

Interactions Between Vegetation and Braiding Leading to the Formation of Single-thread  
Channels in a Laboratory Experiment

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## Dedication

This dissertation is dedicated to my family - Adam, Yael, Hadas, and Neta Tal,  
for being everything a family should be.

## Abstract

Most rivers on Earth today flow as a single channel, in some cases with occasional islands, and follow a more or less sinuous course. However, single-thread channels have proven difficult to reproduce and study experimentally: experimental self-formed channels tend to widen and subdivide, leading to a braided pattern. We show how laboratory experiments using real vegetation to stabilize banks can organize the flow and convert the planform morphology from braided to single-thread. Our experimental strategy, a repeated cycle of short periods of high water discharge alternating with longer periods of low discharge accompanied by plant seeding and growth, leads to the evolution of a dynamic self-maintaining single-thread channel with well defined banks and floodplain. By eliminating weak flow paths the vegetation “corrals” the water into a single dominant channel until the reduction in total wetted width leads to a new self-organized state in which the flow removes vegetated area as fast as it is produced. The resulting system maintains a dynamic steady-state via similar mechanisms to those that operate in meandering channels in the field, specifically erosion at the outside of bends, bend growth, bar development, and avulsion.

The dominant channels that emerge from the vegetation-channel interactions organize to a geometry such that nearly all the flow is carried in the channels at high discharge. The organization to a bankfull geometry is directly linked to the tendency for plants to colonize exposed riverbed at low-flow and making it difficult for higher flows to reoccupy vegetated riverbed. The result is a reduction in wetted area with minimal difference between the wetted area at high flow and low flow. Vegetated islands that survive subsequent floods expand and merge with other islands and eventually form a continuous floodplain.

Our methodology provides a basis for experimentally developing, self-sustaining high-amplitude meanders, and has applications for river management and basic research purposes.

## Table of Contents

Acknowledgements.....	i
Dedication.....	iii
Abstract.....	iv
List of Tables.....	viii
List of Figures.....	ix
Overview.....	1
Application to river management.....	2
Timescale of interactions between vegetation and channels as a key organizing parameter of rivers.....	2
Estimating $T^*$ for the experiments.....	4
Tables.....	5
Figures.....	7
General Methods.....	10
Overview of methodology.....	10
Details of the experimental channel and methods.....	11
Tables.....	17
Figures.....	18
Chapter 1: Riparian Vegetation as a Primary Control on Channel Characteristics in Multi-Thread Rivers.....	25
Abstract.....	26
Introduction.....	27
Combined human-vegetation effects.....	28
Background and methods.....	31
Waitaki River: Description.....	31
Waitaki River: Methods.....	32
Flume Experiments: Methods.....	34
Cellular Model: Methods.....	35

Basic algorithm.....	36
Simulation of vegetation.....	38
Results.....	39
Vegetation parameters.....	39
Waitaki River.....	40
Comparison of results from the Waitaki River, experimental flume, and cellular model.....	41
Discussion.....	43
Case studies: Platte River, Nebraska and alluvial fan, northern Minnesota tailings mine.....	45
Bank Strength and Sediment Flux.....	47
Conclusions.....	49
Acknowledgements.....	50
References.....	50
Tables.....	55
Figures.....	56

Chapter 2: Dynamic Single-Thread Channels Maintained by the Interaction of Flow and Vegetation.....	67
Abstract.....	68
Background and motivation.....	69
Experimental methods.....	70
Results.....	72
Self-organization and dynamic steady-state.....	72
Mechanisms for maintaining steady-state.....	74
Conclusions.....	75
Acknowledgements.....	75
References.....	76
Figures.....	80

Chapter 3: Effects of Vegetation on Channel Morphodynamics: Results and Insights from Laboratory Experiments.....	85
Introduction.....	86
Morphodynamics.....	88
Bend growth, point-bar formation, and cutoffs.....	89
Avulsions.....	91
Width production and remnant channels.....	92
Floodplain channels.....	93
Sediment storage and transport fluctuations.....	94
Bankfull geometry.....	94
Figures.....	96
 Chapter 4: Floodplain formation as an aggregation process driven by vegetation	115
Introduction.....	116
Methods.....	117
Image classification.....	117
Transition matrices.....	118
Fluctuating flow and vegetation establishment.....	119
Abandonment of vegetated area.....	120
Planform change.....	120
Evolution of floodplains.....	121
Percolation theory applied to the organization of a channel and floodplain.....	123
A neutral model of island growth.....	124
Acknowledgments.....	126
Tables.....	127
Figures.....	130
 Bibliography.....	152

## List of Tables

1.	Basic outline of each experiment	5
2.	$T^*$ values for the experiments based on measured braidplain widths and erosion rates	6
M-1.	Root length of alfalfa sprouts	17
1-1.	Average number of flowing channels and total width of flowing channels at $\sim 150 \text{ m}^3/\text{s}$ , 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.	55
4-1.	Average characteristics of each vegetation class that was identified visually for runs 02 and 03. The seeding density at every cycle was approximately $10000 \text{ seeds}/\text{m}^2$ .	127
4-2.	Transition matrix calculated for pairs of images captured at 5-minute intervals during the high flow.	128
4-3a.	Transition matrix between images taken at the start of each low flow and at the start of each subsequent high flow.	129
4-3b.	Transition matrix between images taken at the end of each high flow and at the start of the low flow immediately following it.	129

## List of Figures

1.	Experiment 01 at the end of the unvegetated phase and after 4 cycles with a 3-day flood interval	7
2.	Experiment 02 at the end of the unvegetated phase and after 16 cycles with a 6-day flood interval	8
3.	Experiment 03 at the end of the unvegetated phase and after 24 cycles with a 3-day flood interval	9
M-1.	Experimental flume	18
M-2.	a. End tank and sediment traps, b. Head tank and sediment feeder	19
M-3.	Size of alfalfa sprouts through time. Solid line represents the mean root length, dotted lines are the maximum and minimum root lengths	20
M-4.	Halogen lights above the flume provided lighting during the high flows and polarizer sheets were used to minimize the glare from the flow	21
M-5.	Tank filled with water and rhodamine dye. Colored water was recirculated during the high flows in Exp. 01, 02, 03	21
M-6.	Non-recirculating flow and dye setup used in Exp. 04 We used an IV pump to add a constant rate of very concentrated liquid blue dye to the flow. The dye and water mixed in the funnel before entering the head tank.	22
M-7.	Cart with laser and camera	23
M-8.	Laser line profile of bed topography Oblique images of a laser line (which in color is red) projected on the bed were taken at 0.25 m spacing along the length of study reach. a. Unvegetated braided phase, b. After several cycles of vegetation growth. Areas with vegetation were ignored in the analysis	24
1-1.	The Waitaki River basin, South Island, New Zealand.	56

- 1-2. The Lower Waitaki River ~ 5 km upstream from the coast, 57  
 photographed in 1936 (a) and 2001 (b) when the river discharge was ~  
 150 m<sup>3</sup>/s. Flow is left to right. Frame bases span 3.7 km; scales are  
 identical.
- 1-3. Photographs of the experimental flume at St. Anthony Falls 58  
 Laboratory during the unvegetated fully braided stage (a) and after the  
 vegetation has been established and only two main channels exist (b).
- 1-4. Width of tall and low vegetation across the Lower Waitaki riverbed 59  
 averaged along the reach within 11 km of the coast. Broken line  
 suggests the trend followed by tall vegetation. Vegetation control  
 began in the early 1960's. A 100-year return period flood occurred in  
 1995.
- 1-5. a. Braiding intensity is the number of active channels normalized to 60  
 the # of active channels for the minimum vegetation value. b. Channel  
 width is the sum of the widths of all active channels along a cross-  
 section, normalized to the width under the minimum vegetation value.  
 Active channels are those above a certain threshold discharge or  
 depth. c. The bed topography correlation coefficient is a measure of  
 channel mobility rate. Successive bed topography data were measured  
 at set intervals (5-7 hours in the flume, and every 100,000 iterations in  
 the model) and treated as a form of time series data for which a  
 correlation coefficient was calculated.
- 1-6. Total channel widths normalized to the width for the unvegetated run 62  
 are plotted against increasing plant strength. Total width in the model  
 is the number of cells along a cross section that have a discharge  
 above a certain cutoff. The plant effect ratio is a measure of the ratio  
 between the erodibility of the bank with no vegetation and a fully  
 vegetated bank under varying plant strength conditions. Five different  
 discharge values (increasing increments of 12 cells) were simulated  
 for three different plant strength conditions. Each line corresponds to a  
 different discharge. The results from the model correspond to the  
 trend seen in Figure 1-8 for the Platte River. Although discharge  
 remains the same, there is a reduction in width as the vegetation effect  
 increases.
- 1-7. Map of the Platte River, Nebraska showing the approximate location 63  
 of the 3 gauging stations from which data was used in this paper.

- 1-8. At-a-station discharge ( $Q^*$ ) and channel width ( $w^*_{obs}$ ) data 64  
 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.
- 1-9. Fractional cumulative discharge is plotted against fractional 65  
 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.
- 1-10. Dimensionless Shields stress ( $\tau^*$ ) is plotted against slope for a 66  
 variety of rivers with noncohesive and cohesive banks. The data are from a compilation by Church and Rood [1983]. Note that the data do not show any significant difference between the two systems.
- 2-1. Plan view of experimental channel 80  
 A braided morphology self-organized to an irregularly sinuous, single-thread channel with well defined banks and a floodplain through ongoing interaction of vegetation and variable discharge. A planview of the 8 m study reach of the flume is shown (a) at initial unvegetated steady state, (b) after 6 flood cycles (24 days), (c) after 18 flood cycles (72 days), (d) after 23 flood cycles (92 days). The channel evolved to a dynamic steady-state such that vegetated area eroded along cut banks at the same rate that new sediment was deposited on point bars and a stable width was maintained.
- 2-2. Distribution of channel depths by wetted area 81  
 The distributions of channel area by channel depth show a trend of deepening channels and a reduction in wetted area as the morphology transitions from a wide, unvegetated braidplain with flow distributed across multiple shallow channels, towards a single, deep, narrow channel. Distributions are from run A with a 6 day flood interval.

- 2-3. Conversion areas and low flow channel and bars 82  
(a) Result of subtracting classified images of consecutive floods (3 and 4) from run A. Gray represents area that did not change, black is area that was converted from wet (channel) to dry (sand and vegetation), and white is area that went from dry to wet. The areas where change occurred highlight how the single-thread channel form is maintained dynamically by erosion along cut-banks and deposition on point-bars leading to active bend migration. Vegetation is eroded by an amount equal to new areas of establishment on freshly deposited bars and the system maintains a dynamic steady-state. (b) Low-flow channel with freshly deposited point bars along inner banks.
- 2-4. Rates of area conversion 83  
The fraction of the total area covered with vegetation through time and time rate of change from wet (channel) to dry (sand and vegetation) for both runs. Vegetation initially occupies large regions of bare sediment that are exposed during low flow. After approximately 3 floods in run A and 15 in run B the system reaches a dynamic steady-state between channel planform and vegetation expansion. Exchange rates from wet-dry and dry-wet are approximately equal in magnitude signifying that the system is in a dynamic steady-state and the net change is approaching zero. Exchanges between wet and dry are normalized to wetted area because they occur primarily along the channel edge (see Figure 2-3).
- 2-5. Linking of zones of high unit discharge 84  
Maps of channels above a threshold color intensity (proxy for depth) illustrate a key effect of the plants: elimination of weak and discontinuous flow paths in the braided state that are not sufficiently strong to remove vegetation, and organization of the flow into a single continuously fast and deep channel capable of preventing further encroachment. Threshold images are from run B with a 3 day flood interval (a) unvegetated steady state, (b) flood 7, (c) flood 13 (d) flood 19.
- 3-1. Vegetated area as a fraction of total area through time. Vegetation 96  
cover increases rapidly early in the experiments eventually reaching a dynamic steady state. At steady state total vegetated area remains the same as new colonized area is in balance with area that is eroded. Run A (circles, 17 floods, 6 day flood interval) and run B (triangles, 31 floods, 3 day flood interval) are plotted through time represented as flood time and plant growth time and shows that steady-state is reached at approximately the same time for both runs in terms of plant growth time but earlier in run A in terms of flood time.

3-2.	Average wetted measured at 5-minute intervals during all of the high-flows for each run.	97
3-3.	Bend migration and point-bar deposition (run A) arrows show the direction of bend growth and point bar formation.	98
3-4.	Erosion rates (run 02)	99
3-5.	Image taken using an environmental scanning electron microscope (ESEM). Rootlets and other material from the root can be seen attached to the sand grain. (Image courtesy of Karen Gran)	100
3-6.	Run 03, a consecutive sequence of channel (chute) cutoffs – markers show the location of the active channel and the abandoned channel after cutoff. Vegetation colonizes the abandoned channel within several flood cycles.	101
3-7.	Run 03, chute cutoff leading to abandoned channel	102
3-8.	Channel cutoffs due to the formation of a debris jams (run 02) - sequence showing a. the original active channel, b. and c. the formation of a debris jam which blocked the main channel, and d. flow diversion into a new channel and abandonment of the blocked channel. Markers show the headcutting channel and the abandoned channel.	103
3-9.	Sequence of images from the unvegetated braided state showing an example of a channel cutoff. An arrow in the top image highlights the original channel. In the middle channel a new channel has cut-off the main channel (55 minutes later) but the old channel does not become abandoned and the two channels coexist. The old channel remains active until the end of the run (here shown 15 minutes after the second image) even though a new active channel exists.	104
3-10.	Avulsion resulting from superelevation of the main channel and redirection of flow into a steeper headcutting channel. The last image shows the abandoned channel completely vegetated and incorporated into the floodplain.	105

- 3-11. Topography profiles along cross section A – A’ shown in Figure 13. 106  
 Solid gray line is a topography profile during the first flood in run 02, the solid black line is a profile 16 floods later immediately before the avulsion depicted in Figure 13 occurred. The profiles show the deepening of the head-cutting floodplain channels (on the left side) relative to the main channel (right side). (Profiles are patchy because they represent elevation in the channels only and exclude areas that were covered with vegetation).
- 3-12. Run 02 – The top two images are binary images during the 107  
 unvegetated braided phase of the run (t1 – top, t2-middle) with a 1-hour interval. White represents (wet) channels, black is (dry) bare sand. The bottom image was created by differencing t1 from t2. Gray is area that has not changed, white is area that was dry in t1 and became wet in t2, black was wet in t1 and became dry in t2. A sequence is shown for unvegetated braiding (run 02) and when the channel is single-thread with a well developed floodplain (run 03).
- 3-13. Run 02: reworking time unvegetated versus vegetated 108
- 3-14. Run 03: reactivation of floodplain channels through increasing 109  
 drainage into the channel and head-cutting. Markers show the location and advancement of two headcuts and their eventual capture of the dominant channel.
- 3-15. Run 02: total sediment output for each flood. Solid straight line 110  
 represents the constant sediment input.
- 3-16. Run 03: total sediment output for each flood. Solid straight line 111  
 represents the constant sediment input, which was lowered towards the end of the run.
- 3-17. Run 02, cumulative sediment input (dashed line) versus cumulative 112  
 sediment output (solid line) measured at 5 – minute intervals during the floods.
- 3-18. Run 03, cumulative sediment input (dashed line) versus cumulative 113  
 total sediment output (solid line) per flood.
- 3-19. Run 02, Braiding index at the high flow (solid line) measured from 114  
 images at 5 minute intervals and braiding index at the start of each low flow (dashed line).

- 4-1. Example of a classified image section from run 03: a. original image, 130  
b. binary image, wet is white, black is dry, c. area that was black in b,  
classified into bare-sparse (black) vegetation, dense vegetation (dark  
gray), very dense vegetation (light gray).
- 4-2. Samples of different stages of vegetation cover identified and sorted 131  
visually into classes and the corresponding grayscale value measured  
for each class.
- 4-3. Pixels from the vegetation samples plotted in color space. Each 132  
color/symbol represents the class that the sample corresponded to in  
the visual classification. The plot shows a general division into classes  
by color value.
- 4-4. Schematic of high flow – low flow image pairs corresponding to the 133  
transition matrices shown in Table 4-3. Light gray circles represent  
the image captured at the beginning of each low flow cycle (the  
camera was shut off after this for the remainder of the low flow). In  
the top image the dark gray circles represent the first image captured  
at high flow following low flow (Table 4-3a) and in the bottom image  
they represent the last image captured at high flow immediately before  
low flow (Table 4-3b).
- 4-5. Probability of abandonment (run 03) 134  
The probability of a pixel that was classified as wet at the end of a  
flood to be classified as dry at the low flow immediately after it.
- 4-6. Probability of reoccupation (run 03) 135  
The probability of a pixel that was dry at low flow to become  
reoccupied by flow (wet) at the following high flow, versus the  
probability of a pixel that was dry at low flow to remain dry at the  
following high flow.
- 4-7. Channel abandonment (run 02) 136  
a. An example of an active channel bifurcation and b. one of the  
channels dry and vegetated 3 floods later as a result of channel  
abandonment and colonization during several low flows.
- 4-8. Total wetted width measured from images at high flow and low flow 137  
through time for run 02 (top) and run 03 (bottom). High flow wetted  
width was measured from images captured at 5-minute intervals and  
smoothed with a moving average over 5 images. Low flow wetted  
width was measured from an image captured at the start of each low  
(the camera was shut off after this for the remainder of the low flow).

4-9.	Braiding index (BI, number of active channels at a cross section) measured from images captured at high flow and low flow through time for run 02 (top) and run 03 (bottom). High flow BI was measured from images captured at 5-minute intervals and smoothed with a moving average over 5 images. Low flow BI was measured from an image captured at the start of each low flow (the camera was shut off after this for the remainder of the low flow).	138
4-10.	Total wetted width, maximum channel width, and average channel width measured from images captured at 5-minute intervals during all of the high flows in run 02 (top) and run 03 (bottom).	139
4-11.	Run 03, probability by vegetation class of an area that was vegetated at $t_1$ to get eroded (become wet) at $t_2$ versus the probability that it will remain dry at $t_2$ . Probabilities were calculated between images captured at 5-minute intervals during all of the high flows.	140
4-12.	Run 03, y-axis is the ratio of the probability of a sparsely vegetated area at $t_1$ to get eroded at $t_2$ versus the probability of a densely vegetated area at $t_1$ to get eroded at $t_2$ , x – axis is the fraction of the bed that was covered with dense vegetation at $t_1$ . Dense vegetation includes both dense and very dense vegetation classes. Probabilities were calculated between images captured at 5-minute intervals during all of the high flows.	141
4-13.	Run 03, images from floods 1 – 8 (left top to bottom right) illustrating how initial vegetated patches became more dense and mature over time and small islands merged together to form a large island.	142
4-14.	Run 03, images from floods 3,5,7,9,11,13,15,17,19 (left top to bottom right) illustrating vegetated islands merging together and forming a floodplain.	143
4-15.	Number of islands at each flood. Islands were mapped manually in GIS.	144
4-16.	Fraction of the entire bed that was mapped as a vegetated patch or island.	145
4-17.	Run 03, Distribution of vegetated island sizes through	146

4-18.	Run 03 a. vegetated floodplain (black) and active channel (white) towards the end of the run, b. the same area shown in a. with the floodplain mapped as a mosaic of the increasingly older and smaller (lighter) islands that it was composed from.	147
4-19.	Growth of white clusters in a neutral model Patterns with 60% white pixels that formed in 4 different versions of a simple neutral model: a. random growth, b. initial random field that grew the 4 nearest neighbors symmetrically, c. initial random field that grew the 4 nearest neighbors asymmetrically with a higher probability of growing up and down than to the sides, d. Limited number of initial random white cells that grew asymmetrically, and e. binary image of the experiments at 60 % vegetation cover (white)	148
4-20.	Number of pixel clusters in a random neutral model.	149
4-21.	Growth of of white clusters Total area of white pixels as a fraction of all the pixels in the models through time (solid black lines) compared to the fraction of vegetated island area of total area in the experiments (dashed gray line)	150
4-22.	Modeling spanning clusters a. A spanning cluster of black cells in the model still exists, b. at the next time step the white cluster grows and a single spanning cluster no longer exists	151

## OVERVIEW

This dissertation is a study of the dynamic interactions among flow, sediment, and vegetation, and is based on a series of physical experiments conducted at the St. Anthony Falls Laboratory between 2001 and 2007. The project started with 2 well-defined goals. The first was to determine if noncohesive banks stabilized by vegetation is a sufficient mechanism to transform braiding to a single-thread channel. The second goal was to investigate if the use of real vegetation in the laboratory could provide a method for producing experimental single-thread channels. The experiments were designed to promote braiding in the absence of vegetation, and we studied how a braided morphology responded to repeat cycles of short periods of high water discharge (floods) alternated with longer periods of low discharge accompanied by plant seeding and growth. Four full-scale experiments were conducted for this dissertation (Table 1). The data analysis has been focused largely on experiments 02 and 03 because of their longer duration and a longer study owing to the addition of a fourth camera. The fourth experiment was still in progress at the time this dissertation was being written. The duration of each experiment was not predetermined; the only rule was that an experiment should continue long enough to show that a planform change was definite and permanent under constant conditions. After that, an experiment continued as long as we felt we were still learning new things by observing the systems behavior, and aspects of this behavior continued to be spontaneous, exciting, and unpredictable. Due to the long duration of each experiment it was not possible to replicate any of them exactly. However, the formation of a single-thread channel in all of the completed experiments (Figures 1,2, & 3) suggests that this is a robust result that can be expected under similar conditions.

One of the key contributions of this work has been a series of movies compiled from time-lapse images showing the evolution of the experiments. Two of these movies are archived in the data repository of the journal *Geology* (item 2007083, 2007) and are open access. All the movies can be accessed through the web archives of the National Center for Earth-surface Dynamics ([www.nced.umn.edu](http://www.nced.umn.edu)).

### *Application to river management*

In addition to the scientific importance of this research, its direct relevance to river management has both motivated and helped focus this work. Some of the most dramatic examples of changes in riparian vegetation cover on short time-scales occur along the corridors of managed rivers and these changes are having profound effects on channel morphology with drastic consequences for riverine habitat. Comprehensive studies of two natural systems in particular have informed this research, the Platte River in Central Nebraska and the Waitaki River in the South Island of New Zealand. The experiments were not designed to model any prototype rivers, and therefore the results cannot be used to prescribe detailed management schemes. However, the results and insights increase our understanding of the causes and effects of vegetation expansion and offer insights on how it can be managed. The experiments also allow us to observe changes in channel morphology caused by vegetation on decadal timescales, and help project the consequences of management practices. Discussions with river managers, engineers, and scientists have served to reinforce the complex nature and feedbacks in these systems, the difficulties of meeting different and often opposing goals of stakeholders, and the need for basic research to help guide decisions and management practices.

### *Timescale of interactions between vegetation and channels as a key organizing parameter of rivers*

Riparian vegetation cover is regulated by several timescales that are set by the seasons, the times for germination and growth-to-maturity of individual species, and the succession rates of species as riparian communities evolve. Johnson (1997, 2000) showed that vegetation recruitment (i.e., deposition and germination of seedlings) and survivability are influenced by water discharge, sedimentation, and the seasonal phasing of floods and plant reproduction. In a sense, riverbeds are arenas in which vegetation attempts to establish itself while the rivers scour it away as floods rework the bed morphology. A face-off must occur on riverbeds between the space/time characteristics of seed dispersal and plant growth and the occupation, abandonment, and reworking of

the bed by flowing water (Hicks et al, 2008). One possible outcome of this competition is that seedling establishment is hindered by large floods shortly after germination when young plants are too weak to survive flood flows. The other possibility is that bed turnover is slow compared to the time for growth-to-maturity of the plants and vegetation that is not removed while young will become permanently established causing an interaction with the flow and sediment dynamics.

Paola (2001) hypothesized that the timescale for establishment of vegetation relative to a characteristic channel or bed mobility time is a key organizing parameter in river systems, and that the planform of a river is in part a manifestation of these timescales: unvegetated braiding represents systems in which the braidplain is reworked by very dynamic channels on timescales fast enough to prevent permanent vegetation establishment, and single-thread meanders migrate across floodplains on time-scales that are longer, enabling vegetation to occupy all but the active channel width required to transport the supplied sediment load. Paola (2001) proposed the following dimensionless timescale as a framework for this hypothesis:

$$T^* = T_{veg}(e/b)$$

$T^*$  is the ratio of the time required for vegetation to grow to a sufficiently mature state that it can resist erosion ( $T_{veg}$ ) to the time required for the channel to migrate the width of the active channel ( $e/b$ ), where  $e$  is the bank erosion rate and  $b$  is the channel width.  $T^* < 1$  indicates vegetation growth that is rapid relative to channel migration while  $T^* > 1$  indicates fast channel migration relative to vegetation growth.

Managed river systems are typically characterized by long periods of low flow and infrequent large magnitude floods. In addition, large flows are often only in short pulses. Stable conditions for longer periods of time afford vegetation the opportunity to grow and become more resistant to erosion. The more mature and dense the vegetation becomes the more difficult it is to erode and higher and longer flows are necessary to rework the bed. The Platte River and the Waitaki River are both managed systems with damped flow regimes due to dams and flow diversions. Both systems show a pronounced increase in vegetation cover coinciding with changes in the hydrologic regime and lend support to the idea that time is an important variable in the organization of fluvial

systems. A survey of river engineers across the Canterbury Plains of New Zealand affirmed this idea. These engineers all described the need to manually remove vegetation using bulldozers or spraying it to kill it off when floods were infrequent. Not doing so created a high risk for flooding at the next high flow due to the immobility of parts of the bed and the inability of the flow to occupy the vegetated bars and islands. Most of the braided rivers that the engineers we interviewed were dealing with did not have managed flow regimes. However, the riparian vegetation consists of predominantly invasive species that grow more quickly and spread more aggressively than the native plants, and thus throws the previously existing equilibrium between the relative timescales off balance.

#### *Estimating $T^*$ for the experiments*

By the second experiment we had successfully met our two original goals. Once we had refined our methodology, making a single-thread channel in a system in which the effect of the plants was strong (i.e. the timescale for vegetation growth was short compared to the channel mobility time) was easy! We decided to focus the next experiments on determining what effect a change in the dominant timescales would have on the system and under what conditions braiding and vegetation could coexist. The relative timescales of vegetation growth and channel migration rates were varied systematically either by increasing the flooding frequency (i.e. reducing the time vegetation had to establish between floods), or increasing the duration of the floods (i.e. increasing the total reworked area of the riverbed). Estimations of  $T^*$  for runs 02 and 03 are summarized in table 2.  $T_{veg}$  for the plants was approximately 168 hours (7 days). As predicted by a  $T^*$  value less than 1, the experiments organized to a single-channel. Future work will focus on continuing to investigate the effect of varying the timescales in the experiments in more detail and to incorporate the results of experiment 04.

TABLES

Table 1. Outline of experiments

Exp.	No. full days between floods and seedings	Flood duration (hr)	Seeding density (seeds/m <sup>2</sup> )	Sediment feed rate Qs (m <sup>3</sup> /s)	No. consecutive floods under constant conditions
01	6	1	20000	1.08 x 10 <sup>-6</sup>	4
02	6	1	10000	1.32 x 10 <sup>-6</sup>	17
03	3	1	10000	1.96 x 10 <sup>-6</sup> 6.5 x 10 <sup>-7</sup>	31
04	3	4	10000	1.96 x 10 <sup>-6</sup>	<i>Experiment in progress</i>

Table 2.  $T_*$  values for the experiments based on measured braidplain widths and erosion rates

Exp.	$b$ average wetted width (m)	$e$ erosion rate (m/h)	$T_*$
02	1.7	0.0016	0.16
03	1.7	0.0044	0.43

FIGURES

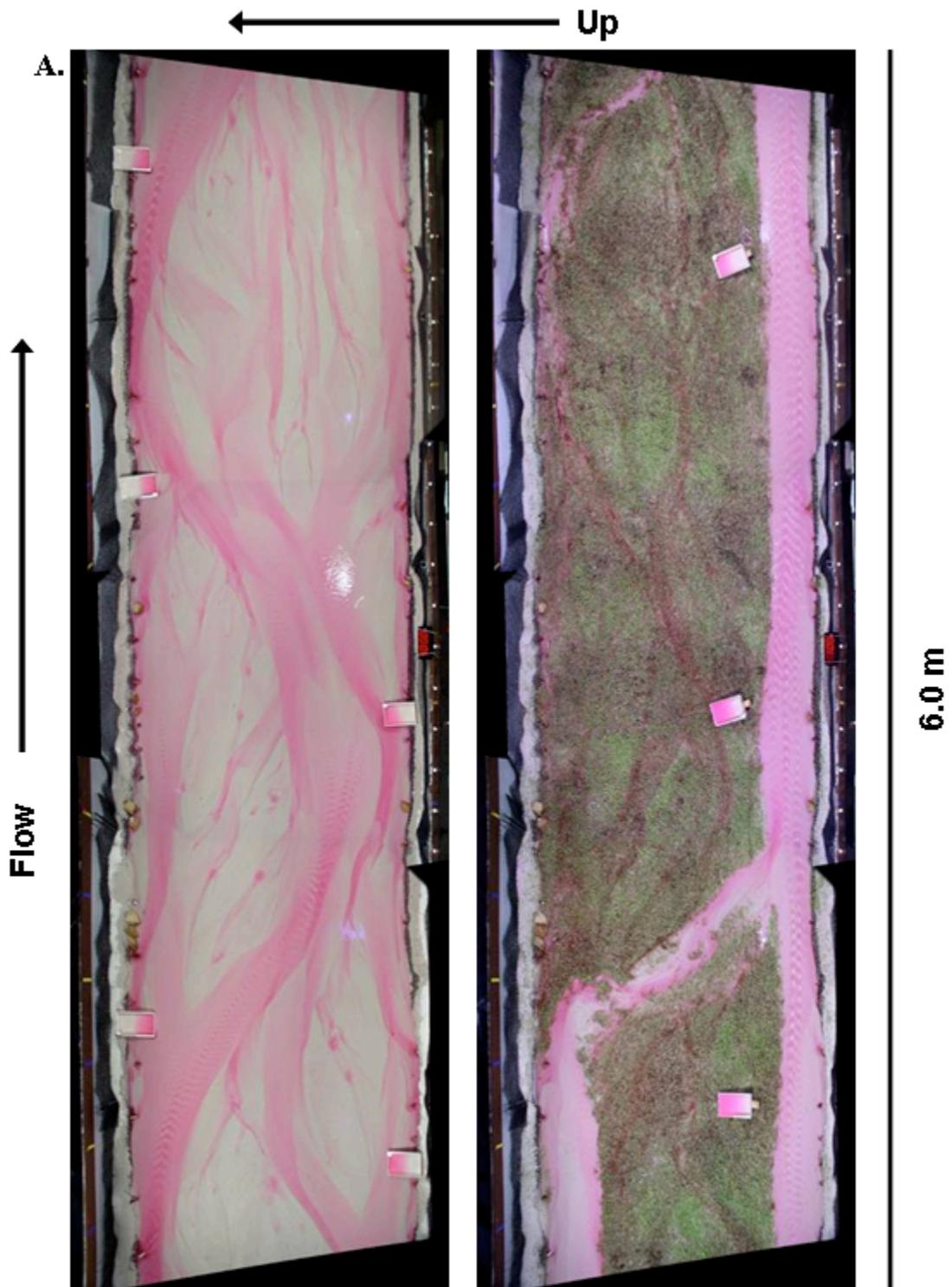


Figure 1. Experiment 01 at the end of the unvegetated phase and after 4 cycles with a 3-day flood interval

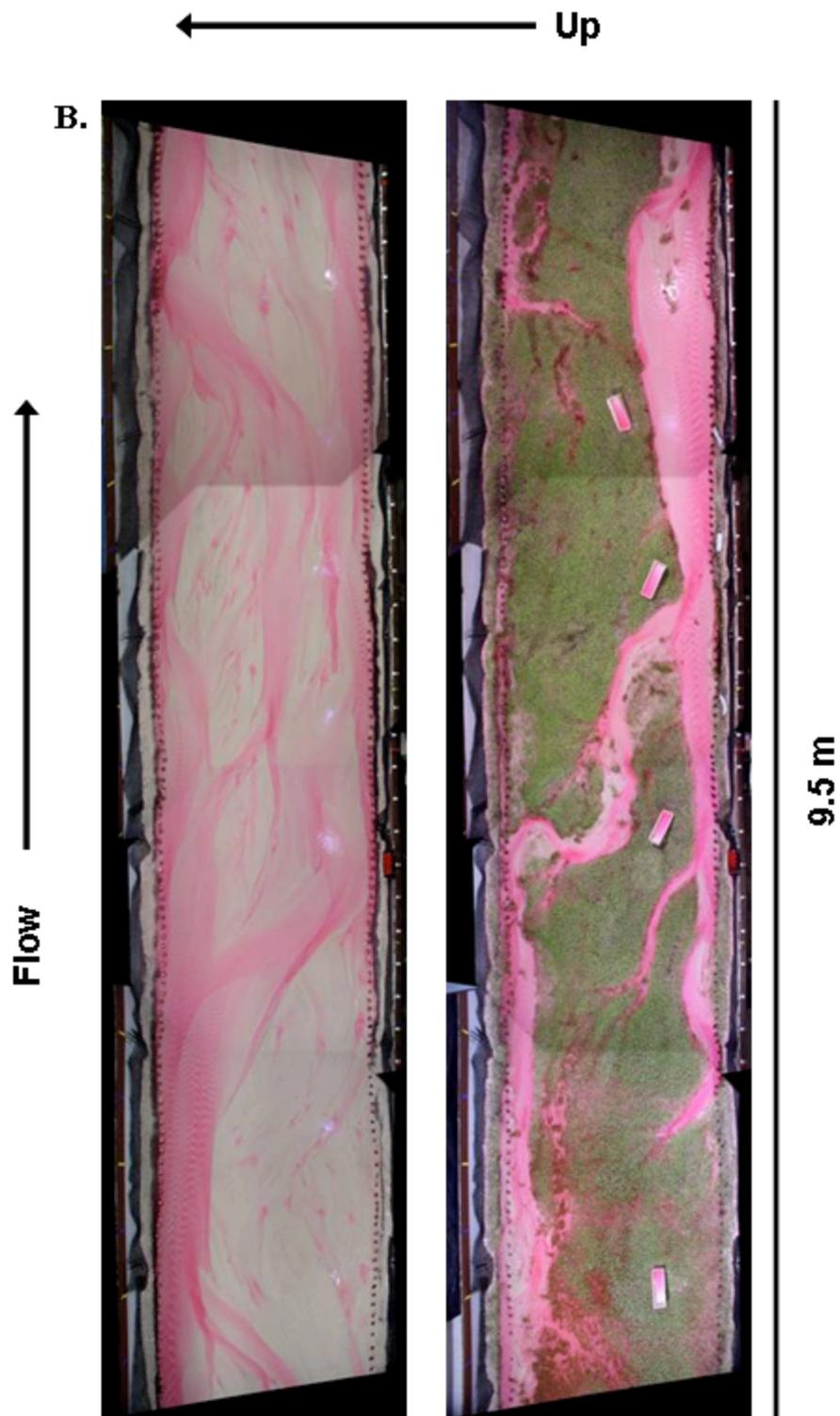


Figure 2. Experiment 02 at the end of the unvegetated phase and after 16 cycles with a 6-day flood interval

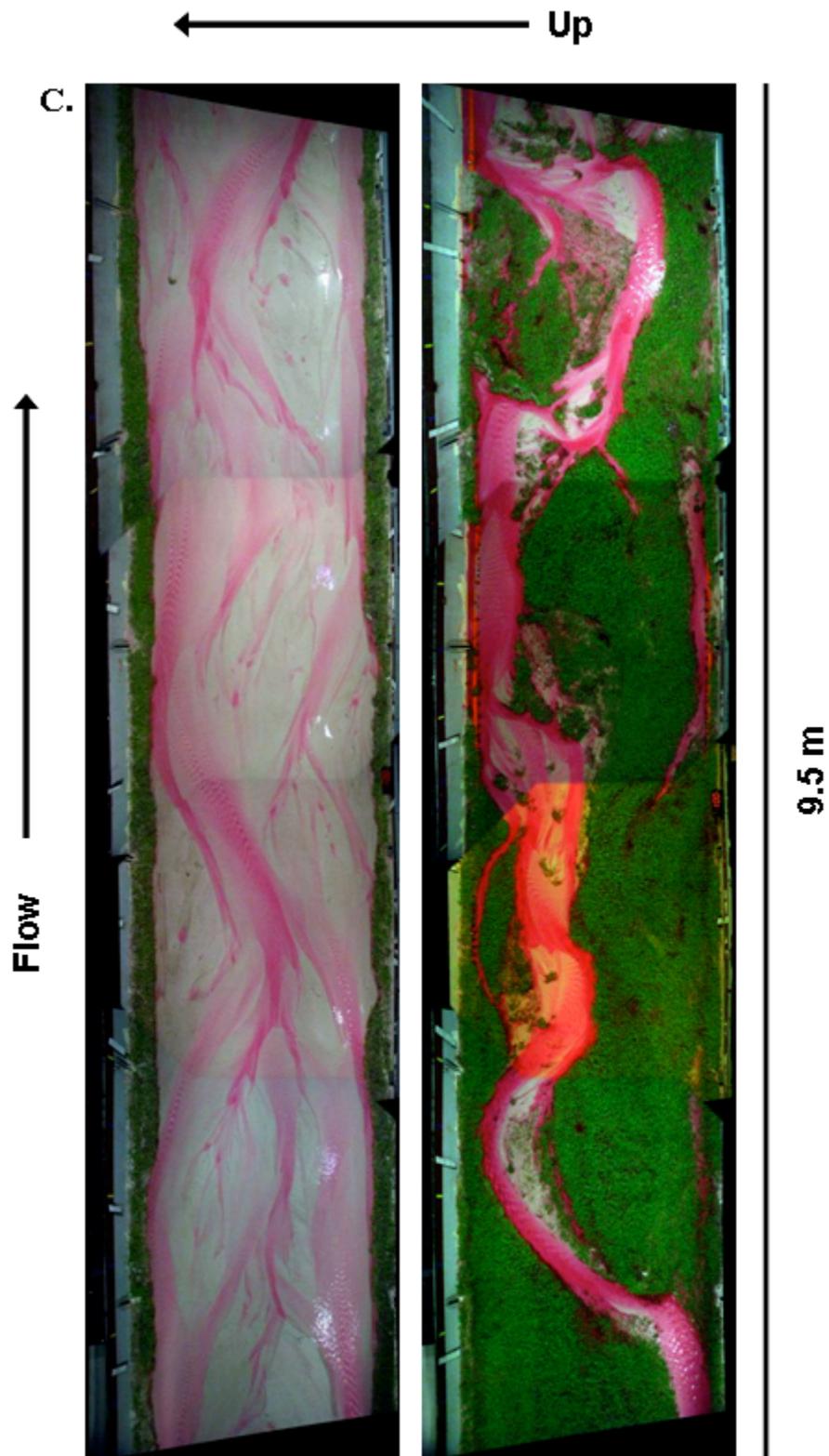


Figure 3. Experiment 03 at the end of the unvegetated phase and after 24 cycles with a 3-day flood interval

## GENERAL METHODS

### 1. Overview of methodology

The experiments for this dissertation were designed to investigate the effects of vegetation under the simplest conditions that capture the essential dynamics of the interactions between vegetation, sediment, and water in natural rivers. Our strategy, in the simple sense, was to simulate an annual cycle consisting of a mean flow during which the channel morphology remains stable, an annual flood which actively transports sediment and reworks the channel morphology in a relatively short amount of time, and annual establishment of vegetation on river bars and banks by windborne seeds.

