Recent Advances in Sedimentation and River Mechanics

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Abstract. This article describes some of the recent and on-going research developments of the author at Colorado State University. Advances in the field of sedimentation and river mechanics include basic research and computer modeling on several topics. Only a few selected topics are considered here: (1) analytical determination of velocity profiles, shear stress and sediment concentration profiles in smooth open channels; (2) experiments on bedload particle velocity in smooth and rough channels; (3) field measurements of sediment transport by size fractions in curved flumes. In terms of computer modeling, significant advances have been achieved in: (1) flashflood simulation with raster-based GIOS and radar precipitation data; and (2) physically-based computer modeling of sediment transport at the watershed scale with CASC2D-SED. Field applications, measurements and analysis of hydraulic geometry and sediment transport has been applied to: (1) gravel-bed transport measurements in a cobble-bed stream at Little Granite Creek, Wyoming; (2) sand and gravel transport by size fraction in the sharp meander bends of Fall River, Colorado; (3) changes in sand dune geometry and resistance to flow during major floods of the Rhine River in the Netherlands; (4) changes in hydraulic geometry of the Rio Grande downstream of Cochiti Dam, New Mexico; and (5) analysis of the influence of water temperature and the Coriolis force on flow velocity and sediment transport of the Lower Mississippi River in Louisiana. Recent developments also include two textbooks on "Erosion and Sedimentation" and "River Mechanics" by the author and state-of-the-art papers in the ASCE Journal of Hydraulic Engineering.

1. Introduction

At the request of the organizing committee of this conference, the author aims at describing some of his recent and on-going research in the field of sedimentation and river mechanics at Colorado State University. There are two main axes of development currently under way that determine the structure of this presentation: (1) basic research and computer modeling; and (2) field applications. There are many activities currently going on and a summary of ten research activities is presented in this paper. The following presentation is inevitably focusing on the author's primary interests and research activities.

In general, the author had the privilege to teach two graduate courses at Colorado State University for about 15 years. These two courses led to the preparation of lecture material published in two textbooks at Cambridge University Press with book titles identical to the course titles: (1) *Erosion and Sedimentation* published in 1995; and (2) *River Mechanics* to be published in May 2002. Both textbooks present a concise description of the topics with pedagogically selected methods for teaching the fundamentals of the field.

They are not meant as encyclopedic references but the concise nature of the presentation were also intended to meet a criterion of affordability at the student level in any country around the world.

The author also has the privilege to serve as Editor of the ASCE Journal of Hydraulic Engineering. The journal fosters presentations of the latest technological developments in hydraulic engineering around the world. In fact about two-thirds of the manuscripts submitted to ASCE-JHE originate from outside the US. Discussion of the theoretical and academic papers and technical notes are encouraged, as in past years. The journal also promotes Case Study papers with engineering applications that are site specific and design oriented. Forum articles of broad hydraulic engineering interest are also encouraged.

The objective of this article is to briefly summarize some of the on-going research results on sedimentation and river engineering. Ten topics are presented without any priority, but broadly classified on one side as basic research and watershed modeling and on the other side field applications.

2. Basic research and computer modeling

Two areas are differentiated under this broad category of basic research and computer modeling. There are several sub-areas that could be covered under basic research and three of them will be briefly discussed here: (section 2.1) shear stress, velocity profiles and sediment concentration profiles; (section 2.2) bedload particle velocity; (section 2.3) sediment transport by size fractions in curved channels. In terms of computer modeling at the watershed scale, two aspects are covered: (section 2.4) flashflood modeling using GIS and remotely sensed rainfall data; and (section 2.5) sediment transport modeling by size fraction at the watershed scale.

