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Dam failure created a 1000-fold increase in bedload supply to Fall River, a sinuous, low gradient, snowmelt-fed stream. This mobile sediment allows channel topography to change with stage. In a reach with resistant banks, the relationships between flow and bed material were studied by measuring bedload, bed and water surface topography, and velocity patterns at different discharges.

At bankfull flows, cross-sections showed maximum asymmetry: point-bars near the water surface and deep thalwegs. Bedload transport was concentrated on the point bar platforms.

At low flows, cross-section symmetry was greatest due to additional erosion of the high-flow point bars, and extensive thalweg filling. Bedload transport was more uniform across the channel.

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STAGE-DEPENDENT CROSS-SECTION ADJUSTMENTS IN A MEANDERING REACH OF FALL RIVER, COLORADO

FINAL REPORT

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Statement of Problem

The interaction between flowing water and the sediment which it moves is one of the primary concerns of fluvial geomorphology. This interaction can take many forms and can occur at different scales, from the formation of ripples at a micro-scale to planform adjustments at a macro-scale. This study evaluates an intermediate level or meso-scale channel adjustment of cross-sectional geometry.

Cross-sectional adjustments are of fundamental importance for river engineering, channel stabilization, erosion control, and navigation. For example, the changes in cross-sectional form, accompanied by changes in the position of maximum velocity and maximum shear stress, are important when deciding on the locations for dikes, jetty fields, or revetment. Also, the influx of large amounts of sediment to a channel can cause many types of channel adjustment, the most dramatic of which is a planform change from meandering to braided. Finally, channel adjustments at low flow are important to navigation.

Specifically, the objective of the study was to determine if changes in cross-sectional geometry and flow patterns are a function of stage when bed material is mobile at most discharge levels.

Fall River, located in Rocky Mountain National Park, Colorado, met the requirement of adequate available bedload of sand and gravel. In addition, the channel is constrained by outer banks which are fixed, at least at the time scale of this study, so that only cross-sectional adjustments will occur. The sediment moving through this stream originates from the 1982 Lawn Lake dam failure. This event increased the supply of bed material to the study reach, which previously had negligible amounts of bedload transport. Bedload transport rates increased by an estimated factor of 1000.

The banks of Fall River are composed of root-bound, fluvially reworked sediments. As a result, the banks are composed of interfingered lenses of different size sediment. Lenses of especially coarse sediment are interspersed with fine grained sediment in the lower bank, and the grain sizes generally decrease upward. Bank failure occurs from undercutting of the upper reinforced bank and subsequent slump-block failure. These slump-blocks remain vegetated and resistant for long periods, showing no noticeable change during several field seasons. They create a high roughness element along the outer banks.

The 90 km^2 drainage area above the study site provides discharge which can vary from 10 m^3/s (spring snowmelt maximum) to less than 0.5 m^3/s. The annual hydrograph is relatively simple, with a sharp rise to the spring high flows, and a more gradual falling limb extending throughout the summer to the autumn and winter lows. Discharges are not dramatically modified by summer thunder storms. Water surface slope varies with the hydrograph (primarily through a change in path length) from 0.00132 at high flows to 0.00122 at low flows.

The channel is sinuous (~2.3), with bankfull width varying from 16 m in the bends to 9 m at the crossings. The concave banks through the bends and both banks through the crossings are vertical, except where there are slump-blocks in various stages of dissection in the bends. Maximum thalweg channel depth ranges from 1.2 to 2.0 m. The ratio of radius of curvature to water surface width for the study site was 1.3 at bankfull stage and 1.9 at low stage. Bedload is predominantly sand, with D_{50} about 1.0 mm, D_{95} 10.0 mm, and D_{05} 0.3 mm. Silt and clay are present in negligible amounts.

Procedure

Data were collected from 22 cross-sections that were established on a two-bend reach about 4 km downstream from the debris fan. During 1986, a complete set of measurements was taken during all portions of the hydrograph: rising stage, bankfull, overbank flow, falling stage, and low flow. At each cross-section, the measurements consisted of bed and water surface elevations, velocity fields (both longitudinal and transverse to the cross-sections) and bedload transport rate. All data were collected from mobile bridges.