The starting state for each experiment was a fully developed, self-formed, steady-state braided channel (Figures 1, 2, & 3). We designed the system with optimal conditions for braiding - cohesionless sand transported predominantly as bedload, high slope, high sediment and water discharges - and a fully braided channel formed after several hours. We set the slope of the flume to 0.015, a typical value for experimental braided channels (e.g., Schumm et al., 1987; Ashmore 1982). The flow rate we chose met the criteria of being sufficiently high to effectively erode mature alfalfa plants, not too high so that the entire bed was submerged, and could be lowered by a factor of 5 while still having flow in some channels. Using common empirical bedload transport equations (i.e. Meyer-Peter Muller) we estimated the sediment transport rate for the given slope and water discharge and then set the sediment feed rate to match this rate. We defined steady-state as being when the sediment input equaled the sediment output. We adjusted our input rate to some extent to match what the system was transporting, based on the sediment output we were measuring at the downstream end, but otherwise we waited (1 – 3 weeks) for the system to adjust on its own to the imposed feed rate.

Our experimental strategy was to cycle high flow and low flow with vegetation seeding. The high flow of  $2.0 \cdot 10^{-3} \text{ m}^3/\text{s}$  is the channel forming discharge for the initial braided channel. This flow actively transports sediment and is capable of reworking the channel morphology. We chose a low flow of  $4.0 \cdot 10^{-4} \text{ m}^3/\text{s}$  that transports almost no sediment; sediment feed was shut off during low flow. We calculated an average ratio of

10/1 for bankfull and mean flows from available data (i.e. Leopold et al., 1964) and we chose a more conservative ratio of 5/1 to ensure that vegetation would not encroach too quickly. At low flow large areas of the bed are exposed and when seeds are dispersed and land on these emergent areas they remain there and establish. Any seeds that landed in the channels were either carried out of the system by the flow or redeposited further downstream.

We conducted 4 experiments in which we varied one of the following: seed density, flood and seeding interval (duration of low flow), and flood duration (Table 1). The high flow duration of one hour was set by approximating the time required for the flow to rework 10% of the bed during the first flood following the first seeding in experiment 01. A seeding density of 2 seeds/cm<sup>2</sup> was initially chosen because it represented half of the lowest seeding density used in earlier experiments by Gran and Paola (2001) in which seedings were not repeated. We adjusted our variables between experiments in order to a) create a system that could evolve slowly (i.e. 2 seeds/cm<sup>2</sup> caused a very rapid change so we halved this density in subsequent experiments), and b) investigate the importance of the competing timescales of vegetation establishment and the frequency and duration of flooding.

## 2. Details of the experimental channel and methods

### *Experimental facility*

All of the experiments for this dissertation were conducted in a flume that is 16 m long by 2 m wide with steel walls (Figure M-1). The flume has a 1.0 m long by 2.0 m high by 2.0 wide head box which fills with water that then gently flows onto the bed via a 0.20 m wide and 0.02 m deep rectangular notch. At the end of the flume there is a 2.0 long by 0.5 m high by 2.0 m wide tail box where the water and sediment collect. Two - 2 meter long boards were placed in a 'V' shape at the downstream end in order to guide the flow and sediment to a single 0.20 m wide outlet (Figure M-2a). We only collected data from the middle 10 meters of the flume in order to avoid entrance and exit effects.

A wooden cart spanning the width of the flume has wheels and could be pushed

along the top of the side rails of the flume across its entire length. While an experiment is in progress all the work is done from the cart (Figure M-1).

### *Flow properties*

Our flows were fully rough and turbulent ( $Re > 2000$ ). Froude numbers ranged between 0.2 and 0.8 but were typically close to critical.

### *Slope*

Two inner rails were placed along the entire length of each side of the flume at a slope of 0.015.

### *Sediment*

The sediment that was used for all of the experiments is well sorted quartz sand with a  $D_{50}$  of 0.0005 m (500 micron). The sand was purchased from U.S. Silica under the name “silurian filter”. The relative roughness ( $H/D$ ) ranged between 50 – 160. The sand is highly well sorted and has a very uniform white color. We chose to use this sand for all of our experiments for the following reasons:

1. Non-cohesive sediment which allows us to isolate bank reinforcement as provided only by the plants.
2. The uniform white color enables us to use dye in the flow as a method for measuring flow depth.
3. The grain size is large enough so that ripples do not form.
4. The sand is transported predominantly as bedload by our flow rate which helps promote braiding .

We used “pea” gravel to fill the space between 0.15 m from the rails down to the floor. The gravel was covered with a plastic tarp and the sand was filled over the tarp to the top of the rails. We used a 2.0 m long blade to grade the sand even with the rails and a smaller blade to carve a 0.20 m by 0.01 m initial channel along the center of the bed over the length of the flume (Figure M-1).

Sediment was fed in at the head of the flume at a constant rate using an Accurate-

spiral feeder (Figure M-2b). We trapped all of the sediment coming out at the downstream end using sediment traps which consisted of a metal basket with a mesh lining. The traps held the sediment while allowing the water to drain out. We separated any vegetation from the sediment by vigorously stirring the sand with water. This separates the sprouts from the sand and causes them to float. We then dried the sediment in an oven and weighed it.

Sediment was fed in at a constant rate during the high flow and was shut off during the low flow. We decided to reduce the sediment feed rate towards the end of experiment 03 in order to match the reduced transport rate that the system had adjusted to.

### *Vegetation*

Alfalfa (*Medicago sativa*) sprouts were used to simulate vegetation in the flume. Our decision to use alfalfa was based on its success in previous experiments by Gran and Paola (2000). We added the vegetation as seeds which we dispersed manually at the end of each high flow with the low flow on. The volume of seeds necessary to cover a 2 m<sup>2</sup> area at the desired seeding density was dispersed by hand as uniformly as possible.

The average size of the vegetation at different stages is listed in Table M-1 and plotted in Figure M-3. Initially, the density of the vegetation increases exponentially in any area of the flume that is dry during consecutive seedings. However, after approximately 4 weeks vegetation begins to die and the density approaches steady state.

### *Time-lapse images*

Four digital cameras were mounted ~2.6 meters above the flume and equally spaced to capture images of the 10 m long by 2 m wide study reach. The images overlapped by ~0.5 m so that they could be stitched together. The cameras we used were Olympus C-4000 Zoom which at the distance they were fixed above the flume captured images at a resolution of approximately 2 mm/pixel. Each camera had a polarizing filter and we hung polarizing sheets (open face linear polarizer on triacetate carrier 38% transmission purchased from American Polarizers, Inc.) below our halogen lights to

achieve cross-polarization and minimize the glare from the flow (Figure M-4). We controlled the cameras remotely and captured simultaneous time-lapse images using share-ware software called Camera Controller by Pine Tree Computing, LLC. We captured images at intervals of 30 seconds – 2 minutes during all of the high flows and of the low flow channels immediately following the high flow.

All of the images were corrected for lens curvature and ortho-rectified. The 4 simultaneous images were stitched together using PTGUI software which utilizes common points (colored pebbles we place on the bed) between images to create a single image of the study reach. Stitched images were compiled using Quicktime to make movies of the experiments.

#### *Flow depth mapping*

We mapped flow depth using an image-based dye-density technique (Winterbottom and Gilvear, 1997). Dye colored water was made in batches in a large tank in which 800 liters of water were mixed with Rhodamine dye at a concentration of 2 ppm. The tank served as the only source of water during the high flow – water was recirculated with a pump - so the dye concentration remained the same (Figure M-5). We used titled trays of known dimensions, in which we had glued sand to the bottom and sides, filled with dye water to calibrate how depth varied with color intensity. The trays were placed at least once during each flood in the field of view of each of the 4 cameras. We quantified the error associated with the calibration trays as being, on average,  $\pm 1$  mm. However, this error is in fact larger due to the sensitivity of this method to minor lighting variations across the flume. In addition, we discovered that the dye photo-degraded slightly over one hour and therefore the color intensity decreased somewhat over the hour. In order to minimize our calibration errors we estimated the depth for each camera separately using the tray for that image only, and as close in time to when the image was captured.

The fact that Rhodamine and other dyes we tried photo-degrade over time required that we set up a constant dye feed with a non-recirculating flow system for experiment 04 in which our high flows lasted 4 hours (Figure M-6). This allowed us to

maintain a uniform color throughout the entire high flow. We used a different color - acid blue # 9 food grade dye - for experiment 04 but the methods for estimating depth remained the same.

#### *Flow between floods*

After seeding the bed at the low flow it was not necessary to keep the low flow running and we decreased the flow to a minimum (approximately  $1.0 \cdot 10^{-4} \text{ m}^3/\text{s}$ ). Keeping a saturated base flow helped maintain the bed uniformly wet for the plants to grow and prevented seeds from coming to rest and establishing in the scour holes in the middle of the channels. It was important to recirculate the base flow during winter because this helped to warm the temperature of the water (supplied from the city line) to at least room temperature. The plants would not grow during our winter experiments when the flow was not recirculated. We continued to recirculate low flow even after we set up a non-recirculating high flow system in experiment 04 until the city water was sufficiently warm.

#### *Bed topography*

We measured bed topography by shining a straight laser line (carpenter laser) on the bed, normal to the mean downstream direction of the channels, and photographing the line with a digital camera mounted at an oblique angle (Figs. M-7 & M-8). Both the camera and laser were mounted on the moving cart and could be pulled across the full length of the flume. The flow was turned off during the scans as well as all overhead lights. Topography was measured at 39 cross-sections spaced 0.25 m apart along the 10 m study reach. All of the images of the laser line were ortho-rectified and the variations in the line location were converted to actual distances using a calibration grid with lines of known distances that we photographed in the plane of the laser. The location of the laser line (Figure M-9) was extracted using software written by Liron Yatziv. The program uses the individual color signature of the sand, vegetation, and laser line to keep track of the pixel location of the line and determine if the line is reflecting off of sand or vegetation. We did not use any topography data from vegetated areas because the laser

was reflected off of the plants and not the bed.

It was reasonable to assume that because our sediment is transported predominantly as bedload there was minimal aggradation of the bed once it became vegetated. At the end of one of our experiments we checked this assumption by carefully removing the vegetation without disturbing the bed and measuring the topography everywhere and comparing the bed elevation under the vegetated areas to the last scan before vegetation established. We were able to extract the vegetation almost perfectly vertically from the bed with no visible impact to the sediment by using a powerful vacuum cleaner hose to suck up the plants while the bed was saturated.

#### *Flow velocity*

We floated confetti particles of paper on the surface of the channels and tracked them with a video camera in order to have sample measurements of surface flow velocities. We used a special type of dissolving paper (Dissolvo™) typically used for embroidery that dissolved after approximately 30 seconds in the flow so that we did not accumulate particles on the bed or in the vegetation.

TABLES

Table M-1. Root length of alfalfa sprouts

No. Days.	Root length (mm)		
	min	max	mean
01	0.0	0.0	0.0
02	7.0	11.0	9.0
03	13.0	25.0	19.0
04	20.0	40.0	28.4
05	27.5	40.0	34.3
06	36.0	42.0	34.3
>6	40.0	42.5	40.8

FIGURES

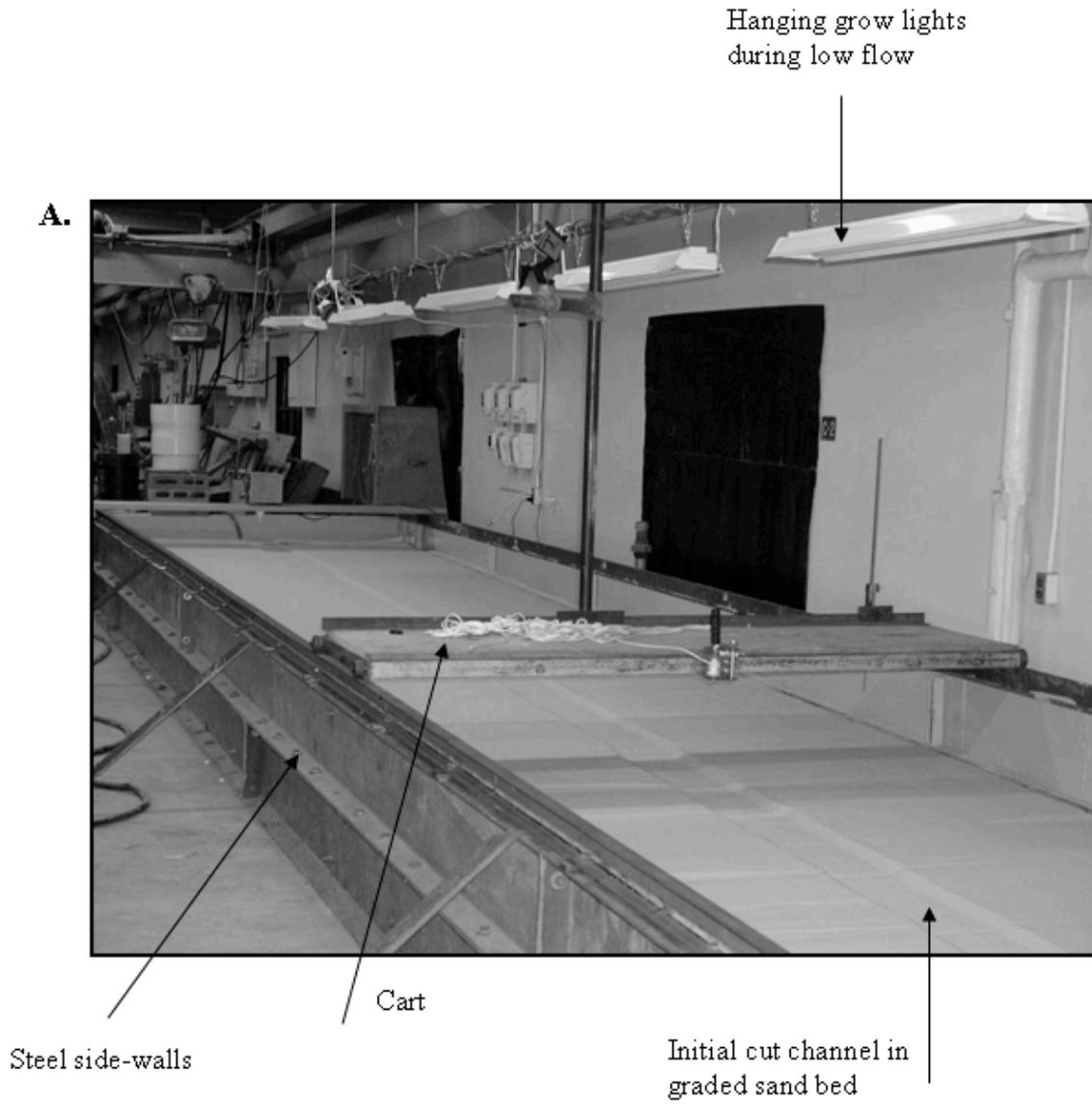


Figure M-1.  
Experimental flume

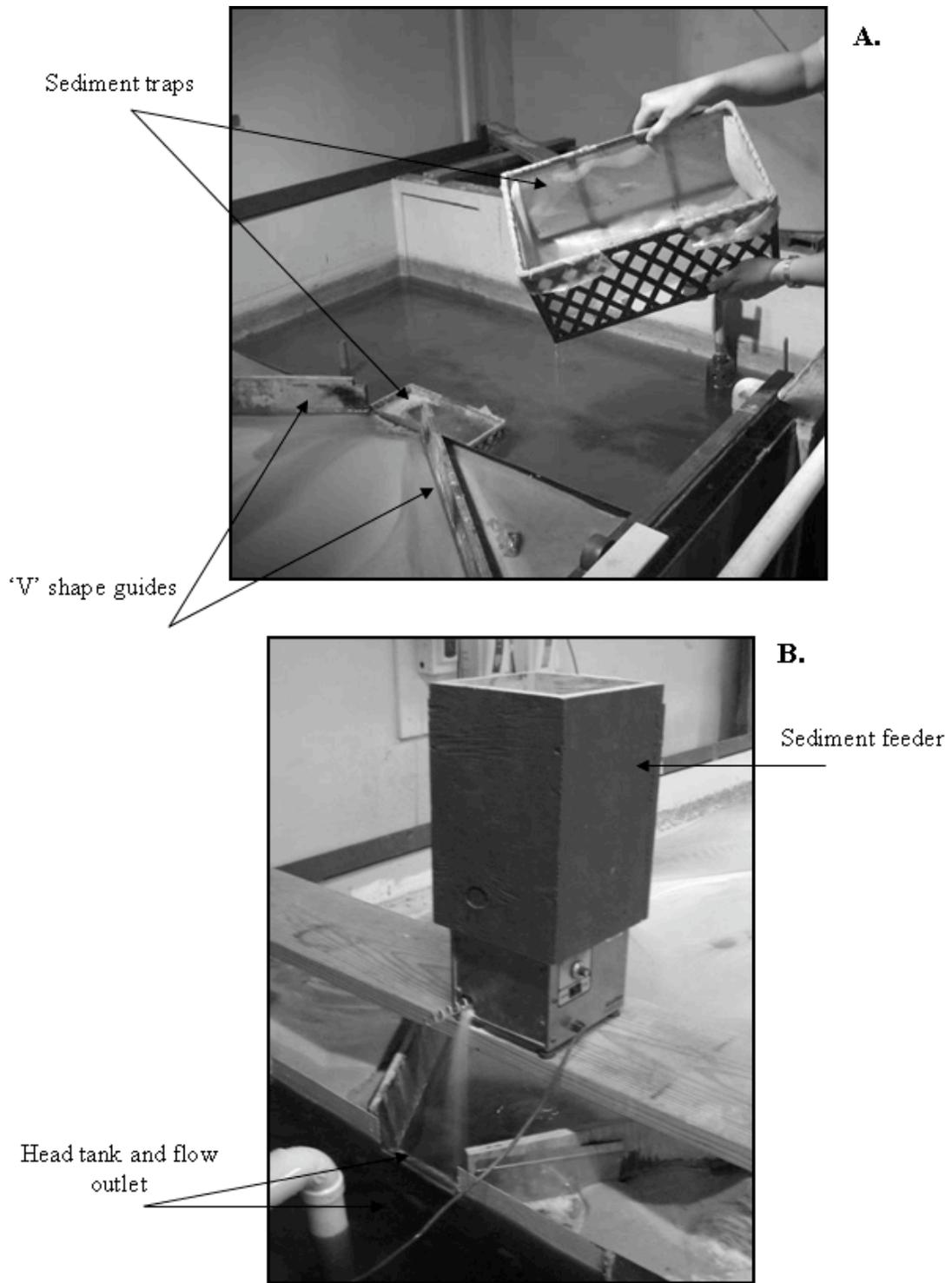


Figure M-2.

a. End tank and sediment traps, b. Head tank and sediment feeder

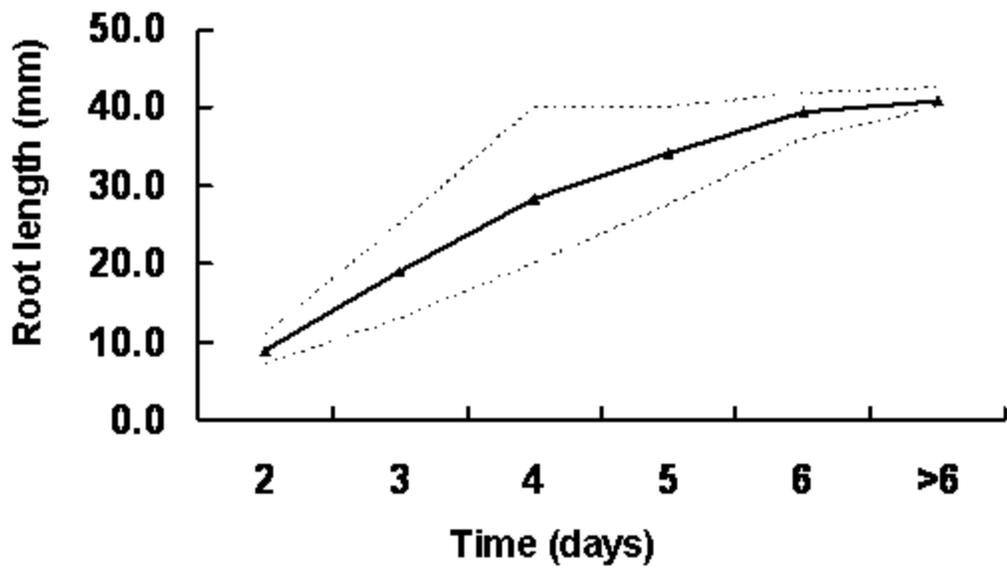


Figure M-3. Size of alfalfa sprouts through time

Solid line represents the mean length, dotted lines are the maximum and minimum length

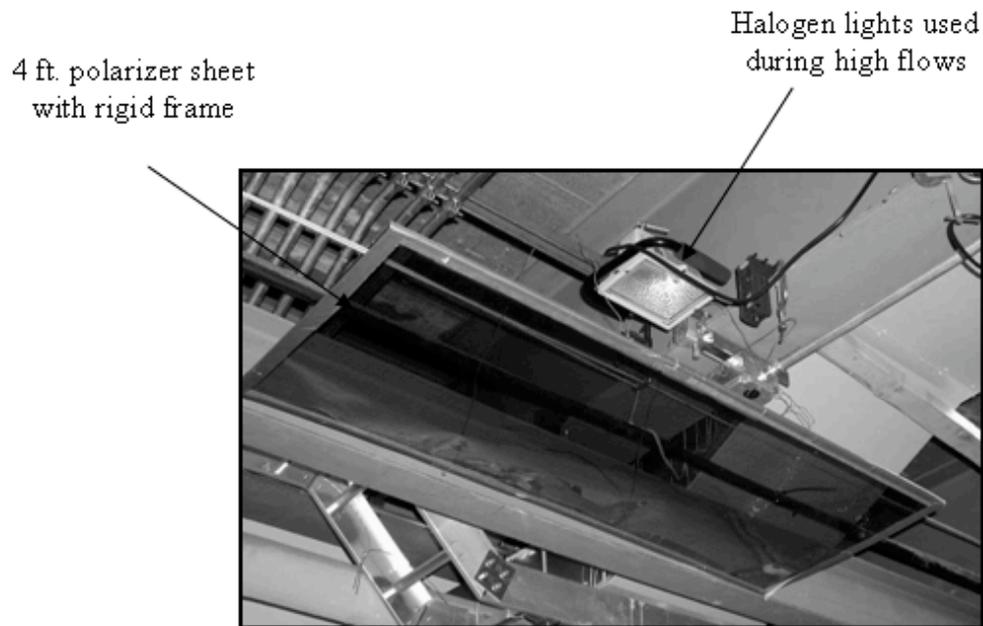


Figure M-4. Halogen lights above the flume provided lighting during the high flows and polarizer sheets were used to minimize the glare from the flow

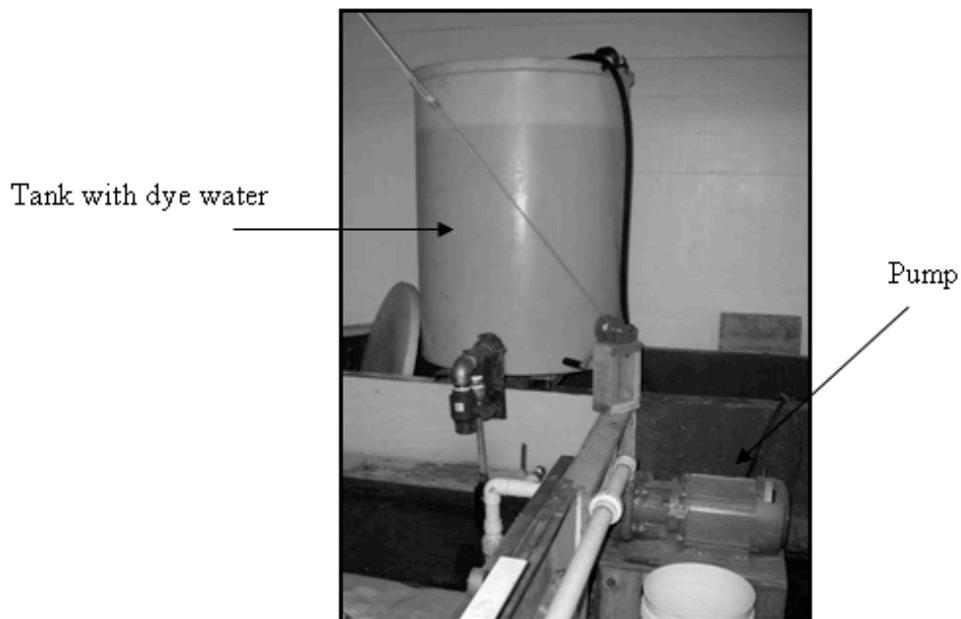


Figure M-5. Tank filled with water and rhodamine dye. Colored water was recirculated during the high flows in Exp. 01, 02, 03

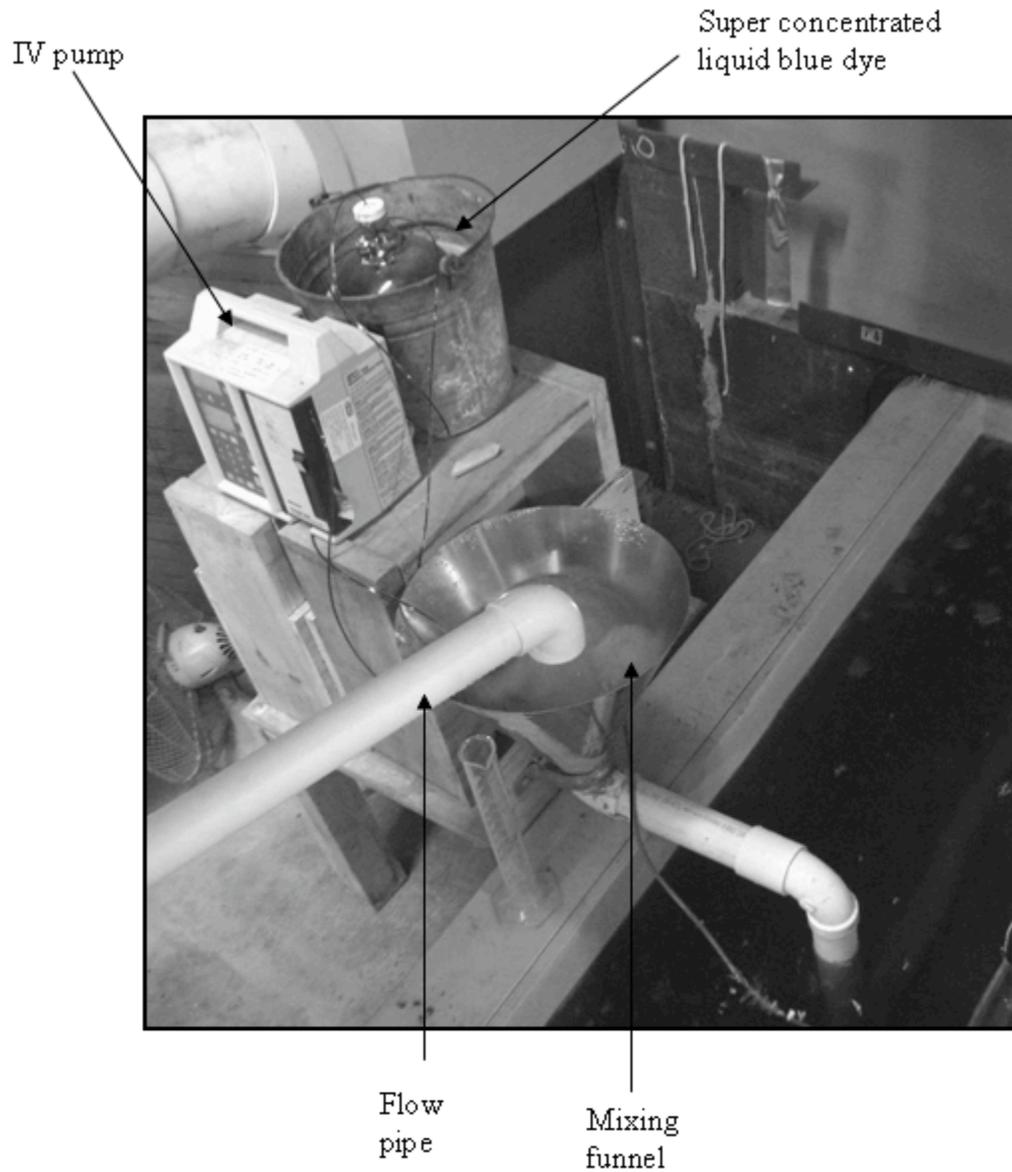


Figure M-6. Non-recirculating flow and dye setup used in Exp. 04

We used an IV pump to add a constant rate of very concentrated liquid blue dye to the flow. The dye and water mixed in the funnel before entering the head tank.

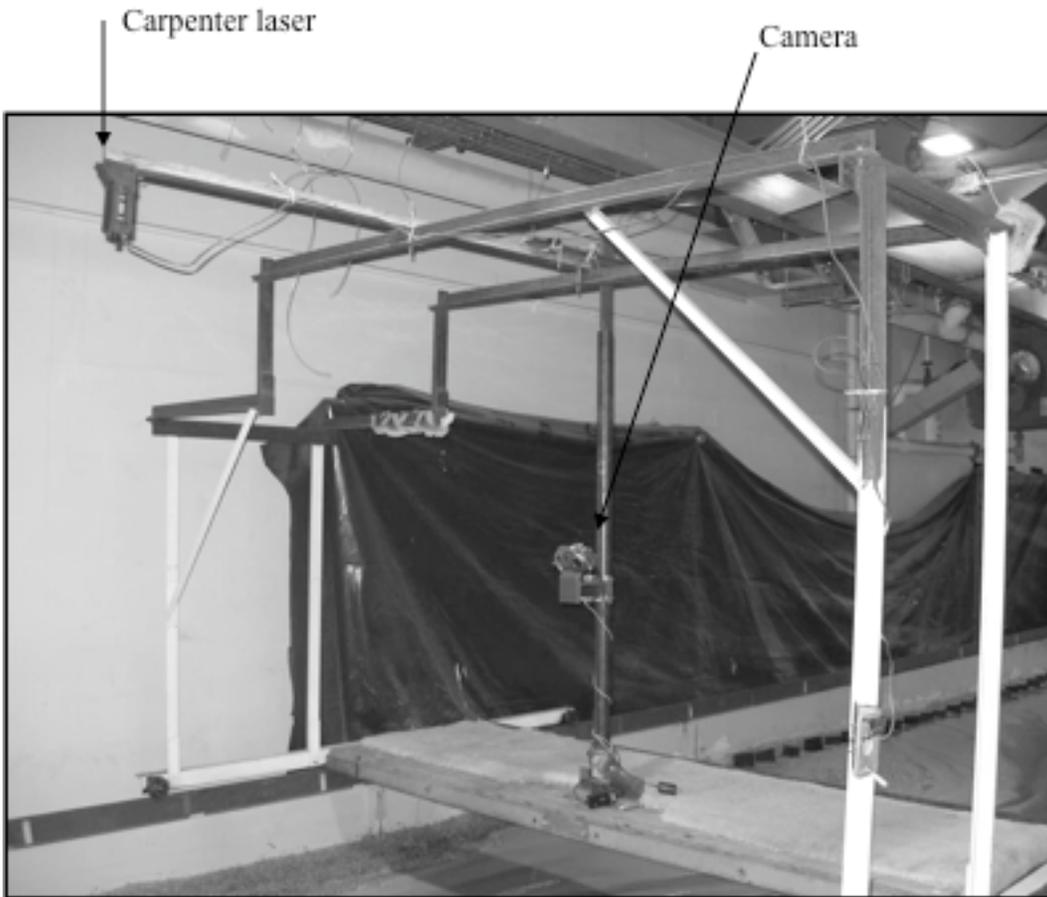


Figure M-7. Cart with laser and camera

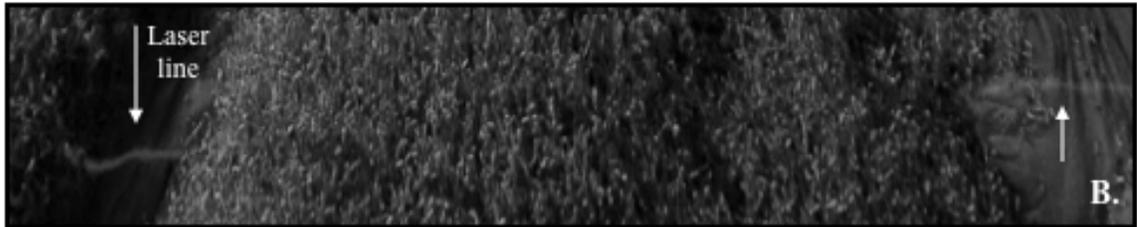
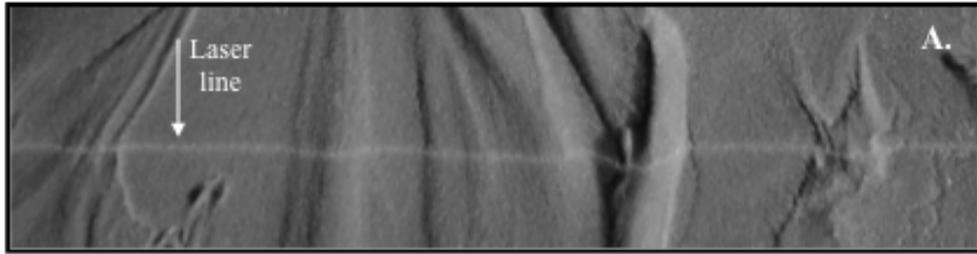


Figure M-8. Laser line profile of bed topography

Oblique images of a laser line (which in color is red) projected on the bed were taken at 0.25 m spacing along the length of study reach. a., Unvegetated braided phase, b. After several cycles of vegetation growth. Areas with vegetation were ignored in the analysis

CHAPTER 1: RIPARIAN VEGETATION AS A PRIMARY CONTROL ON  
CHANNEL CHARACTERISTICS IN MULTI-THREAD RIVERS<sup>1</sup>

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## ABSTRACT

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. Therefore, 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 fine grained 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 multithread 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 colonizeable 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 colonizeable 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  $\sim 358 \text{ m}^3/\text{s}$ ) 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  $\sim 70 \text{ km}$  from the furthest downstream dam (Waitaki Dam) to the sea (Figure 1-1). 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  $1434 \text{ m}^3/\text{s}$  to  $1171 \text{ m}^3/\text{s}$ . Tributary sediment budget estimates plus reservoir surveys indicate that the dams have reduced the bed-material supply to the Lower Waitaki River 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 1-2a). 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 1-2b). 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 1-2b). 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<sup>3</sup>/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 1-2a). A near identical discharge was photographed during a low-flow trial in 2001, when the flow was kept steady at 150 m<sup>3</sup>/s for 24 hours (Figure 1-2b).

