CHAPTER 3 – EXPERIMENTAL STUDY OF THE RESPONSE TO INCREASED SEDIMENT SUPPLY OF A CHANNEL WITH ALTERNATE GRAVEL BARS

The field example of channel adjustments to an increase in sediment supply presented in Chapter 2 demonstrates several adjustments. The increase in sediment supply was accommodated by slope increases, changes in topographic variability, and a decrease in the bed grain size. Two years after the dam removal, the bed planform configuration was similar to the pre-removal condition, but the transient configuration was quite different. Laboratory flume experiments provide the opportunity to study the response of a channel under controlled conditions and support high resolution observations. This chapter presents results from experiments in a near-field scale recirculating flume during which an increased sediment supply was applied to a gravel bed with alternate bar topography. Frequent and high spatial resolution topographic measurements, grain size derived from photographs, and sediment flux measurements coupled with a hydrodynamic model allow detailed documentation of bed adjustments to increased sediment supply. The ensemble of measurements are used to focus especially on the transient bed response.

3.1. Methods

The experiments were conducted in the main channel at St. Anthony Falls Hydraulic Lab. The flume is rectangular in cross section, 2.75 m wide and 80 m long with a 55 m long test section. Water discharge is controlled with an adjustable headgate and was held relatively constant throughout the experiment (mean = 0.42 m$^3$/s, standard deviation = 0.026 m$^3$/s). Sediment exits the flume via five bedload traps spanning the width of the test section and is recirculated via a slurry pump to the top of the test section. An adjustable tailgate is used to maintain a constant downstream depth (mean = 0.139 m, std dev = 0.0094 m).

The experimental plan involved a combination of sediment recirculation and sediment feed. An initial run was conducted to establish an alternate bar configuration using the
sediment recirculation system, reaching a steady state transport rate of 30 kg/min. The recirculating sediment feed was then manually augmented to achieve a rate of 65 kg/min. This was done by monitoring the flux rate entering the recirculation system every 5 minutes and manually supplementing the input to maintain an approximately constant input rate. As the channel adjusted, the recirculated flux approached 65 kg/min and the amount of supplemented load dropped to zero. The flume was then operated in full recirculation mode for 15 hours, allowing the bed to fully adjust to the higher rate during which time the transport rate persisted at 65 kg/min. This is the first instance we are aware of in which supplemental feed has been used to change the internally adjusted state of a recirculating flume. The sediment feed was augmented a second time with manual input, holding the rate at 130 kg/min for 6.4 hr, at which point the sediment available for supplementation was exhausted. This was not sufficient time to allow the system to achieve the target transport rate and the system equilibrated to a transport rate of approximately 90 kg/min. The run was divided into 15 segments, each lasting approximately 6 hours. Between each run segment the bed was drained, allowing detailed measurements of the bed topography and grain size as the bed adjusted to the two increases in sediment supply.

To begin the experiment, the bed was mixed and graded to a planar configuration. At a point 15 m upstream of the test section, the right 25% of the flume entrance was obstructed with sandbags to produce a flow perturbation that would enhance alternate bar growth. This obstruction remained in the channel throughout the experiment. The initial bed topography was established by running the flume in the recirculating mode. Steady flow conditions with a mean depth of 0.145 m (std dev = 0.03, width/depth ratio = 18.9; Table 1) and transport rate of 35 kg/min were established before initiating the feed augmentation. The initial bed had a mean slope of 0.009 and the topography was dominated by long alternate bars with a maximum relief (difference between maximum and minimum elevation at any cross section) of 0.127 m.
Prior to the experiment, bulk samples of the bed surface and subsurface were taken at several locations throughout the flume. The initial bed was unarmored. The median grain size of the sediment larger than 2 mm ($D_{50g}$) was 10.2 mm for both surface and subsurface, and sand content ($F_s$) was 15% for the surface and 16% for the subsurface (Figure 18). Also before the experiment, the sediment used to supplement the feed was obtained by running the flume and diverting the recirculation to capture approximately 20m$^3$ of sediment. The augmented sediment was finer than the flume bed material ($D_{50g}$: 8.7 mm $F_s$: 24%; Figure 18) but similar in grain size to transport samples collected during the experiment. The augmented sediment contained approximately 5% more sand than average transport measured during the runs.