Water surface and bed elevations were measured from a level line strung between the cross-section endpoints, with a probable sag of 1 - 1.5 cm. These endpoints were surveyed to a common datum. Depth was measured from the line with a stadia rod.

The longitudinal and transverse components of the velocity field were measured with a Marsh-McBirney directional current meter, and the net vector was calculated. Velocity measurements were made at verticals one meter apart across each cross-section. At each vertical, measurement points were spaced about 15 cm apart, with closer readings near the bed.

Bedload was sampled using a Helley-Smith sampler. At each location where velocity was measured, bedload was sampled for two separate one-minute intervals. These samples were each weighed, and a portion was bagged for later grain size analysis.

The velocity measurements were subsequently plotted to identify the characteristics of the longitudinal and transverse fields. From the measurements for each cross-section, the net velocity, the net water discharge, the longitudinal discharge, and the transverse discharge were calculated. In addition the shear stress at the bed was calculated.

Bedload sediment was sieved, and the D_{05}, D_{16}, D_{50}, D_{84}, D_{95}, mean grain size, and a sorting value were calculated for each sample. Bed shear stress necessary to move both the mean grain size and the D_{95} for each sample also was determined. Dry bedload transport rate was calculated for each measurement, and bedload transport rates were mapped for the entire reach. Grain size data were graphed for each cross-section for all flow levels.

Results

The most significant change during the annual hydrograph was the cross-section adjustment to flow level. At bankfull and overbank flow, channel cross-sections were most asymmetric; the thalweg was at its maximum depth; and the point-bar at its maximum volume. The cross-sectional geometry changed slowly through the hydrograph, so that most of the cross-sections tended to be somewhat symmetric by September low discharges.

The channel was first surveyed during the rising stage from mid-May to the beginning of June, when discharge had increased from less than 0.5 m^3/s to between 2.2 to 3.3 m^3/s. The cross-sections at this time were slightly asymmetric, and they showed some distinct point-bar accretion and thalweg scour.

As stage rose in June to bankfull and higher discharges (with in-channel measured discharge between 4.1 and 6.1 m^3/s), the asymmetry increased. The thalweg was scoured to depths up to 2.0 m below the floodplain level, and the point-bars along the inner banks were built up almost to the water surface. In planform, the channel showed one point-bar in each bend and one continuous thalweg along the outer bank. High discharge lasted through June, with two distinct peaks.

During July, falling stage measurements were made while discharge ranged from 2.5 to 3.9 m^3/s. Channel cross-section asymmetry decreased again, primarily due to point-bar erosion. A several centimeter stage drop exposed most of the point-bar platform. Lateral planation both up- and downstream of the bend apex occurred, causing a "point" to form on the exposed point-bar platform. However, new active point-bars formed up- and downstream of the bend apex, so that two secondary submerged point-bars were located in each bend.

The change in point-bars from high to intermediate discharges was not accompanied by a significant change in the thalweg region. This is in contrast to the intermediate flows that occurred during the rising stage, when the point-bars were not yet at their maximum height, and the thalwegs were not excavated to their maximum depth. This caused a pronounced hysteresis effect, with stage being higher during the rising limb than during the falling limb for the same discharge.

By the time low flows of 1.1 to 0.5 m^3/s were reached in late August and early September, many channel cross-sections were almost rectangular. These rectangular cross-sections had wide, shallow flow, and appeared as riffles. Thalweg filling was predominant during this stage, and deposition of up to 1.0 m occurred. Two pools remained in each bend. These pools were preferentially located downstream from abrupt curvature changes. The channel form had adjusted, from a single point-bar and thalweg in each bend, to two pool-riffle sequences.

The velocity fields displayed trends which helped to explain the topographic adjustment. The longitudinal velocity fields showed little variation from high to low flows. However, the transverse velocity fields changed dramatically.