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 1-2.

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<sup>3</sup>/s, matching these with ground-cover measurements made from air-photographs taken in 1985. These relations are  $N = 1.17Q^{0.28}$  and  $W = 24Q^{0.50}$ , 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 ( $\text{m}^3/\text{s}$ ). 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 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 1-3a). 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 1-3b), 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/ $\text{cm}^2$ . 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 crosssections 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  $\eta_2$ )

$$r_0 = \frac{\text{cov}(\eta_1, \eta_2)}{\sqrt{\text{var}(\eta_1) \text{var}(\eta_2)}} \quad (1)$$

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.

#### 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 in the first row, and the braid plain was 48 cells wide.

An iteration begins with the introduction of water into cells at the upslope end. From each of these cells, the water moves into any of the three immediate neighbors in the overall downhill direction that have lower elevations (positive slopes). The amounts of water going to each of these cells are determined by the slopes to those cells. The water routing rule is designed not to represent actual flow with maximal accuracy, but to capture in a simple way the tendency for more water to flow where slopes are steeper.

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  $\epsilon$ , is added to the local stream power. In runs reported here,  $\epsilon = 0.25$ , and the coefficient relating the adjusted stream power to sediment transport,  $K$ , =  $5 \times 10^{-23}$ . 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:

$$Q_{sl} = K_l S_l Q_{s0} \quad (2)$$

where  $K_l$  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,  $K_l$ , 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,  $K_{lmin}$ , which is inversely related to plant-enhanced bank strength, as an independent variable in some of the experiments reported below. We vary  $K_{lmin}$  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 density of 9.2 stems/cm<sup>2</sup> [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 1-1 and Figure 1-4) 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 1-4). Both braiding index and total flowing channel width (at ~150 m<sup>3</sup>/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 1-5a,b,c). Increasing vegetation decreases the size and number of active channels (braiding intensity) in all three study systems (Figure 1-5a,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 1-6). 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 1-5a). 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 1-5a,b). The channel mobility as measured by  $r_0$  for the flume and the cellular model decreased by approximately 25% (Figure 1-5c).

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 1-5c. 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 1-5c.

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 1-5a,b,c and Figure 1-6). 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 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 1-5a). 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 1-3a,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 1-5b,c and Figure 1-6). These trends are also clearly seen in field and experimental data (Figure 1-

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 “corralling” 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 1-7), 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  $w = aQb$  [Leopold and Maddock, 1953], where  $w$  is the width,  $Q$  is the discharge, and  $a$  and  $b$  are constants (Figure 1-8a,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 1-8a,b,c).

Figure 1-8a,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 1-8c). 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 1-8b).

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 1-8b,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 around a minimum value. We observe this trend for the Platte River (Figure 1-8) as well the cellular model (Figure 1-6). 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 1-5b). 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 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 1-9). 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 1-5b) 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 1-10) 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.

## 6. 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 “ratchet” 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 bankstrength 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.

## ACKNOWLEDGEMENTS

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TABLES

	1936	1985	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

Table 1-1. Average number of flowing channels and total width of flowing channels at ~ 150 m<sup>3</sup>/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.

FIGURES

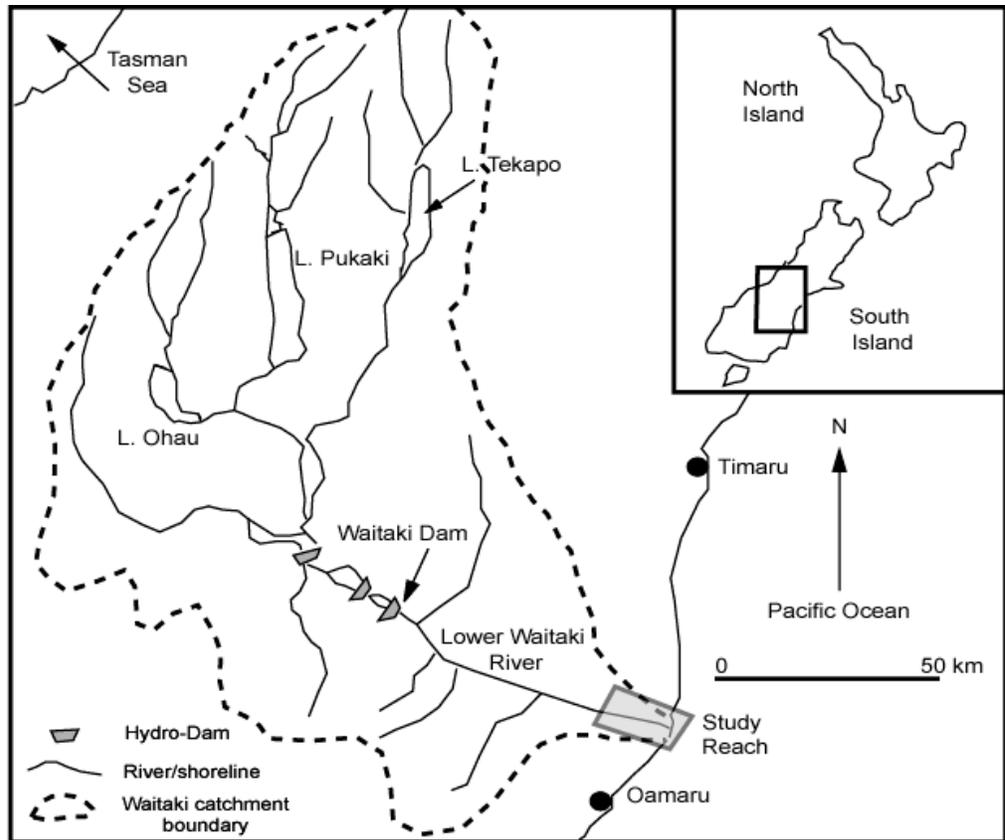
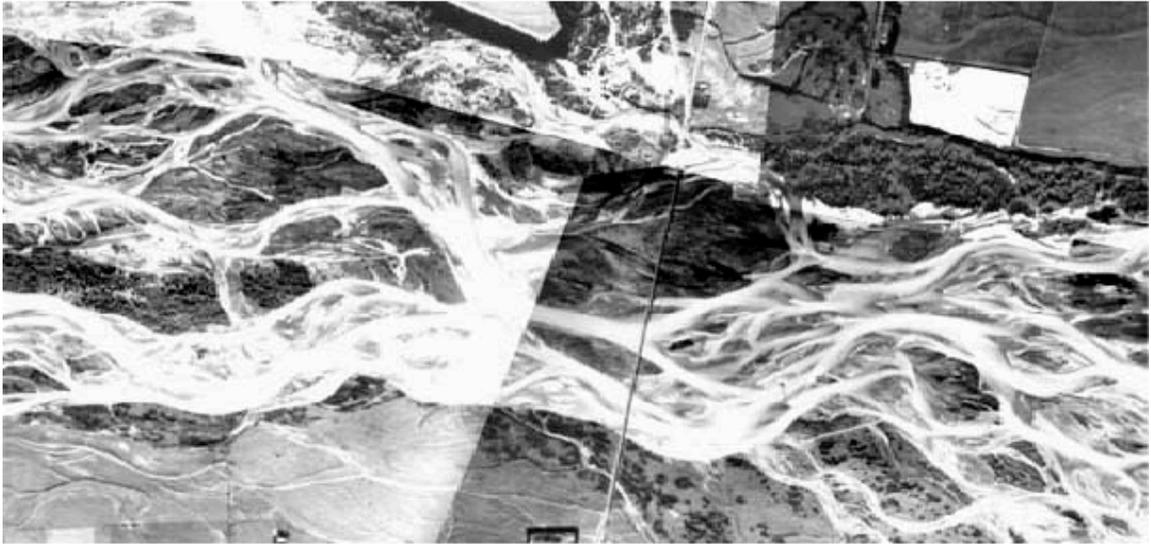


Figure 1-1. The Waitaki River basin, South Island, New Zealand.

A.



B.



Figure 1-2. The Lower Waitaki River ~ 5 km upstream from the coast, photographed in 1936 (a) and 2001 (b) when the river discharge was ~ 150 m<sup>3</sup>/s. Flow is left to right. Frame bases span 3.7 km; scales are identical.

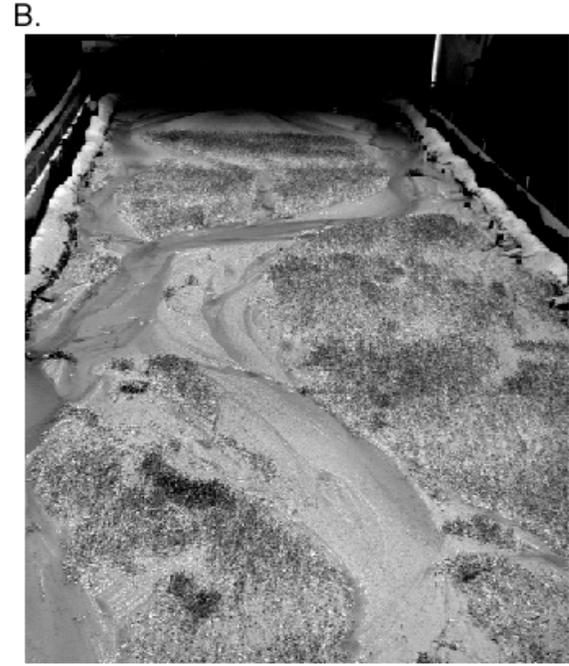


Figure 1-3. Photographs of the experimental flume at St. Anthony Falls Laboratory during the unvegetated fully braided stage (a) and after the vegetation has been established and only two main channels exist (b).

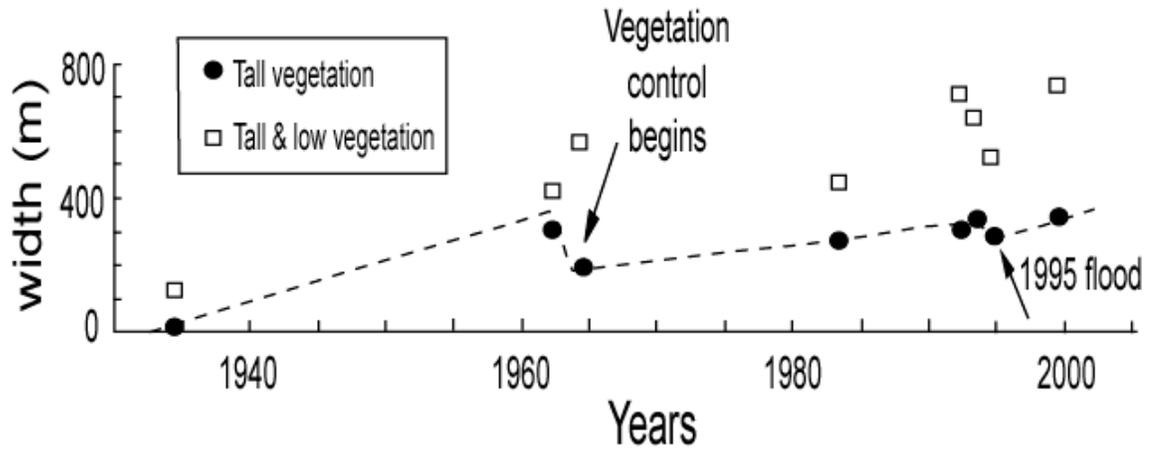


Figure 1-4. Width of tall and low vegetation across the Lower Waitaki riverbed averaged along the reach within 11 km of the coast. Broken line suggests the trend followed by tall vegetation. Vegetation control began in the early 1960's. A 100-year return period flood occurred in 1995.

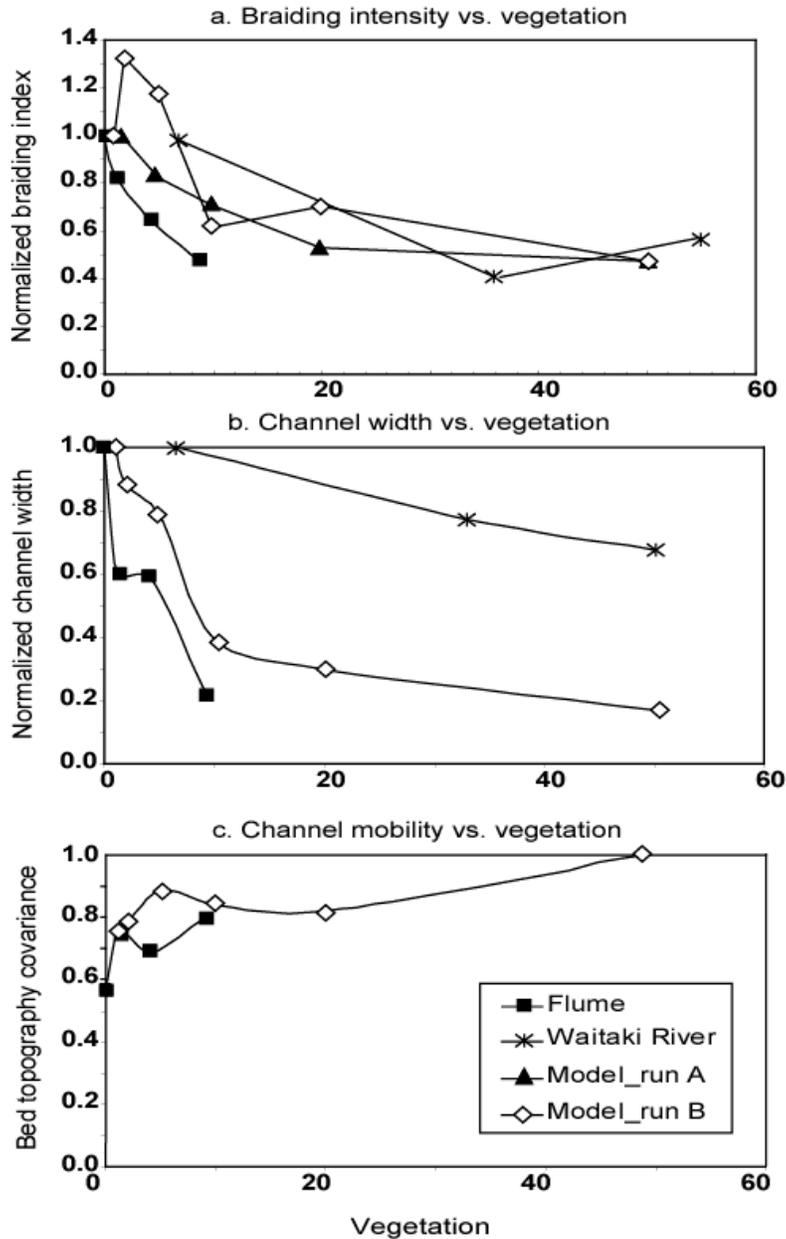


Figure 1-5. Channel characteristics from an experimental flume [Gran and Paola, 2001], cellular model [Murray and Paola, 2003], and Waitaki River, NZ [Hicks et al., 2002] are plotted against vegetation. The vegetation parameter in the flume varied as different densities of alfalfa sprout stems, from 0 – 9.2 stems/cm<sup>2</sup>. Vegetation in the model is represented by the plant effect ratio, the ratio between the lateral transport coefficient in the absence of cohesion to the coefficient value for a fully vegetated bank under varying plant strength conditions. Lateral transport is inversely related to plant enhanced bank

strength. Therefore, stronger plants are simulated by decreasing the magnitude of the lateral sediment transport (erodibility) out of a vegetated cell. Model runs A and B use the same parameter for bank strength, however, run A uses a different set of sediment transport rules [Murray and Paola, 2003] than the ones described in this paper. Both methods maintain the same trend. Vegetation in the field is represented by a change in the total width of vegetation cover along a cross-section, referenced as a percent of the total river bed width.

- a. Braiding intensity is the number of active channels normalized to the # of active channels for the minimum vegetation value.
- b. Channel width is the sum of the widths of all active channels along a cross-section, normalized to the width under the minimum vegetation value. Active channels are those above a certain threshold discharge or depth.
- c. The bed topography correlation coefficient is a measure of channel mobility rate. Successive bed topography data were measured at set intervals (5-7 hours in the flume, and every 100,000 iterations in the model) and treated as a form of time series data for which a correlation coefficient was calculated.

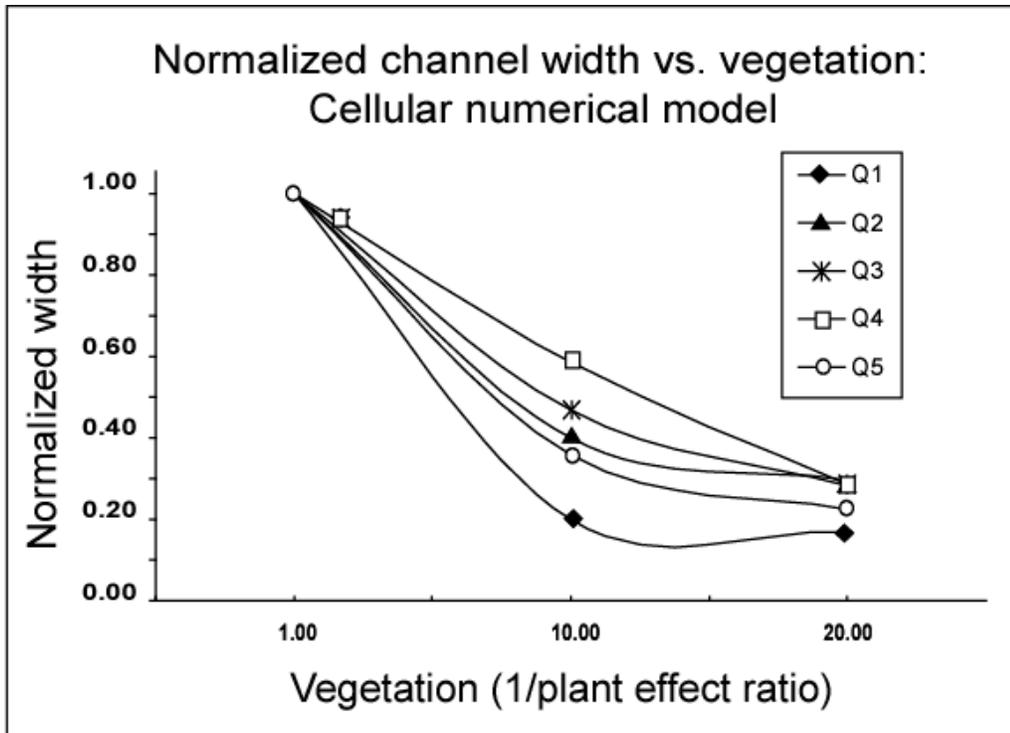


Figure 1-6. Total channel widths normalized to the width for the unvegetated run are plotted against increasing plant strength. Total width in the model is the number of cells along a cross section that have a discharge above a certain cutoff. The plant effect ratio is a measure of the ratio between the erodibility of the bank with no vegetation and a fully vegetated bank under varying plant strength conditions. Five different discharge values (increasing increments of 12 cells) were simulated for three different plant strength conditions. Each line corresponds to a different discharge. The results from the model correspond to the trend seen in Figure 1-8 for the Platte River. Although discharge remains the same, there is a reduction in width as the vegetation effect increases.

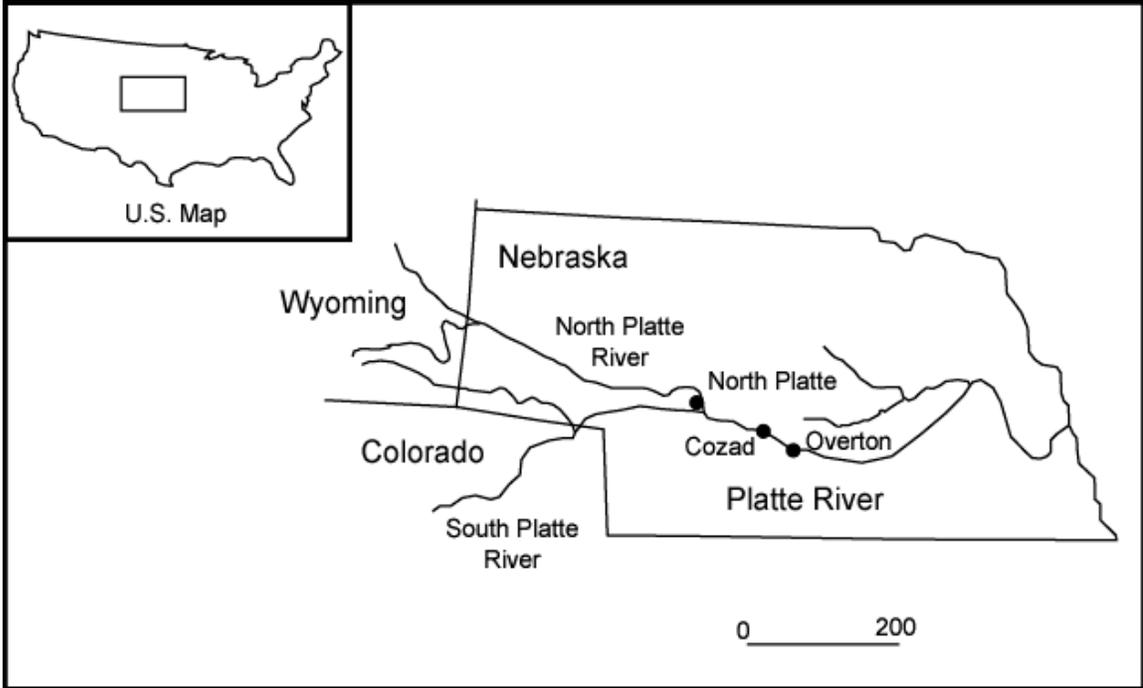


Figure 1-7. Map of the Platte River, Nebraska showing the approximate location of the 3 gauging stations from which data was used in this paper.

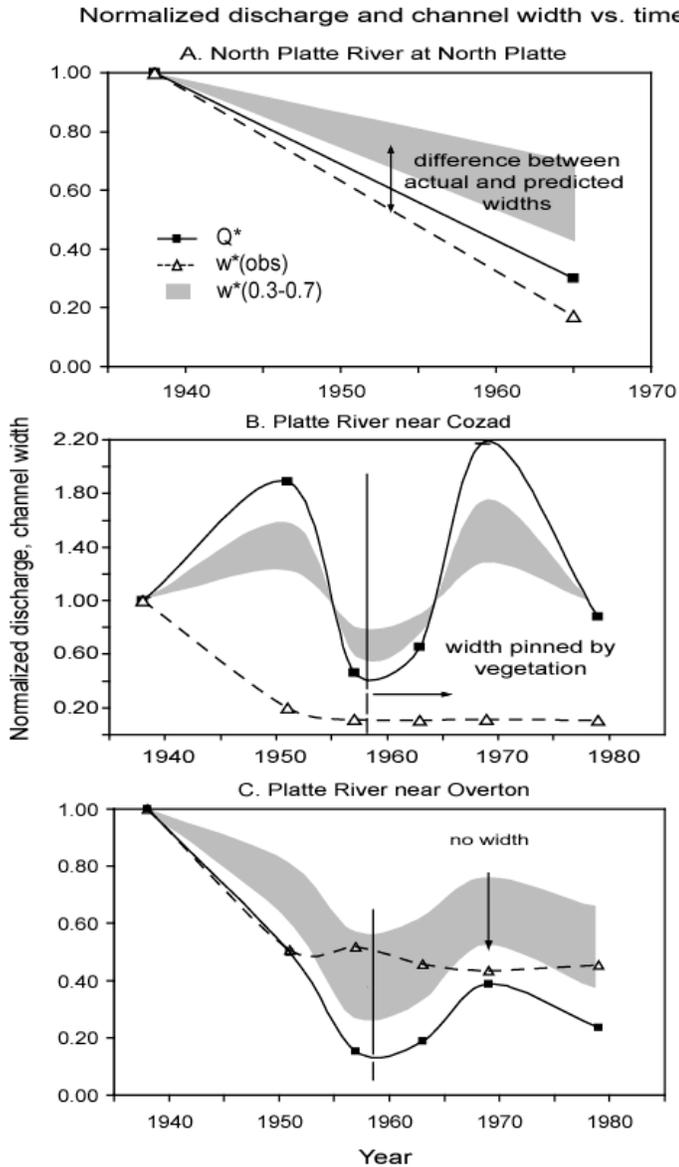


Figure 1-8. At-a-station discharge ( $Q^*$ ) and channel width ( $w^*_{obs}$ ) data normalized to the values of the earliest recorded year for both are plotted against time for three different stations along the North Platte and Platte Rivers. An expected channel width ( $w^*$ ) is calculated using the 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.

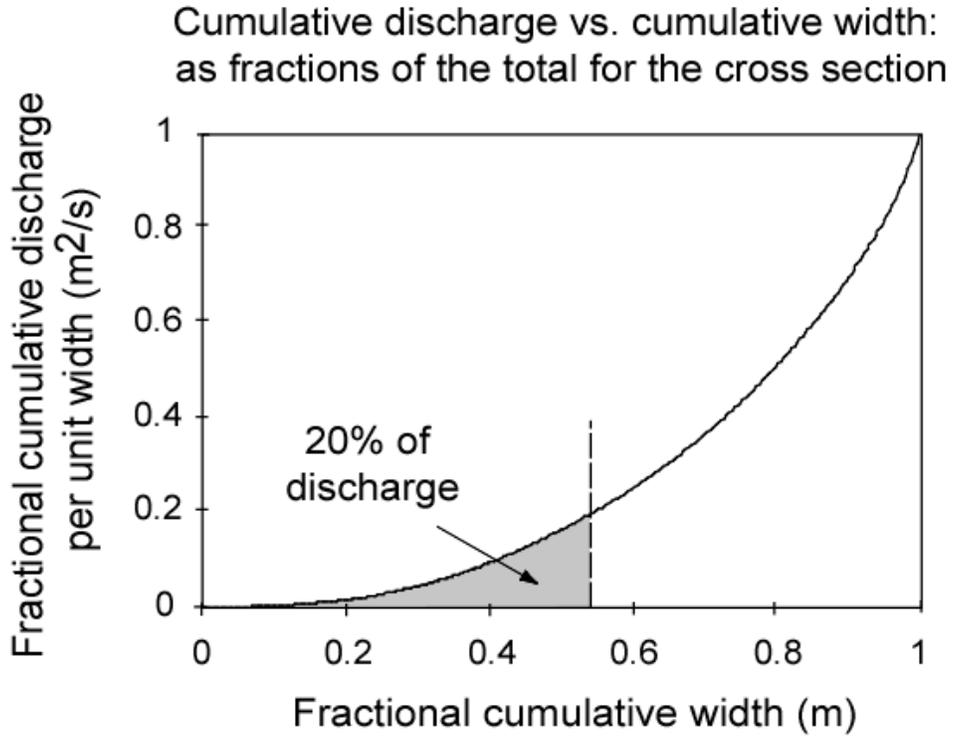


Figure 1-9. Fractional cumulative discharge is plotted against fractional cumulative width, both as fractions of the total for the cross section, for a sandy, braided alluvial fan in northern Minnesota [Paola *et al.*, 1999]. Note how a 20% reduction in the discharge would lead to a 50% reduction in channel width.

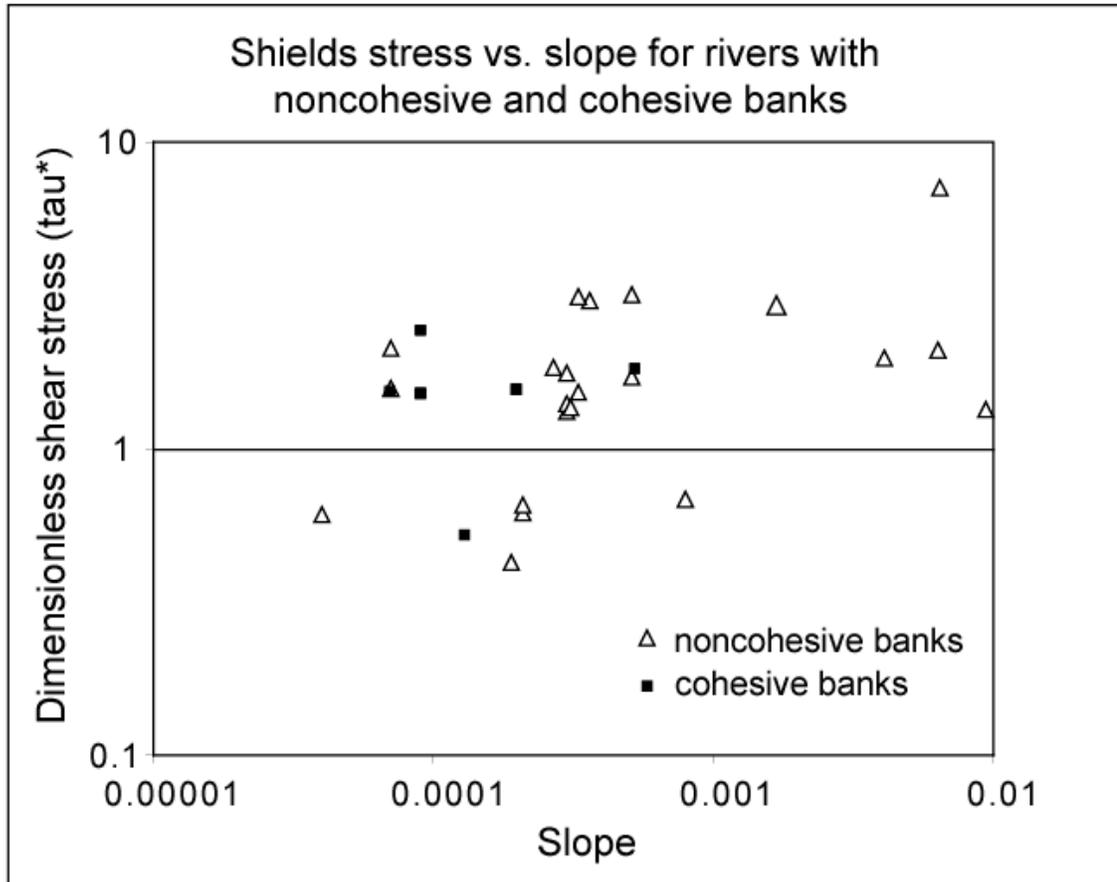


Figure 1-10. Dimensionless Shields stress ( $\tau^*$ ) is plotted against slope for a variety of rivers with noncohesive and cohesive banks. The data are from a compilation by *Church and Rood* [1983]. Note that the data do not show any significant difference between the two systems.

CHAPTER 2: DYNAMIC SINGLE-THREAD CHANNELS MAINTAINED BY THE  
INTERACTION OF FLOW AND VEGETATION<sup>2</sup>

*Michal Tal and Chris Paola*

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## ABSTRACT

Most rivers on Earth today flow as a single channel, in some cases with occasional islands, and follow a more or less sinuous course. However, single-thread channels have proven difficult to reproduce and study experimentally: experimental self-formed channels tend to widen and subdivide, leading to a braided pattern. Cohesive sediment has been the main mechanism studied for stabilizing banks and producing a single-thread channel. We show how laboratory experiments using vegetation to stabilize banks can organize the flow and convert the planform morphology from braided to single-thread. Our experimental strategy, a repeated cycle of short periods of high water discharge alternating with longer periods of low discharge accompanied by plant seeding and growth, leads to the evolution of a dynamic self-maintaining single-thread channel with well defined banks and floodplain. By eliminating weak flow paths the vegetation “corrals” the water into a single dominant channel until the reduction in total wetted width leads to a new self-organized state in which the flow removes vegetated area as fast as it is produced. The new channel is deeper and has a broader distribution of depths than the braided one, with channel size adjusted to carry almost all the flood flow. The resulting system maintains a dynamic steady-state via similar mechanisms to those that operate in meandering channels in the field, specifically erosion at the outside of bends, bend growth, and bar development. Our methodology provides a basis for experimental development of self-sustaining high-amplitude meanders and has applications for river management and basic research purposes.

Keywords: braided channels, vegetation, meandering, self-organization, floodplains, experimental studies

## BACKGROUND AND MOTIVATION

Rivers with a single well defined channel flanked by floodplains are so common (Leopold and Wolman, 1957) that one might assume that this must be the natural form for water flowing over loose sediment. Experimentation with sand and water, however, shows that this is not the case. Instead, in such experiments, the flow subdivides into a network of unstable interacting channels: a braided river (Schumm et al., 1987). The tendency to braid, which is seen even if sediment and water discharges, grain size, and slopes are set to values that should theoretically lead to meandering (Parker, 1976; Schumm et al., 1987), has proved difficult to overcome. This disparity between types of channel patterns that can be produced experimentally and those most commonly seen in nature limits experimental study of river dynamics to either a braided pattern unlike many natural rivers, or a pattern that is constructed by the experimenter, and thus limited in its ability to evolve on its own. The most significant advance to date in making laboratory meanders is by Smith (1998) who used cohesive sediment and small flows. Smith's channels formed spontaneous high amplitude bends but they did not cut-off and regenerate themselves.

A good deal of research has documented the influence of riparian vegetation on channel morphology and flow dynamics in the field (e.g. Graf, 1978; Johnson, 1994; Micheli and Kirchner, 2002; Simon and Collison, 2002) as well as experimentally (e.g. Gran and Paola, 2001; Coulthard, 2005) and numerically (Murray and Paola, 2003). Much of this work is motivated by interest in morphodynamic changes and subsequent loss of riverine habitat associated with vegetation encroachment that often results when flow variability and peak discharges are reduced. This can be due to anthropogenic changes in hydrology (e.g. dams, flow diversions (Eschner et al., 1983; Collier et al., 1996)) or climate change (Prentice et al., 1991). Through root binding, vegetation increases bank stability and increases the threshold shear stress needed to initiate sediment transport. In addition, vegetation increases flow resistance by increasing drag and reducing local velocity, thus decreasing the fluid stress available for erosion and transport (Thorne, 1990). Vegetation also increases bank stability by promoting

deposition of cohesive fine sediment (Reinfelds and Nanson, 1993). The geometry of braided rivers, characterized by high width to depth ratios and low topographic relief, makes them particularly susceptible to vegetation encroachment because low flow conditions result in large areas of the bed being exposed (Paola et al., 1999; Tal et al., 2004).

An earlier set of experiments (Gran and Paola, 2001) showed that increasing densities of bar and bank vegetation can significantly influence the morphology of a braided river. Here we report the results of a set of experiments at the St. Anthony Falls Laboratory (SAFL) that explore how dynamic interactions between vegetation and physical channel processes transform a braided morphology to single-thread sinuous. We identify some of the key processes that lead to this change as well as the mechanisms for maintaining a new dynamic steady-state (i.e. the system is not static, changes occur locally while the global average remains constant). The experiments provide a technique for reliably producing experimental single-thread channels useful for environmental management and restoration studies.

## EXPERIMENTAL METHODS

The experiments were designed to investigate the effects of vegetation under the simplest conditions that capture the essential dynamics of the interactions between vegetation, sediment, and water in natural rivers. The flume was 16 m long and 2 m wide, with initial slope of 0.015, and sediment consisting of well-sorted cohesionless sand ( $D_{50} = 0.5$  mm) transported predominantly as bedload. The starting state for each experiment was a fully developed, self-formed, steady-state braided channel (sediment input equal to sediment output). We imposed a two-stage hydrograph comprising a low flow (0.4 l/s) with no sediment transport, and a high flow (2.0 l/s) that transported sediment and reworked the channel morphology. We report results from two experiments, A and B, in which the only variable that differed was the duration of low flow (i.e. flood frequency). The flood intervals were 6 days and 3 days respectively. The effect of varying flood frequency is not discussed in this paper, however we draw on results from the two

experiments because both showed the same trends despite the difference in flood interval and support the ideas presented in this paper. Water was re-circulated and sediment feed was set at a constant rate (matched to the output transport rate for the desired experimental slope) of 3.5 g/s in run A and 5.2 g/s in run B. We reduced the sediment feed for the last 5 floods of run B to 1.7 g/s because of an imbalance between the sediment input rate and output sediment flux, which we detected by measuring the output at the downstream end using a box trap. Sediment was supplied during high flow only, since sediment flux during low flow was near zero. Flow velocities in the range of 0.2 – 0.3 m/s and flow depths between 0.01 – 0.03 m indicate that our flows were mostly turbulent with Froude numbers around critical.