Sediment flux was measured at five bedload traps at the downstream end of the test section. Each trap contained a drum that collected sediment, recorded continuous weight, and periodically rotated to dump the sediment into an auger leading to the slurry pump. Each drum was connected to a load cell that recorded the mass at 1-second intervals. During the augmentation runs, a 10 minute moving average was reported every five minutes to determine the supplement needed to meet the target flux. A small amount of bed

<table>
<thead>
<tr>
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<th>Duration</th>
<th>Discharge</th>
<th>Mean Upstream Sediment Flux</th>
<th>Bed Slope</th>
<th>Mean Depth</th>
<th>W/D ratio</th>
<th>Mean bed shear stress</th>
<th>Mean surface $D_{50g}$</th>
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<tr>
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<td>29.9</td>
<td>0.18</td>
<td>0.009</td>
<td>18.3</td>
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<td>0.041</td>
<td>65.1</td>
<td>0.39</td>
<td>0.143</td>
<td>19.2</td>
<td>11.2</td>
<td>6.5</td>
</tr>
<tr>
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<td>15</td>
<td>0.044</td>
<td>66</td>
<td>0.4</td>
<td>0.010</td>
<td>18.6</td>
<td>11.8</td>
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<td>6.8</td>
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<td>136.1</td>
<td>0.82</td>
<td>0.135</td>
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<td>6.2</td>
</tr>
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<td>Recovery 2</td>
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<td>90.3</td>
<td>0.55</td>
<td>0.012</td>
<td>20.5</td>
<td>12.9</td>
<td>6.2</td>
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</table>
material load passed unmeasured over the weighpans and settled downstream of the test section. Measurements of this sediment indicated that it was on average 1.5% of the total load for each run segment.

At the end of each run segment (approximately every 6 hours of run time), the flume was drained to allow high-resolution measurement of the bed topography. An automated data acquisition cart equipped with a laser rangefinder traversed the flume and measured the height of the bed on a 1 cm x 1 cm grid. During the flume runs, the cart was equipped with a sonic range finder to measure water surface elevation (WSEL) and a submersible sonar to measure bed elevation. At 80 minute intervals, water surface elevation was measured at 1 cm spacing along five streamwise transects spaced 0.42 meters apart. Also at 80 minute intervals, bed elevation and water surface elevation were measured at 1 cm spacing along nine cross-stream transects spaced 5.25 meters apart.

Figure 18. Flume experiment grain size distribution. Surface and subsurface GSD are composites of six samples taken before the experiment. Augmented GSD is the sediment used to augment sediment supply. Transport samples are from multiple grab samples taken from the recirculating sediment. Photo limits indicate range of GSD from manual counts on 15 photographs. Boxplot displays distribution of the mean surface grain size for 8,184 samples measures with automatic photo classification system.
Each time the bed was dried, maps of areas with similar grain size distribution (GSD) were sketched. The facies were categorized by the estimated relative abundance of sand (<2 mm), fine gravel (2-8 mm), and medium gravel (8-32 mm). Additionally, images of the drained bed were captured with high resolution digital photographs with a Nikon D70 digital SLR camera mounted to the data acquisition cart. The photographs covered 43.5 meters of the test section and were taken at an average height above the bed of 2.72 meters, yielding a resolution of 2 pixels/mm for each of the 6 megapixel images. Errors in the camera position program resulted in under-sampling 5% of the bed (primarily along the right half) for run segments 1-11, and 24% of the bed for segments 12-14. The images were cropped to produce 0.38 m x 0.38 m images, each of which was analyzed with an automatic routine to extract grain size information.

There are two general methods currently used to extract grain size information from photographs: 1) individual gain size identification and measurement producing an area-by-number GSD and 2) correlation of GSD statistics and image statistics to produce a GSD equivalent to a grid-by-number GSD. Here a method is applied which uses two-dimensional autocorrelation of the image intensity to estimate the mean grain size in an image [Buscombe et al., 2010]. Tested against over 400 sediment samples of natural sediment mixtures (grain sizes between 0.1 and 100 mm), Buscombe et al. [2010] found the image-derived grain size to be well correlated with the mean grain size from manual point counts of the same images for over 400 sediment samples of natural sediment mixtures (between 0.1 and 100 mm). Their RMS error was 16%, and was reduced to 11% when the image-derived grain size was calibrated with manual measurements from a subsample of the images. Applying the Buscombe et al. [2010] methods to 8,184 images from the flume experiments produced a grid of mean grain size throughout the flume. The automated mean grain size observations were consistently coarser than the median grain size computed from a manual 100-pebble count on 15 photographs (Figure 19). A linear correlation was used to report the automated mean size in terms of the equivalent median size by pebble...
counting. The grid-by-number GSD statistics from the photographs are directly comparable to the volume-by-weight GSD derived from bulk samples of the reserved sediment, flume bed, and recirculating sediment (Figure 18) [Bunte and Abt, 2000].