2.1. Shear stress, velocity and concentration profiles

In terms of basic research on shear stress distribution, velocity profiles and sediment concentration profiles, is has become increasingly clear that the logarithmic velocity profile cannot describe the near-surface flow velocity. In many cases, particularly in relatively narrow channels, the maximum flow velocity in a cross section occurs below the free surface and this cannot be described by any logarithmic profile. In recent years, and effort to include the law of the wake and add wake flow functions to the logarithmic velocity profile increased the applicability of the log-wake flow model. There again, the wake flow component could not replicate velocity measurements with a maximum below the free surface. Recent development by Guo and Julien (2001) suggested a modified log wake flow velocity profile by adding a term that accounts for the boundary condition at the free surface as shown in Figure

1. This enhanced model can replicate the very accurate laboratory measurements compiled at several different laboratories around the world. The analysis with the modified log-wake flow model usually shows that for smooth boundaries, the von Karman kappa remains constant at about 0.42. The wake flow function is a function of the width-depth ratio in channels with rectangular cross sections. The added term accounts for the upper boundary condition such as wind effects at the free surface.

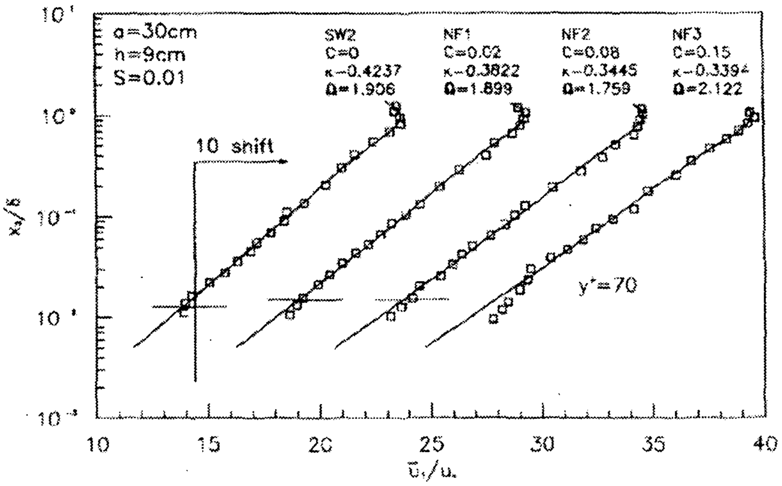

Figure 1. Agreement between the modified log-wake model and measurements, after Guo and Julien (2001)

Accordingly, shear stress distributions in smooth rectangular channels can also be analyzed with conformal mapping and the results are very close to those measured experimentally and published in the literature. The sidewalls affect the wake flow function by inducing secondary flows. Finally, the mixing coefficient can be defined from the modified log-wake function and the agreement with the field measurements is much better than with the traditional parabolic model, or with the layered models that have been proposed in the literature.

2.2. Bedload particle velocity

On-going experimental research on bedload particle velocities shows that on smooth boundaries, coarser spherical gravel particles move slightly faster than spherical sand particles. The measured particle velocities are quite comparable to the theoretical flow velocities calculated using the Reichardt equation for the transition between the laminar sub-layer and the turbulent layer. When the boundary roughness is increased, the velocities of all particles decrease but the coarser grains still move faster than the smaller grains. This also corroborates other experiments in the literature.

2.3. Sediment transport by size fraction in curved channels

Experimental research in a small sharply curved rectangular flume showed that under identical flow conditions the morphology of point bars was strikingly different for coarse sand than for fine sand. The analysis of Kawai and Julien (1996) based on a moment stability analysis of particles of different sizes under given secondary flow conditions in sharp bends showed different results for different size fractions as shown in Figure 2. The measured point bars of fine sands are larger than the corresponding point bars of coarse sands under identical flow conditions.