Alfalfa seeds (*Medicago sativa*) were introduced and allowed to establish on emergent surfaces during the low flow intervals. Seeds typically germinate within 24 hours and develop clear roots and stems 1-2 cm in length and approximately 1 mm in diameter by the next flood. Sprouts are slightly larger and stronger at 6 days than at 3 days and the roots are more firmly embedded in the sediment. In both experiments all high flows lasted 1 hr. This flood duration was determined by estimating the time required for the channel to rework approximately 10% of its width during the first high flow (flood 1) conducted at the end of the first low flow vegetation establishment period of run A. Seeds were applied immediately after each high flow, at low flow conditions. Seeds were scattered uniformly by hand over the flume with a density of approximately 1 seed/cm<sup>2</sup>. Seeds that landed on emergent bars became established, while seeds that landed in the channels were transported out of the system or re-deposited elsewhere. As the two experiments ran continuously for 119 and 138 days respectively, spatial heterogeneity in vegetation density and age increased as established vegetated areas were repeatedly seeded, and vegetation that was not removed by the high flow continued to mature.

Data reported in this paper come from time-lapse vertical photography collected using four digital cameras mounted approximately 2.6 m above the flume and equally spaced to monitor a 10 m long and 2 m wide study reach. The cameras were connected to a computer and captured photographs of the flume simultaneously. Images were

corrected for camera angle and lens distortion and stitched together (Figure 2-1). Stitched images were compiled to make movies of the experiments (see videos DR1 and DR2 in data repository). Image area was classified based on color as wet or dry (“dry” here is equivalent to “vegetated” because vegetation grows on any part of the bed that is not under water), and conversion rates between wet and dry areas were calculated by subtracting consecutive classified images. Channel depths were mapped using an image-based dye density technique (Winterbottom and Gilvear, 1997). We used similar methods to those described in Gran and Paola (2001): rhodamine dye mixed into the flow at 2 ppm and calibrated with tilted sand-bedded trays of known geometry and filled with water that were placed around the flume within the field of view of the cameras. We quantified the error associated with the calibration trays as being on average  $\pm 1$  mm. However, this error could be somewhat larger for areas that are further from the location of the tray due to minor lighting variations across the flume.

## RESULTS

### *Self-organization and dynamic steady-state*

Once the experiments developed a braided channel pattern, the only thing we did was alternate discharges and apply seeds as explained above. The experiments thus show how an initial physically-controlled braided system reorganizes itself through ongoing interaction with vegetation of increasing age and density. The bank stability and increased roughness offered by increasingly dense mature vegetation led to the elimination of weak braid channels (channels that were not active at low flows and smaller channels with lower velocities and almost no sediment transport), and corralling of dispersed flows into one or two channels with well defined banks and a floodplain (Figure 2-1 and videos DR1 and DR2 in data repository). The single-thread channel planform that developed as a result of increasing vegetation is best described as fluctuating between a wandering (Neill, 1973) and irregularly sinuous channel (Desloges and Church, 1989).

Both experiments evolved to a dynamic steady-state with vigorous exchange

between vegetated and unvegetated area. This state was characterized by a relatively stable channel width and a dynamic balance between the mean areal rates of vegetation establishment and vegetation destruction in each flood (Figure 2-1 and videos DR1 and DR2 in data repository). The channel configuration (depth, sinuosity, bar structure) was maintained by a spatial distribution of channel shear stress sufficient to erode vegetated area (mostly outer bend areas) as fast as new surface area (mostly point bars on the insides of bends) was deposited and then colonized by plants. The planform changes associated with the evolution from braided to single-channel (e.g. reduced number of channels, increased sinuosity, and reduced wetted width) can be seen clearly from the time-lapse images (Figure 2-1) and videos of the experiments (DR1 and DR2 in data repository), and are also quantitatively represented by the distribution of active channel depths through time (Figure 2-2). The distributions show a trend of deepening channels and a reduction in wetted area as the morphology changes from a broad, unvegetated braidplain with flow distributed across multiple shallow channels, towards a single narrow channel with a well defined vegetated floodplain. The single channel is on average deeper and includes a wider distribution of depths than the braided channels.

The steady-state single-thread channels were dynamic. Erosion along the outside of bends was accompanied by point-bar development which led to bend growth and approximately constant width. Initially, when the system is braided, the effect of decreased water discharge is primarily to reduce wetted width (Smith et al., 1996), exposing large areas of bare sand that become available for colonization by plants. As the flow organizes itself toward a single channel, discharge variation influences flow depth more than wetted width. At this stage, only freshly deposited point bars are exposed at low flow. These point bar deposits are roughly equal in area to the vegetated area eroded along the cut bank, so that the wetted area and vegetated area reach a steady state (Figure 2-3). Temporal changes in area classified as wet versus dry (Figure 2-4) show that the conversion from one class to another is rapid initially and then slows down. The exchange rates between wet and dry area are approximately equal in magnitude signifying that the system is in a dynamic steady-state and that the net change is approaching zero. At steady-state, the exchange rate (wet to dry or vice versa) during

each flood is typically about 20% of total wetted area (Figure 2-4). Run B has greater variability between wet and dry due to a shorter flood interval and thus greater removal of vegetation.

#### *Mechanisms for maintaining steady-state*

One of the mechanisms which characterize the evolution towards dynamic steady-state is the linking of zones of high unit discharge, which are dispersed in the braided case, into a continuous path as a result of corralling of the flow into a single channel. We mapped zones of high unit discharge in the channels through time by choosing a threshold color intensity. We verified that these deep areas are also zones of fast moving flow (and not deep pools of standing water) by tracking floating particles on the water surface. Figure 2-5 shows how, in the braided configuration, high unit discharge zones are localized and separated by less energetic flow. As vegetation corrals the flow, a channel that is continuously fast and deep develops and prevents vegetation establishment along its path.

It is especially noteworthy that the dominant channels that emerged from the vegetation-channel interactions organized to a geometry such that nearly all the flow was carried in the channels at high discharge, and only a small amount of very slow-moving flow was on the floodplains. We identified three effects that force the system to adjust to approximately bankfull geometry:

1. The tendency of bars to grow to the full height of the high flow in the braid channels. This leads to bar tops being exposed and colonized under low-flow conditions.
2. The ability of the vegetation to quickly occupy any excess channel area. Any excess channel area, i.e. area not wetted at high flow, is colonized by plants that survive the flood discharge. This mechanism means the steady-state channel(s) cannot be oversized, i.e. wider and/or deeper than necessary.
3. The ability of the vegetation to block overland flow while allowing for bank erosion during floods. The inability of the vegetated areas to convey flow tends to force the open channel(s) to pass the supply discharge, and the ability of the

channels to remove existing vegetation along the channel margins makes this possible. This mechanism means that the steady-state channels tend not to be undersized.

The net result of all three effects is channels that are just able to convey the flood discharge.

## CONCLUSIONS

The experiments demonstrate how a cycle of high and low water discharge, together with plant seeding, leads to self-organized, dynamic sinuous single-thread channels. The channels show important characteristics of natural single-thread channels: a stable width maintained by a balance between cut-bank erosion and point-bar deposition, and cross-sectional area adjusted such that the flood discharge just reaches the bank top. Because we did not use fine sediment in our experiments, we conclude that fines are not essential but are also sufficient (Smith, 1998) for the formation of such channels. The common factor appears to be some form of bank stabilization (Murray and Paola 1994; Dietrich and Perron, 2006) - vegetation, net incision into resistant material (e.g. bedrock meanders (Leopold et al., 1964)), or cohesive sediment (e.g. submarine channels (Damuth et al., 1983; Imran et al., 1999)). Variable water discharge, a factor often cited as promoting braiding in the field (Miall, 1977), plays an important role in the formation of dynamic single-thread channels by giving plants a chance to colonize freshly deposited sediment.

## ACKNOWLEDGEMENTS

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## FIGURES

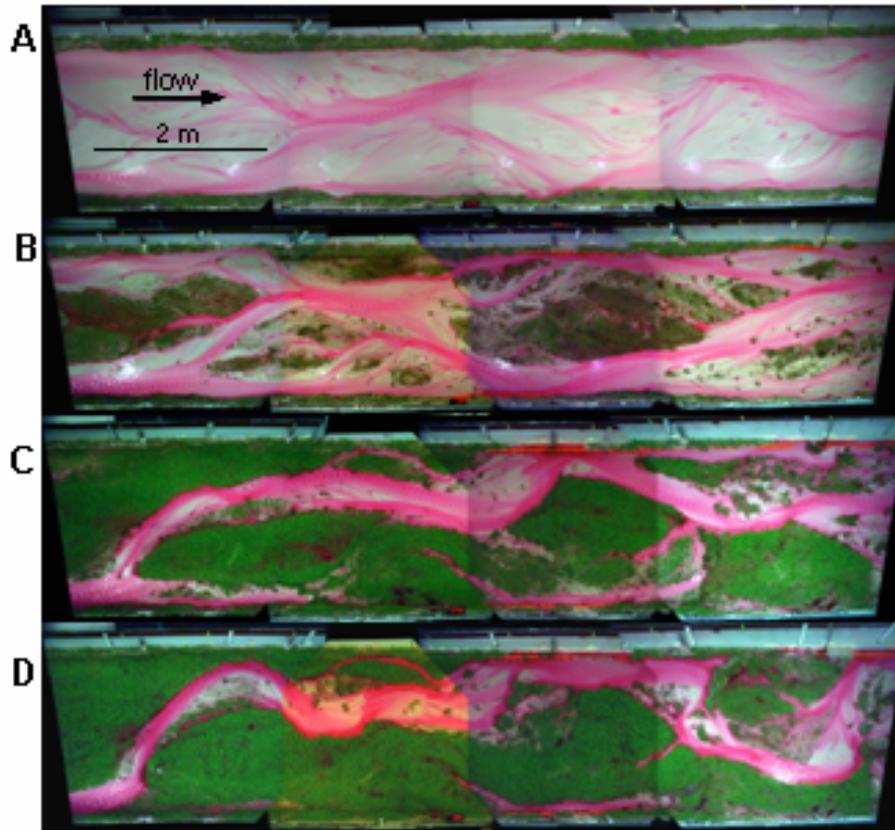


Figure 2-1. Plan view of experimental channel

A braided morphology self-organized to an irregularly sinuous, single-thread channel with well defined banks and a floodplain through ongoing interaction of vegetation and variable discharge. A planview of the 8 m study reach of the flume is shown (a) at initial unvegetated steady state, (b) after 6 flood cycles (24 days), (c) after 18 flood cycles (72 days), (d) after 23 flood cycles (92 days). The channel evolved to a dynamic steady-state such that vegetated area eroded along cut banks at the same rate that new sediment was deposited on point bars and a stable width was maintained.

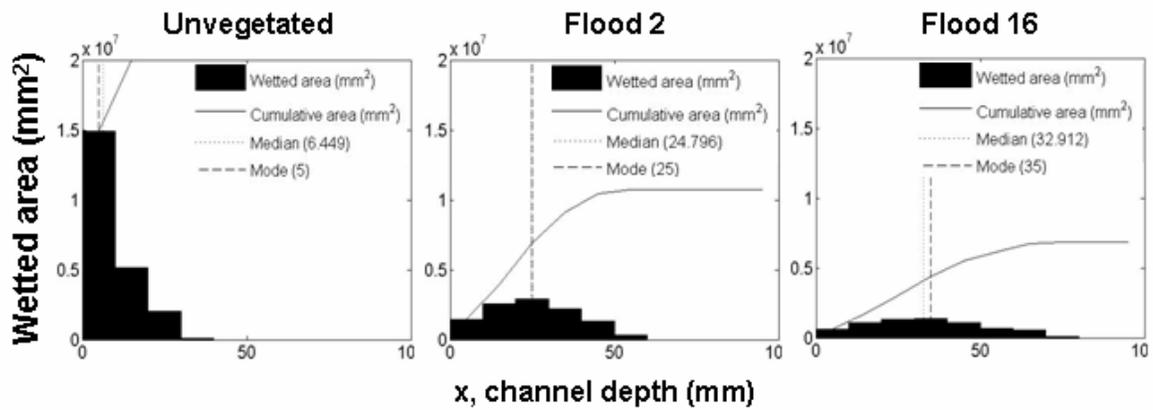


Figure 2-2. Distribution of channel depths by wetted area

The distributions of channel area by channel depth show a trend of deepening channels and a reduction in wetted area as the morphology transitions from a wide, unvegetated braidplain with flow distributed across multiple shallow channels, towards a single, deep, narrow channel. Distributions are from run A with a 6 day flood interval.

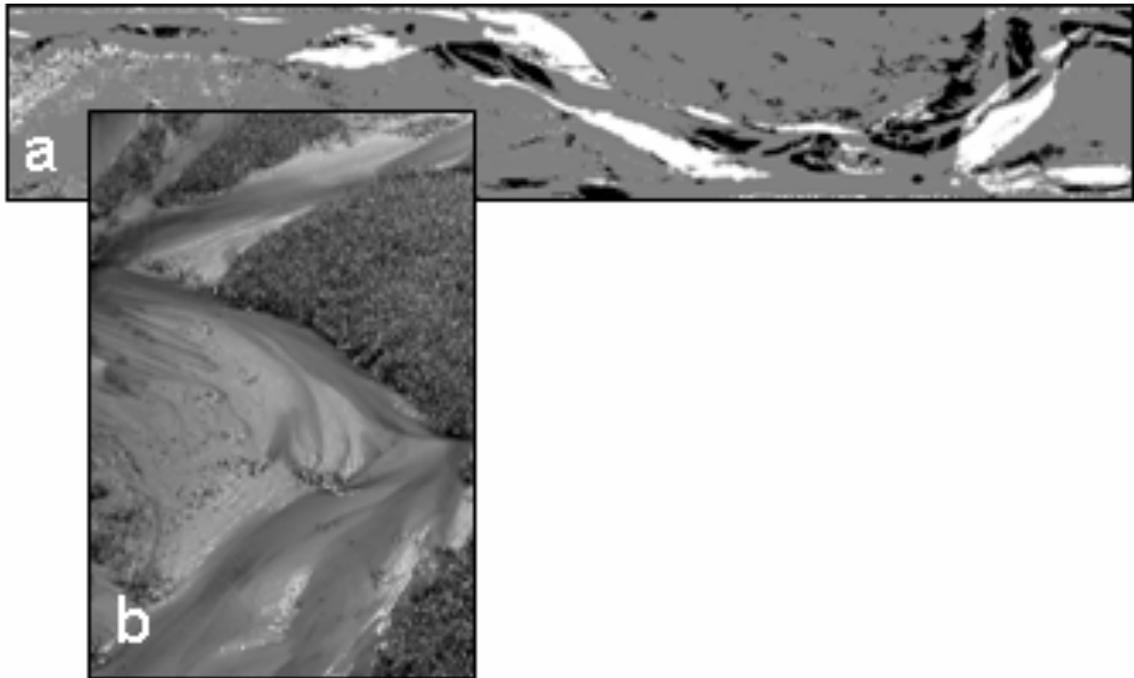


Figure 2-3. Conversion areas and low flow channel and bars

(a) Result of subtracting classified images of consecutive floods (3 and 4) from run A. Gray represents area that did not change, black is area that was converted from wet (channel) to dry (sand and vegetation), and white is area that went from dry to wet. The areas where change occurred highlight how the single-thread channel form is maintained dynamically by erosion along cut-banks and deposition on point-bars leading to active bend migration. Vegetation is eroded by an amount equal to new areas of establishment on freshly deposited bars and the system maintains a dynamic steady-state. (b) Low-flow channel with freshly deposited point bars along inner banks.

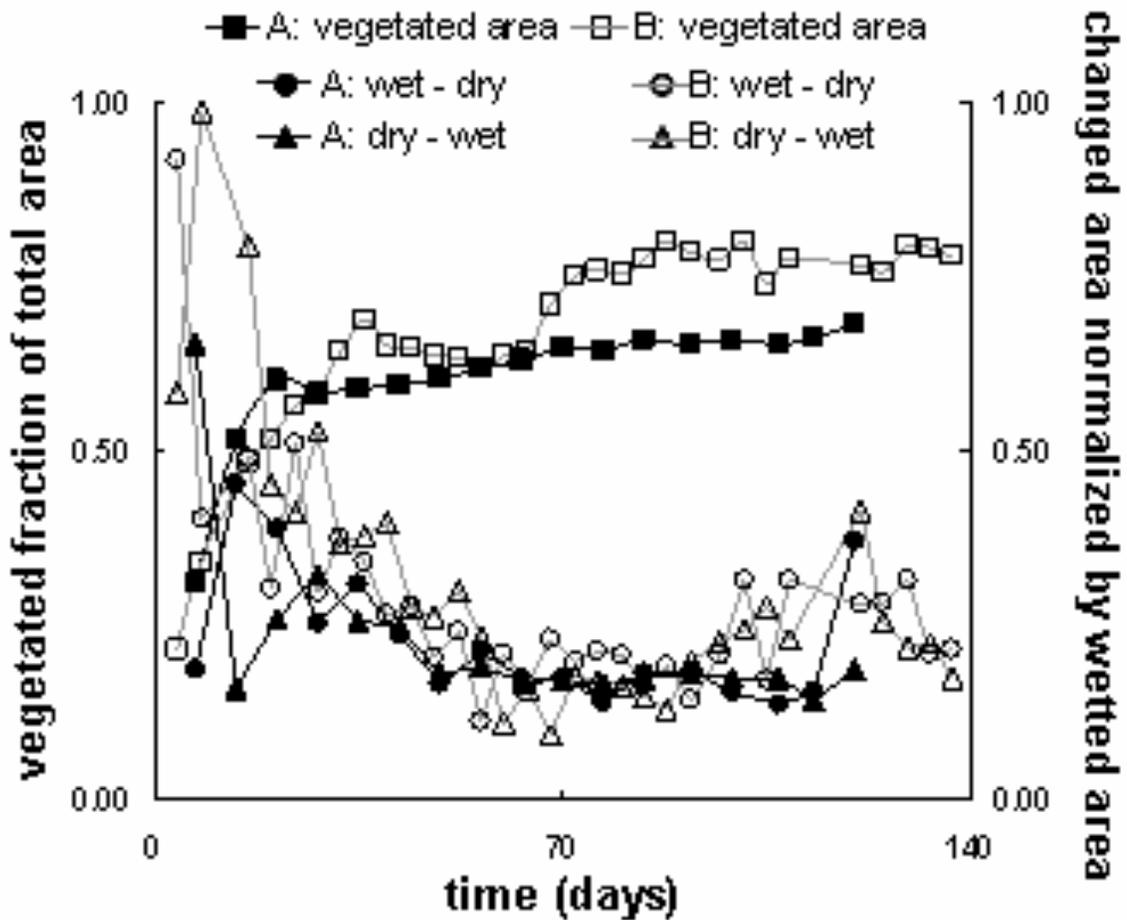


Figure 2-4. Rates of area conversion

The fraction of the total area covered with vegetation through time and time rate of change from wet (channel) to dry (sand and vegetation) for both runs. Vegetation initially occupies large regions of bare sediment that are exposed during low flow. After approximately 3 floods in run A and 15 in run B the system reaches a dynamic steady-state between channel planform and vegetation expansion. Exchange rates from wet-dry and dry-wet are approximately equal in magnitude signifying that the system is in a dynamic steady-state and the net change is approaching zero. Exchanges between wet and dry are normalized to wetted area because they occur primarily along the channel edge (see Figure 2-3).

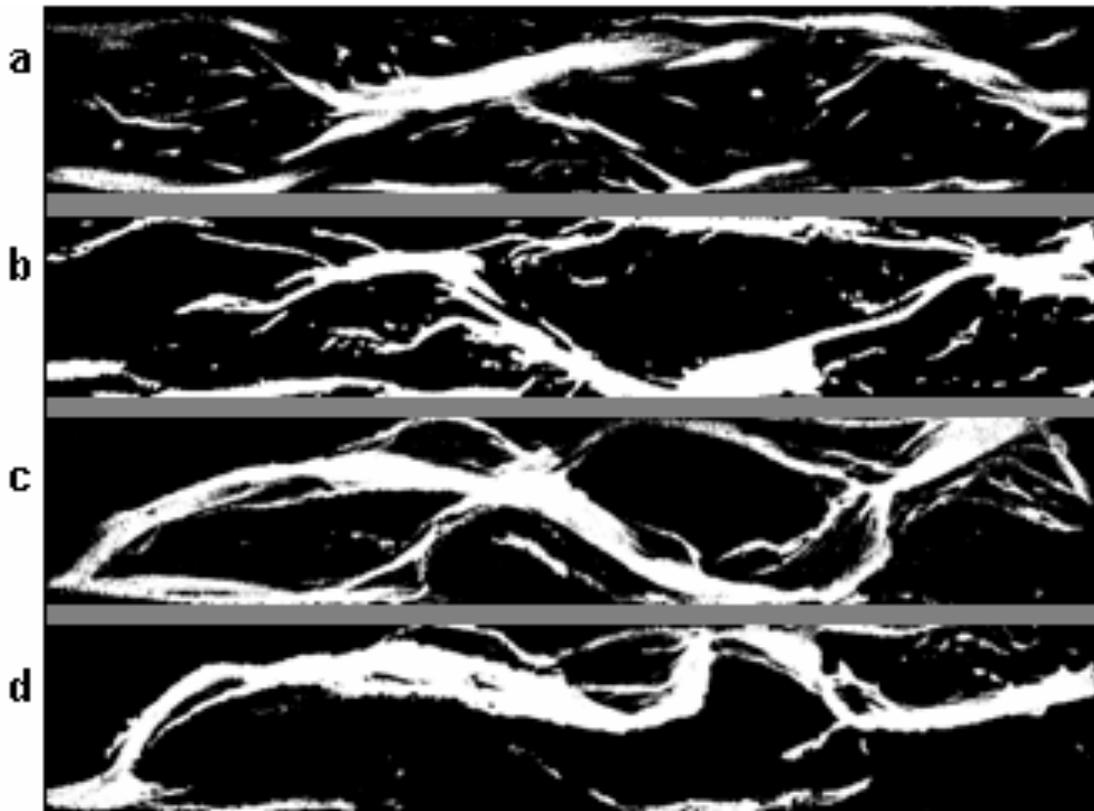


Figure 2-5. Linking of zones of high unit discharge

Maps of channels above a threshold color intensity (proxy for depth) illustrate a key effect of the plants: elimination of weak and discontinuous flow paths in the braided state that are not sufficiently strong to remove vegetation, and organization of the flow into a single continuously fast and deep channel capable of preventing further encroachment. Threshold images are from run B with a 3 day flood interval (a) unvegetated steady state, (b) flood 7, (c) flood 13 (d) flood 19.

CHAPTER 3: EFFECTS OF VEGETATION ON CHANNEL MORPHODYNAMICS:  
RESULTS AND INSIGHTS FROM LABORATORY EXPERIMENTS

*Michal Tal and Chris Paola*

## 1. INTRODUCTION

Laboratory studies of single-thread rivers have long eluded researchers. Experimental self-formed channels composed of sand-sized particles and larger widen and subdivide to form braiding. Sinuous single-thread channels produced experimentally (e.g., Friedkin, 1945) were transient, with chute cutoffs and widening eventually leading to the formation of multiple threads when the experiments ran long enough. This problem supports the idea that braiding is the fundamental instability of streams flowing in noncohesive material and that the key to developing meandering is to slow the rate of widening and discourage channel cutoffs (Paola, 2001). More recent efforts to reproduce single-thread channels experimentally have focused on stabilizing banks by using a variety of sediment types and mixtures. Jin and Schumm (1986) successfully produced a meandering pattern by forming a bed that consisted of an erodible sand substrate capped by a cohesive layer of fine sand and clay. However, the ad hoc bed could not be reconstructed by the channels and was therefore not self-maintaining. Smith (1998) produced high-amplitude sinuous channels using cohesive banks composed of a mixture of kaolinite, cornstarch, white China clay, and diatomaceous earth. Although Smith's channels eventually reached a static planform equilibrium (i.e., no longer actively migrated) and did not generate cutoffs, they were the closest anyone had come to producing true laboratory meanders. Smith's results reinforced the idea that fortified banks capable of deterring cutoffs is key to the formation of meandering. Peakall (2007) reported on experiments that produced meandering using a combination of sand and silica flour (rather than clay). Silica flour that settled out of suspension increased the pointbar elevation and filled in chute-channels, both of which deter the flow from splitting (Peakall, 2007; Brauderick et al, 2007). However, water discharges in these experiments were kept deliberately low to prevent the flow from overtopping the bars and occupying new channels.

Researchers at the St. Anthony Falls Laboratory pioneered the use of real vegetation to stabilize banks in order to produce single-thread channels (Gran and Paola, 2001; Tal and Paola, 2007). Although Smith's (1998) experiments suggest that cohesive materials

may be enough to produce meandering, the majority of meandering rivers on Earth flow through non-cohesive beds (e.g. sand or gravel) and are flanked by forested floodplains. Meandering through cohesive material such as tidal channels, submarine channels, and bedrock channels are less common. Riparian vegetation impacts a variety of flow and sedimentation processes. At local scales, vegetation influences flow velocities and depths by adding drag and reducing the area available for water flow. Vegetation imposes strength or ‘cohesion’ to non-cohesive bed and bank material through root reinforcement, protection of underlying substrate by litter and leaf mats, bank protection by large-woody debris, and water-capillary effects. Reduced flow velocities through vegetated areas hinder scour and encourage the deposition of suspended sediment, while velocity reduction in the wakes of large trees can focus bed-material accumulation to form proto-islands. In turn, deposition creates favorable conditions for new vegetation establishment and increases the height of bars and islands, helping them to attain greater permanency. But it is the initial presence of plants that traps and retains the fine sediment and prevents it from being washed away. At the channel scale, the effects of vegetation act to suppress braiding by slowing down bank erosion, narrowing channels, and assisting bank accretion. Indeed, many field studies have documented changes in riparian vegetation leading to channel narrowing and the stabilization of channels that become separated by permanently vegetated islands.

In chapter 2 we reported preliminary results from a series of experiments designed to study the effect of adding vegetation to an unvegetated braided morphology. One of the main goals of the experiments was to determine if the addition of plants alone could cause a transition from braiding to other planforms such as anastomosing or meandering. The results demonstrated that a cycle of short periods of high water discharge alternating with longer periods of low discharge accompanied by plant seeding and growth could lead to the evolution of a braided morphology to a dynamic self-maintaining sinuous single-thread channel (Fig. 2-1). The methodology provided a basis for experimental development of self-sustaining sinuous single-thread channels. The experiments we performed differed fundamentally from other experimental studies of meandering in that all the experiments started out as fully braided, and a single-thread sinuous channel

evolved on its own purely through interactions with the vegetation. All other studies (e.g., Friedkin, 1945; Smith, 1998; Peakall, 2007) focused on maintaining a single-thread sinuous channel that evolved from a straight channel (with or without an initial upstream bend or angled inlet channel), with the effort placed on preventing the channel from widening and splitting. Furthermore, nothing in our systems was set to promote meandering, e.g., low slopes, cohesive sediment, etc. In fact, the opposite was true: the physical conditions promoted braiding. The evolution to a single-thread channel when plants were added was a robust and reproducible result and demonstrates that vegetation can play a dominant role in how rivers self-organize to and then maintain a meandering pattern.

This chapter focuses on the feedbacks that emerged among flow, vegetation, and sediment, and the specific effect of the vegetation on channel morphodynamics in the experiments reported in chapter 2. The experimental channels showed important characteristics of natural single-thread channels. These included a stable width maintained by a balance between cut-bank erosion and point-bar deposition, a cross-sectional area adjusted to just contain the bankfull flow, actively migrating bends, channel cutoffs, and avulsions. We describe each of these morphodynamic features and the specific role plants play in how these features evolve and are maintained. The extent to which simplified, unscaled laboratory experiments such as these reproduce key elements of complex natural river behavior suggests a high degree of scale independence in the relevant dynamics. The results indicate that the influence of plants goes beyond simply the geotechnical reinforcement of the banks, and that the morphodynamic features that characterize meandering are directly related to sustained interactions among plants, flow, and sediment, and specifically the capacity of these variables to evolve dynamically and continuously adjust.

## 2. MORPHODYNAMICS

As reported in chapter 2, the major effect of the plants in the experiments was to eliminate weak flow paths in the braided state and focus the flow into one main channel

that conveyed most of the flow. As a result, the system organized itself to a new state consisting of a dominant channel with well-defined banks and a vegetated floodplain (Fig. 2-1). Vegetation initially occupied large areas of bare sediment that were exposed at low flow, driving a reduction in wetted width. The channel narrowed until a steady-state width was achieved that coincided with a maximum vegetated area (Figs. 3-1 & 3-2). This steady-state condition was maintained by erosion of vegetated areas along cutbanks during the high flow, which was balanced by the creation of new vegetated area on freshly deposited point bars (Fig. 3-3). The single-thread channels that developed were dynamic and actively migrated across the vegetated floodplain throughout the experiments.

### *2.1. Bend growth, point-bar formation, and cutoffs*

Once the flow in the braided channel converged to a single dominant channel, the total wetted width was reduced significantly (Fig. 3-2). In the braided state, bank erosion by local high shear stresses is rapid, and thus often not matched to deposition on the opposing bank. This imbalance leads directly to channel widening, bar formation, and in some cases, channel splitting (e.g., Ashmore, 1991b; Repetto et al, 2002). In the new dynamic steady state with vegetation, the plants slow the rate of bank erosion (Fig. 3-4) allowing deposition on the opposing bank to keep up and (where the channel is curved) creating a point bar. Matching of point-bar development along the inner bar with erosion on the outer bend allows time for existing channels to develop relatively high sinuosity while preventing creation of new channel width within an existing channel (Fig. 3-3). Here the critical role of the vegetation is to slow the rate of bank erosion through binding of the sediment by roots (Fig. 3-5). Since vegetated area redevelops as fast as it is removed, the high-sinuosity channels are likewise dynamically maintained.

Experimental single-thread channels typically develop multiple channels when the flow occupies and enlarges chute channels that occupy the swale between the bar and the inner bank (e.g., Schumm, 1987; Ashmore, 1991b). One of the main challenges to achieve self-sustaining experimental meandering is to discourage the flow from occupying these chute channels for time long enough to allow the main channel to

undergo significant lateral migration. A related effect that discourages chute cutoffs and maintains a single-thread channel is to maintain a strong connection between bars and banks, creating what are commonly referred to as 'bank-attached bars'. Cohesive sediment used in other experimental studies (Peakall, 2007, Brauderick et al, 2007), in addition to slowing the process of new channel creation, was deposited in chute channels. Suspended sediment deposition filled in the topographic low and reduced the potential for flow to cut across it. In the experiments described here, the vegetation was responsible for reducing the rate of creation of new channels as well as physically blocking the flow from reactivating chute channels (even when remnant chute topography continued to exist underneath the vegetation cover).

The role of the vegetation in regulating the cutoff process can be seen by examining several cutoffs that developed during the single-thread channel phase of the experiments (Figs. 3-6, 3-7 & 3-8). These cutoffs typify the behavior of steady-state natural single-thread channels, in contrast to the braided state. The major characteristic of the cutoffs in the fully vegetated case is that they involve the wholesale diversion of flow and sediment at some point along the channel into a newly activated reach, gradually leaving behind a completely abandoned reach that becomes vegetated and incorporated into the floodplain. In the braided state, analogous events lead to formation of multiple channels (Figure 3-9).

Channel cutoffs occurred through old chutes as well as through reactivation of abandoned braid channels in the floodplain. Cutoffs played a significant role in maintaining the self-formed single-thread channels by redirecting the flow and sediment to different areas of the floodplain when the main channel filled with sediment and aggraded (Tornqvist, 1994; Bryant et al, 1995). Aggradation in the main channel was often associated with vegetation debris jams that formed and effectively blocked the flow of water and sediment, resulting in a local bottleneck that caused the channel to widen and sometimes locally rebrand (Fig. 3-8). Cutoffs diverted the flow and sediment into steeper channels, in effect acting like local avulsions, and enabled the transport of water and sediment through a single dominant channel to continue. Without the mechanism of spontaneous cutoffs, deposition would have continued and likely resulted in localized

rebraiding or areas of non-channelized flow.

## 2.2. *Avulsions*

In addition to cutoffs that diverted channel reaches over longitudinal distances comparable to a single bend wavelength ( $<1$  m), large scale avulsions occurred that diverted much longer reaches of the channel (several meters) to a new course (Fig. 3-10). Avulsion is the process by which flow is diverted out of an established section of channel to a new flow pathway elsewhere on the floodplain (Mohrig et al, 2000; Slingerland and Smith, 2004). Aggradation leads to the channel becoming perched above the surrounding floodplain and therefore unstable (Mohrig et al, 2000; Slingerland and Smith, 2004; Jerolmack and Mohrig, 2007). The experimental avulsions, like those in natural rivers, were due to superelevation of the active channel above the mean elevation of the floodplain and in particular relative to the elevation of floodplain channels with active headcuts. Figure 3-11 shows topographic cross sections along section A – A' (Fig. 3-10) during the first flood and 16 floods later, immediately before the avulsion occurred. The main channel (right) can be seen super-elevated relative to the floodplain channels (left). Mean elevation difference just before the avulsion was approximately 36 mm. This unstable condition caused the flow to avulse into the steeper and deeper floodplain channels and to abandon the old one completely (Fig. 3-10). Flow depths measured separately using a dye-density technique had a mean of 32 mm (see chapter 2, Fig. 2-2), indicating that superelevation of the channel was on average 1.1 times the flow depth. This result supports the findings of Mohrig et al (2000) that the magnitude of channel incision and superlevation scales with flow depth.

In contrast with the braided system, where channel switching is a nearly continuous process with persistent flow shifting among multiple channels following slight gradient differences, the vegetated state produced less frequent but more distinct avulsions. Because of the added difficulty of cutting a new path across vegetated surfaces, the channel avulsion required a larger superelevation, which led to abandonment of the old channel and relatively complete diversion of flow to the new one. Once the flow abandoned a channel it became vegetated and incorporated into the

floodplain (Fig. 10). As in the case of channel cutoffs, the vegetation caused wholesale diversion of the flow and discouraged the coexistence of multiple channels.

### *2.3. Width production and remnant channels*

A generic mechanism of width production in the braided state is the opportunistic creation of new channels. As existing flow paths become slightly less favorable, for example by increase in sinuosity or bar deposition, new ones are readily created in areas that are not currently occupied by flow. This effect is one that has made maintenance of experimental single-thread channels difficult. Figure 3-12a shows the location of flow (wet) and dry areas at 1-hour intervals during the unvegetated braided phase in the experiments and a differenced image of these two times. The location of active channels at the initial time ( $t_0$ ) is decoupled from their location one hour later. Furthermore, the differenced image demonstrates the difficulty of predicting where new areas of flow will be located based on their previous location. In contrast, Figure 3-12b shows changes in wet and dry areas when the channel is single-thread. The changes are highly localized in space – predominantly along the channel margin – and thus more predictable because they are associated with lateral migration of the channel. The incoherent pattern of new flow paths in the braided state reflect the incoherent pattern of a braided channel, while the more orderly changes in the single-thread state reflect the coherent nature of the channel. The effect of the vegetation is therefore to organize the flow so that it is conveyed in a single well-defined channel in which localized changes in wetted area reflect coherent migration of the channel as a whole.

The ability of the flow to migrate freely and change its course dramatically is further expressed by the timescale on which the flow pattern erases the ‘memory’ of a pattern at an earlier time. We measured the timescale for loss of pattern information using binary images (white = wet, black = dry) thresholded to represent the dominant flow path(s). A series of unvegetated braided images and a series of images spanning the vegetated-floods were compared to the first image in the series. For the vegetated series the reference image was the main channel at the end of the braided state before the first seeding. We tracked the number of pixels with flow in the first image that continued to

have flow at each subsequent time step. We did not count pixels that had become dry (abandoned or vegetated) at any previous time step and then wet again. Thus, we measured the time required for the initial channel pattern to be reworked once. Figure 3-13 shows the faster reworking time of an initial channel pattern in the unvegetated braided state than when the system was vegetated. The longer reworking time is due to a combination of slower erosion rates (Fig. 3-4) and the limited ability of opportunistic creation of new channel in areas not occupied by the flow (Fig. 3-12). Finally, at low flow, vegetation occupies areas that are dry thereby reinforcing the dominant flow paths.