At high discharges, each topographic zone had distinct transverse velocity components. The helical flow cell was confined to the central third of the channel, over the point-bar slope. Flow over the point-bar platform was outward (toward the concave bank) only. The outer third of the channel, in the thalweg region, was a zone of high turbulence. Short lived cells, of 5 - 15 minute duration, occurred in this region. These generally were of opposite rotation to the helical flow cell, and their development and decline could be seen as eddies on the water surface. In this study reach the entire outer zone, extending up to a third of the channel width from the bed to the water surface, was a zone of fluctuating, turbulent, short-lived cells. The primary cause of this phenomenon was the high roughness provided by the slump-blocks of various heights and in various stages of breakdown occurring along the base of the outer banks. Slump-blocks thus exerted a major control on velocity distribution.

At intermediate flows, the transverse velocity patterns changed spatially in both cross-section and planform views. Patterns for rising and falling stage were similar. The helical flow cell expanded in the plane of the cross-section, filling the outer two thirds of the channel, including the thalweg zone. The zone of bed- and bank cells correspondingly diminished, so that it was almost non-existent in most cross-sections. The zone of outward flow over the point-bar platforms was maintained. However, during falling stage, two point-bars formed in each bend, one upstream and one downstream of the bend apex. At cross-sections measured between these two secondary point-bar platforms, flow was inward over the entire channel bed, and at times the helical cell disappeared. This pattern also occurred during rising stage, but the two subaqueous point-bars in each bend were not recognized. Thus at intermediate flows, although the helical flow cell occupied more area in most bend cross-sections, it was effectively divided into two separate cells in each bend.

At low (20-30 cm deep) flows most of the bed was flat, and cross-sections were somewhat rectangular. Transverse velocity profiles were chaotic and weak, showing little recognizable pattern. The primary control on the transverse velocity appeared to be the bed forms. These were up to 10 cm in height, and still migrating downstream. However, in the pool areas some remnants of the helical cell still existed.

The bedload transport pattern also provided some insight into the mechanisms of cross-section adjustment. The unit bedload transport rate ranged from 0.33 to 0.10 kg/m-s during high flows and from 0.14 to 0.02 kg/m-s during low flows. The D_{50} of the bedload varied from about 1.4 mm at high flows to 0.8 mm at low flows.

However, the most important variations were in the cross-section distribution of unit bedload transport rate and the change in the locations of transport across the cross-section with changing stage. At high discharges, almost all bedload moving through the bends was concentrated on the point-bar slope. Large dunes, with heights up to 50 cm, traveled across the point-bar slope, while only a thin layer of moving sediment with no discernible bedforms was transported across the point-bar platform. Almost no sediment transport was measured in the thalweg region, except near the bend exit. When sediment was measured in the upstream portions of the thalweg, it consisted of gravel or small pebble clasts, and a small amount of very fine, dark sediment of local origin. Thus at bankfull discharges, the thalweg region was sediment starved. This factor, along with the associated high velocities and high turbulence in the thalweg, caused the fluvial entrainment of non-cohesive sediments at the toe of the bank during high flows. This entrainment, in turn, led to subsequent slump-block failure.

At intermediate flows, higher transport rates were measured in the thalweg region. The zone of maximum sediment transport was shifted outward, but was still located on the point-bar slope, which was also shifted toward the outer bank. Transport rates were higher during rising stage than during falling stage.

During low flows, there was no preferential location for maximum bedload transport rate. Rather, sediment transport was at a maximum in the channel center, and decreased gradually to zero at the water's edge.

The location of the maximum shear stress zone (as defined by the velocity gradient) coincided with the position of maximum bedload transport rate at all flow levels. At high discharges, the zone of highest bed shear stress was confined to the point-bar slope through most of the bend, only shifting to the thalweg region near the bend exit. The maximum bed shear stress zone shifted outward at intermediate flows, and became muted at low flows.

