Uncertainty in Sediment Transport Balance Estimates using Sediment Load and River Transect Data

Robert A. Mussetter, Program Manager, Tetra Tech, Inc., Fort Collins, CO, bob.mussetter@tetratech.com

Abstract

Two common, data-driven methods for estimating the sediment transport balance in rivers for aggradation/degradation studies rely on: 1) differences in sediment loads from rating curves developed from measured sediment transport data, and 2) differences in field-surveyed transects collected over a defined time-period. Analysis of an extensive data set collected in the central Platte River in Nebraska in 2009 through 2016 indicates that results from these methods are subject to substantial uncertainty, which limits our ability to draw firm conclusions regarding the sediment transport balance in the river. Because of the important role of such conclusions in management decisions, this uncertainty must be clearly understood and methods for limiting uncertainty incorporated into monitoring and analysis programs.

The monitoring data for this study included 8 successive annual surveys at 20 study locations distributed along the approximately 100-mile study reach, each of which consisted of 3 transects, and a series of 15 to 20 individual bed and suspended sediment load measurements at each of 5 locations. Best-estimate aggradation/degradation trends using the field surveyed transect data and the sediment rating transport rating curves were often in conflict. Uncertainty in the sediment transport-based estimates, quantified using the bootstrap method, indicated that the best-estimate trends were not statistically significant in most subreaches. The small size of the data sets was a key factor in the sediment load-based uncertainty. Only limited data were available to perform a rigorous sensitivity analysis on the transect-based estimates. Analysis of green LiDAR data, that penetrates through the water to the bed, that were collected in 2016 and 2017, after the field survey program was complete, suggests that error in the transect-based estimates is also substantial because, in several cases, changes at the clustered transects at each survey site do not adequately reflect changes in the river away from the study sites. As a result, conclusions drawn from the best-estimate values from the transect data are suspect.

Introduction

The sediment transport balance (i.e. the balance between the bed material sediment supply and the transport capacity) is a key factor in driving the dynamic behavior of rivers, including overall river stability, impacts to flood carrying capacity, and the quality of aquatic and riparian habitat. A deficit in bed material sediment supply compared to the transport capacity can lead to degradation (or downcutting) that can further lead to bank instability and damage to infrastructure including bridges, water-supply facilities, and flood protection works (Lagasse, et al. 2012; NTSB, 1988 and 1990). Excess bed material supply can lead to braiding and lateral instability, channel infilling, and reduced flood carrying capacity (Copeland, et al. 1999). Related processes can also affect the quality of instream and riparian habitat (Wohl, et al. 2015 Kondolf, et al. 1996; Gurtz, et al. 1984).

Two common, data-driven methods for estimating the sediment transport balance are based on: 1) differences in sediment loads from rating curves developed from measured sediment transport data, and 2) differences in field-surveyed transects collected over a defined time-period. The rating-curve method has the advantage of providing higher temporal resolution, but the spatial resolution is limited by the locations of the gages. The transect-based method provides high spatial resolution, at least in the area of the survey, but the temporal resolution is limited by the frequency with which the surveys can practically be conducted. Both methods are subject to substantial uncertainty, which limits our ability to draw conclusions regarding the sediment transport balance in the river. Because of the important role of such conclusions in management decisions, this uncertainty must be clearly understood and methods for limiting uncertainty incorporated into monitoring and analysis programs.

Sediment load-based estimates are typically developed by fitting a regression equation to sediment transport data, integrating the resulting curves over the appropriate flow record, and applying mass conservation principals to quantify aggradation/degradation trends. Uncertainty from this method derives from variability in the underlying measurements, uncertainty in the sediment transport rating curve, and lack of information on lateral inputs/sinks from tributaries, bank erosion and diversions between the gage sites. Transect-based estimates of the sediment transport balance are obtained by estimating the change in bed sediment volume based on changes in elevation along the transects between the successive surveys. Properly collected survey data accurately represent the elevation profile along the individual transects at the point in time when the surveys are conducted, but uncertainty in the balance estimates can still be quite large because of uncertainty in how well the changes at the individual transects represent changes in the remainder of the river bed away from the transects.