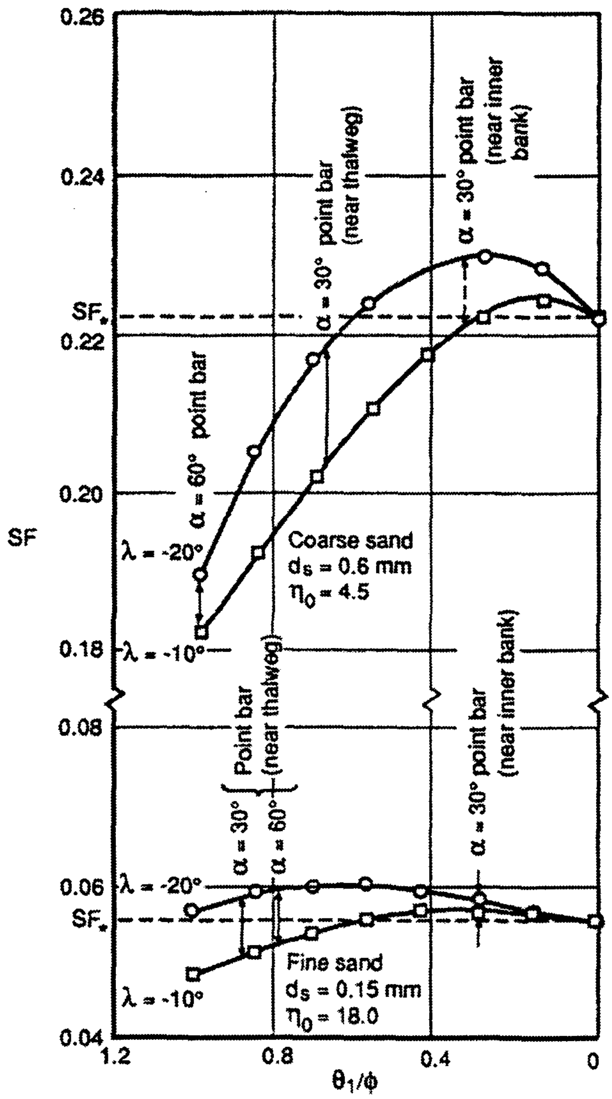

Figure 2. Particle stability diagram in curved channels (after Kawai and Julien,1996).

2.4. Flashflood modeling using GIS and remotely sensed data

The two-dimensional physically based rainfall-runoff model CASC2D developed at CSU by Julien et al. (1995) simulates spatially varied surface runoff while fully integrating GIS and radar-rainfall data. The model uses the inverse-square distance algorithm to distribute rainfall precipitation from a set of raingages, or uses radar rainfall data from either NEXRAD or Dual-Doppler radars like the CSU-CHILL radar at Greeley, Colorado. Infiltration is calculated using the Green-Ampt algorithm. The diffusive wave approximation of the Saint-Venant equations is used in two dimensions for sheet flow calculations in upland areas and one-dimensional flow calculations in channels. CASC2D offers unique color capabilities to display the spatio-temporal variability in rainfall, cumulative infiltration, surface runoff, flow depth and discharge. The model has been calibrated on about a dozen watersheds around the world and has provided adequate simulations of flashfloods for steep mountain watersheds in Colorado, Idaho, Arizona, Mississippi, and in Europe. The model can accurately simulate surface runoff from flashfloods caused by intense thunderstorms moving across partial areas of a watershed.

Jorgeson (1999) recently linked the model to NEXRAD radar data for the advanced prediction of peak flow discharge from localized thunderstorms for Cave Creek and the Hassyampa watersheds in Arizona. Flashfloods from intense local thunderstorms in arid areas were adequately simulated and he demonstrated that a gain in about 8-11 hours in lead time in the prediction of peak runoff discharges is possible from scanning the skies with NEXRAD radars and linking with a model like CASC2D.

Along the line of defining the rainfall characteristics of moving rainstorms in semi-arid climates, May and Julien (1998) examined several moving rainstorms monitored though a nested grid of raingages near Denver Colorado. The one-minute rainfall data from 76 raingages was examined to define the correlation structure of convective rainstorms in both Eulerian and Lagrangian frames of reference. It was demonstrated that the Lagrangian rainfall field shows considerable improvement and a significant reduction of the data scatter on correlation plots versus distance. The increase in correlation coefficients from Eulerian to Lagrangian reference frames typically ranged from 0.5 to 1.1.