The bedload size distribution pattern also differed through the various flow levels. Differential size transport, causing subsequent bedload sorting, is a function of both cross-stream bed slope and cross-stream or transverse flow. Since both controlling factors varied with discharge, the overall bedload size distribution and sorting patterns varied as well. Between high and intermediate discharges, little variation in pattern occurred. At these discharges, both cross-section asymmetry and strong helical flow develop. Differential grain size transport and sediment sorting and resorting at these discharge levels were continuous. At each bend entrance, the coarsest sediment was located near the inner bank, and the finest near the outer bank. As sediment moved through the bend, the coarser fraction moved preferentially down-slope toward the outer bank, while the finer fraction was swept inward. By the time sediment reached the bend apex, some of the coarsest sediment had been transported to the outer bank. However, the process continued through the remainder of the bend, so at the bend exit the grain sizes were most segregated, and the bedload samples were most well sorted.

At low discharges this continuous process did not occur. Cross-sectional asymmetry was confined to the pools in each bend, as was any helical flow. At each bend entrance, the bedload size distribution pattern was the same as for higher discharges. However, as the sediment moved through the bend, no gradual resorting occurred until a pool was reached. Then abrupt changes in the grain size distribution were measured. Downstream from each pool, no additional change occurred until the next pool was reached. Thus differential size transport and subsequent sorting were gradual, continuous processes at high and intermediate flows, and abrupt and discontinuous at low flows.

Fall River can be viewed as a system dominated by both positive and negative feedback mechanisms. Within its outer, rigid banks, changing discharge levels affect the strength of the helical flow cell and the amount of sediment in transport. The helical flow cell and the bed- and bank cells that form at higher discharges control the position of the zone of maximum sediment transport. The interactions between the patterns of sediment transport and shear stress in the downstream direction control the bed topography, creating the point-bars and excavating the thalweg. When discharge changes, the new flow patterns are influenced by the preexisting channel topography.

During the rising limb of the annual hydrograph, starting with roughly symmetrical cross-sections, increasing discharge causes the helical flow cell to become stronger as the width-depth ratio of the flow decreases and the velocities increase. The stronger helical cell erodes the sediment deposited at low flow in the outer part of the cross-section, thereby causing excavation of the thalweg. The outward movement of sediment from the bend entrance, coupled with the decreasing bed shear stress along the inner bank, builds up the point-bar platform while the helical flow cell creates the point-bar slope. The meeting of the outward velocity over the point-bar and the helical cell defines the sharp break between the point-bar platform and slope. As stage rises higher, the point-bar approaches the flood plain level. Bed- and bank cells caused by the high concave bank roughness elements (i.e. the slump-blocks) occur in the thalweg region. These high velocity, high turbulence cells, in conjunction with the helical cell, keep the thalweg sediment transport minimal, and transport is confined to the point-bar slope. Cross-section asymmetry is at a maximum.

The change in bed topography due to falling stage reverses the sequence. High velocity flow erodes laterally into the subaerially exposed platform, causing the inner edge of the channel to retreat while new point-bars are formed upstream and downstream of the bend apex. The bed and bank cells which were strong at high discharges become weakened, and the helical flow cell extends into the thalweg. The highest bedload transport rates are closer to the concave bank, and the thalweg, which was sediment-starved at high flows, becomes a region of sediment transport. As stage falls farther, both the strength of the helical cells and their size in each bend decrease. The thalweg starts to aggrade, since sediment is no longer being swept away from the outer bank. Aggradation of the thalweg increases the width-depth ratio of the flow in the area of helical flow. This further weakens the helical flow cell, causing positive feed-back that induces more thalweg aggradation. Weak helical flow and cross-section asymmetry remained at the lowest flows. However, the affected areas were small in comparison to the rest of the channel. The new pools, or areas of cross-section asymmetry, were associated with narrow zones in the channel, downstream from sharp curvature changes. This tends to confirm the importance of the width-depth ratio in determining the strength of the helical cell.