3.2. Observations

Figure 20 provides a summary of the topographic and textural character of the bed over the course of the flume experiment. Figure 20A shows sediment transport rate measured at the downstream end of the flume along with the two periods of sediment augmentation. The persistence of the sediment transport rate following the first augmentation is evident as is the increase in transport in response to the second augmentation. At the end of the experiment, the mean sediment flux was triple that at the beginning (Table 1).

3.2.1. Topography

During and following both increases in sediment supply, preferential deposition in the upstream portion of the flume caused the bed slope to increase (Figure 20B). Bed slope is calculated from the line that best fits the bed longitudinal profile (Figure 21).

Figure 19. Comparison of point count and automated measures of grain size. Comparison of the mean grain size from automated algorithm to median grain size derived from manual counts (n=100) on 15 photographs. The linear relationship displayed was used to correct the automated algorithm.
Figure 20. Time series of bed adjustment during the flume experiments. A. Bedload flux measurements and sediment augmentation. B. Bed and water surface slope. C. Mean and standard deviation of the median surface grain size. D. Contours of the power spectral density (log scale) for topographic bed scans and (E) sediment flux. F. Standard deviation of bed heights and correlation coefficient between bed shear stress (Figure 30) and bed grain size (Figure 23). G. Mean and standard deviation of the bed stress calculated from the 2-D model. Run segment indicated along the top and elapsed run time shown along the bottom. The vertical dotted lines indicate periods with sediment augmentations.
Slopes were also computed from the more frequent bed cross sectional profiles and water surface elevation profiles (Figure 20B). During the first augmentation, the bed steepens from 0.009 to 0.01 (Table 1). The second augmentation produced a larger slope response, corresponding to a larger increase in supply, with a steady state slope 0.012. An error in setting the downstream stage during run segment 10 caused downstream erosion (Figure 21) and a transient slope adjustment (Figure 20B).

The spatial distribution of local topography is presented in a digital elevation model (DEM) of bed height for each run segment (Figure 22). Bed height is computed by subtracting the elevation of a plane inclined at the mean slope of the profiles (Figure 21) from the DEM of bed elevation. At the beginning of the experiment (Run segment 0), the major topographic feature was a single cycle of a large alternate bar 15-20 meters in length. There is no sediment augmentation between the first and second bed scans (segments 0 and 1) and the overall pattern of bed topography persists. However, the DEM for run segment 1 also captures two scales of smaller, mobile features. Smaller bars (3-5 meter wavelength) can be seen at the upper end of the channel and small dunes are evident in the downstream end of the pool near the center of the flume in the segment 1 bed scan.

The first sediment augmentation occurs during Run segments 2, 3, and 4. As the bed steepens during run sediment 2 (Figure 20B, Figure 21), the broad pattern of high and low elevations persists (high areas at the upstream right side, mid-flume left side, and downstream right side), although the size and location of the dominant bar shifts downstream somewhat (the bar is centered at 37 meters during run segment 0 and at 44 meters during segment 2). Superimposed on this pattern is a series of shorter wavelength bars most prominent on the left side of the flume between 25 and 35 meters during run segments 3 and 4. The bedforms shapes vary from small u-shaped features with faces approximately 30 degrees to the downstream direction to larger v-shaped features with have faces closer to 60 degrees to the direction of flow. In run segment 3 the small dunes in the pools are less prominent than earlier or later. The broad alternate bar pattern pres-
Figure 21. Longitudinal profiles of the flume bed. A: First augmentation and recovery, B: Second augmentation and recovery. The profiles are derived from the laser bed scans following each run segment (Figure 22). Segment 10 profile shows downstream erosion caused by erroneously setting the downstream water stage too low.
ent before the first augmentation (segments 0 and 1) reemerges during the first recovery period (segments 5 and 6). Smaller dunes are superimposed on the bars, primarily in the upstream (segments 1, 5, 6) and small to large dunes migrating in the downstream half of the test section.

The second sediment augmentation occurs during run segments 7 and 9. Mobile alternate bars with a 7-8 m wavelength become well defined after the beginning of the second augmentation and persist through run segment 8. During the second recovery period, these bars gradually become less well defined and by segment 10, the broad topographic pattern established before the augmentations emerges once again. As the pools opposite the zones of high topography become reestablished, small dunes are visible in their downstream portions. Like segment 10, the topography after run segments 12 and 14 resembles the initial (segment 0) topography – the tail end of a bar is visible on the upstream right side and a long bar is present midway down the left side of the flume. Although persistent, the mid-flume bar varies somewhat in the sharpness of its boundaries and simplicity of its form. When it is less-well defined (e.g. segments 9,11,13, as well as segments 1 and 5), the right side mid-flume pool becomes divided by smaller dunes and bars. By the final run segment, the configuration of the bed topography largely resembles that of the initial configuration – a single cycle of large alternate bars 15-20 meters in length, and three well-defined pools, with smaller dunes in the pools.