2.5. Sediment transport modeling at the watershed scale

The model CASC2D has undergone significant developments in recent years regarding sediment transport modeling. The CASC2D-SED model has been pioneered by Johnson et al. (2000) and improved by Julien and Rojas (2002). The model uses a modified version of the Kilinc and Richardson proposed by Julien (1995) for the simulation of upland erosion. The modifications include some factors of the Universal Soil-Loss Equation, and a function of slope and unit discharge. Sediment transport in channels is calculated using the Engelund-Hansen algorithm. Sediment transport by advection considers both the suspended load and the bed material sediment transport. Transport is determined under the limitations between supply and capacity, and sediment settling is calculated for each size fraction at each time step. Some details of the algorithm are provided in the companion paper at this conference.

The model CASC2D-SED has been applied to the Goodwin Creek watershed in Mississippi for comparison with field measurements of surface runoff and sediment discharge at the outlet and at other internal locations within the basin. GIS data at 30 m resolution defines the surface topography and surface slopes. The channel network is also defined from a combination of GIS algorithms and analysis of channel planform geometry. The soil types are determined from the USDA soil classification maps available at the same scale. Land use and land cover data is also available from aerial photography. The Goodwin Creek watershed is also sub-divided into fourteen nested sub-catchments with a flow-measuring flume constructed at each of the drainage outlets monitored by USDA-ARS. The drainage areas above these stream-gaging sites range from 1.63 to 21.3 km^2.

The runoff event on October 17, 1981 was calibrated for the 90-m resolution grid. Outflow results for the described event show that CASC2D-SED is able to simulate the overall shape of the hydrograph, peak flow and time to peak at the basin outlet (see Figure 3). The sediment graphs calculated for this storm are also in very good agreement with the field measurements. Calculations by size fractions for sand silt and clays are readily possible and are the subject of on-going research.

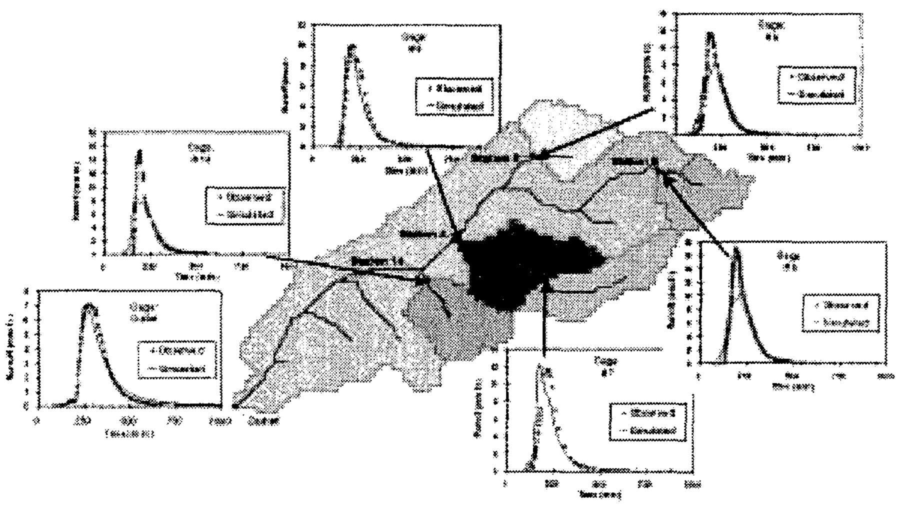

Figure 3. Observed and simulated hydrographs at the watershed outlet and at internal locations.