An extensive set of monitoring data that provides a means of assessing the uncertainty in both types of estimates in a wide, sand-bed river were collected in the central Platte River in Nebraska from 2009 through 2016 for the Platte River Recovery Implementation Program (PRRIP). The dataset includes annual transect surveys at 20 study sites distributed along the approximately 100-mile study reach (Figure 1), each of which consisted of 3 primary transects. The dataset also includes a series of approximately 20 individual bed and suspended load measurements at each of 5 locations distributed along the reach. In addition, a detailed topographic/bathymetric surface of the river bed was developed from LiDAR flights in Fall 2016 and Fall 2017 that integrated the traditional near-infrared spectrum with the green wavelength to sample both the subaerial and subaqueous portions of the river bed (Quantum Spatial, 2017 and 2018). This dataset provides a limited means of assessing the uncertainty in the transect-based estimates.

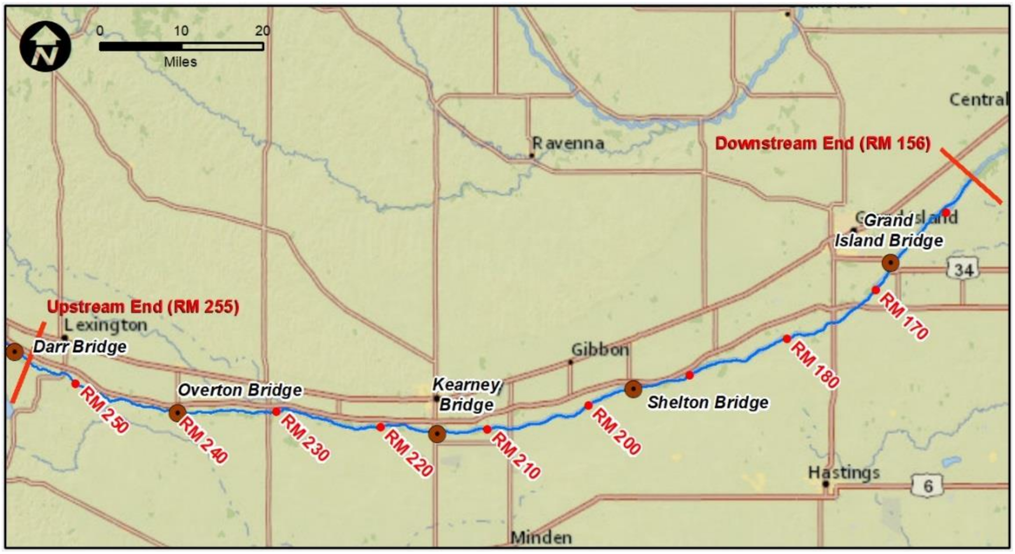

Figure 1. Central Platte River study reach. Sediment Transport measurements at labelled bridges.

Context for the Platte River Data Collection Program

The PRRIP was initiated in 2007 between Nebraska, Wyoming, Colorado, and the Department of the Interior to rehabilitate habitat in the Platte River for three bird species of concern (whooping crane, piping plover, and interior least tern) by restoring a braided channel morphology with sand bars free of vegetation, increased channel widths, and unobstructed views, while avoiding impacts to pallid sturgeon. Because of uncertainty in how the river will respond to proposed management actions, the Program developed several hypotheses related to the linkage between channel geomorphology, in-channel vegetation, and habitat (PRRIP, 2006). Among other hypotheses, the PRRIP postulated that eliminating the average annual sediment imbalance of approximately 400,000 tons in eroding portions of the reach will reduce net erosion of the river bed, restore and increase the sustainability of a braided planform, contribute to channel widening, and shift the river over time to a more vertically stable condition. Prevailing estimates at inception of the PRRIP indicated that an average annual sediment deficit of approximately 185,000 tons existed in the upper part of the reach between Overton and Kearney (~19 mi).