3.2.2. Bed Texture

The mean surface $D_{50}$ showed a general fining in response to the first augmentation (Figure 20C), as would be predicted by transport relations [Parker and Wilcock, 1993]. The response during run segments 2 and 3 fell within the broader trend but was more varied, perhaps as a function of rapid bed adjustments. Changes in the spatial distribution of bed grain size can be seen in the photograph-derived median grain sizes (Figure 23). The initial bed fining is more prevalent in the pool (Figure 22 and Figure 23) along the left side
of the flume between 30-45 meters. During the first recovery the upper and lower ends of the flume become finer, whereas the zones of higher elevation between 30-40 meters remain coarser. During the second augmentation, the mean surface $D_{50}$ became coarser and remained in this coarser state until the final segment. By the end of the second augmentation the 7-8 meter alternate bar pattern is also evident in the grain size pattern, with the high portion of the bars (22-25 meters, 32-37 meters, 40-44 meters) also being the coarsest portions of the bed. As the second recovery progresses, grain size patterns become closer to their initial configurations, with the left side of the flume between 35-50 meters again becoming the coarsest part of the bed. There is a clear correlation between bed elevation and bed grain size, indicating that both downstream and lateral interactions among topography, texture, and transport are influencing the bed response.

3.3. Discussion

When sediment supply exceeds transport capacity some of the supplied sediment will not be transported and must deposit on the bed. The amount of deposition that results typically decreases in the downstream direction and causes an increase in the bed slope. As slope increases, the bed stress and transport also increase, moving the system back toward steady state. Where there is a range of grain sizes, an increase in sediment supply can also produce a finer bed surface texture, which will also increase transport capacity. In addition, to changes in mean slope and grain size, patterns of deposition and sorting may increase the variance in topography and grain size, which will also affect transport capacity.

3.3.1. Topography Adjustments

Because deposition directly increases bed slope and mean stress, a dominant response to an increased sediment supply is an increase in slope. The bed slope adjusted from 0.009 to 0.01 during the first supply increase and from 0.01 to 0.012 during the second (Figure 20B, Table 1). The bed and water surface slopes adjust nearly simultaneously, and
Figure 22. Flume bed topography. Maps of bed height (bed elevation relative to tilted plane of mean bed) derived from bed topography scans at the end of each run segment. Flow is from left to right. Shaded bars between maps indicate run segments with sediment augmentation.
Figure 23. Flume bed texture. Median surface grain size for 0.38 m square bed segments, derived from photographs with automatic algorithm. Lines show facies boundaries mapped from visual inspection. Light grey areas indicate areas with no photographs. Flow is from left to right. Shaded bars between maps indicate run segments with sediment augmentation.
their rate of adjustment closely follows that of the sediment flux (Figure 20A and B).

The bed height frequency distribution at the end of each run segment is given in Figure 20. During the first augmentation, the topographic variability, as measured by the standard deviation ($\sigma$) of bed heights decreases from 0.02 m to 0.016 m (Figure 20F) and is reflected in a narrowing of the distribution in Figure 24A. The decreased variability persists through the first recovery ($\sigma = 0.016$ m). The bed height distribution becomes more variable through the second augmentation, and reaches maximum variability ($\sigma = 0.03$ m) at run segment 9. Throughout the second recovery, the bed heights are less variable and reach a value close to the pre-augmentation state ($\sigma = 0.023$ m) (Figure 23B). Using the 80th and 15th percentiles of the run segment 0 height distribution to approximate bar and pool area, the final bed topography shows slightly more pool area (20% vs. 15%) and less bar area (78.3% vs. 80%) than the initial. Using the same definition of pools and bars, Figure 25 shows the spatial distribution and sizes of bars and pools throughout the experiment. During the first augmentation (run segments 3 and 4) the

Figure 24. Cumulative frequency distribution of bed heights. (bed elevation relative to tilted plane of mean bed). A: First augmentation and recovery. B: Second augmentation and recovery. Bar areas on Figure 25 are defined as bed height >0.0165 m (80th percentile for Day 0) and pools are defined as bed height < -0.0196 m (15th percentile for Day 0). Standard deviation of the frequency distribution shown in Figure 20F.
pools become smaller and much of the bed is neither a bed nor a pool. By run segment 7, there is nearly the same total bar and pool area as there was initially (run segment 0), but they are arranged in smaller and more numerous bars and pools. In run segment 10, the bar and pool configuration resembles, in total size and location, the initial configuration. Figure 26 shows the locational persistence in bedform type (bar, pool, intermediate) at individual points on the bed. Much of the bed (74%) finishes the experiment as the same category as it started, highlighting the similarity in bedform location between the initial and final bed.