3. Applied research in sedimentation and river mechanics

The applied research considered in this section includes specific field sites where recent or on-going research is taking place. There are several sub-areas that could be covered under applied research. Five examples are summarized in the following: (section 3.1) steep mountain cobble-bed stream in Wyoming; (section 3.2) sediment transport by size fractions in a gravel-bed stream in Colorado; (section 3.3) changes in bedform geometry and resistance to flow during major floods of the Rhine River in the Netherlands; (section 3.4) hydraulic geometry changes of the Rio Grande downstream of Cochiti Dam in New Mexico; (section 3.5) temperature effects on sand transport in the Lower Mississippi River.

3.1. Gravel transport in Little Granite Creek, Wyoming

Little Granite Creek in Wyoming has been the subject of detailed sediment transport measurements by size fractions using Helley Smith samplers and sediment traps. Weinhold (2002) recently examined the hiding effect between non-uniform sediment particles on a streambed in terms of hiding factor. The Parker-Klingeman model was site calibrated and the optimized value of the exponent was found to be 0.973, which is very comparable to the value of unity found for equal mobility. The value of the reference shear, previously thought to remain constant, was also shown to vary with discharge. Common bedload equations typically overpredict sediment transport when applied by size fraction. This is due to the fact that most of the sediment transport in cobble-bed streams is transported as washload and is supply limited. A much better agreement with traditional equations like Meyer-Peter and Mueller or Einstein-Brown is obtained when using the surface material, or pavement layer, as shown in Figure 4. The Parker-Klingeman model with the Oak Creek calibration parameters also largely overpredicts the measured transport rates. Calculated results with the particle size distribution of the sub-pavement layer and the hiding factor are in good agreement with the field measurements at high discharge. Sampling techniques also appear to affect the field measurements of sediment transport. Helley-Smith measurements are typically in excess of the sediment trap measurements at low flows. The reason is that Helley-Smith samplers tend to disturb the bed and release sediment from the bed in near equal quantities. Sediment traps are less disturbing of the bed material and do not tend to wash out lots of finer material at low flows.

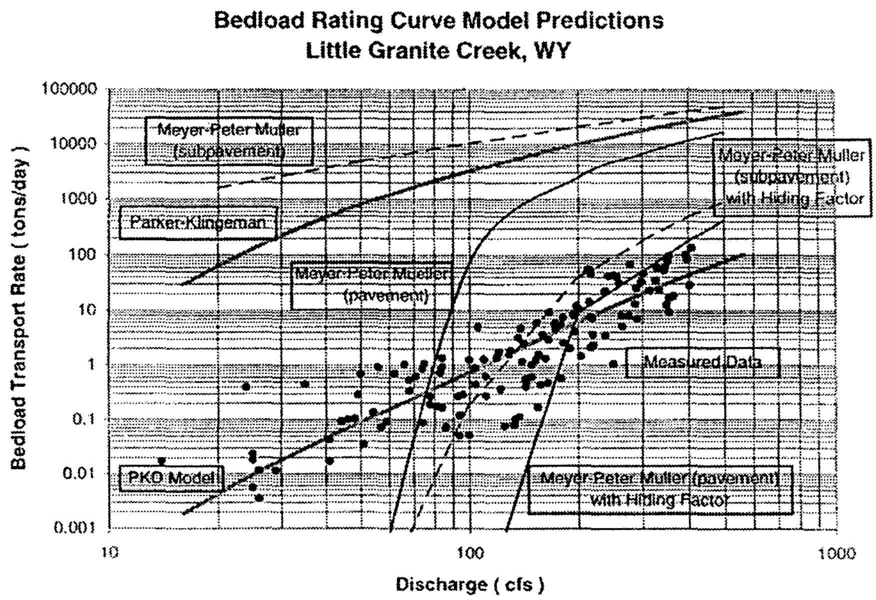

Figure 4. Sediment rating curves at Little Granite Creek from Helley-Smith measurements after Weinhold (2001)

