircher and Karlinger [1983]. Moreover, the Platte River presents an opportunity to examine a case where, unlike the experimental and cellular model examples that we have presented, plant colonization accompanies reduction in discharge. In natural rivers, reduction in discharge often sets the stage for vegetation to colonize newly exposed areas of channel resulting in an overall width decrease. Is the vegetation passively colonizing what the reduced discharge offers, or is it also playing an active role in reducing the width?

Historical documents and aerial photographs through the 1900s show that vegetation cover along the river is much higher today than in the past [Eschner et al., 1983]. This increase in vegetation coverage has been accompanied by a decrease in overall width [Eschner et al., 1983; Kircher and Karlinger, 1983]. However, during the same period discharge also decreased substantially from pre-settlement values as a result of upstream dams, irrigation withdrawals, and periods of widespread drought [Eschner, 1983; Eschner et al., 1983; Kircher and Karlinger, 1983]. While the dams have led to an altered flow regime, the changes in channel morphology resulting from a reduction in the sediment supply have been very small [Simons and Simons, 1994]. Was the decrease in channel width the result of lower discharges, increased vegetation density, or both? As local groups remove forest vegetation in an attempt to restore the riparian system to its former state, it is important to know how much of the width change is due to increased vegetation and how much is due simply to reduced discharge and lower peak flows.

To isolate the width reduction due to vegetation from that due to discharge reductions [Eschner et al., 1983; Kircher and Karlinger, 1983], we calculated the expected width decrease from lower discharges using the standard hydraulic geometry relationship $w = aQ^b$ [Leopold and Maddock, 1953], where $w$ is the width, $Q$ is the discharge, and $a$ and $b$ are constants (Figure 8a,b,c). We used a range of values, 0.3 – 0.7, for the width exponent $b$ [Leopold et al., 1964; Richards, 1982]. We plotted discharge data only for years in which width data was available. To smooth short-term fluctuations in annual peak discharges, we plotted the maximum of annual at-a-station peak discharges for the 5 years prior to the year for which width data was available (Figure 8a,b,c).

Figure 8a,b shows that at North Platte and Cozad, the observed width reductions cannot be explained by discharge reductions alone. In fact, at Cozad, the discharge actually increases from 1936 to 1950, while the width drops sharply. Lack of data during the 1940s makes it difficult to determine exactly what drove the width decrease. The behavior at Overton is also complicated (Figure 8c). Initially, width decreases more or less as expected from the reduction in discharge. However, after 1960, when discharge rises again, the width remains low. This same trend is also apparent at Cozad after 1960 (Figure 8b).

Despite the limitations of the Platte River data, two important insights emerge from the analysis. One is the interplay of the two effects (“ratchet” and selective colonization) discussed above. The stabilizing of the banks and narrowing of channels occurs readily as discharge decreases. The vegetation quickly occupies the exposed banks and stabilizes them; it also chokes off the smaller and weaker channels and corrals the flow into several dominant channels. However, this narrowing process is much harder to reverse. Although the discharge shows a substantial increase in the late 1960s at Cozad and Overton, the width of the channel is unable to recover after the vegetation has taken hold (Figure 8b,c). The second main observation is that channel width does not decrease indefinitely. We observe a strong initial decrease in width which then seems to stabilize.

![Figure 7](image_url)
around a minimum value. We observe this trend for the Platte River (Figure 8) as well the cellular model (Figure 6). Although we did not continue the flume experiments to extremely high vegetation density, the observed trends suggest that here too the widths would not decrease indefinitely (Figure 5b). Apparently, as the channel becomes narrower and the velocity becomes consistently high across the channel, near-bank deposition and production of colonizable area are reduced. Although shear stress is not explicitly represented in the cellular model, a comparable effect emerges: as channels narrow with increasing vegetation influence, the stream power in cells next to the banks increases. As a result, erosion and deposition in these cells also increases which prevents plants from taking hold. Johnson [1997] points out that the open channel area on the Platte River reached a general equilibrium due to the fact that as portions of the river were taken over by new woodland and rendered inactive, water depth and coverage had to increase in the remaining channels.

In a braided river, most of the discharge is accounted for by a relatively small fraction of the width. This is in part because braided rivers tend to have high width/depth ratios, and low mean topographic relief. Thus, the flow is free to spread opportunistically over a variety of flow paths that are distinguished by only slight topographic differences. A study of a well-controlled alluvial fan at a tailings basin in northern Minnesota [Paola et al., 1999] shows how the discharge is distributed over the width of a braided river reach, and illustrates how blocking of relatively low-discharge parts of

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**Figure 8.** At-a-station discharge ($Q^*$) and channel width ($w^{*obs}$) data normalized to the values of the earliest recorded year for both are plotted against time for three different stations along the North Platte and Platte Rivers. An expected channel width ($w^*$) is calculated using the formula ($w = aQ^b$) [Leopold and Maddock, 1953] for a range (0.3–0.7) of $b$ values. The predicted range of widths shown in gray is plotted along with the observed width in order to highlight the effect of increasing vegetation cover in further reducing channel width from an expected reduction attributed solely to a decrease in discharge. The graph also illustrates how the vegetation pins the river at the banks so that it cannot recover its previous width when the discharge is raised.