#### *2.4. Floodplain channels*

The experiments we report on here started as unvegetated braided systems with braid channels migrating across the entire width of the bed. Floodplains evolved gradually as braid-bars became vegetated during low flows and expanded, eventually merging with other vegetated bars and islands. Once the system had developed into a distinct single channel, the remaining vegetated area formed, in effect, a floodplain. This floodplain continued to evolve through lateral erosion and point bar accretion. The sand bed in all the experiments was composed of uniform sediment, and the same uniform sediment was fed into the system throughout the experiments. Therefore, the sediment composition of the floodplain was exactly the same as that of the active channel, meaning that the floodplains were purely morphological regions of the bed that were defined by semi-permanent establishment of spatially continuous vegetation. Water depth on the floodplain during the high-discharge events (floods) ranged from zero to a few mm, and for the most part, floodplain flow rates were negligible.

Due to the absence of fine sediment, gradual infilling of abandoned channels did not occur, so the remnant topography of old channels persisted in the floodplain beneath the vegetation cover. These abandoned channels often focused sufficient flow to become reactivated, forming floodplain channels (Mertes et al, 1996; Figs. 3-10 & 3-14). These channels were smaller than the main channel and were typically not active during low flow, although groundwater kept them relatively wet even at low flow. This persistent dampness was unfavorable for the alfalfa plants and helped keep the channels open.

Floodplain channels commonly developed active headcuts (Figs. 3-10 & 3-14) and thus played an important role in driving avulsions. Headcutting intensified as increasing discharge was diverted from the main channel, which was undergoing aggradation, into one of the steeper floodplain channels. This condition was eventually followed by an avulsion or a channel cutoff. Because the vegetation delays new channel creation until a significant elevation difference has developed, once the avulsion occurred and the vegetation was removed (either buried or eroded) the new channel quickly enlarged, making it the dominant one. This is a major cause of the effect discussed above, that avulsions in the vegetated, single-thread case are less frequent but more complete than in the braided case. The presence of a meander bend in the dominant channel sometimes aided the avulsion process by pushing the flow and sediment in the direction of the steeper channel (Fig. 3-14), an observation that has been made in other studies (i.e., Slingerland and Smith, 2004; Kleinhans et al, 2008)

#### *2.5. Sediment storage and transport fluctuations*

As shown in Figures 3-15 and 3-16, the experimental system produced large fluctuations in total sediment output, comparable to those observed in braided rivers. Although sediment output rate fluctuated, it was almost always below the constant sediment input rate, suggesting that the system was storing sediment. Figures 3-17 and 3-18 show the cumulative output of sediment versus the cumulative input of sediment. Cumulative sediment storage occurred as wetted width decreased (Fig. 3-2) and therefore may be related to a reduction in net width.

#### *2.6 Bankfull geometry*

The dominant channel that formed as a result of vegetation-channel interactions self-organized to a bankfull geometry that just contained the flood flow. There was almost no active flow on the floodplain. Once a bankfull geometry was achieved, it maintained itself throughout the experiment. Key to both of these processes was the tendency for bars to grow to the full height of the high flow in the braid channels and later the single-thread channels (Tal and Paola, 2007), causing them to become exposed

at low flow. The addition of vegetation at the end of each high flow ensured that at least some of these freshly deposited surfaces became stabilized. Vegetation forced the flow to migrate away at the next high flow, thereby dynamically building the bars and, later, point bars. This dynamic process has been missing in other experiments that maintain low flows in order to prevent overtopping of the bars. In our experiments, high flows promoted the dynamic construction of bars. This in turn helped the channel geometry evolve to convey the imposed flow rather than matching the flow to the channel geometry.

Another key effect was the ability of the plants to quickly occupy parts of the bed that were abandoned (dry) at low flow (Tal and Paola, 2007). This had the effect of reinforcing the wetted width at low flow and organizing the dominant channel to a geometry such that it contained both the high flow and low flow with minimal difference in wetted area between them. As bankfull geometry developed the braiding index at the high flow and the low flow approached one (Fig. 3-19).

FIGURES

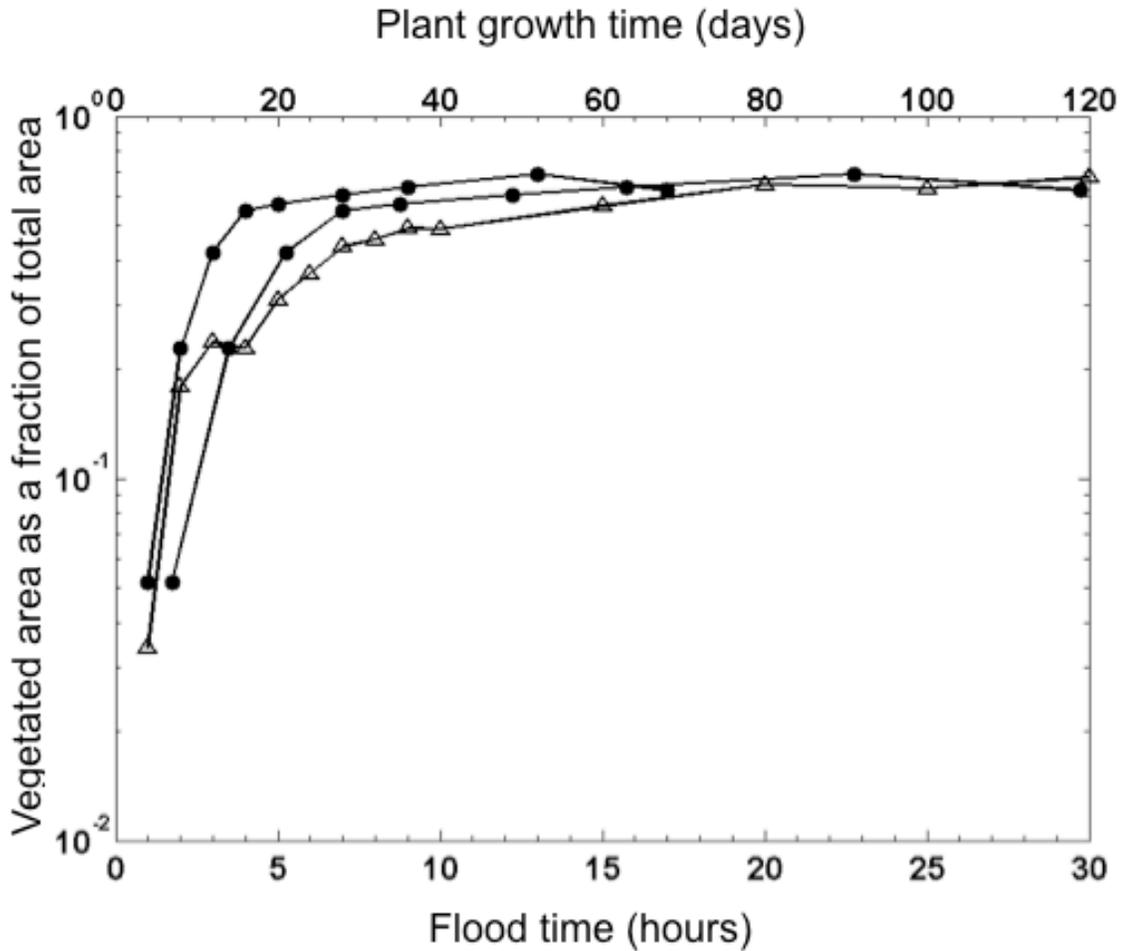


Figure 3-1. Vegetated area as a fraction of total area through time. Vegetation cover increases rapidly early in the experiments eventually reaching a dynamic steady state. At steady state total vegetated area remains the same as new colonized area is in balance with area that is eroded. Run A (circles, 17 floods, 6 day flood interval) and run B (triangles, 31 floods, 3 day flood interval) are plotted through time represented as flood time and plant growth time and shows that steady-state is reached at approximately the same time for both runs in terms of plant growth time but earlier in run A in terms of flood time.

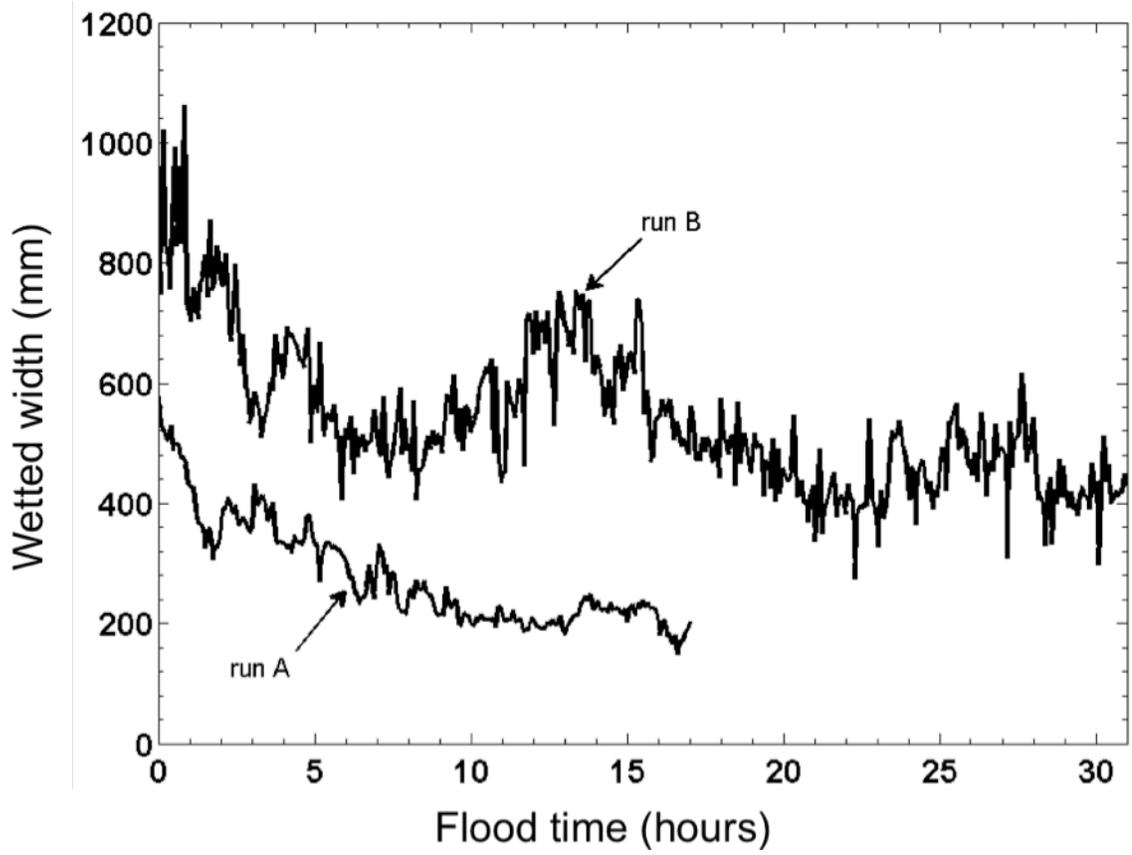


Figure 3-2. Average wetted measured at 5-minute intervals during all of the high-flows for each run.

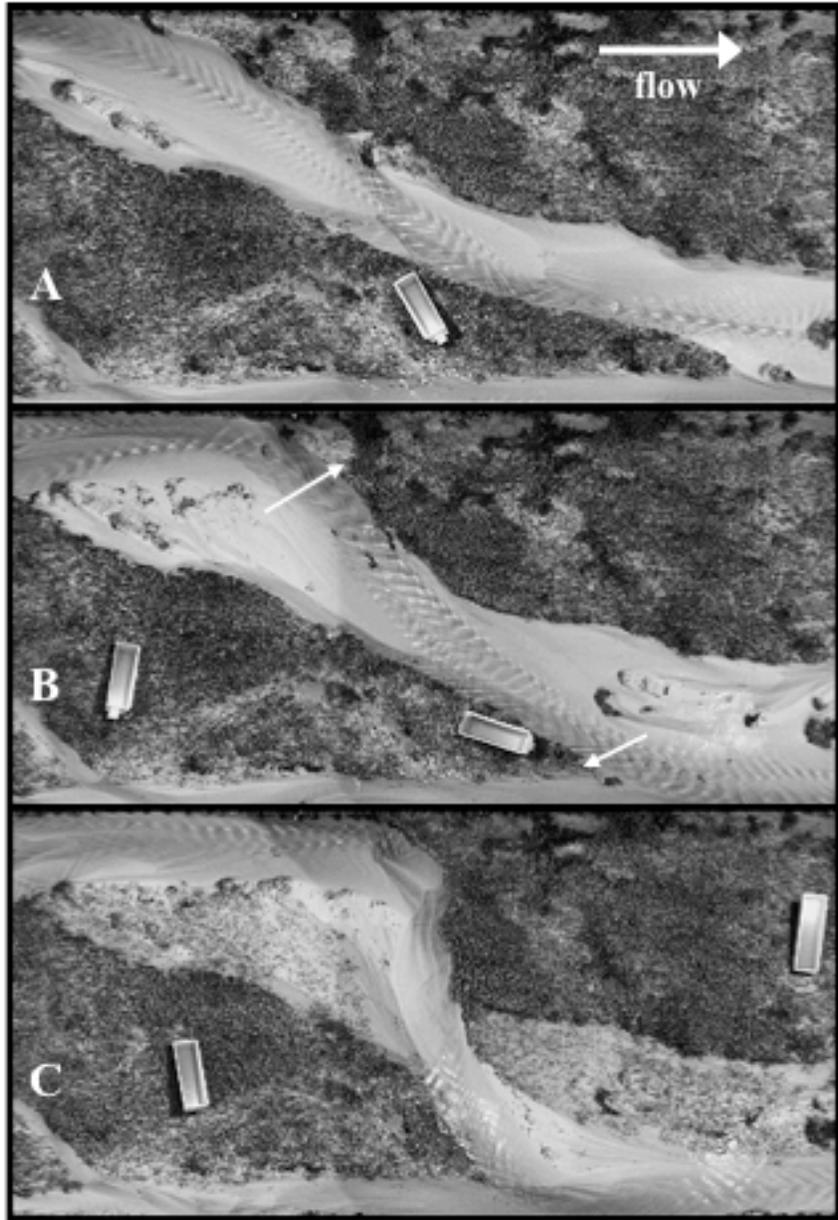


Figure 3-3. Bend migration and point-bar deposition (run A) arrows show the direction of bend growth and point bar formation.

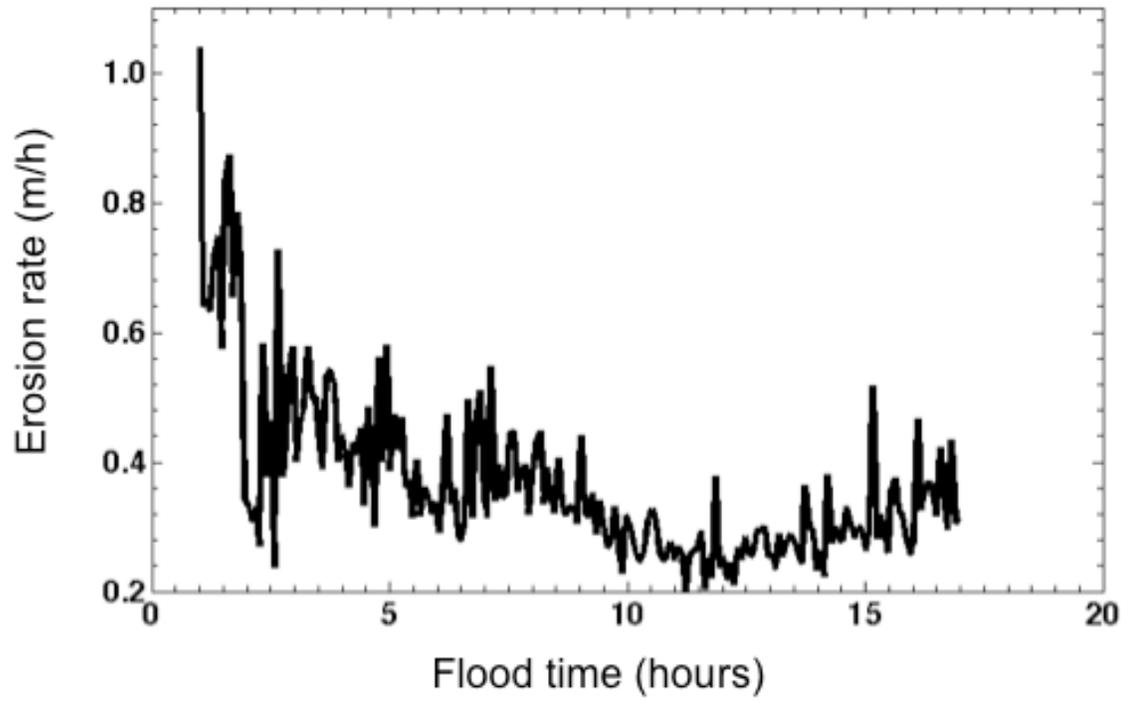


Figure 3-4. Erosion rates (run A)

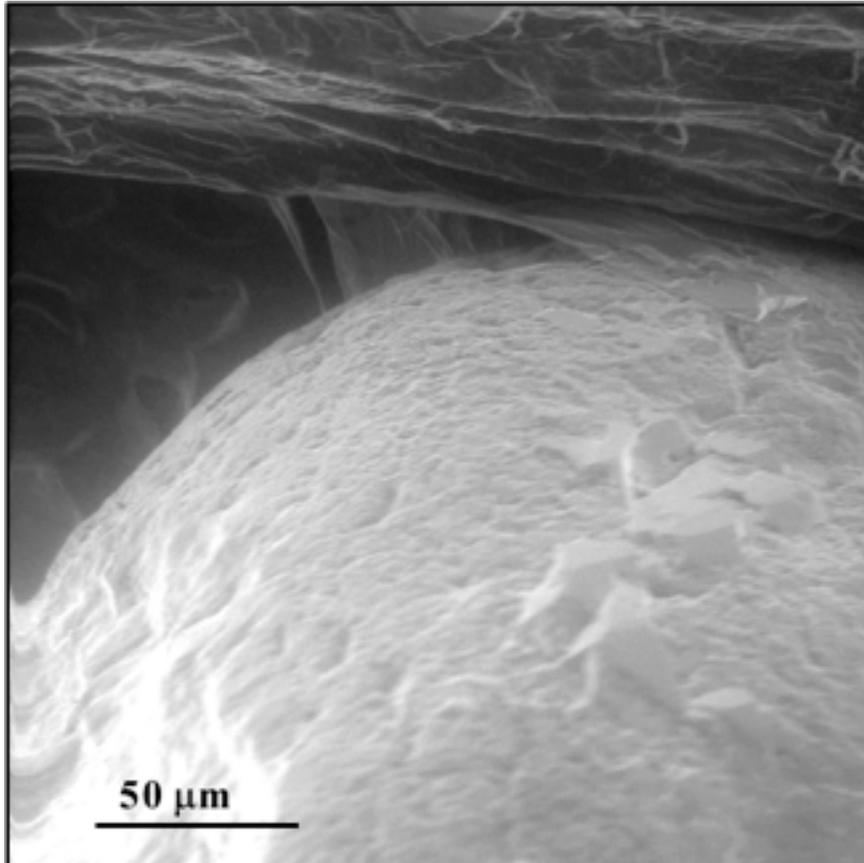
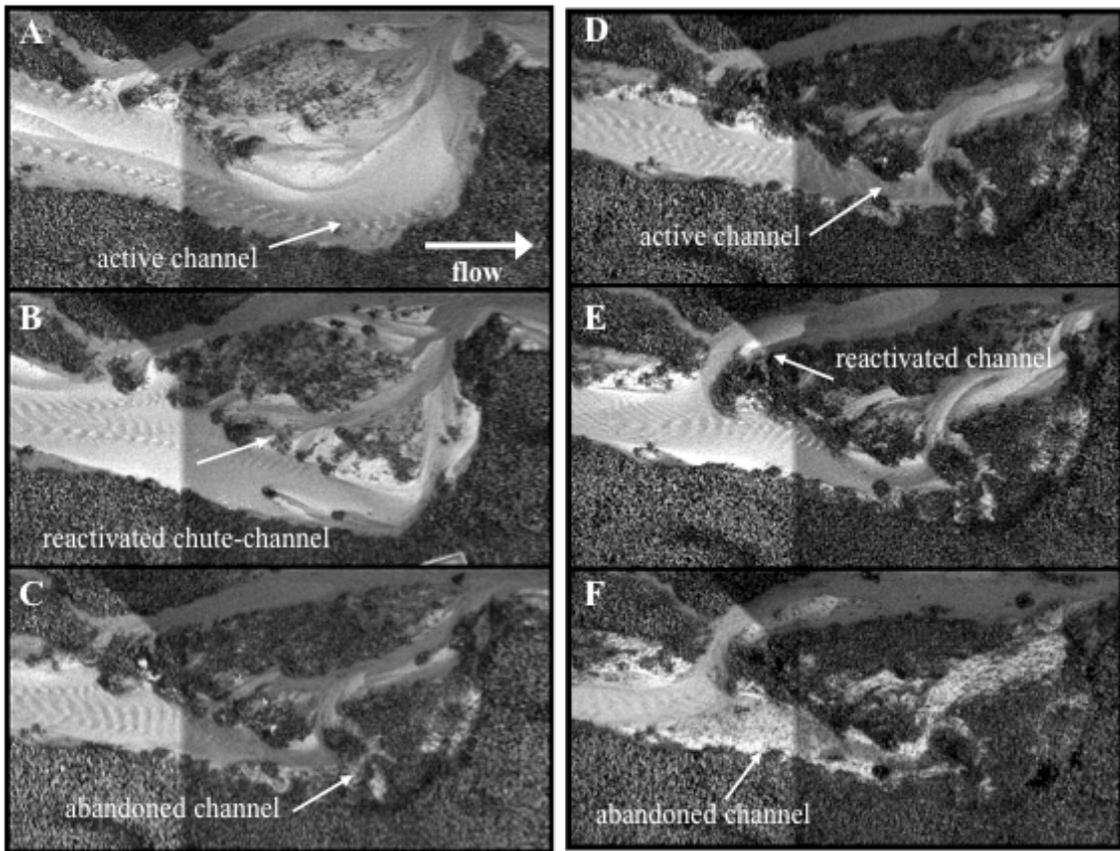


Figure 3-5. Image taken using an environmental scanning electron microscope (ESEM). Rootlets and other material from the root can be seen attached to the sand grain. (Image courtesy of Karen Gran)



Figures 3-6. Run 03, a consecutive sequence of channel (chute) cutoffs – markers show the location of the active channel and the abandoned channel after cutoff. Vegetation colonizes the abandoned channel within several flood cycles.

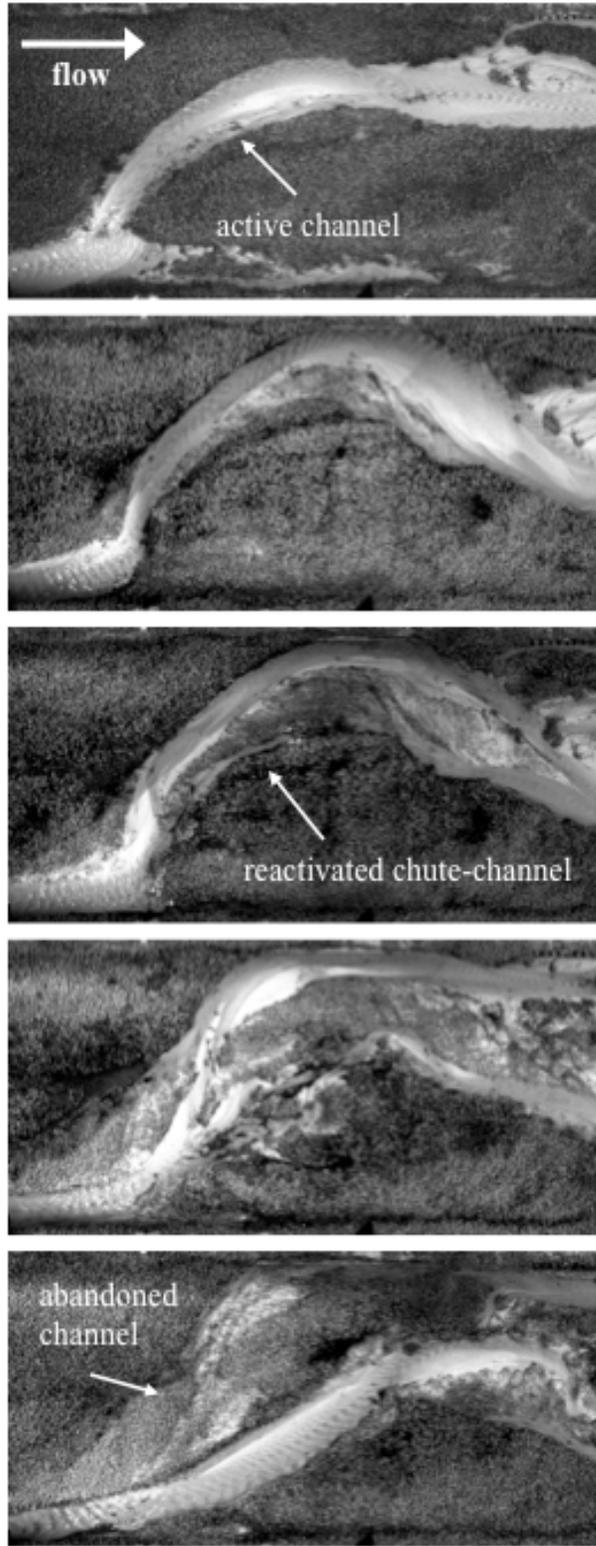


Figure 3-7. Run 03, chute cutoff leading to abandoned channel

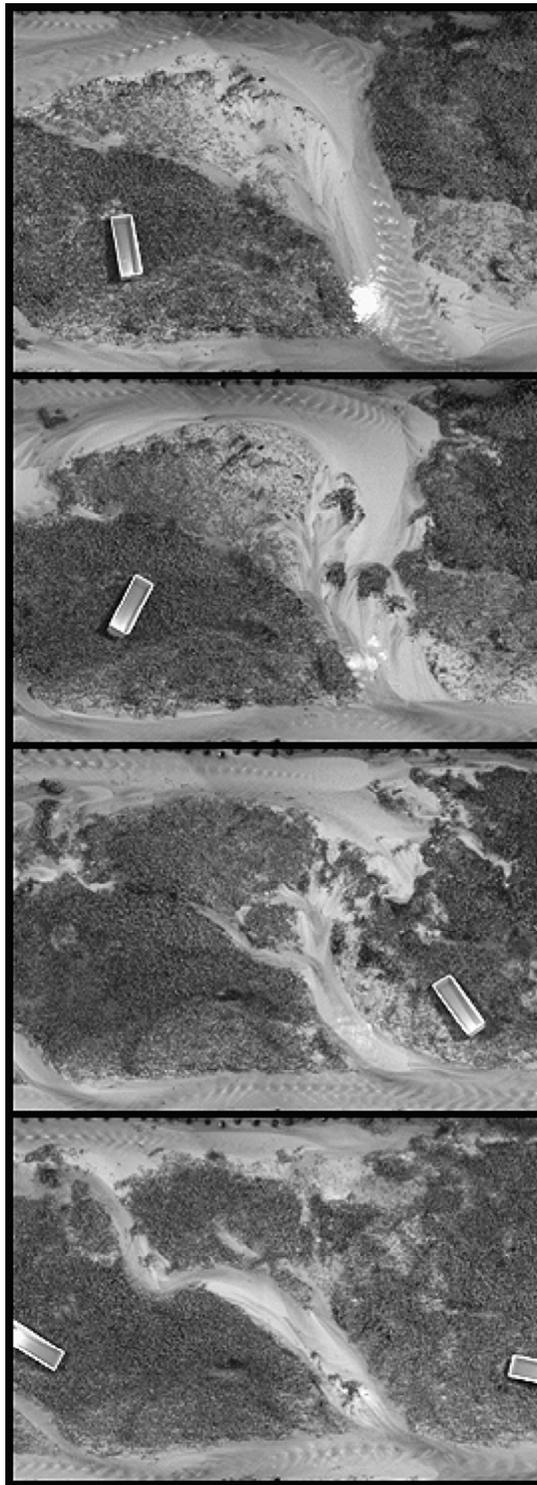


Figure 3-8. Channel cutoffs due to the formation of a debris jams (run 02) - sequence showing a. the original active channel, b. and c. the formation of a debris jam which blocked the main channel, and d. flow diversion into a new channel and abandonment of the blocked channel. Markers show the headcutting channel and the abandoned channel.

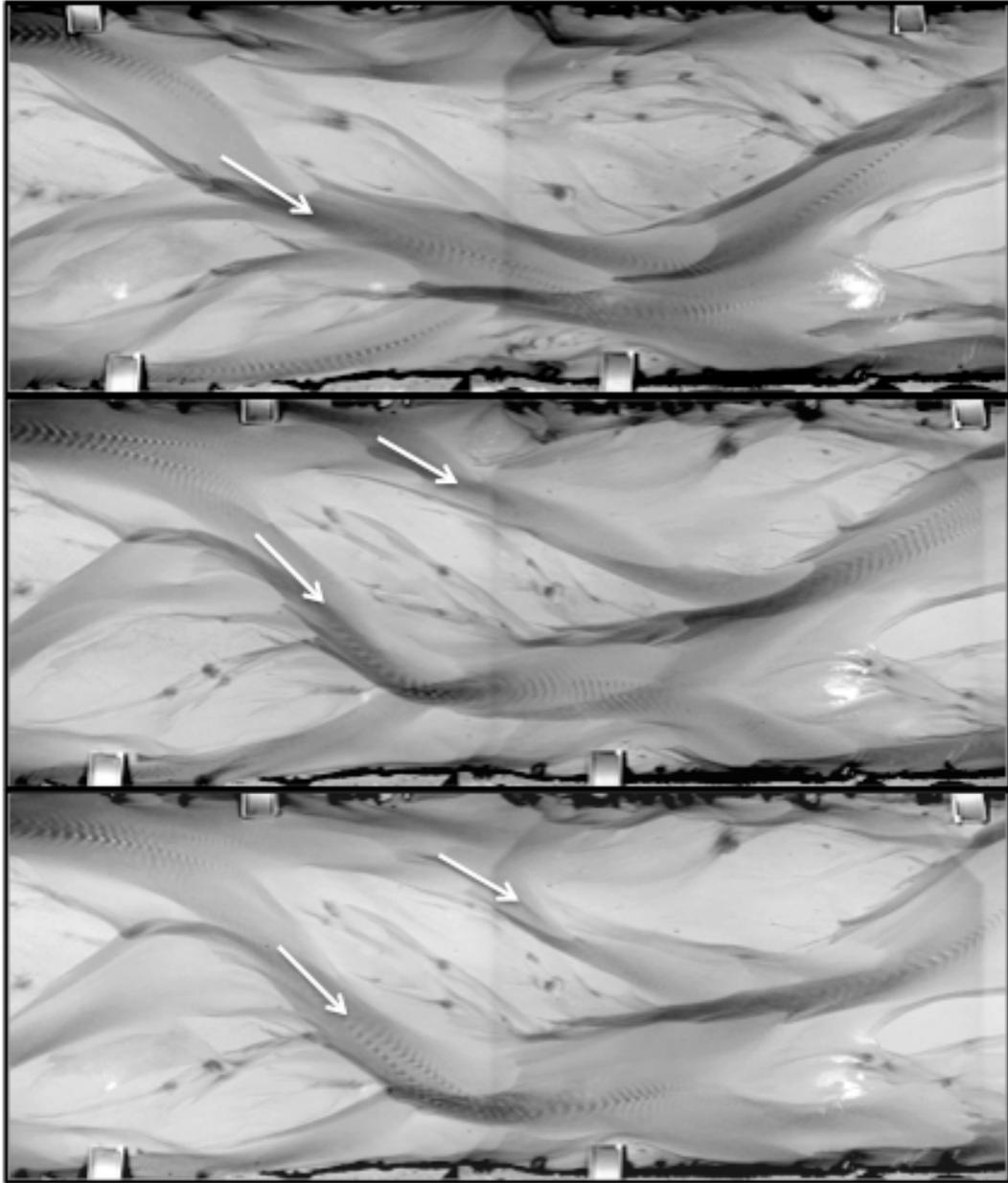


Figure 3-9. Sequence of images from the unvegetated braided state showing an example of a channel cutoff. An arrow in the top image highlights the original channel. In the middle channel a new channel has cut-off the main channel (55 minutes later) but the old channel does not become abandoned and the two channels coexist. The old channel remains active until the end of the run (here shown 15 minutes after the second image) even though a new active channel exists.

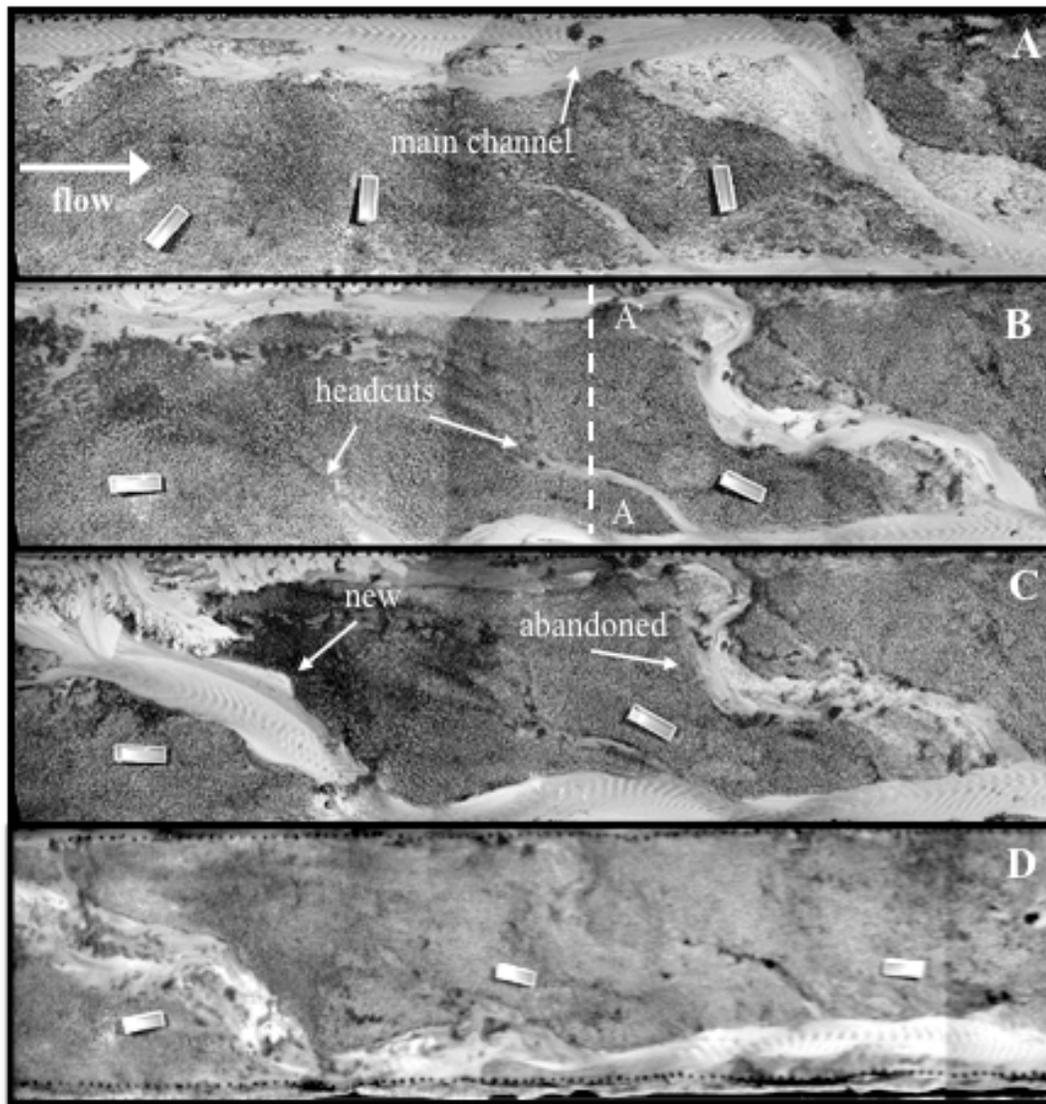


Figure 3-10. Avulsion resulting from superelevation of the main channel and redirection of flow into a steeper headcutting channel. The last image shows the abandoned channel completely vegetated and incorporated into the floodplain.