From the evidence provided by topography, velocity patterns, and grain size information, it appears that at bankfull and overbank discharges, the river is in equilibrium with its outer planform. The thalweg is relatively continuous, and it is deepest from just before the bend apex to the crossing, not downstream from the apex, as some models assume. One point-bar forms in each bend, centered on the bend apex, while the crossings are located at the bend inflection points. One helical flow cell dominates each bend, and it is continuous through the bend. Finally, the processes that result in bedload sorting are continuous throughout the bend.

As stage drops, these patterns change. The helical cell splits into two zones in each bend, and two smaller point-bars form. At low flows, the spacings of pools and riffles or crossings bear no relationship to the channel planform. It thus appears that bed topography in Fall River is a function of stage, and that only bankfull discharge creates a bed topography consistent with the channel planform.

Several discrepancies with currently accepted ideas, and some patterns not previously noted, were found in this study:

(1) The outer zone of cross-stream flow, located over the thalweg, is not occupied by the helical flow cell during high discharges. Instead this is a zone of high turbulence and short lived bed- and bank cells. These bed- and bank cells form due to the high roughness element represented by the jagged outer banks, and their strength is a function of stage.

(2) While the helical flow cell occupies more of the thalweg in some cross-sections at slightly less than bankfull flows, it does not follow that it is "stronger" at just under bankfull flows, because the cell itself splits into two, and occupies less of the channel.

(3) Cross-stream flow over the point-bar platform is outward over the entire depth of flow at high discharge, and does not constitute part of the helical cell. This is due primarily to shoaling over the point-bar platform which builds up close to the water surface. During falling stage, most flow was outward over the new lower elevation platforms, but between the two halves of the helical cell in each bend, flow was inward.

(4) At high flows, sediment transport through the thalweg, especially that portion close to the concave bank, was almost zero, and the thalweg was not a zone of high bedload transport.

(5) The zone of maximum bedload transport shifted closer to the concave bank as stage dropped, rather than maintaining the same position through the channel at all flow levels.

(6) The zone of maximum bed shear stress is located over the point-bar slope, and only shifts to the thalweg near the bend exit.

(7) Sorting of bedload occurs at all discharge levels, but it is continuous through the entire bend at higher discharges, and is abrupt and discontinuous at low discharge.

The primary conclusions from this study on a reach of Fall River are:

(1) Cross-section symmetry is controlled by stage when there is a significant amount of mobile bed material available to be transported within a channel with resistant banks.

(2) Three-dimensional flow patterns, especially the cross-stream portion of the flow vectors, change with stage and control bedload transport and sorting patterns.

(3) The introduction of large amounts of sediment into a river can be accommodated by stage-dependent changes in cross-section geometry when the concave banks are very erosion resistant, rather than by adjustment of the channel planform.

(4) Given a fully mobile bed, the channel planform is in equilibrium with the bed topography only at bankfull and higher discharges.

The study has provided additional information on how flow patterns can change as a result of change in stage in a meandering reach. While other rivers with lower bedload may not show the same magnitude of cross-sectional adjustment, the velocity patterns may have the same trend with respect to stage. This change, particularly in the cross-stream patterns, should help in understanding phenomena such as bank erosion at various flow levels. High turbulence, combined with bed- and bank cells in the thalweg at high discharge may be much more important than helical flow in undermining cutbanks and causing meander migration.

The primary finding of the investigation, that cross-section shape in meander bends is stage-dependent, has significant implications for river management, and helps to explain anomalous adjustments. For example, bank revetments are emplaced to prevent lateral migration of many rivers that are used for commercial navigation, but revetment of a low-radius-of-curvature bend on Red River, Arkansas, caused the channel to become shallower and wider during periods of low discharge. The changes in cross-section shape caused reduced flow depths for navigation through the entire bend, rather than just in the crossings, which is the normal problem during low flows. It appears that cross-section geometry in the revetted bends is stage-dependent, and that changes similar to those observed in Fall River occurred over the duration of flood hydrographs.

List of Publications

Anthony, D.J. and Harvey, M.D., 1990. Stage dependent cross-section adjustments in a meandering reach of Fall River, Colorado: Manuscript to be submitted to Earth Surface Processes and Landforms.

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