The bed response involves adjustment in the bed configuration – the type, shape, and location of bedforms. The topographic distribution at the beginning and end of the experiment (run segment 0 vs. run segment 14 in Figure 22) is similar in terms of bedform types (large alternate bars), sizes (7 cm above the mean elevation), and locations (upper right, mid-flume left, and downstream right).

The distribution of bedform sizes can be further explored using a frequency analysis of the bed topography. A fast Fourier transformation was performed on 251 streamwise profiles (spaced 1 cm apart) from each daily bed scan. The mean power across all 251 profiles is computed at each frequency. The evolution of the power spectral density plots of the bed (Figure 27) can be visualized as contours of power plotted on a wavelength vs. flume run time graph (Figure 20D). Increases in power at a specific wavelength indicate that bars of that wavelength are prominent in the bed and should be observed in the bed topography (Figure 22). The power in the longer wavelengths (30-40 meters) is greatest in run segment 0, diminishes through segment 8, and then reappears during segment 9 through the end. This corresponds to the observed large-scale bars (upper right, mid-flume left, and downstream on the right) that are more prominent in the beginning and end of the run. During the first and second augmentations, increased power is observed in the 6-9 meter wavelength. These bars are especially visible along the right side of the flume between 27 and 42 meters in the run segment 3 scan, and through the entire flume.
Figure 25. Locations of bars and pools throughout the flume experiment. Bars are defined as areas with a height above 0.0165 m and pools are defined as areas with a height below -0.0196 m. Shaded bars between maps indicate run segments with sediment augmentation.
in the segment 7 scan. The 2-3 meter wavelength shows increasing power during segments 1-7 with a gradual decrease after that time. These bedforms are prominent between 25 and 30 meters on the segment 6 scan (Figure 22).

Although the topographic measurements are not of sufficient frequency to resolve bedform celerity, the downstream sediment flux was sampled at 1 Hz and can be used to estimate the size and celerity of sediment waves. First, gaps in the flux record (up to 10 minutes in length) were filled with a moving average, and a fast Fourier transformation (16,385 point) was applied to periods of record for which there were unbroken data blocks of at least 6 hours. Like the bed topography frequency analysis, the power spectral density plots (Figure 27) are plotted through time (Figure 20E) to display variations in sediment flux. The frequency analysis shows a pattern of shifting power peaks from longer period fluctuations to shorter period fluctuations following both augmentations. Bedform celerity was not directly measured, however Singh et al. [2011] measured bedform

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**Figure 26. Transition matrix between bars and pools for initial and final beds.** Percent of the bed with indicated starting and ending category (i.e. 14% of the bed locations classified as bar in both the initial and final bed scans). The sum of diagonals (74%) indicates the percent of the bed with same designation before and after sediment augmentation.

<table>
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<th>Initial State</th>
<th>Pool</th>
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<th>Bar</th>
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<td>Pool</td>
<td>11%</td>
<td>9%</td>
<td>0%</td>
</tr>
<tr>
<td>Neither</td>
<td>4%</td>
<td>49%</td>
<td>6%</td>
</tr>
<tr>
<td>Bar</td>
<td>0%</td>
<td>8%</td>
<td>14%</td>
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Percent of the bed with indicated starting and ending category (i.e. 14% of the bed locations classified as bar in both the initial and final bed scans). The sum of diagonals (74%) indicates the percent of the bed with same designation before and after sediment augmentation.
celerity in the same flume with the same bed material at slightly higher transport stage 
\(Q=2.8 \text{ m}^3/\text{s}; \text{depth}=0.64 \text{ m}; \text{slope} = 0.0029; \text{bed stress} = 18.2 \text{ Pa}\). They had bedforms 
with similar heights (7-9 cm) and were able to demonstrate scale-dependent bedform 
celerity. In the current experiments, the topographic record indicates the dominance of 
shorter wavelength bars as the sediment supply in increased (Figure 22), and this is borne 
out in the frequency analyses of the bed topography (Figure 20D). The fluctuations in the 
sediment flux are presumably related to changes in the bedform size and celerity during 
the transient phase.

The dimension of the larger bedforms (Figure 22) scale to the flume width and depth. 
The upstream bar (the tail of which is visible in Figure 22, run segment 0) begins im-
mEDIATELY below the flow obstruction at the entrance to the test section. As sediment 
deposits on the bed through the first augmentation, the bed heights become less variable 
(Figure 20F & Figure 24). From this more planar bed state beginning with run segment 
4, a progression of bars with increasing wavelength occurs through run segment 10. Bars
with 4-5 meter wavelengths are prominent between 22 and 38 meters in run segments 3 and 4. Longer wavelength bars (8-10 meters) begin to appear in the 30-40 meter range in run segment 5, become well defined through run segments 6-8, and are superimposed on longer wavelength (30 m) alternate bars in run segments 10 and 11.