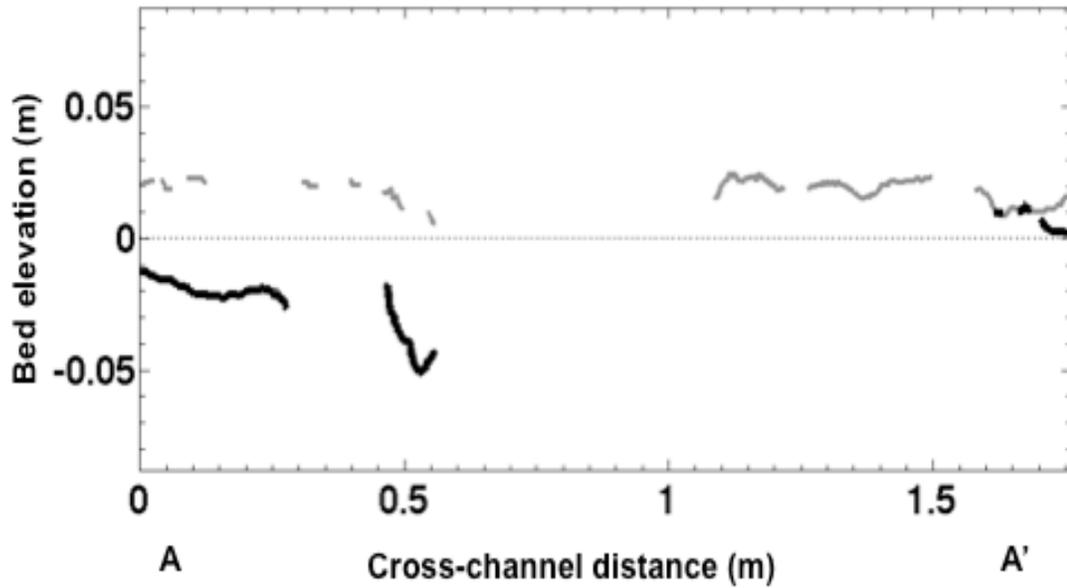


Figure 3-11. Topography profiles along cross section A – A' shown in Figure 13. Solid gray line is a topography profile during the first flood in run 02, the solid black line is a profile 16 floods later immediately before the avulsion depicted in Figure 13 occurred. The profiles show the deepening of the head-cutting floodplain channels (on the left side) relative to the main channel (right side). (Profiles are patchy because they represent elevation in the channels only and exclude areas that were covered with vegetation).

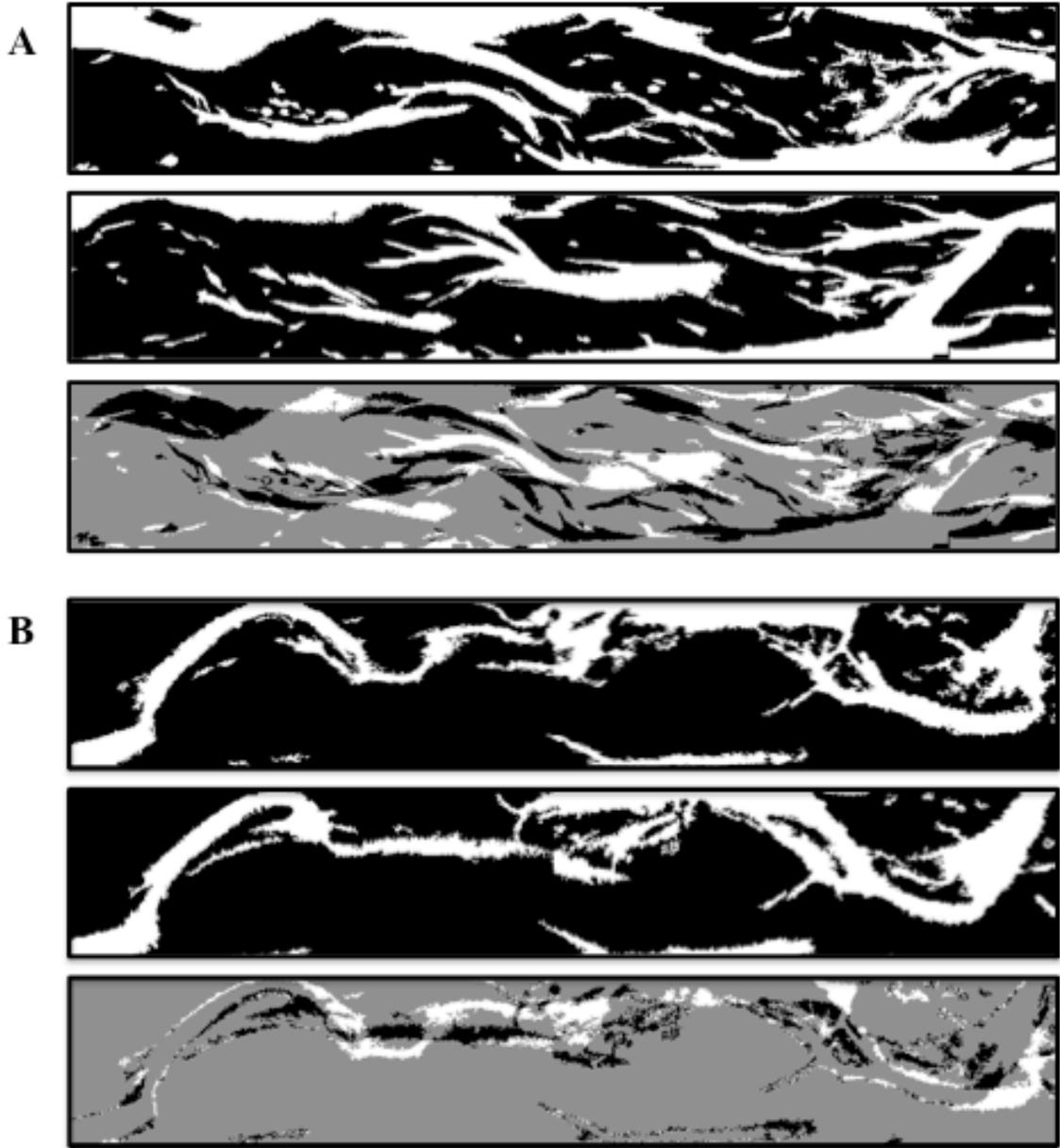


Figure 3-12. Run 02 – The top two images are binary images during the unvegetated braided phase of the run (t1 – top, t2-middle) with a 1-hour interval. White represents (wet) channels, black is (dry) bare sand. The bottom image was created by differencing t1 from t2. Gray is area that has not changed, white is area that was dry in t1 and became wet in t2, black was wet in t1 and became dry in t2. A sequence is shown for unvegetated braiding (run 02) and when the channel is single-thread with a well developed floodplain (run 03).

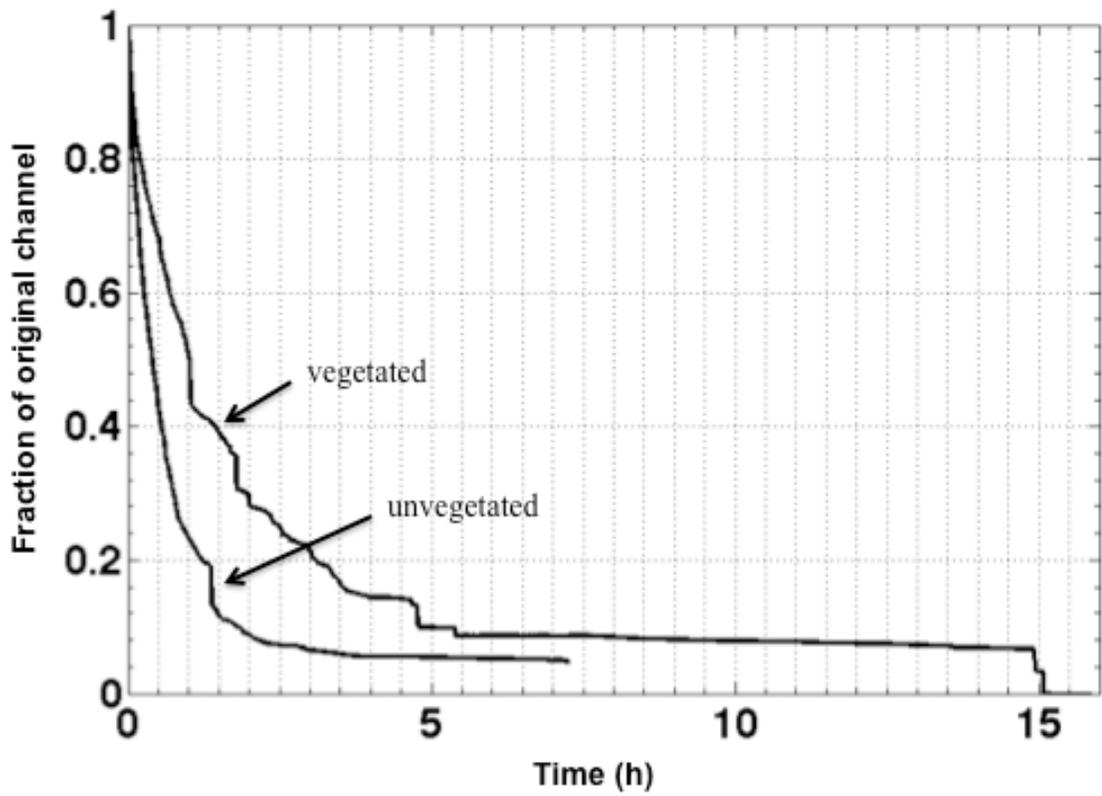


Figure 3-13. Run 02: reworking time unvegetated versus vegetated

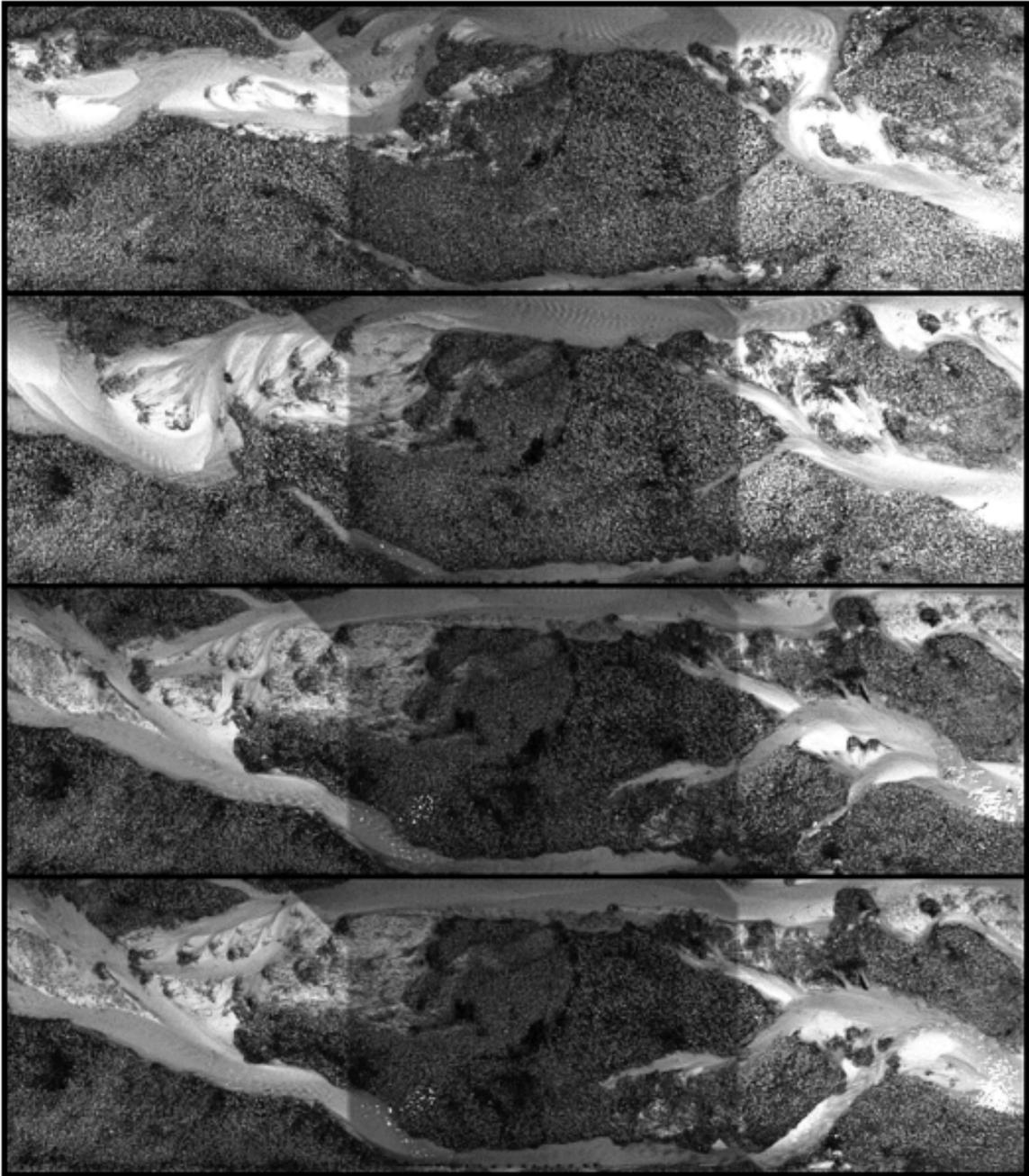


Figure 3-14. Run 03: reactivation of floodplain channels through increasing drainage into the channel and head-cutting. Markers show the location and advancement of two headcuts and their eventual capture of the dominant channel.

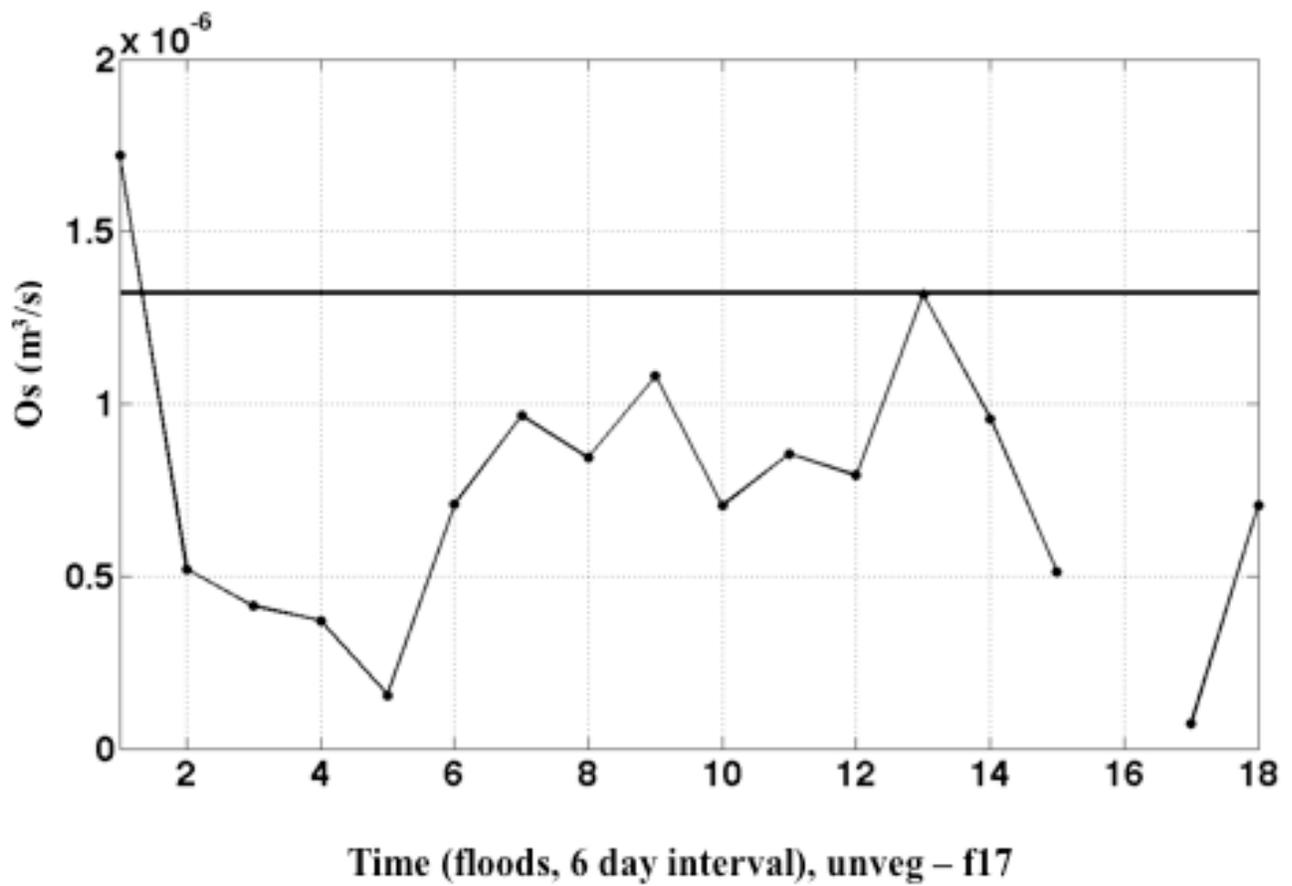


Figure 3-15. Run 02: total sediment output for each flood. Solid straight line represents the constant sediment input.

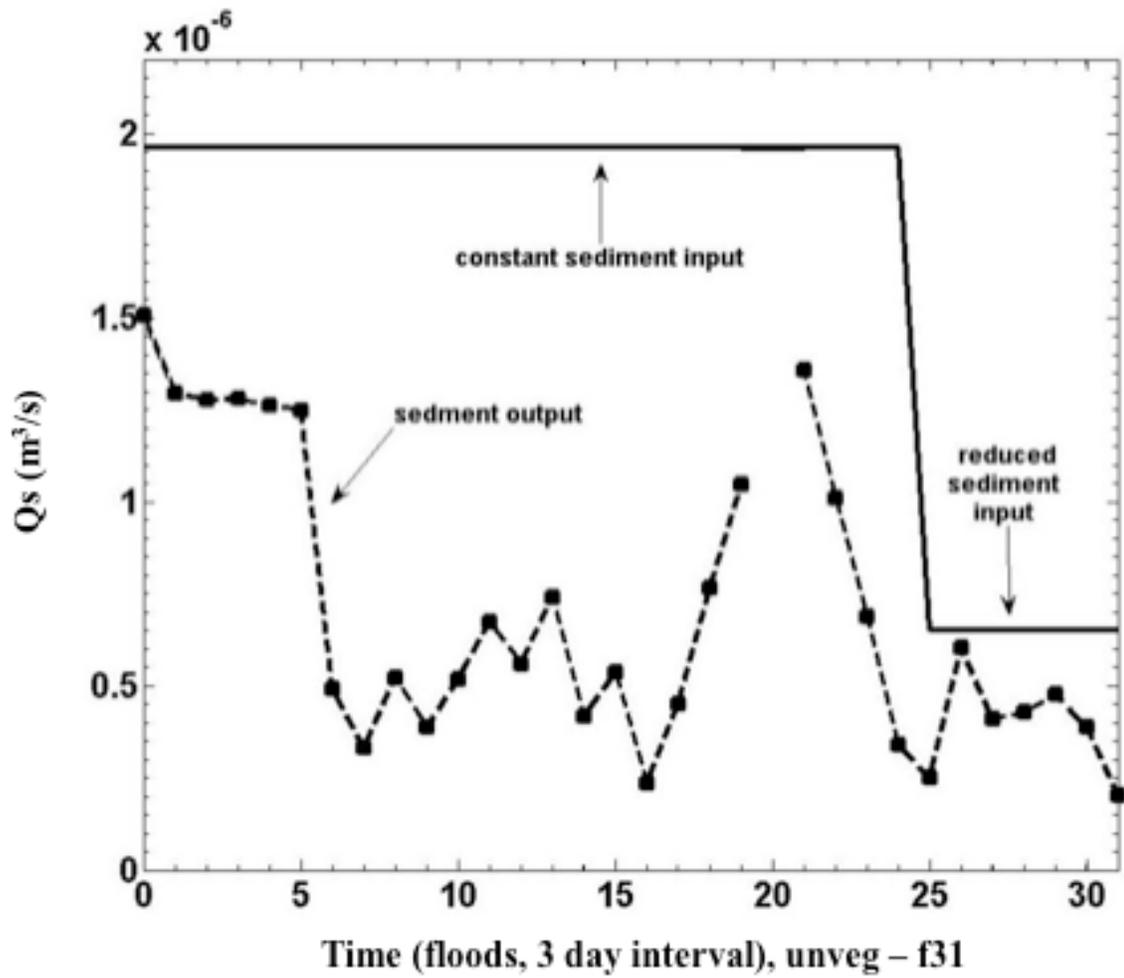


Figure 3-16. Run 03: total sediment output for each flood. Solid straight line represents the constant sediment input, which was lowered towards the end of the run.

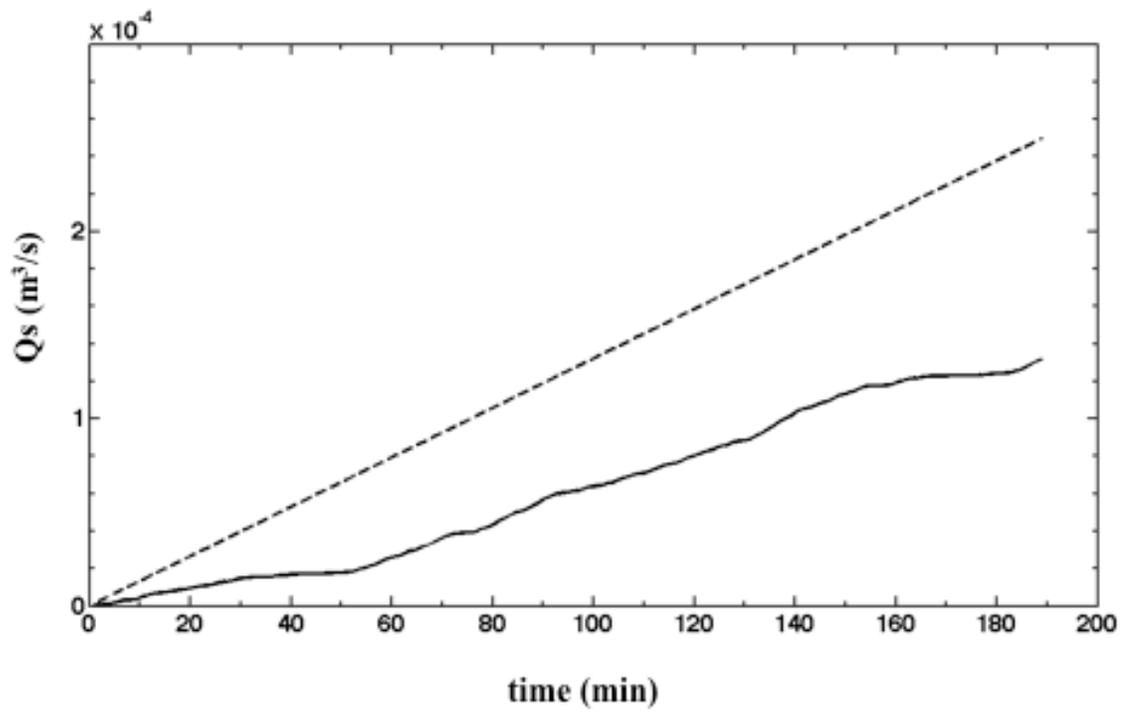


Figure 3-17. Run 02, cumulative sediment input (dashed line) versus cumulative sediment output (solid line) measured at 5 – minute intervals during the floods.

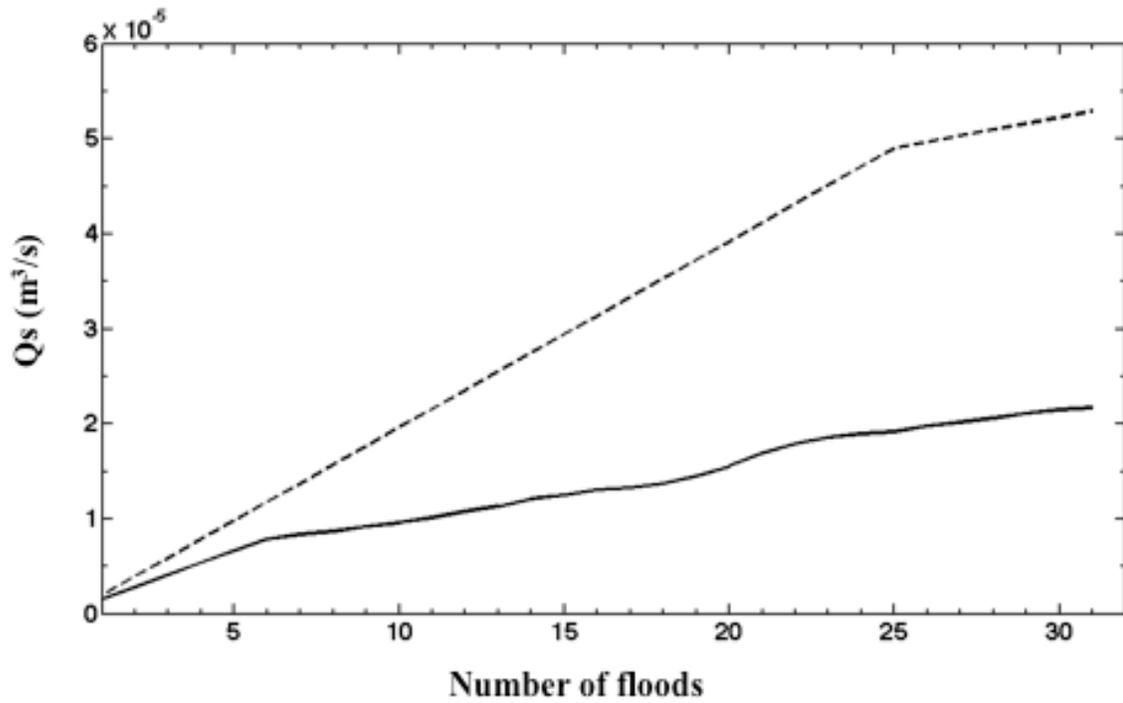


Figure 3-18. Run 03, cumulative sediment input (dashed line) versus cumulative total sediment output (solid line) per flood.

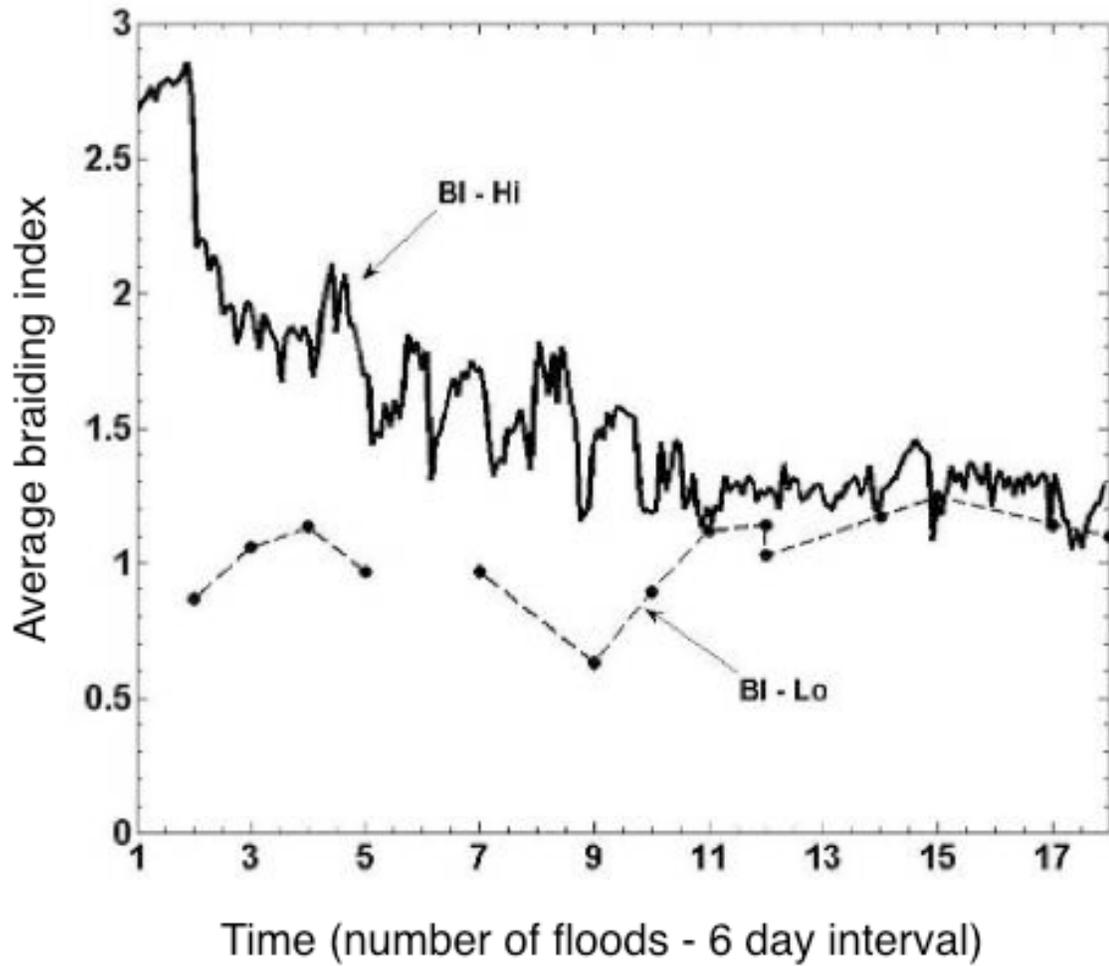


Figure 3-19. Run 02, Braiding index at the high flow (solid line) measured from images at 5 minute intervals and braiding index at the start of each low flow (dashed line).

CHAPTER 4: FLOODPLAIN FORMATION AS AN AGGREGATION PROCESS  
DRIVEN BY VEGETATION

*Michal Tal and Chris Paola*

## 1. Introduction

The conventional picture of a temperate river is a discrete channel adjusted to convey water discharges with a 1-2 year recurrence interval, linked to a relatively flat, vegetated floodplain wetted by flow in excess of the bankfull discharge. This picture seems so reasonable that it is easy to overlook the fact that we do not in fact understand why rivers so commonly organize themselves into this particular configuration.

It is tempting to think of floodplains as passive players in the fluvial system, created by simple inundation and particle settling. But recent research reveal surprisingly complex active morphodynamics in floodplains. As an active part of the fluvial system, and also as the support for the world's most diverse ecosystems (Tockner and Stanford, 2002), there is a broad spectrum of practical reasons to be interested in the origin of floodplains, ranging from their role in storage and release of pollutants bound to fine sediment particles to their importance in river restoration and in providing source rocks and seals when preserved in alluvial stratigraphy.

Most studies on floodplains have focused on specific processes such as overbank flow and vertical accretion of sediment, and on the exchange of flow and sediment between the active channel and the floodplain. Less often considered is the question of where floodplains come from in the first place (e.g., Reinfelds and Nanson, 1993; Howard, A.D., 1996; Dykaar and Wigington, 2000). In particular, it is far from obvious how the balance that sets up a coherent channel, sets its capacity, and creates a spatially connected floodplain emerges from the simple, chaotic braided channel that develops when an unbounded water flow interacts with noncohesive sediment.

We conducted a series of experiments at the St. Anthony Falls Laboratory designed to study the effects of adding vegetation to a braided morphology self-organized to a single-thread channel with a bankfull geometry and a vegetated floodplain (chapter 2). The experiments offered a unique opportunity to observe the evolution of these features in a system in which they did not exist previously, i.e., an unvegetated braidplain with multiple channels migrating across the entire width. The most consistent feature of these experiments was organization to a single channel that transported the majority of

sediment and water, associated with a major reduction in wetted width (see chapters 2 & 3). A vegetated floodplain established on areas of previously active braid channels that became progressively abandoned. The evolution from braiding to single-thread occurred in response to a simple binary fluctuation of discharge and the addition of plants. These experiments, in which nothing was done to influence the resulting morphology, suggest that the formation of floodplains and the adjustment to a bankfull geometry are directly related to feedbacks between periods of high and low flows and colonization by plants, which provide bank stability and roughness. Furthermore, the results demonstrate that the creation of dry/vegetated land causes changes to the channel just as channel processes construct and affect floodplains. The sediment used in the experiments was well-sorted non-cohesive sand, with no silt or clay. Therefore, there was neither variation in grain size across the floodplain nor vertical accretion of fine suspended sediment. Here we focus on how a floodplain emerged in the experiments. By *floodplain* we mean a contiguous region of the experimental fluvial system adjoining the active channel and covered with vegetation and, for the most part, standing water. There was little active flow on the floodplain with the important exception of headcutting floodplain channels (see chapter 3).

## 2. Methods

The experimental methods are described in the methods section. Following is a description of the data analysis used to obtain the results presented in this chapter.

### *Image classification*

We classified the pixels from the time-lapse images of the experiments into 4 classes based on their color value: one class represented flow (wet) and three classes represented dry riverbed with different stages of vegetation cover (increasing age and density). The first step in the classification process was to create a set of binary images from the original images in which all the flow had a value of 1 (white) and all dry areas had a value of 0 (black; Fig. 4-1). A threshold hue value of 0.8 and a saturation value of

0.3 were used to distinguish between wet and dry. Wetted widths and braiding indexes were measured from the binary wet/dry maps. The next step was to automate the classification of pixels representing the remaining dry areas (black in step 1) into three classes based on density and maturity of the vegetation cover. To do this we first visually identified three main stages of vegetation cover in the images (Table 4-1), and then verified that there was a distinct signature in color space corresponding to each class (Figs. 4-2 & 4-3). The classification was automated by comparing the distance of the color value for each pixel ( $Gr$ ) to the centroid value for each class and assigning it the value of the class to which it was closest (Figs. 4-2 & 4-3). The mean grayscale value ( $Gr0$ ) and the standard deviation ( $dGr0$ ) were calculated for each class. The distance of each pixel to the centroid was defined as  $(Gr - Gr0) / dGr0$ . It is important to note that the color value of vegetation represented a combination of both plant age and density. Thus dense clumps of young vegetation could have a color value that was the same as sparse patches of mature plants.

#### *Transition matrices*

Using the classified images we calculated transition probabilities from one class to another between pairs of images. Table 4-2 shows the transition matrix that was computed for pairs of images at 5-minute intervals during all of the high flows. Tables 4-3a and 4-3b are transition matrices computed between high and low flow. Image pairs for Table 4-3a consist of an image at the start of the low flow immediately at the end of flood ( $i$ ) and the first image at the beginning of flood ( $i+1$ ) for the entire run. Image pairs for Table 4-3b consist of the high flow image captured at the end of flood ( $i$ ) and the image captured at the start of the low flow immediately following the end of flood ( $i$ ). A schematic of these pairs is shown in figure 4-4. At low flow there is almost no sediment transport and the channels are stable during the growing period. We can thus make the comparison between low flow channels at the start of the low flow period with the high flow channels at the next flood.

### 3. Fluctuating flow and vegetation establishment

In chapter 1 we suggest that plants cause net channel narrowing by opportunistically establishing on regions of abandoned riverbed and then holding their ground on some of those areas at the next high flow. In large braided rivers, areas of the riverbed become abandoned intermittently at lower flows or when active channels are focused elsewhere on the braidplain (Reinfelds and Nanson, 1993). Given the limited width of the flume in our experiments, much of the braidplain was wet at high flow; significant parts of the bed were exposed only at low flow. Because plants can establish only on emergent parts of the braidplain, the fraction of the bed that is exposed at low flow determines the potential area for vegetation to colonize. In the experiments, if a constant high discharge were maintained with no fluctuation, the fraction of the exposed bed would have remained close to zero and very few plants would have succeeded in establishing. Had the high flow alternated with periods of zero flow, during which all of the bed would have been exposed, it would have resulted in plants establishing on the bars as well as in the channels, which would have led to a system of inundated vegetation and unchannelized flow – a kind of fen – unless the growth period were kept short. Alternating between high and low discharge as was done in these experiments promoted interaction between the dominant processes that occurred in each phase: erosion and deposition during high flow, vegetation growth during low flow, and therefore led to a co-organization of flow and vegetation.

High and low flows can be considered as expansions (high) and contractions (low) of the wetted area. When the system was contracted, vegetation established on all non-wetted surfaces. When the system expanded, some of that vegetation was removed and some survived. Figure 4-5 shows that the probability for a wet point becoming dry when the flow was reduced from high flow to low flow fluctuated around a mean of 50 % throughout the entire experiment. Therefore, each time the flow was lowered, approximately half of the high flow wetted area became exposed and covered with seeds.