3.2. Sand and gravel transport in the Fall River, Colorado

The very sharp meandering bends of the Fall River in the Colorado Rocky Mountain National Park have been monitored for several years. The analysis of sediment transport by size fraction by Julien and Anthony (2002) shows the differential direction of motion of 8 mm gravel compared to 0.25 mm sand particles in Figure 5. Coarse grains tend to move toward the thalweg of the sharp meander bends while under the same flow conditions, the finer sand fractions tend to move preferentially toward the point bars. This can be explained with a moment stability analysis of particles of different sizes under the same flow conditions. Also, the flow directions of particles of different sizes near the river crossings are nearly parallel and tend to cross over near the apex of river bends. This explains why the point bars of meandering channels tend to be primarily composed of the finer fraction of the sediment mixture carried by natural streams. This field analysis also corroborates the laboratory observations of Kawai and Julien (1996). The field measurements of the cross-section geometry of the sharp meander bends of the Fall River near the apex show that the cross-sections are nearly triangular in shape during floods with the thalweg shifting to the concave river bank. At low flows, the cross-section geometry becomes nearly rectangular, with near uniform flow depths and weaker secondary flows. The point bars are much smaller at low flows and tend to form during the major floods of Fall River.

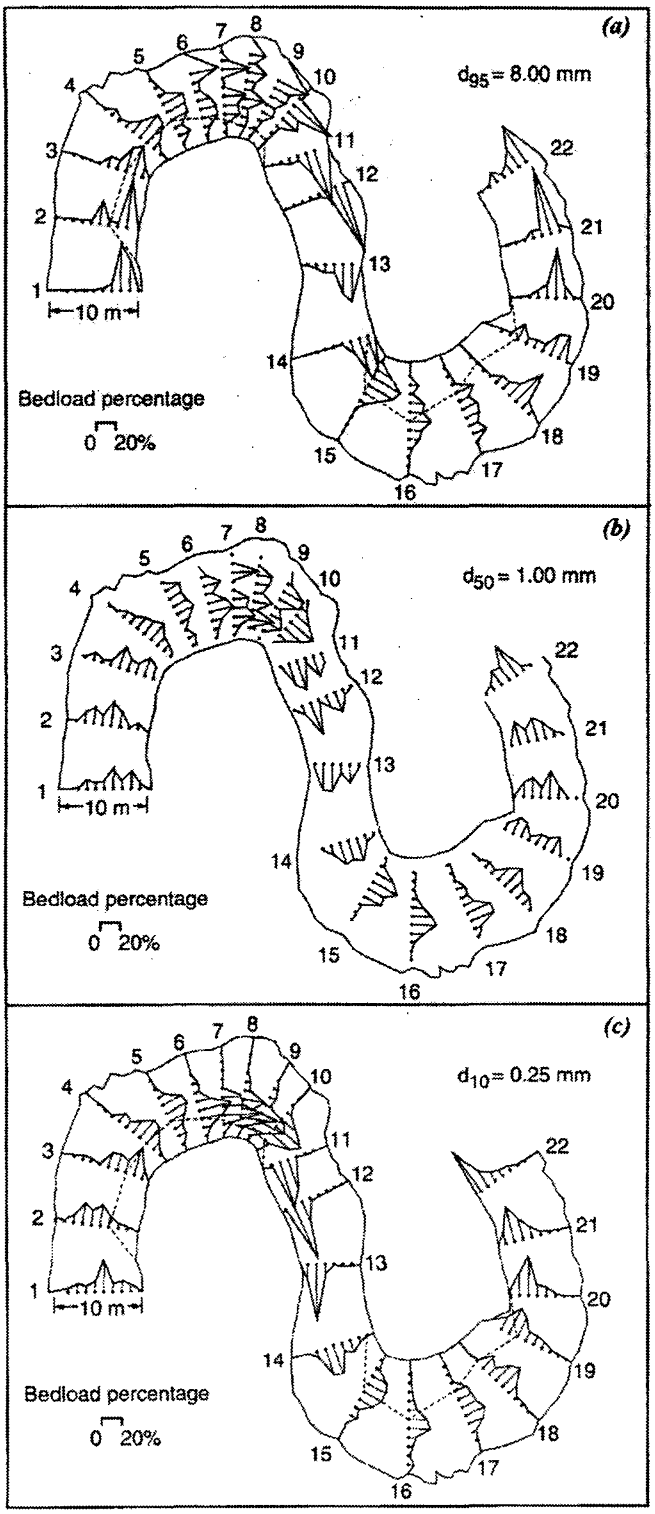

Figure 5. Differential motion of bedload material in sharp meander bends of the Fall River (after Julien and Anthony, 2002)

3.3. Changes in bedform geometry and resistance to flow during major floods of the Rhine River in the Netherlands

The Rhine River in the Netherlands experiences major floods exceeding 10,000 cubic meters per second. Julien (1992) examined the changes in dune properties measured during such major floods and observed that the dunes were growing in amplitude during the flood. More recently, Julien (2000) examined the changes in bed roughness and resistance to flow incurred during the 1998 flood of the Rhine River. A direct determination of bed resistance to flow was possible with high quality field measurements including hourly water surface elevation data, daily bedform measurements from single and multi-beam echosounders and detailed ADCP measurements of velocity profiles and flow depth. The field measurements in 1998 confirmed the earlier findings that dunes tend to grow during floods. The field measurements also clearly showed that Manning n and the Darcy-Weisbach friction factor increase