A progression of migrating alternate bars with wavelengths that grow through time, has been observed in previous flume experiments on bar growth. Ikeda [1983] fed a mixture of sand and gravel at a constant rate into a similarly large flume at similar transport stages. He initially observed small migrating u-shaped bedforms with widths 1/4 to 1/5 of the flume width (Figure 28). As the experiment progressed the bars grew to a width equal to the flume width, and had a wavelength equal to several flume widths (Figure 28, 2 hour point) – similar to the bars observed during run segment 7 (Figure 22). His bedforms continued to grow in length, and decrease in celerity. The final bed condition was one of non-migrating long wavelength (equal to 10-12 times the flume width) alternate bars.

Alternate bar topography is a stable equilibrium state [Colombini et al., 1987] in which sediment moves over and around the bars that remain fixed in space. When disequilibrium is introduced with the addition of sediment to the bed [Ikde, 1983] or an increase in sediment supply, some of the increased transport is contained within dunes and smaller mobile bars. As these smaller bedforms move through the system, they gradually reduce in size and become ephemeral of disappear altogether. Apparently, the persistant channel-scale dynamics that produce static alternate bars gradually extract sediment from the mobile bars in building static bars in a configuration able to pass the increased sediment load.

3.3.2. Stress Adjustments

Adjustments to the bed slope and topographic distribution affect the sediment transport capacity by changing the stress distribution. A quasi-three-dimensional hydrodynamic model, FaSTMECH (Flow and Sediment Transport and Morphological Evolution of
Channels, available online at http://wwwbrr.cr.usgs.gov/projects/GEOMORPH_Lab/project-MDSWMS.html, was applied to compute the bed shear stress field for each run segment (see Lisle et al., [2000] for a more complete description of FaSTMECH). The model assumes steady and hydrostatic flow and solves the vertically averaged and Reynolds averaged momentum equations on a channel-fitted curvilinear coordinate system. The FaSTMECH model was constructed in the iRIC (International River Interface Cooperative) user interface on a grid with 10 cm spacing and topography derived from the laser bed scans. The model used a spatially uniform isotropic eddy viscosity to model
momentum flux due to turbulence. The upstream boundary condition was the average discharge (0.39-0.49 m$^3$/s) for the run segment, and the downstream boundary condition was the constant water surface elevation measured in the flume. The magnitude of the mean bed stress was computed from the streamwise and cross-stream velocity components using a spatially uniform coefficient of drag ($C_d$).

The model was calibrated by varying the eddy viscosity and $C_d$. An eddy viscosity of 0.0019 m$^2$/s and $C_d$ = 0.012 minimized the root-mean-squared (RMS) error between the predicted and observed WSEL (mean RMS = 0.0115 m, standard deviation = 0.0028 m). Model convergence (computed as the largest percent difference – from all cross sections - between input discharge and the model-computed discharge) ranged between .087 and 2.6 percent (mean = 0.50 percent, standard deviation = 0.66). Point velocities were not observed in these experiments, although Nelson et al. [2010] found model predicted velocities to be within 10% of the measured values for a flume run with similar conditions and nearly identical model parameters.

Transport capacity may be expected to increase with mean and variance of stress. The probability distributions of stress are shown in Figure 29 and the mean and standard deviation are shown in Figure 20G. Both mean stress and its standard deviation clearly increase during the second augmentation and recovery, but any increase during the first augmentation and recovery is minor.

The calculated bed stress patterns (Figure 30) shows the effects of the changing topographic distribution. In the initial bed, the larger stress values are along the left side of the flume at the upstream end and cross to the right side 15 meters downstream. Large stresses are concentrated in the pool (35-40 meters) and the smallest stress values are found on the coarser, higher elevation locations along the left side (40-45 meters). During and following the first augmentation, the cross-stream variation in stress diminishes (Days 3-6). As the topography begins to reestablish three alternate bars (Figure 22, Day 10), the cross-stream variation in stress reappears. By run segment 10, the zone of greatest stress
is back to the left side at the upstream end and against the right side in the 40 meter area as it was for the initial bed topographic distribution.