#### 4. Abandonment of vegetated areas

Plant roots add cohesion to sediment and plant leaves and stems increase surface roughness. As a result, it is harder for flow to reoccupy an area of the bed that has been colonized by plants because it would require either eroding or submerging the plants. Figure 4-6 is a graph of the probability for reoccupation at high flow of areas of the bed that were dry during the low flow immediately preceding it. This shows a strong tendency for dry low flow areas to remain dry at the next high flow compared to the tendency for reoccupation. These trends demonstrate that an area that was dry at low flow and therefore colonized, was less likely to become reoccupied by the flow when the discharge was raised. Instead, the flow preferentially moved away from parts of the bed that were vegetated and focused in areas that had remained wet. The probability for flow reoccupation decreased through time as vegetation density and age increased. Figure 4-7 is an example of typical channel abandonment at a bifurcation. The flow became focused into one channel while the other channel that had been dry during several low flows and became vegetated was progressively abandoned. Because the high and low discharges were constant throughout the run, the tendency for high flows to occupy channels that remained wet during low flow caused the total wetted width to decrease through time (Fig. 4-8).

#### 5. Planform change

Upon initiation of the flood-seeding sequence described above, the combination of a wetted width that was reduced by about half at each low flow and a lower probability for the flow to reoccupy dry low flow channels due to vegetation establishment resulted in a reduction in wetted width between consecutive floods and a net gain in vegetated area. This led to a major planform change from a braided system to a single-thread channel (chapters 2 & 3). This planform change was expressed primarily as a reduced wetted width as well as a reduction in braiding index, i.e., number of active channels at a given cross section (Figs. 4-8 & 4-9).

In addition to reduction in the total wetted width we observed a convergence of the total wetted width, maximum channel width, and average channel width (total wetted width/number of channels; Fig. 4-10). Furthermore, the total wetted width at high flow, which was greatly reduced through time, converged with the wetted width at low flow, which changed much less (Fig. 4-8). The same was true for the braiding index (Fig. 4-9). Because vegetation colonizes abandoned areas of the bed at low flow, the potential for colonization is largest when there is a large difference between the area of the bed covered by water at high and low flow. The potential for vegetation expansion is minimized when the difference between them is small. This is a major reason why braided morphologies are especially vulnerable to changes in vegetation cover. This idea is supported by many studies that have shown expansions in vegetation suppressing braiding. It also offers an explanation as to why single-thread channels adjust to a bankfull geometry: at this geometry the difference between the wetted width at commonly recurring floods and mean flows is at a minimum, and vegetation has colonized all but the channel width required to transport the flood discharge.

Our results also support an idea introduced in chapter 2: that the effect of the plants is to choke off the smallest and weakest channels and focus the flow into the one or two channels that were the dominant active channels in the braided state. In a recent experimental study, Egozi (2006) carefully measured the number of braid channels that actively transport sediment (*ABI*) in comparison with the total number of braid channels (*TBI*) in a braided system. Their results showed that  $ABI \ll TBI$ . In our experiments the vegetation exploited the difference between *ABI* and *TBI* and progressively eliminated the least active channels until the ratio of *ABI* to *TBI* approached one. We referred to this process as *corralling* of the flow in chapters 1 and 2.

## 6. Evolution of floodplains

To quantify the aggregation process that created the experimental floodplain, we mapped islands manually in ArcGIS from the time-lapse images. The formation of floodplains in the experiments was directly linked to the elimination of subordinate

channels and the concomitant growth of vegetated islands. Island growth has been shown to be an important mechanism in natural systems (Dykaar et al, 2000), and can be readily measured in our experiments. During the first low flow, vegetation established itself on emergent parts of the bed. Not all of this young vegetation was eroded at the next high flow. Young plants that survived the next flood remained on the bed continued to grow. In addition, areas where plants survived became denser following subsequent reseeding of the entire bed. The more mature and dense a vegetated patch became, the more robust it was and the smaller its chance of being eroded. The probability of an area classified as having vegetation cover being eroded (i.e., dry to wet in the transition matrix, Table 4-2) versus remaining dry (i.e. dry to dry in the transition matrix, Table 4-2) is shown in figure 4-11. Younger, sparsely vegetated areas had a higher probability of being eroded than mature densely vegetated areas, which were more resistant. Figure 4-12 shows that the tendency for sparsely vegetated areas to be preferentially eroded relative to densely vegetated areas increases greatly as more of the bed is covered with dense vegetation. Vegetation colonization was a highly self-reinforcing process. Areas where plants survived early in the experiment provided a more stable surface for new plants to grow. As new vegetation established it further stabilized these areas and increased the chances of them surviving subsequent floods. Thus high areas (bar tops) distributed by chance over the experimental area served as nuclei around which the vegetation-stabilized domain grew. The vegetated islands expand through time and merge with other islands to form larger islands, even as new islands are nucleated on local high areas. This continuous process of accretion and amalgamation of islands eventually resulted in the formation of a floodplain in which most of the area was unlikely to be replaced by channel in any given flood (Figs. 4-13 & 4-14). The number of islands increased sharply in the early stages of the experiment when they were beginning to form. This was followed by a decrease in the number of islands as the process of merging began (Fig. 4-15). The fraction of the bed mapped as vegetated patch or island increased quickly and eventually reached a steady-state value (Fig. 4-16; see chapter 2). Early in the experiments only a small area was vegetated and though islands were numerous, they were relatively small. As the islands grew and the floodplain became established, a larger

vegetated area was organized into several very large islands and few small islands (Fig. 17).

The floodplains in these experiments were assemblages of increasingly older and smaller vegetated patches that expanded and merged together. Figure 4-18 shows a floodplain at the end of an experiment mapped as a single body versus the same floodplain as a mosaic of all the cumulative vegetated areas that compose it.

## 7. Percolation theory applied to the organization of a channel and floodplain

Percolation theory is a tool used to find critical thresholds in connectivity and tells us when a system is macroscopically open to a given phenomenon (Dietrich and Aharony, 1994; Sahimi, 1994). In percolation theory randomness is ascribed to the medium and it is the medium that dictates the paths of the particles (for example the flow of coffee in a percolator) in contrast to diffusion which ascribes the randomness to the particles (Dietrich and Aharony, 1994; Sahimi, 1994). Percolation has been applied to a wide range of problems such as the spread of fire across a forest, oil availability in a reservoir, and the flow of traffic from one side of town to the other. In each of these problems how the phenomenon moves (fire, oil, traffic) will depend on the connectedness of the medium by which it travels (trees, porosity, open roads; Dietrich and Aharony, 1994; Sahimi, 1994).

In the classical (bond) percolation problem the bonds of a network are either occupied (open to flow) randomly and independently of each other with probability  $p$  or vacant (closed to flow) with probability  $1-p$ . Two sites are considered connected if there exists at least one path between them consisting solely of occupied bonds. A set of connected sites bounded by vacant bonds is called a cluster. If  $p$  is small the size of any connected cluster is small, if  $p$  is close to 1 the network should be entirely connected. At some well defined value of  $p$  there is a transition of the random network from a macroscopically disconnected structure to a connected one. This value is called the bond percolation threshold ( $p_c$ ) and has been shown to be at  $\sim p = 0.6$  for widely different systems. At this threshold a cluster that spans the network (called a percolating or a spanning cluster) exists for the first time (Dietrich and Aharony, 1994; Sahimi, 1994).

The formation of a channel and floodplain can be considered in terms of a reverse percolation problem. The transition probabilities show that there is a strong preference for flow to reoccupy areas that were wet at low flow and avoid those that were dry. Therefore, wet areas are the open bonds and dry-vegetated areas are the vacant bonds. The transfer of water and sediment from the upstream end of the flume to the downstream outlet is via open clusters (channels) that span the length of the flume. When the system is braided at the beginning of the experiments there are multiple spanning clusters. The effect of the vegetation is to isolate many of these clusters so they become small and non-spanning or vacant. It is at the percolation threshold, when only a single channel exists, that the floodplain ceases to grow and a coupled channel-floodplain system begins. In our experiments the area of vegetated islands reached steady state at approximately 0.6 of the total area (Fig. 3-16).

One measure that the system changed from a regime in which the channels avoid the vegetation to a regime with coupled channel-floodplain interactions is the amount of densely vegetated areas that are eroded in a given flood. We have shown that there is a strong preference for flow to move away from densely vegetated areas throughout the run, however, once the floodplain has grown to its maximum extent the channel can no longer steer away from it and instead it migrates through it eroding both young-sparse vegetation as well as dense-mature vegetation (see Fig. 3-1).

#### 8. A neutral model of island growth

A neutral model is a minimum set of rules required to generate a pattern in the absence of a particular process or set of processes being studied (Pearson and Gardner, 1997). Neutral models provide a useful way of testing the effect of the measured process on patterns that are actually observed. These models are popular in landscape ecology because of the emphasis in this field on the complex relations between landscape pattern and ecological processes (Pearson and Gardner, 1997).

We have started exploring island growth and percolation thresholds with a simple neutral model (random) and a hierarchical neutral model (random maps with control over pattern at successively finer spatial scales) and comparing the results of the model with

the island growth in the experiments. In the first 3 models the initial condition was an all black matrix and 5% (1000) of the pixels were changed to white at each time step. Each run consisted of 31 time steps. Five percent is approximately the area covered by vegetation in the experiments after the first seeding, and 31 is the number of seeding cycles in one of the experiments. The first 3 models were run as follows:

1. A simple random model in which pixels changed to white at random for the entire run (Fig. 4-19a).
2. 5% of the pixels were changed at random in the first time step and in all the next time-steps the 4 nearest neighbors of every white pixel were changed to white so that white patches grew symmetrically (Fig. 4-19b).
3. 5% of the pixels were again changed random in the first time step and in all the next time-steps the vertical set of neighbors of every white pixel were changed to white with a probability of 0.5 while the lateral set of neighbors of every white pixel changed to white with a probability of 0.25. White patches grew asymmetrically (Fig. 4-19c).

The distribution of the initial 5% vegetation cover in the experiments was not random because seeds establish on exposed braid-bars. Therefore, in our next model only 10 initial pixels were changed and grown asymmetrically (Fig. 4-19d). A qualitative comparison of the patterns from models 1 – 4 after 60 % of pixels turned white and an image of the experiment at 60 % vegetation cover (white; Fig. 4-19e) highlights the non-random growth of the vegetation. The random models have an increase in the number of patches followed by a decrease as the patches merge, as do the experiments, however in the model the number of patches approaches one (Fig. 4-20) . The growth rate of the vegetated islands in the experiments was most closely simulated by models 2 and 3, however all of the models approached a maximum area of 1 while the experiments reached steady-state at approximately 0.6 (Fig. 4-21).

The next phase in the neutral model will be to incorporate simple rules about how patches can grow to try and simulate the co-organization of the flow and the vegetation. As a first step, the open paths of black cells (spanning clusters) across the entire field

from top to bottom were tracked, and the model stopped as soon as a single spanning cluster no longer existed(Figs. 4-22).

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TABLES

Table 4-1. Average characteristics of each vegetation class that was identified visually for runs A and B. The seeding density at every cycle was approximately 10000 seeds/m<sup>2</sup>.

	Number of seedlings/ growing cycles	Stem length (mm)	Mean leaf size (mm)
Class 1 'bare-sparse'	Bare sand - 1	15 – 35 mean = 26	10 - 25
Class 2 'dense'	2 – 4	15 – 42.5 mean = 35.8	15
Class 3 'very dense'	>4	<i>mixed</i>	<i>mixed</i>

Table 4-2. Transition matrix calculated for pairs of images captured at 5-minute intervals during the high flow.

		<i>Wet</i>	<i>Dry</i>		
		<b>Flow</b>	<b>Class 1</b>	<b>Class 2</b>	<b>Class 3</b>
<i>Wet</i>	<b>Flow</b>				
	<b>Class 1</b>				
	<b>Class 2</b>				
	<b>Class 3</b>				
<b>Dry</b>	<b>Flow</b>				
	<b>Class 1</b>				
	<b>Class 2</b>				
	<b>Class 3</b>				

Table 4-3a. Transition matrix between images taken at the start of each low flow and at the start of each subsequent high flow.

	<i>Hi - Wet</i>	<i>Hi - Dry</i>
<i>Lo - Wet</i>		
<i>Lo - Dry</i>		

Table 4-3b. Transition matrix between images taken at the end of each high flow and at the start of the low flow immediately following it.

	<i>Lo - Wet</i>	<i>Lo - Dry</i>
<i>Hi - Wet</i>		
<i>Hi - Dry</i>		

FIGURES

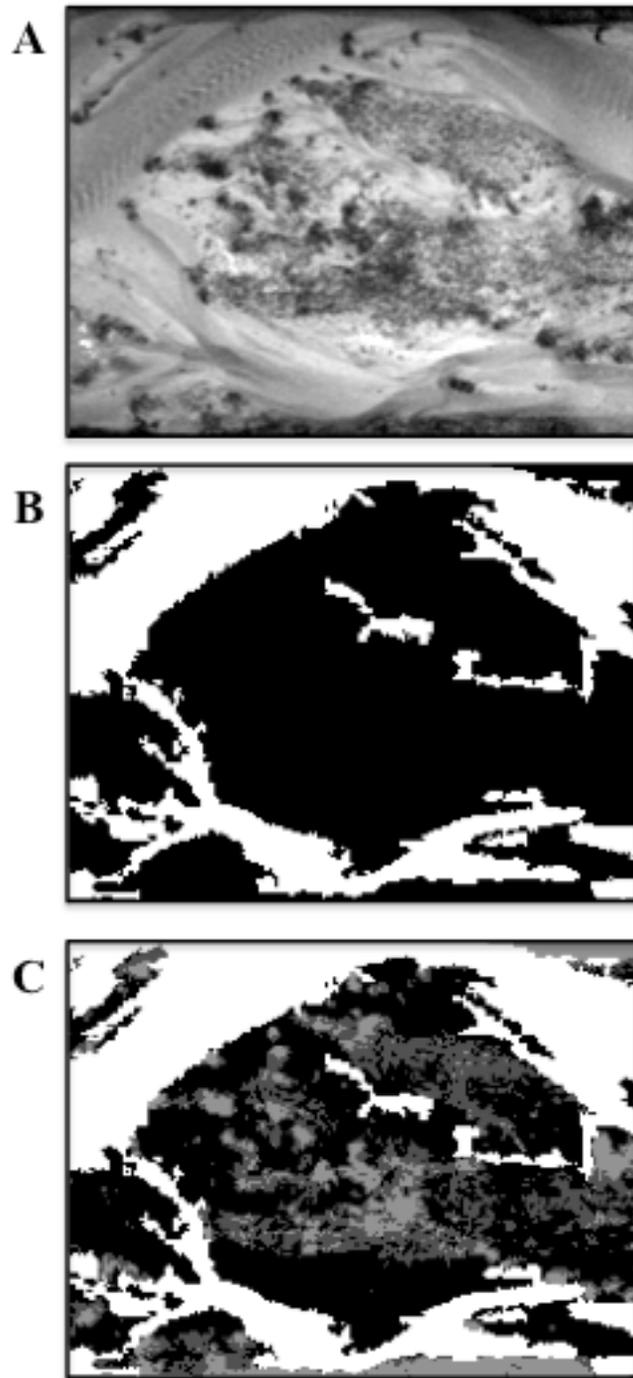


Figure 4-1. Example of a classified image section from run B: a. original image, b. binary image, wet is white, black is dry, c. area that was black in b, classified into bare-sparse (black) vegetation, dense vegetation (dark gray), very dense vegetation (light gray).

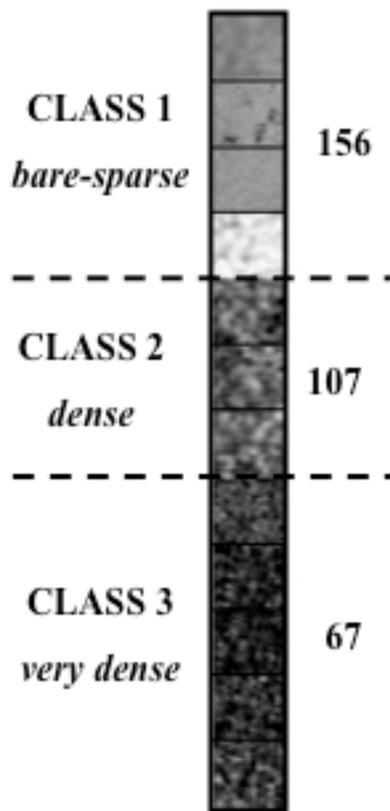


Figure 4-2. Samples of different stages of vegetation cover identified and sorted visually into classes and the corresponding grayscale value measured for each class.

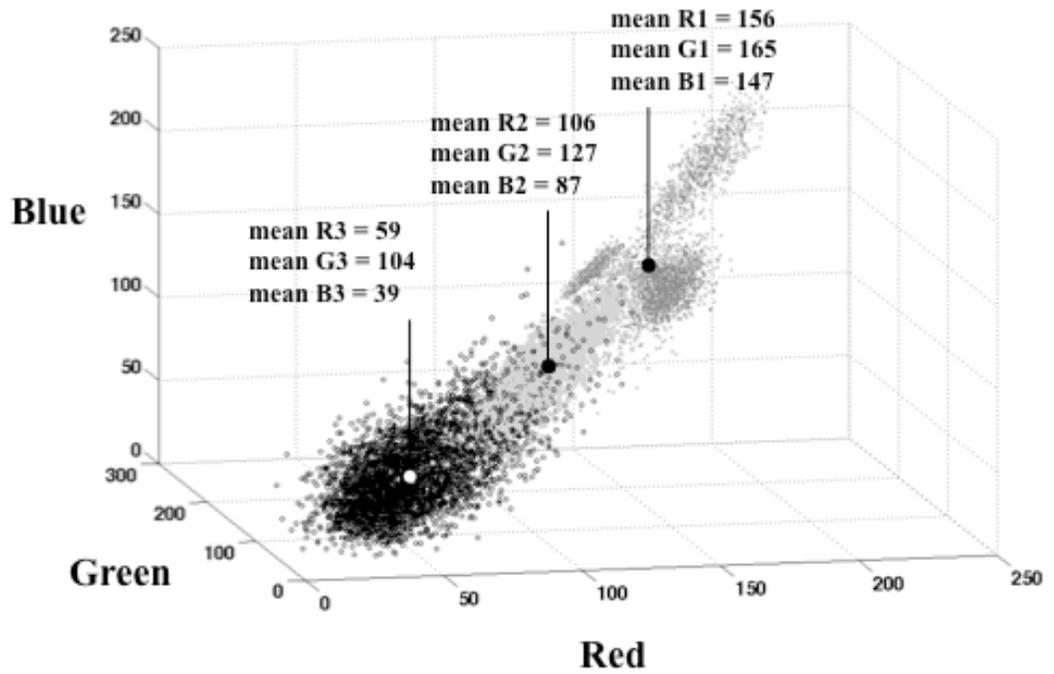


Figure 4-3. Pixels from the vegetation samples plotted in color space. Each color/symbol represents the class that the sample corresponded to in the visual classification. The plot shows a general division into classes by color value.

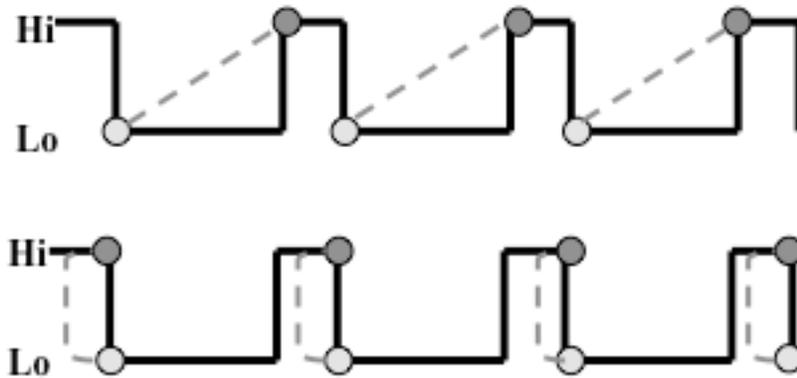


Figure 4-4. Schematic of high flow – low flow image pairs corresponding to the transition matrices shown in Table 4-3. Light gray circles represent the image captured at the beginning of each low flow cycle (the camera was shut off after this for the remainder of the low flow). In the top image the dark gray circles represent the first image captured at high flow following low flow (Table 4-3a) and in the bottom image they represent the last image captured at high flow immediately before low flow (Table 4-3b).

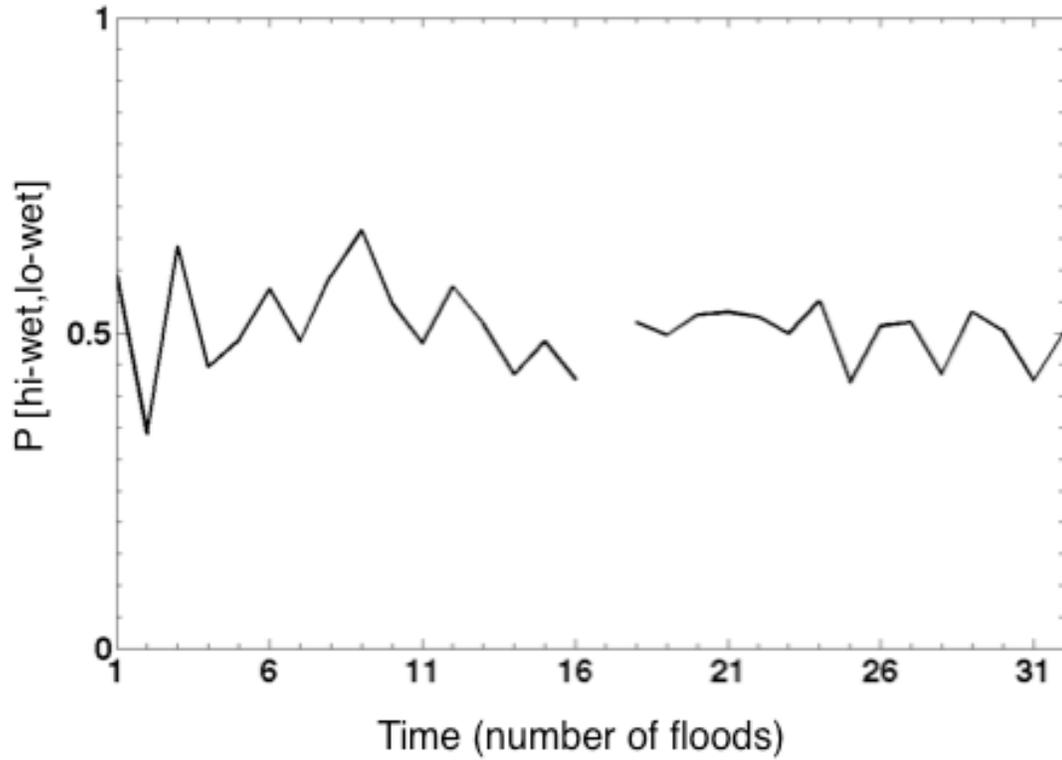


Figure 4-5. Probability of abandonment (run 03)  
The probability of a pixel that was classified as wet at the end of a flood to be classified as dry at the low flow immediately after it.

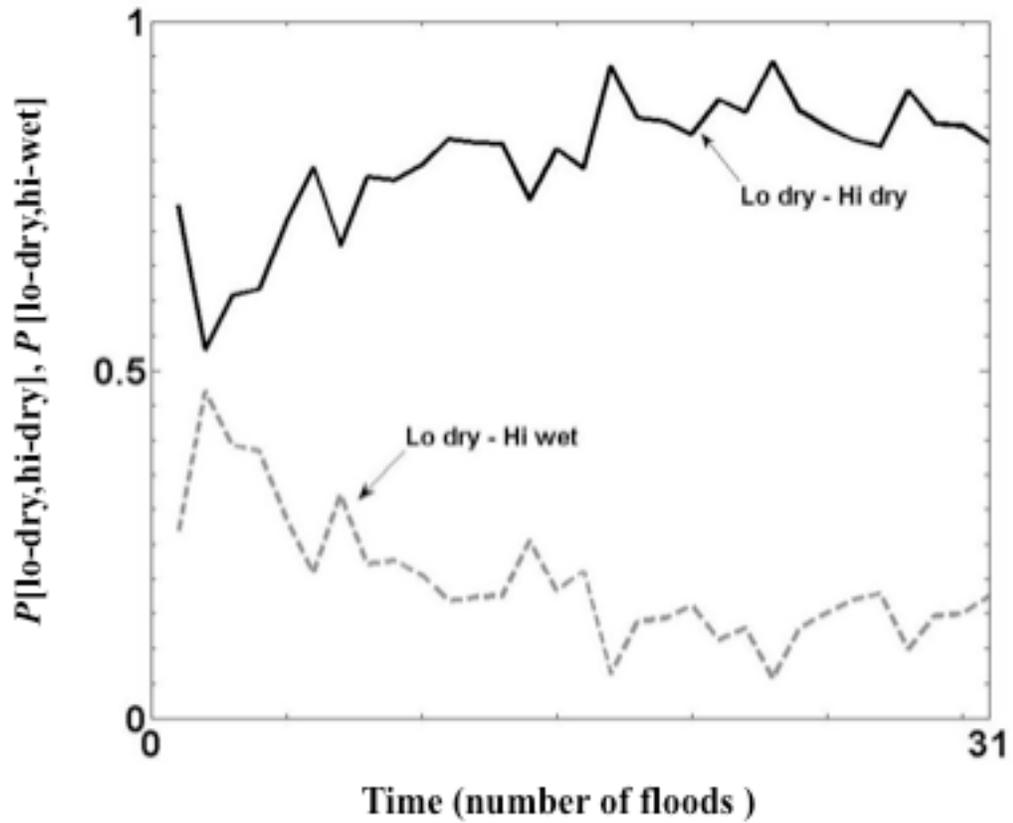


Figure 4-6. Probability of reoccupation (run 03)  
 The probability of a pixel that was dry at low flow to become reoccupied by flow (wet) at the following high flow, versus the probability of a pixel that was dry at low flow to remain dry at the following high flow.

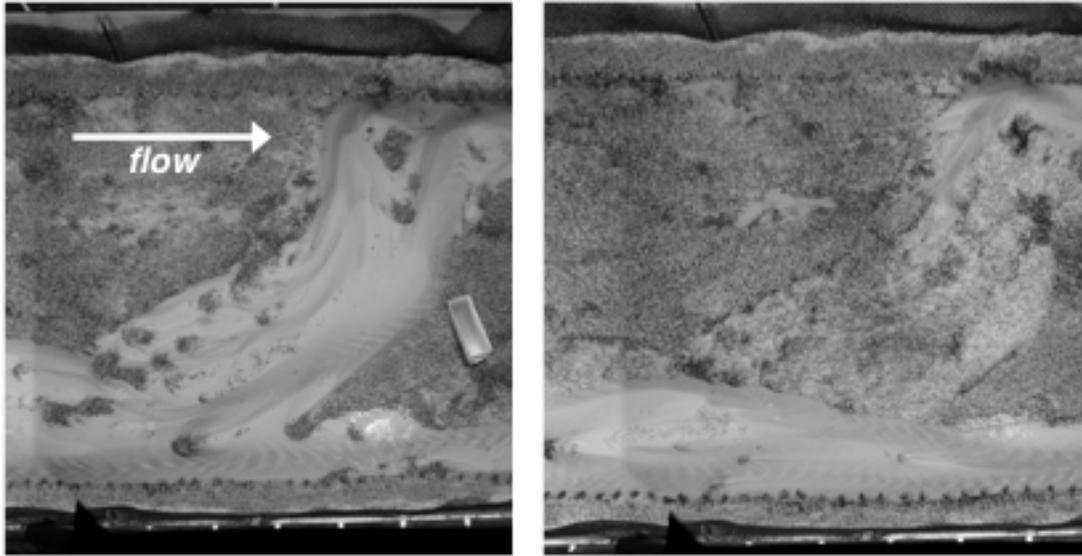


Figure 4-7. Channel abandonment (run 02)  
a. An example of an active channel bifurcation and b. one of the channels dry and vegetated 3 floods later as a result of channel abandonment and colonization during several low flows.

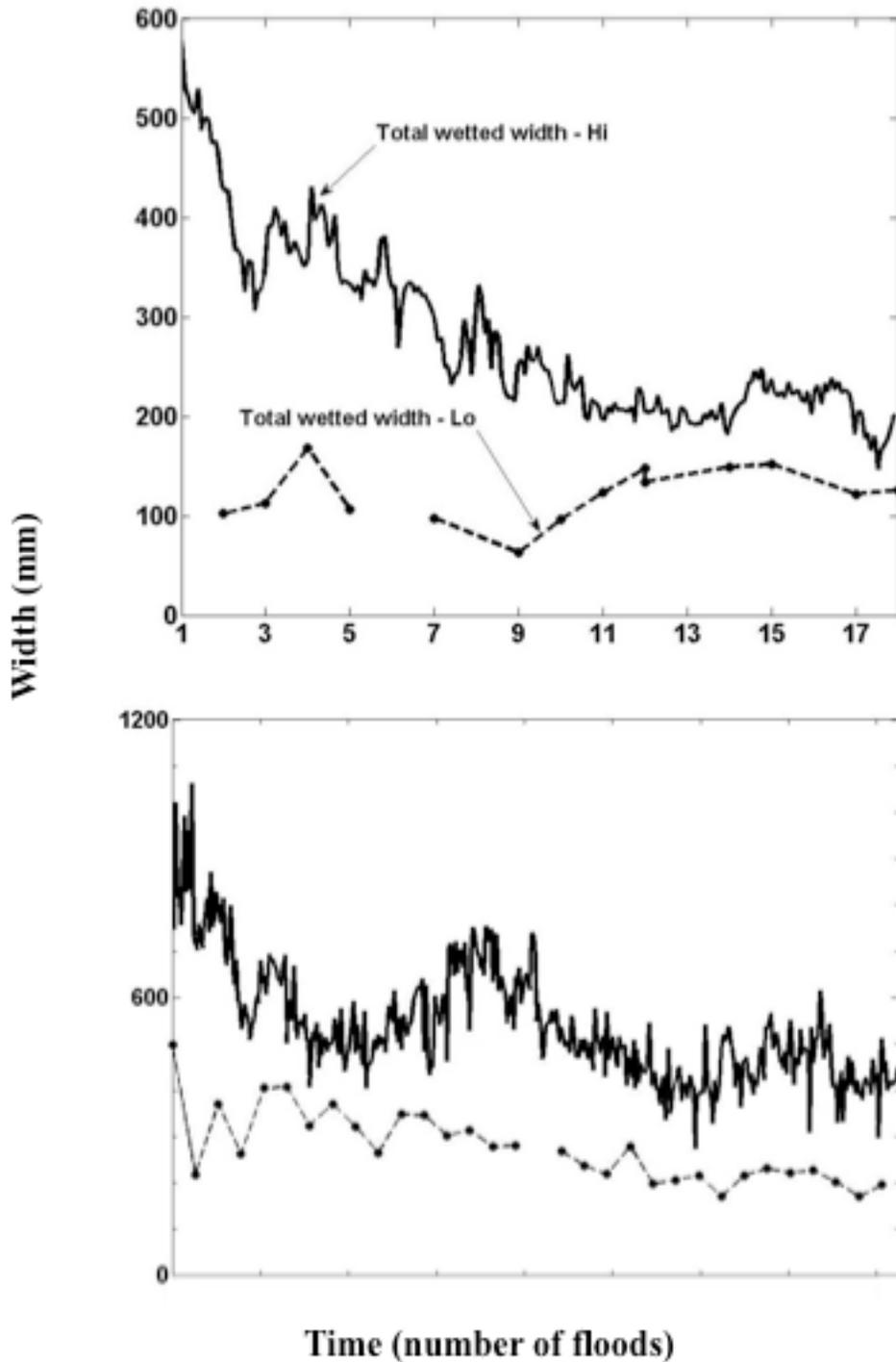


Figure 4-8. Total wetted width measured from images at high flow and low flow through time for run 02 (top) and run 03 (bottom). High flow wetted width was measured from images captured at 5-minute intervals and smoothed with a moving average over 5 images. Low flow wetted width was measured from an image captured at the start of each low (the camera was shut off after this for the remainder of the low flow).

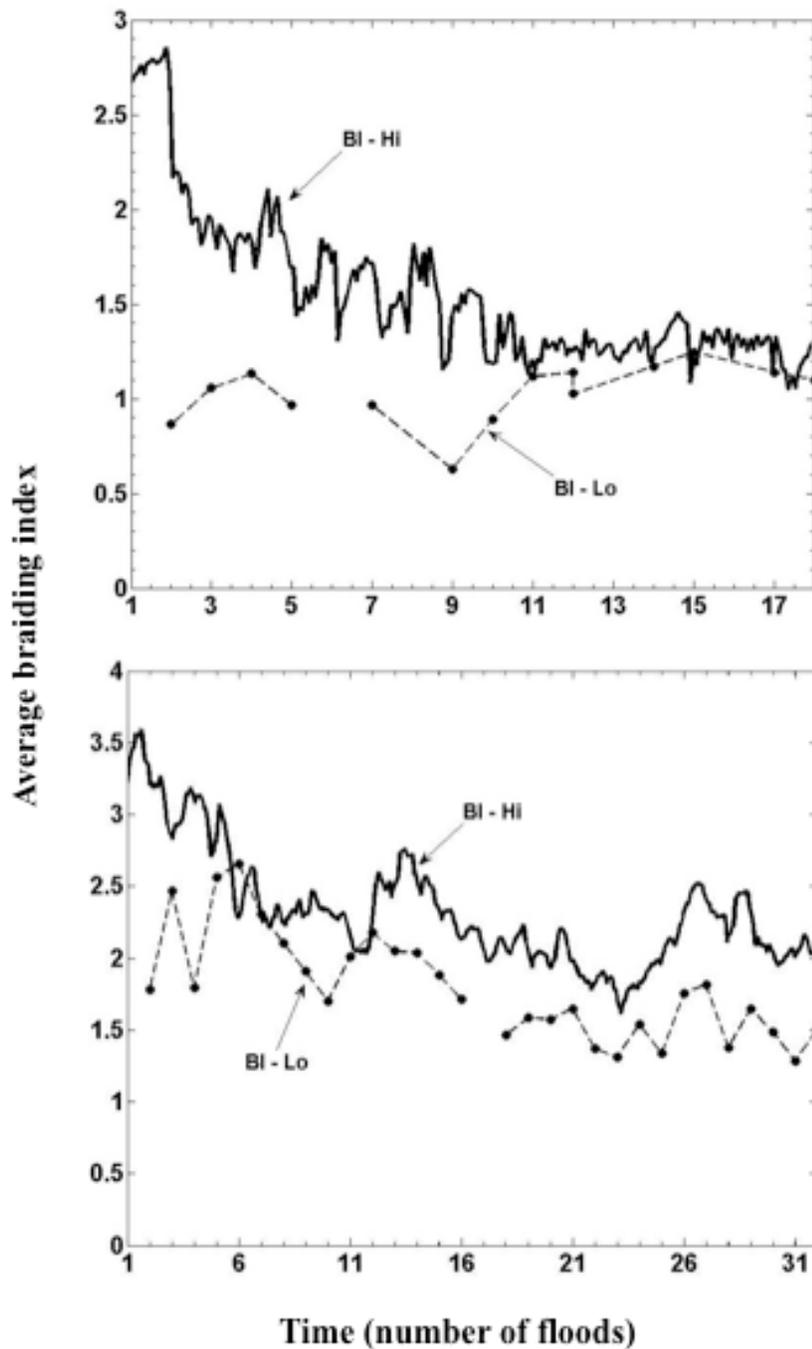


Figure 4-9. Braiding index (BI, number of active channels at a cross section) measured from images captured at high flow and low flow through time for run 02 (top) and run 03 (bottom). High flow BI was measured from images captured at 5-minute intervals and smoothed with a moving average over 5 images. Low flow BI was measured from an image captured at the start of each low flow (the camera was shut off after this for the remainder of the low flow).