with discharge in the Rhine River. Predictions of form drag with either Engelund or Vanoni-Hwang turned out to be fairly comparable but tended to overestimate the total bed resistance to flow when combined with the grain resistance calculations using the method of van Rijn. This shows that large rivers do not necessarily plane out during floods. The tendency to move toward upper-regime plane bed during floods thus cannot be applied to all rivers.

The formation of upper-regime plane bed and the determination of resistance to flow were also examined by Julien and Raslan (1998). Interestingly, two types of conditions for upper-regime plane bed emerge from: (1) the transition to hydraulically smooth boundary where the laminar sub-layer thickness, thus water temperature, plays a role; and (2) the transition to hydraulically rough boundary where the relative submergence is the main parameter, thus independent of water temperature. The field measurements of the Missouri River where the bedform geometry changes from dunes to plane bed as a function of temperature could be explained with the method proposed in the paper.

3.4. Changes in hydraulic geometry of the Rio Grande below Cochiti Dam, New Mexico

The Rio Grande has been the subject of recent studies of hydraulic geometry as a result of the decrease in sediment load resulting from the construction of Cochiti Dam in 1975. In a recent dissertation at CSU, Richard (2001) utilized an extensive database that has tracked changes in the river since 1895. The rates of lateral migration of the river were quantified using seven sets of aerial photographs spread over a time span of 74 years. Four indices of lateral movement and two indicators of lateral stability were measured from the digitized active channel delineation. The historic geomorphic analysis of the river shows that the river has moved toward a more stable state as the peak discharges decreased prior to and following the construction of the dam. Lateral movement rates have declined since 1918 and the channel has shifted from a multi-thread to a single thread pattern as shown in Figure 6 from Richard (2001). The lateral changes that began prior to the construction of Cochiti dam appear to be the results of changes in the hydrologic regime rather than changes in the sediment regime. A model describing the lateral movement of the Rio Grande has been defined and seems independent of the construction of Cochiti Dam. Interestingly enough, the planform geometry predictors to delineate meandering-straight-braided rivers predict the patterns of the Rio Grande in almost a random fashion. There is little evidence that any of the existing predictors in the literature really works for this river.