### 3.3.3. Bed Texture Adjustments

The spatial distribution of the bed grain size generally follows the spatial patterns of topography and stress. The patterns near the beginning (Day 1) and end of the experiment (Day 11) show the clearest correlation with larger stress and finer grain size in the pools and smaller stress and coarser grain size on the bars (Figure 23, Figure 30). In the same flume with similar equilibrium topography Nelson et al. [2010] found similar patterns – finer grain sizes in high-stress, low elevation portions of the bed. The grain size-stress correlation became less strong during the transient phases. The cross-stream gradients of stress are as large during run segment 2 as they are during segment 1, but the bed is more uniform both in terms of the standard deviation of the bed surface median grain size
Figure 30. Flume bed stress. Maps of bed shear stress (computed with FaSTMECH numerical model) normalized by mean bed shear stress at the end of each run segment. Flow is from left to right. Shaded bars between maps indicate run segments with sediment augmentation.
(Figure 20C) and the spatial patterns (Figure 23). Similarly after run segment 6, there are cross-stream variations in bed texture, with relatively little cross-stream variation in bed shear stress (Figure 30).

3.3.4. Role of Bed Adjustments in Changing Transport Capacity

Sediment supply augmentation produced a general pattern of bed steepening and fining (Table 1). The Shields number, a non-dimensional ratio of stress \( \tau_0 \) to grain size \( D \),

\[
\tau^* = \frac{\tau_0}{(s-1)\rho g D}
\]

where \( s \) is the sediment specific weight (set as 2.65), \( \rho \) is water density, and \( g \) is the acceleration of gravity, can be used to estimate the relative contribution of stress (topography) and grain sizes to the increase in transport capacity (Table 2). The Shields number formed using the spatially averaged stress and grain size increased from 0.092 for Day 1, to 0.0113 for Day 4 to 0.129 for Day 14, consistent with the increase in transport rate. An approximate estimate of the relative effect on transport rate of stress and grain size can be developed by calculating the Shields number using the stress for Days 4 and 14 while holding the grain size at its value for Day 1, or using the grain size for Days 4 and 14 while holding the stress at its value for Day 1. Although small in magnitude (<1mm), changes in grain size account for 30-40% of the increase in Shields number while holding

<table>
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<th>Grain size adjustment only</th>
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<td></td>
<td>( \tau^* )</td>
<td>( % \text{ of total increase} )</td>
</tr>
<tr>
<td>1</td>
<td>0.092</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.113</td>
<td>0.104</td>
</tr>
<tr>
<td>14</td>
<td>0.129</td>
<td>0.123</td>
</tr>
</tbody>
</table>

Table 2. Shields number response for constrained runs. Mean Shields number is computed from the mean bed shear stress and the mean surface \( D_{50} \) (Table 1). Stress adjustment only indicates bed shear stress is computed holding \( D_{50} \) constant. Grain size adjustment only indicates that grain size change is calculated holding bed shear stress constant.
stress constant. The increase in stress accounts for 54-66%. The partition is only approximate because it used spatially averaged values and does not account for the interaction between stress and grain size via hydraulic roughness.

The spatial distribution of Shields number can affect sediment transport in ways not reflected by changes in mean values. Because of the non-linear relationship between bed shear stress and sediment transport rates, a bed with a non-uniform stress distribution can have a higher sediment flux than a uniform bed with the same mean bed shear stress [Paola, 1996; Nicholas, 2000; Ferguson, 2003; Francalanci et al., 2012]. Francalanci et al. [2012] use a numerical model to suggest that the relation between spatial variation and transport can be complex, producing increased flux given lateral topographic and stress variation and decreased flux given longitudinal variation.

The bed height distribution (Figure 20F) became slightly more uniform during the first augmentation whereas the bed stress distribution (Figure 20G) remained unchanged. During the recovery period, variability in the bed height distribution remains stable, whereas the bed stresses become more variable (Figure 20G, Figure 29, Figure 30). Taken alone, the expected effect of decreasing stress variability would be a decrease in transport capacity during the first augmentation followed by an increase in transport capacity during the recovery. During the second augmentation and recovery, both the bed height and bed stresses become more widely distributed (Figure 20F and G) in terms of standard deviation and spatial pattern of bed stresses (Figure 30, segments 6 to 14) driving an increase in transport capacity.