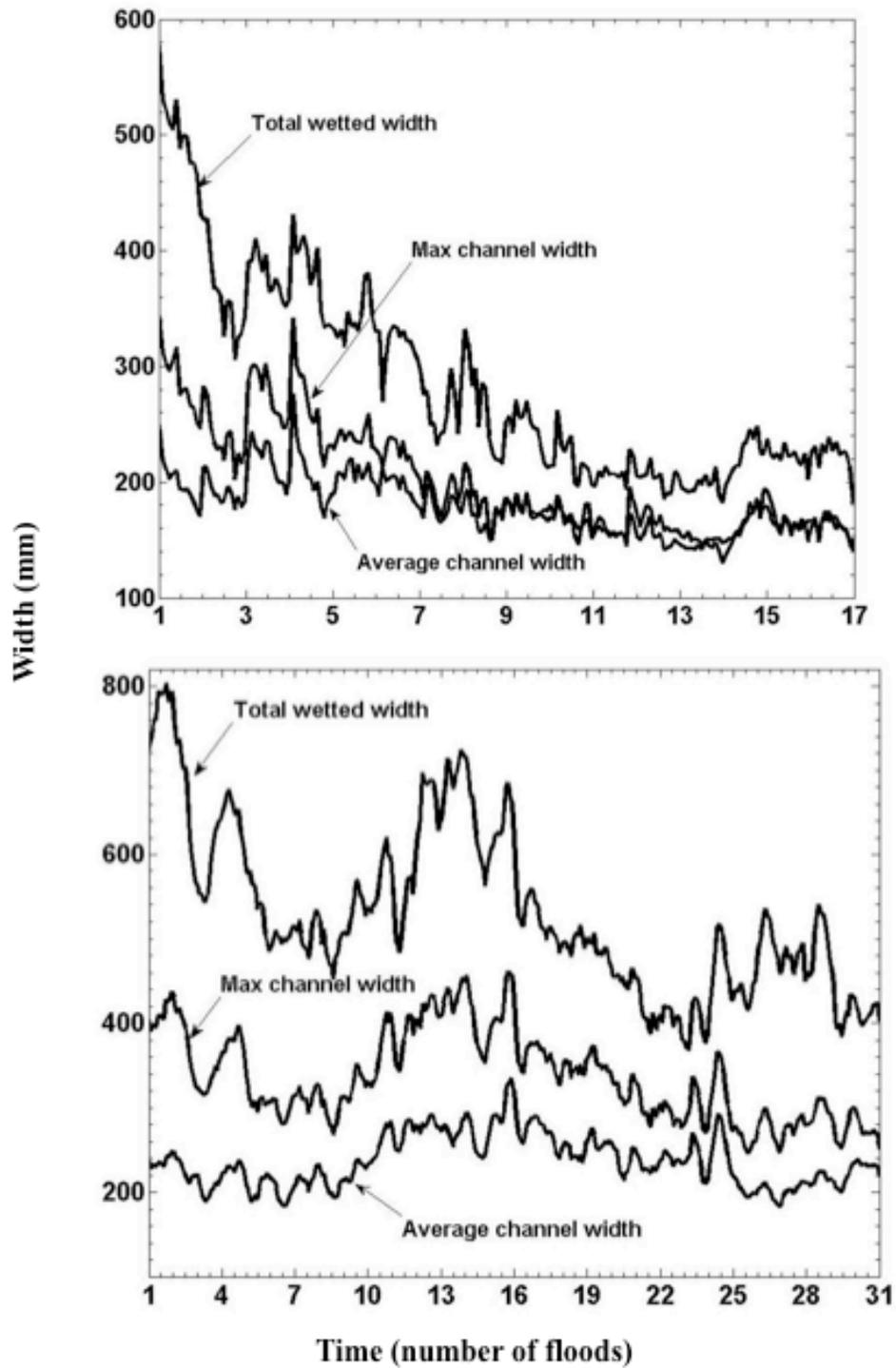


Figure 4-10. Total wetted width, maximum channel width, and average channel width measured from images captured at 5-minute intervals during all of the high flows in run 02 (top) and run 03 (bottom).

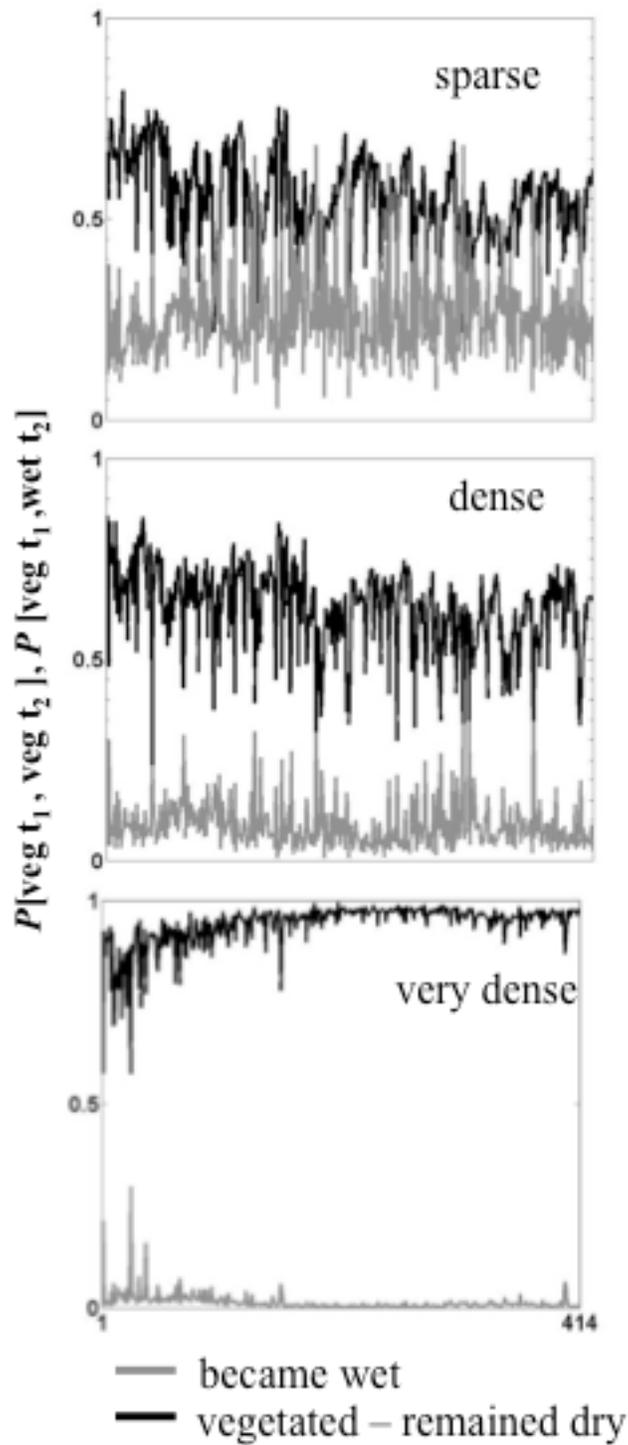


Figure 4-11. Run 03, probability by vegetation class of an area that was vegetated at  $t_1$  to get eroded (became wet) at  $t_2$  versus the probability that it will remain dry at  $t_2$ . Probabilities were calculated between images captured at 5-minute intervals during all of the high flows.

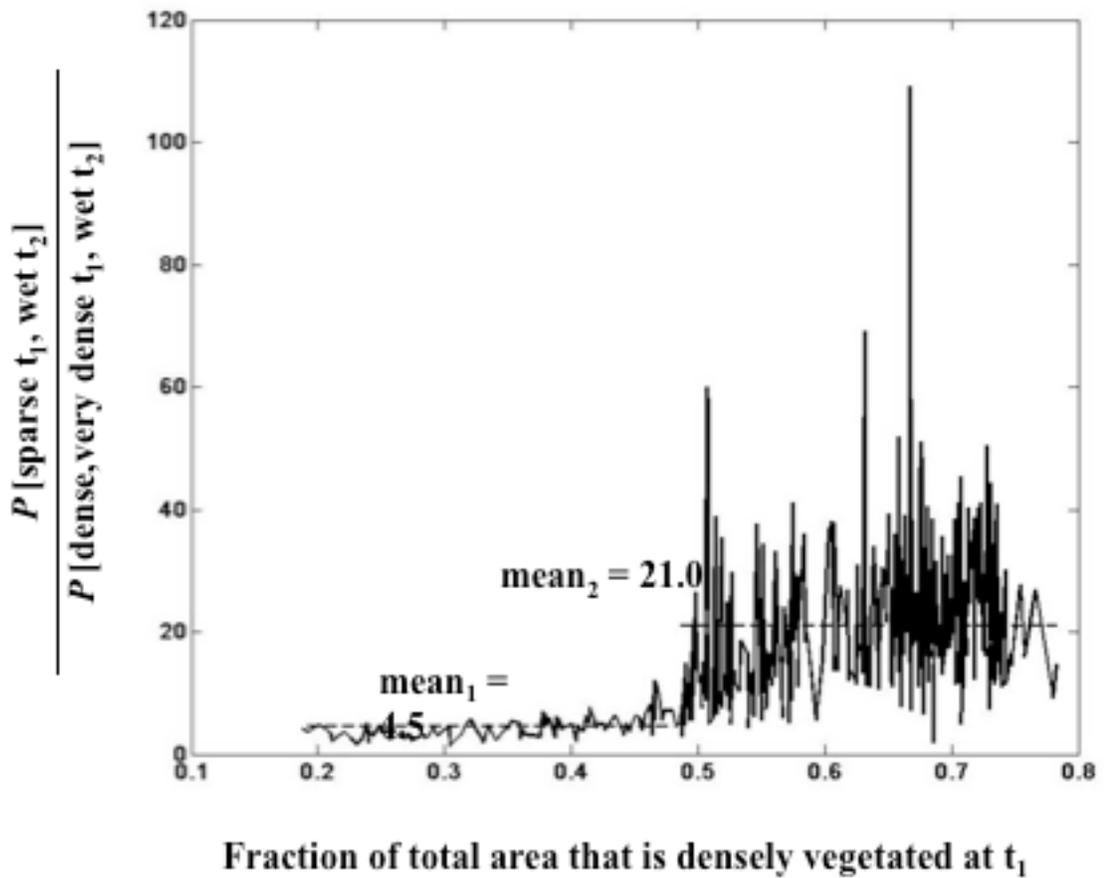


Figure 4-12. Run 03, y-axis is the ratio of the probability of a sparsely vegetated area at  $t_1$  to get eroded at  $t_2$  versus the probability of a densely vegetated area at  $t_1$  to get eroded at  $t_2$ , x – axis is the fraction of the bed that was covered with dense vegetation at  $t_1$ . Dense vegetation includes both dense and very dense vegetation classes. Probabilities were calculated between images captured at 5-minute intervals during all of the high flows.

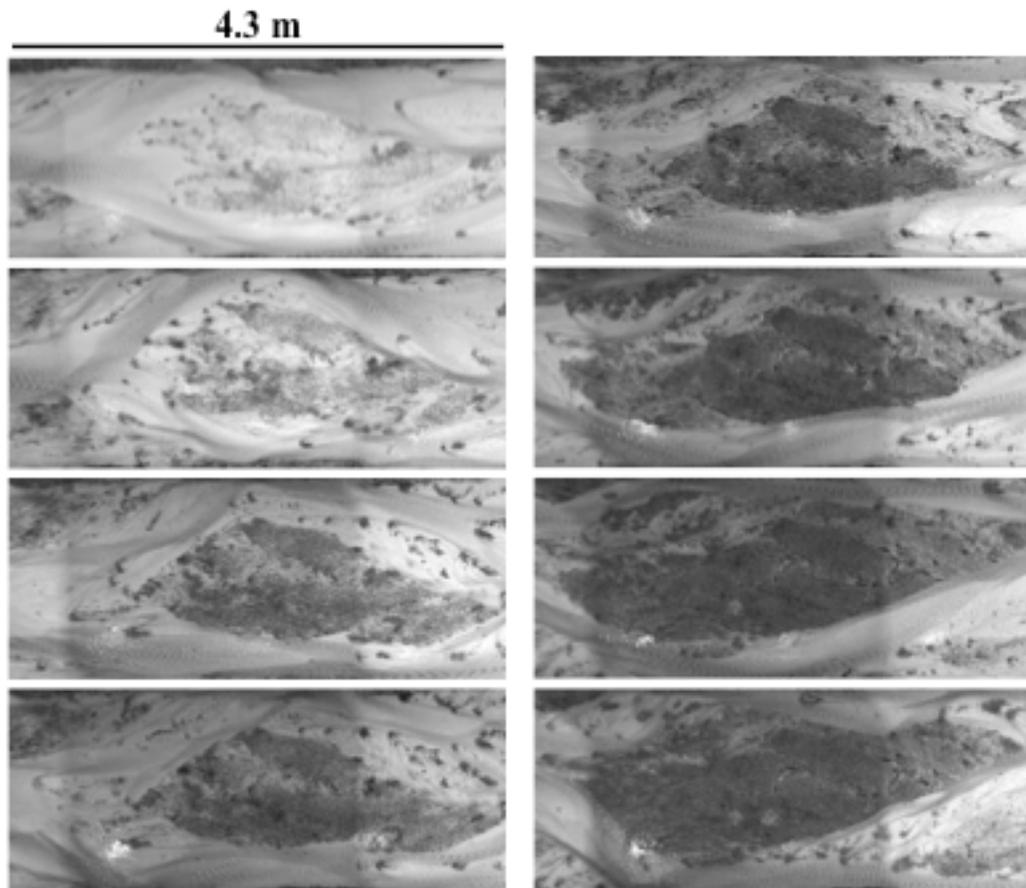


Figure 4-13. Run 03, images from floods 1 – 8 (left top to bottom right) illustrating how initial vegetated patches became more dense and mature over time and small islands merged together to form a large island.

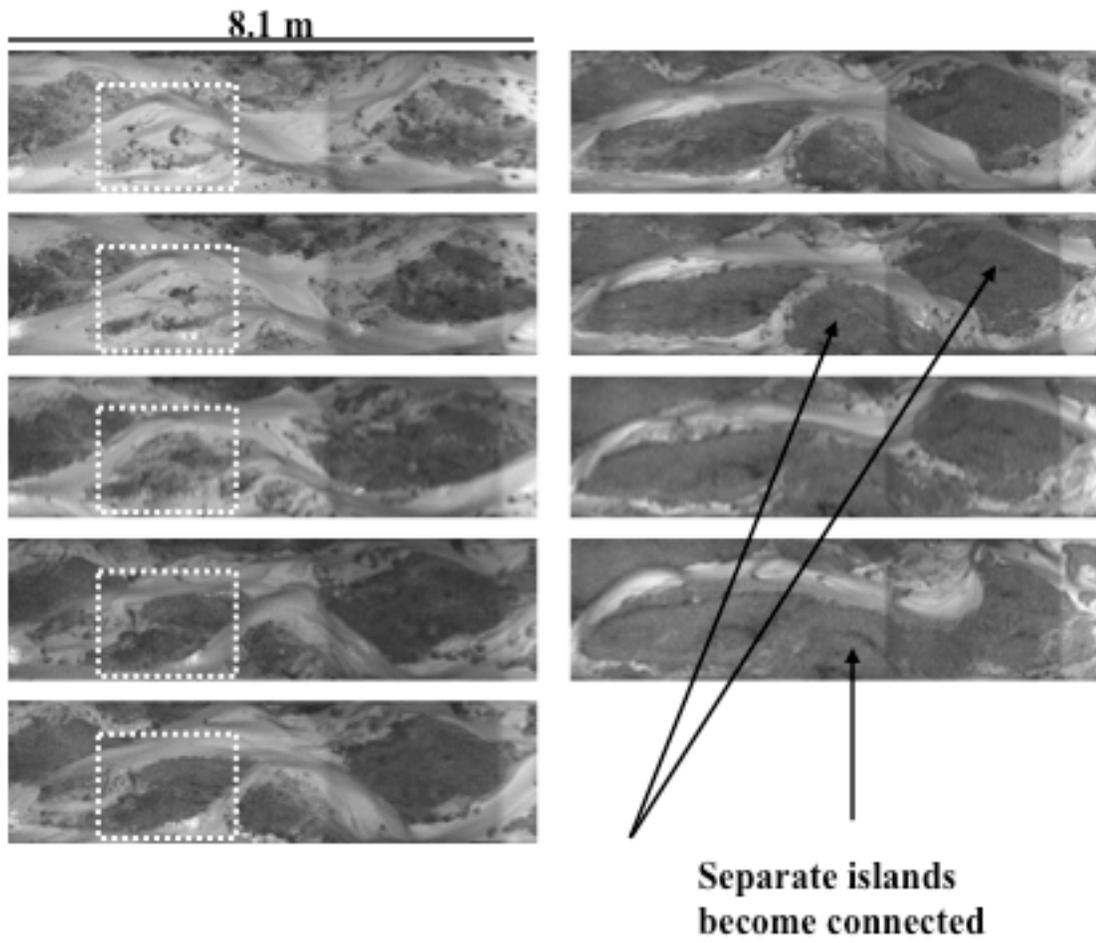


Figure 4-14. Run 03, images from floods 3,5,7,9,11,13,15,17,19 (left top to bottom right) illustrating vegetated islands merging together and forming a floodplain.

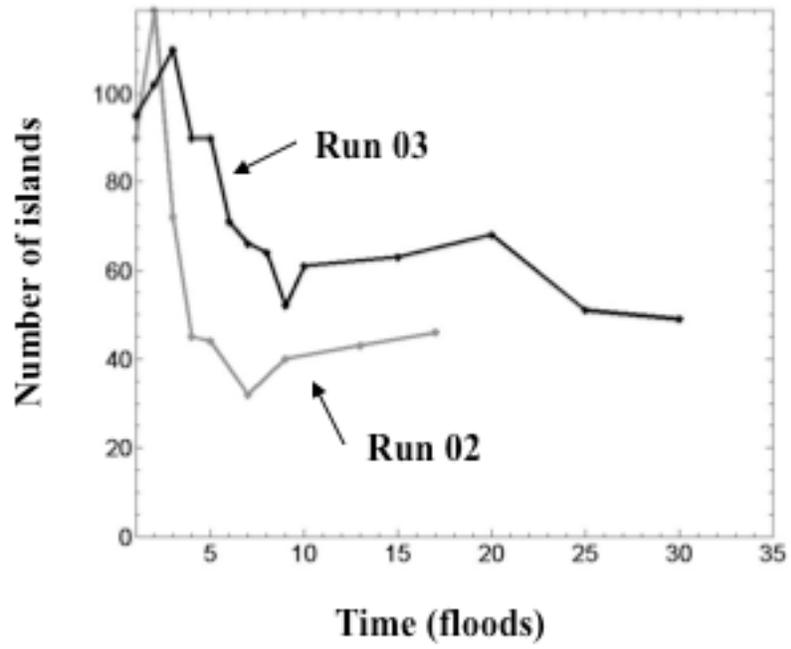


Figure 4-15. Number of islands at each flood. Islands were mapped manually in GIS.

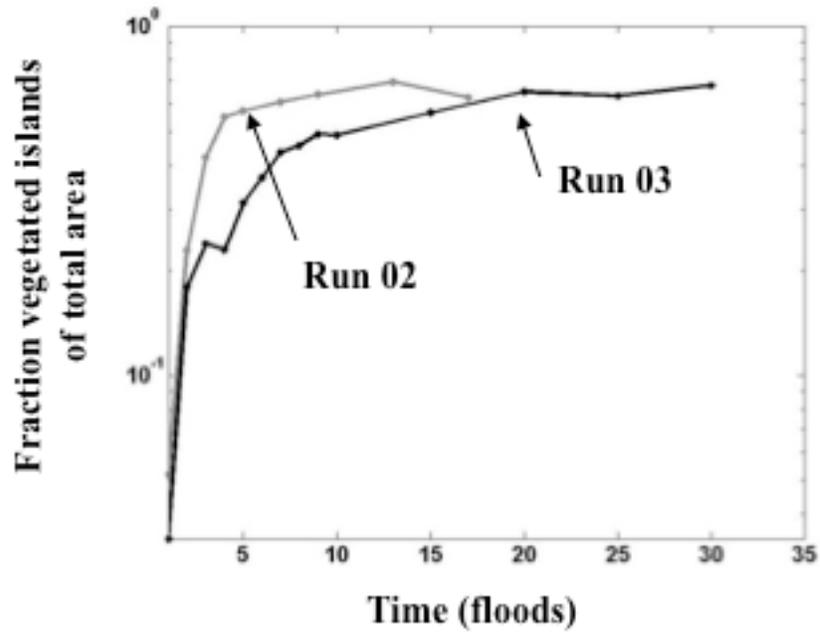


Figure 4-16. Fraction of the entire bed that was mapped as a vegetated patch or island.

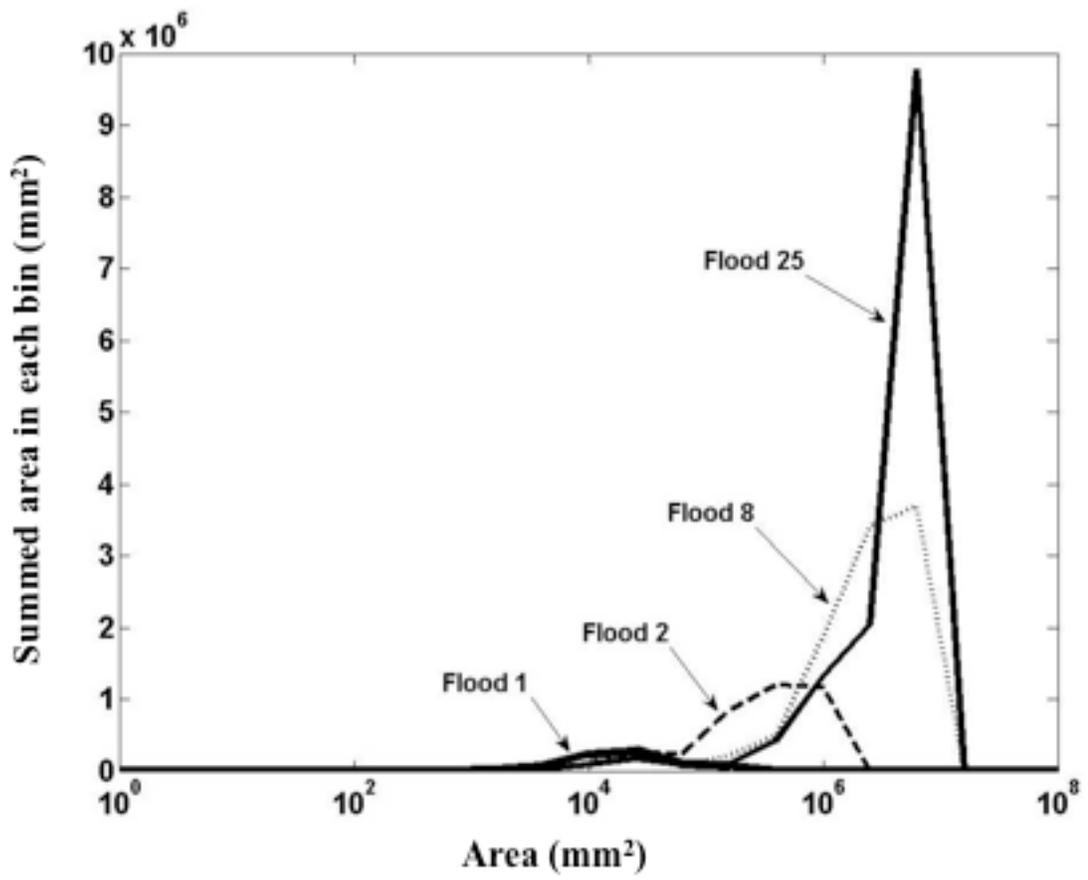


Figure 4-17. Run 03, Distribution of vegetated island sizes through

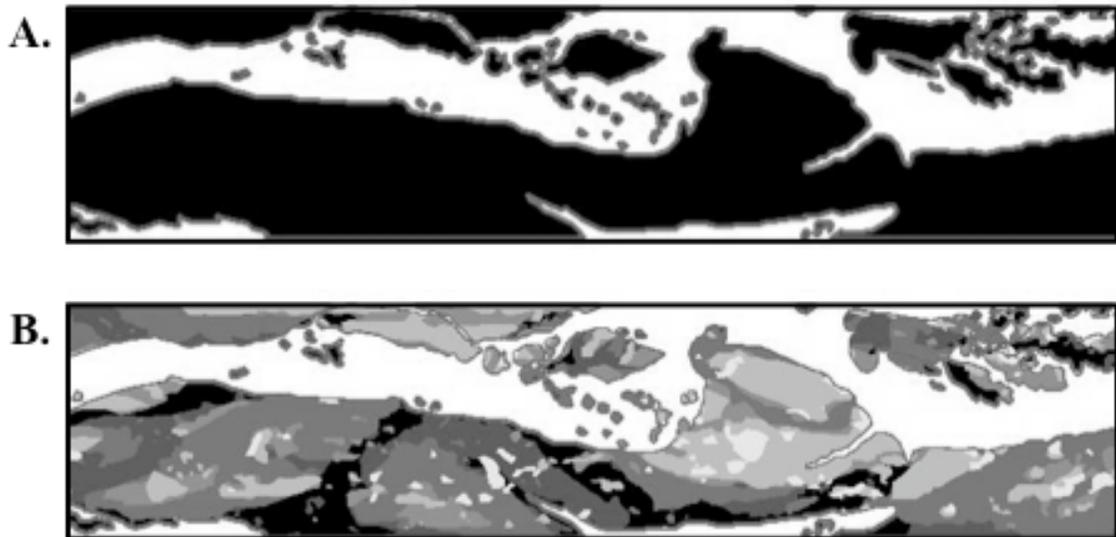


Figure 4-18. Run 03 a. vegetated floodplain (black) and active channel (white) towards the end of the run, b. the same area shown in a. with the floodplain mapped as a mosaic of the increasingly older and smaller (lighter) islands that it was composed from.

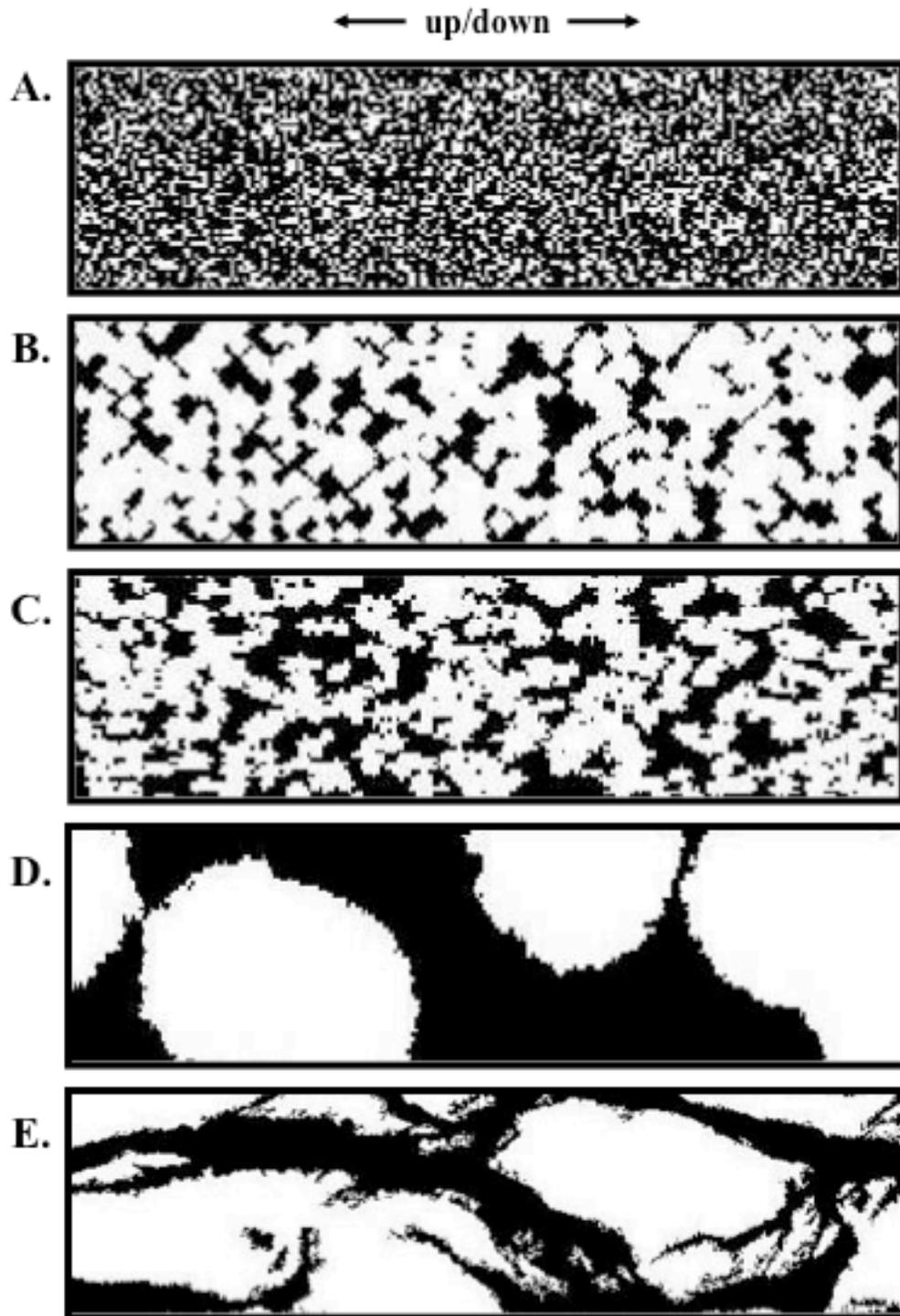


Figure 4-19. Growth of white clusters in a neutral model  
 Patterns with 60% white pixels that formed in 4 different versions of a simple neutral model: a. random growth, b. initial random field that grew the 4 nearest neighbors symmetrically, c. initial random field that grew the 4 nearest neighbors asymmetrically with a higher probability of growing up and down than to the sides, d. Limited number of initial random white cells that grew asymmetrically, and e. binary image of the experiments at 60 % vegetation cover (white)

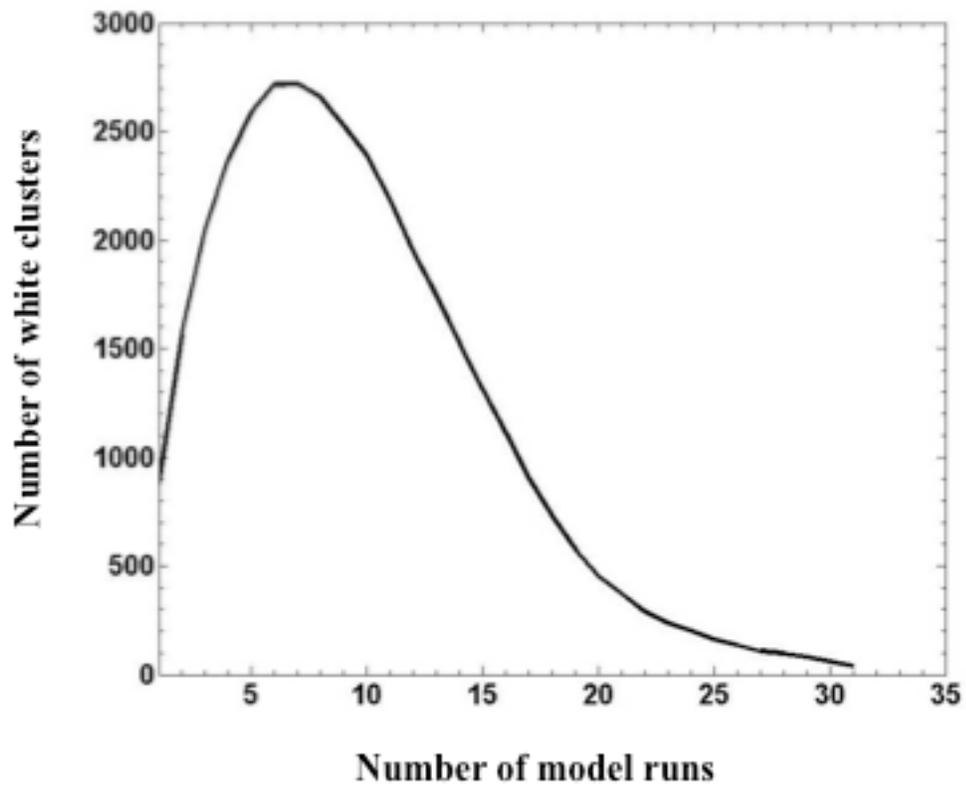


Figure 4-20. Number of pixel clusters in a random neutral model.

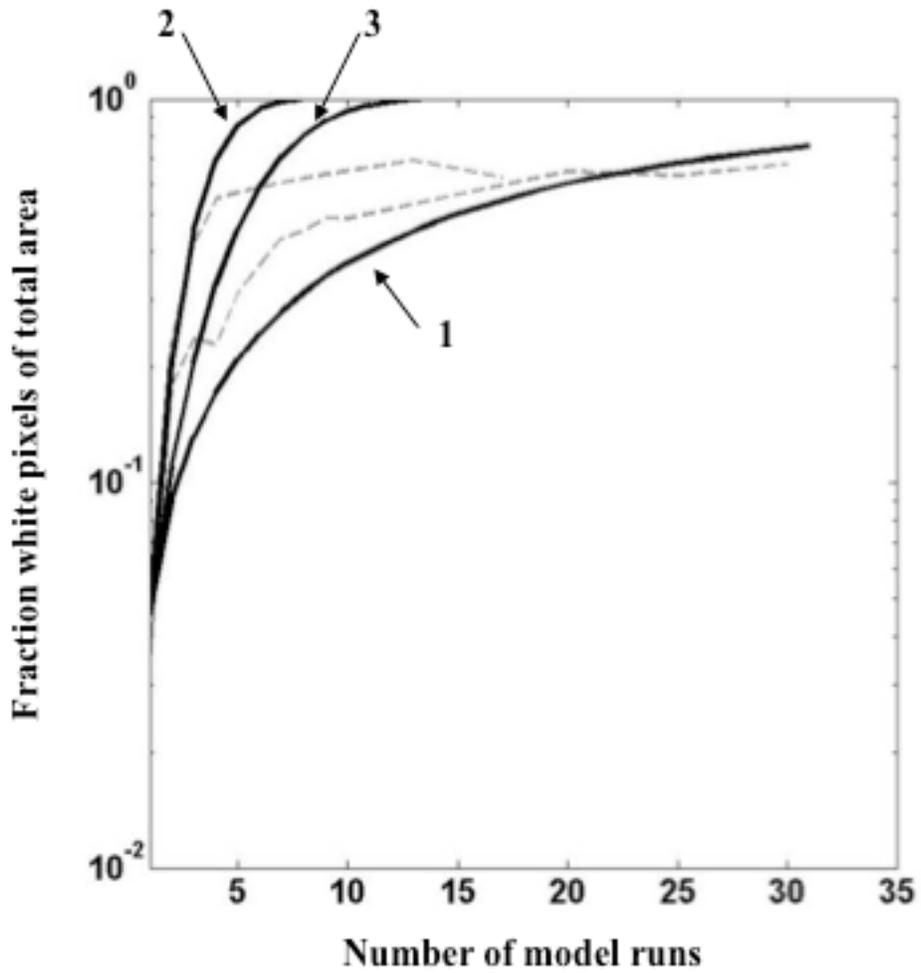


Figure 4-21. Growth of of white clusters  
 Total area of white pixels as a fraction of all the pixels in the models through time (solid black lines) compared to the fraction of vegetated island area of total area in the experiments (dashed gray line)

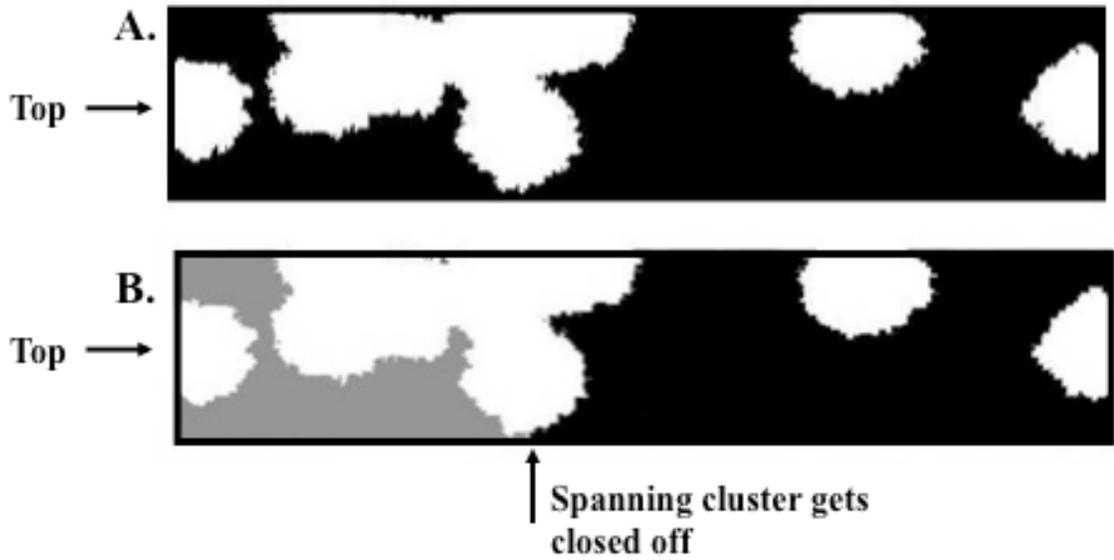


Figure 4-22. Modeling spanning clusters  
a. A spanning cluster of black cells in the model still exists, b. at the next time step the white cluster grows and a single spanning cluster no longer exists

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