**Figure 9.** Fractional cumulative discharge is plotted against fractional cumulative width, both as fractions of the total for the cross section, for a sandy, braided alluvial fan in northern Minnesota [Paola et al., 1999]. Note how a 20% reduction in the discharge would lead to a 50% reduction in channel width.
the braided system could lead to substantial reductions in width. Eliminating flow width representing the lowest 20% of the discharge would result in a loss of over 50% of the total channel width (Figure 9). Thus, on the Platte River, we believe that the low discharge values in the late 1950s allowed a large portion of the braidplain to become exposed and then colonized by vegetation. This vegetation then kept the width pinned at the lower values, even though the discharge subsequently increased. Therefore, the initial width reduction may be primarily related to the discharge reduction, but the maintenance of the reduced width is driven by vegetation. Thus vegetation acts to amplify the effect of a reduction in discharge.

4.2. Bank Strength and Sediment Flux

Bed topography data in the flume experiments [Gran and Paola, 2001] show a decrease in lateral mobility as the vegetation density increased (correlation between sequential bed topography profiles increased; Figure 5c), meaning that the banks were eroding or aggrading more slowly. In addition, these channels became narrower (Figure 5b) and deeper. These tendencies offer an additional insight: as the banks become stabilized by the vegetation, the bank-attached bars no longer serve as storage and source areas for bed-material, as in the classic braiding process. Thus, as the flow converges into a deepening main channel, bedload should move through the system more continuously as temporary storage and release in bars is reduced. This hypothesis is currently being tested in a new set of experiments.

One might conclude that if river banks are strengthened (made more cohesive) with vegetation, they should be able to resist higher shear stresses in the channel without eroding. Therefore, one might expect a higher unit sediment flux in a river with vegetated banks. We do not have data that allow systematic comparison of shear stresses between vegetated and unvegetated rivers. However, comparison of dimensionless Shields stresses in sand-bed rivers with cohesive and noncohesive banks (Figure 10) shows no systematic difference between the two cases. In addition, Gran and Paola [2001] found no correlation between vegetation density and mean velocity. What did change was the variability in velocity, which was reduced: “corralling” the flow into a smaller number of well-defined channels led to a reduction in velocity variability by eliminating small ineffective side channels.

Based on this, there is no indication that vegetation would increase overall bedload transport capacity. Based on the arguments given in Paola [1996] on the effect of stress fluctuations on total sediment flux, it is even possible that bank stabilization could reduce total sediment flux by reducing the frequency of formation of ephemeral high-stress zones typical of active braiding. Overall, at this point the indications are that vegetation may not have much effect on overall sediment transport efficiency, if it acts mainly to eliminate small side channels that do not move much sediment anyway. It may also be that the width of natural channels is effectively limited by transient deposits of relatively fresh, unvegetated sediment along the insides of the longer-lived, vegetated banks, which could produce the same result. The overall picture seems to be that plants can dramatically reduce the total width of the wetted surface and organize the flow by corralling it into fewer stronger channels, but their effect on bedload transport capacity and the width of the ‘effective’ sediment-carrying channels is much weaker.

5. CONCLUSIONS

The common trends that represent the robust effects of vegetation on multi-thread rivers include:

1. A decrease in channel lateral mobility; channels become more stable and have lower lateral migration rates.
2. A decrease in the braiding intensity and the total wetted width; the number of active channels is reduced and the channels are narrower and deeper.
3. A nonlinear change in channel parameters with increasing vegetation intensity. The effects of the vegetation are strong initially, and then weaken as easily occupied channels are eliminated.

In addition, we conclude that:

4. While in natural rivers an increase in vegetation often coincides with a decrease in discharge, vegetation reduces
channel widths beyond the width reduction expected solely from the change in discharge.

5. Vegetation effects on overall channel dynamics take two main forms: selective colonization of small, low-discharge channels; and a “ratcheting” effect such that once the vegetation has taken hold (e.g. due to a reduction in discharge), the effects are not easily reversed even if the discharge is returned to its previous value.

6. Vegetation leads to a reduction in velocity variability as smaller, weaker channels are choked off and the flow is forced into fewer channels with more consistently high velocities.

7. Based on evidence thus far, increased bank strength does not appear to lead to a consistent increase in shear stress in the main (sediment-carrying) channels and therefore there is no reason to expect major increases in total sediment transport capacity.

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REFERENCES


Church, M., and K. M. Rood, Catalogue of alluvial river channel regime data, Department of Geography, University of British Columbia, Vancouver, 1983.


Kircher, J. E., and M. R. Karlinger, Effects of water development on surface-water hydrology, *Platte River basin in Colorado,*


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