Increased variance in bed stress can increase the sediment transport relative to a uniform bed; however it is the spatial distribution of both grain size and bed stress, that drives the transport rates. The effects of increased variability in the bed shear stress field can be offset by changes in the variability in the bed grain size patterns. Where high stress areas are also coarse areas (positively correlated grain size and stress), the increase in transport from stress alone can be diminished. At the beginning of the first augmentation,
the bed shear stress and grain size are slightly negatively correlated (Figure 20F) (correlation coefficient = -0.32). The spatial patterns of bed grain size (Figure 23, Run Segment 1), and bed shear stress (Figure 30, Run Segment 2) are such that the areas of high stress have slightly finer bed textures than the areas of low stress. During both augmentations, the stress-texture correlation becomes weaker. However, after both augmentations cease, there is a strengthening of the stress-texture correlation. The strongest correlation occurs at run segment 10 (correlation coefficient = -0.52). At this time, the bed shear stress has the greatest variability, elevating the transport rate relative to a uniformly distributed stress. At the same time the shear stress-grain size correlation is the most negative, meaning that both the patterns of stress and texture are arranged in such a manner to elevate the sediment transport. The largest increase in sediment transport rates from topography and texture patterns occurs when the patterns are most strongly correlated, and this occurs as the topography first adjusts back to the match the initial bar configuration. Although, during this run segment (10) the downstream WSEL was set erroneously low, inducing erosion from the downstream end (Figure 21B) and increasing the sediment flux rates making it unclear how much of the increased flux is attributable to the WSEL and how much is due to the spatial coherence of stress and grain size.

**3.3.5 Timing of Adjustments**

The bed and water surface slopes adjusted together and on the same timescale as the downstream sediment flux (Figure 20A and B) indicating that bed slope and mean bed stress were dominant controls of the bed response and transport capacity. The slope and sediment flux were adjusted by run segment four, however the bed grain size continued with small adjustments throughout the first recovery (Figure 20C). During the first recovery, there is a progression from the smaller (5 m) bedforms evident in the 25-40 meter range to longer ones (8-10 m) (Figure 22), and there is a decrease in the dominant period of the sediment flux fluctuations (Figure 20E). Similarly, the sediment flux and slope
both stop adjusting after the second augmentation (Figure 20A and B). During the second recovery, the bed configuration progresses through a series of mobile bedforms (Figure 20D), the dominant period in the sediment flux fluctuations decreases (Figure 20E), and the grain size becomes more strongly correlated with the bed stress (Figure 20F). The distinction between steady state sediment flux and fully adjusted patterns of topography and texture is important when evaluating both the nature and duration of bed response to an increase in sediment supply. The major bed slope adjustments occur while the flux rates (and slope) equilibrate, but the topographic distribution and grain size patterns that make up the bed configuration may still be changing and require more time to reach a steady state.

In flume experiments Pryor et al. [2011] found that the bed configuration resulting from a pulsed increase in sediment supply differs depending on whether the aggradation had reached equilibrium (defined by upstream and downstream sediment fluxes being in equilibrium). However, the results of the current experiments indicate that the bed configuration and texture may continue to adjust after the sediment fluxes equilibrate and that this later period of adjustment returns the bed configuration and texture closer to its original state. Madej et al. [2009] also observed that an increase in sediment supply produced pronounced changes in the topographic distribution, although these runs were halted before the sediment flux reached equilibrium and therefore represent the transient case. Again, additional operation of the system may have reduced or eliminated the differences in topography and texture from the initial bed state. Bed response to an increase in sediment supply can include a number of mechanisms interacting over different timescales. Mean grain size and topography (or slope) may adjust over one time scale, bringing the system close to steady state transport condition. Subsequent adjustments in the spatial patterns of topography and texture can take longer and may influence further adjustment in mean grain size. These considerations have important implications for the time scale of adjustment at the grain to bar scale which can influence habitat for aquatic organisms.
3.4. Conclusions

A series of flume experiments are presented to investigate the response of a gravel bed to an increase in sediment supply. The sediment supply augmentation was accomplished by manually supplementing the upstream supply in a recirculating flume to produce a constant, larger feed rate. In effect, a sediment-recirculating flume at steady state was switched to sediment feed conditions at a higher transport rate. The first augmentation was of sufficient duration to allow the bed to adjust to the higher imposed flux. When the augmentation ceased, the bed persisted in a recirculating mode at the higher load. The second augmentation was of insufficient duration to allow the transport to adjust to the supplied load. After augmentation ceased, the bed persisted in a condition that maintained the transport rate developed at the end of the second augmentation.

The bed and water surface slopes adjusted simultaneously and at the same rate as the increase in the downstream sediment flux. As the upstream and downstream fluxes equilibrated, the slopes stopped adjusting. Three other adjustments in bed topography and texture can influence transport rates: the spatial distribution of topography, and the mean and spatial distribution of bed grain size. These adjustments were observed to occur over a longer timescale, continuing to adjust after the slope and sediment flux had nearly fully adjusted. In this forced bar experiment, the initial and final distribution of topography (type, size, and location of bedforms) were similar. However, the intermediate states, even after the slope and fluxes stopped adjusting, were very different from the initial and final states. A progression of multiple scales of bedforms were observed migrating at varying celerities during the transition state.