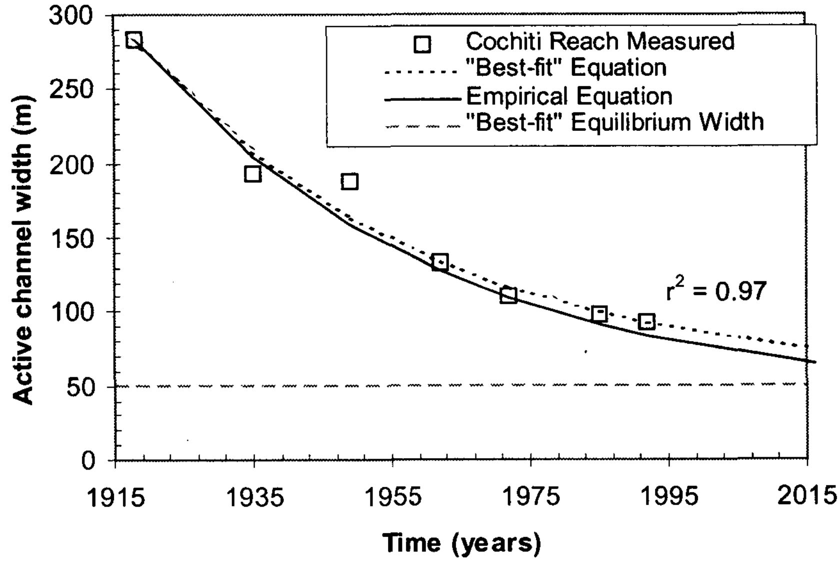

Figure 6. Active channel width of the Rio Grande below Cochiti Dam (after Richard, 2001)

3.5. Temperature effects on velocity and sediment transport of the Lower Mississippi River, Louisiana

The analysis of the effects of water temperature on sediment transport and velocity profiles of the Lower Mississippi River by Akalin (2002, dissertation in final preparation) shows that under the same flow discharge, there is a definite decrease in sand transport in summer compared to winter. The reason can be attributed to the decrease in near bed sediment concentration of fine and very fine sand as temperature increases. The near-bed sediment concentration of medium sand is comparatively unchanged. This also points to the fact that fine and very fine sand are considered as washload in the Mississippi River and constitutes most of the total sediment load. The medium sand fractions are found in the bed and the bed material transport, which is a smaller fraction of the total load, does not change much with temperature.

The effects of the Coriolis force due to the rotation of the Earth in this large fluvial system were also examined. Theoretically, the Coriolis acceleration represents up to 30% of the downstream gravitational acceleration. The ADCP measurements provide instantaneous measurements of volume-averaged velocity magnitude and direction. This data was compared with the theoretical calculations to find out that the agreement is very good in some cases, but an equal number of graphs with inverse relationships was also observed. In conclusion, no definite trend of the effect of the Coriolis force could be detected. The random variability associated with large-scale turbulence and possibly also bedforms seems to dominate the random variability observed in the measured velocity profiles. This random variability masks the likely influence of the Coriolis force even in very large rivers.

4. Conclusions

This article summarizes some of the recent developments and on-going research on sedimentation and river mechanics at Colorado State University. The importance of conducting basic research in parallel with field research is emphasized. The example of the analysis of particle direction from the flume scale (Kawai and Julien, 1996) to field applications in the Fall River by Julien and Anthony (2002) underlines the importance of using experimental research to explain field observations and to feedback field observations into basic research in the laboratory.

Recent advances in the modeling of surface runoff and sediment transport by size fractions at the watershed scale may lead to significant breakthroughs in the combined analysis of bed material load and washload. The field measurements discussed in this article point to the fact that washload is dominant in many streams from steep cobble-bed mountain streams like the Little Granite in Wyoming to the sand load of the large and flat alluvial Lower Mississippi River. The prediction of washload from watershed characteristics can only supplement all the river measurements of sediment transport based on riverbed material.

More recent research developments are worthy of mention. The ASCE Journal of Hydraulic Engineering has become the primary source for the most recent technical and case study papers on sediment transport and river mechanics. The journal features articles from all parts of the world with the largest possible audience.

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