A channel geomorphology and vegetation monitoring program was carried out from 2009 through 2016 to collect and analyze a suite of data over a multi-year time-frame to test these and other key hypotheses (Tetra Tech, 2017; PRRIP, 2012). As part of this program, transect surveys were conducted once per year during mid- to late-summer at 20 study sites distributed along the approximately 100-mile reach. Each study site included 3 primary transects spaced at approximately 500-foot intervals (Figures 2 and 3), the endpoints of which were marked with permanent monuments to insure consistency in location during repeat surveys. In addition to the annual surveys, a series of 15 to 20 individual bed and suspended load measurements were made at each of 5 bridge crossings distributed along the reach (Figure 4). The data from the surveys and sediment load sampling were used to make independent estimates the sediment transport balance within the reach.

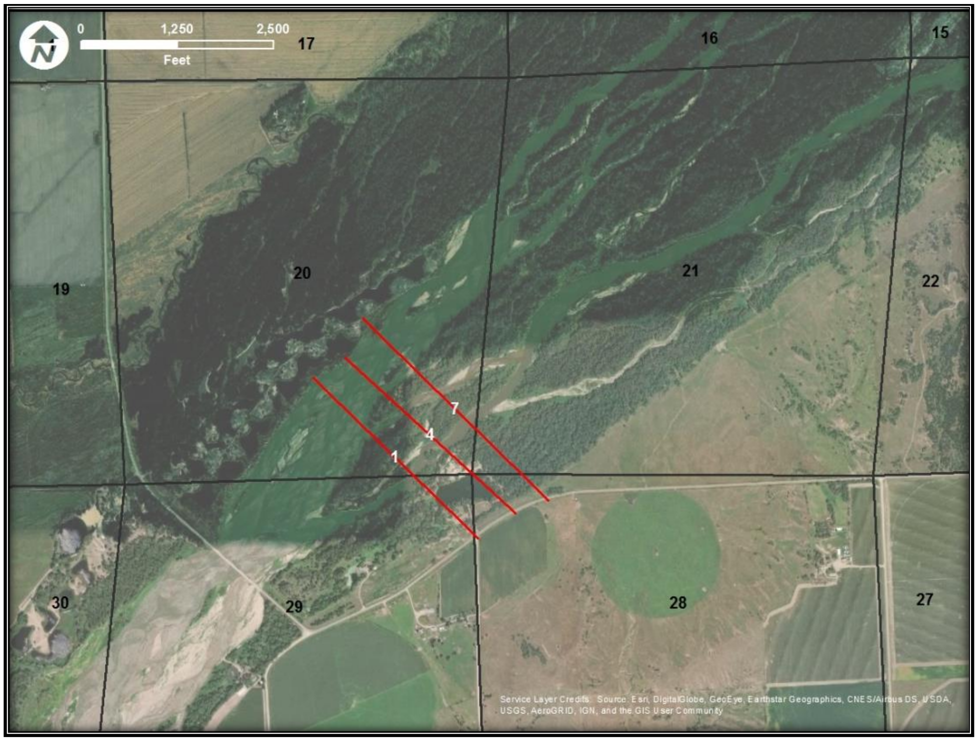

Figure 2. Typical layout of the 20 individual study sites

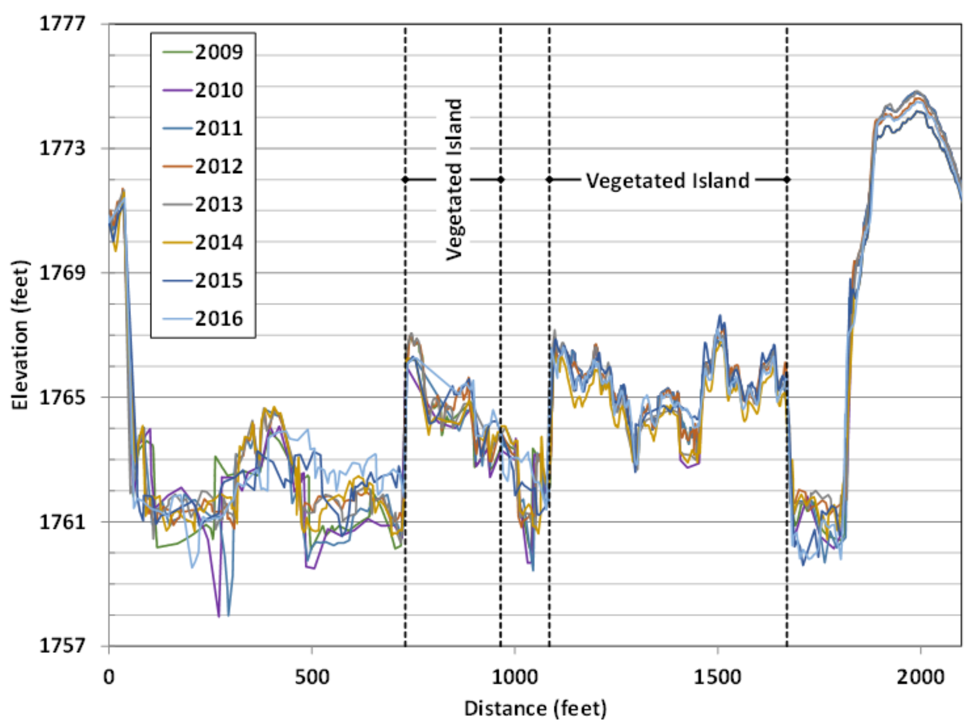

Figure 3. Profiles from repeat surveys of Transect 4 at the site shown in Figure 2.

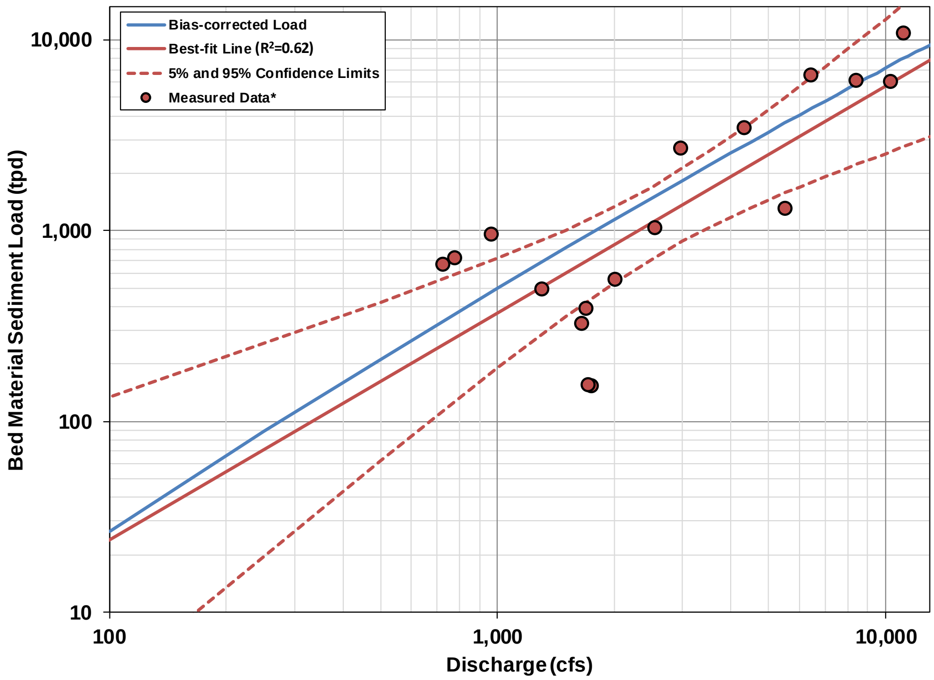

Figure 4. Example results of sediment transport monitoring, bed load measurements and bed load regression curves at Darr

Geomorphic Characteristics of the Central Platte River

An understanding of the current and historical geomorphic characteristics of the study reach are important to put the current condition into the context of anthropogenic activities, and particularly appreciating the challenges in collecting both the sediment load and survey data. Prior to European settlement of the Great Plains, the Platte River had a wide, braided planform that was driven primarily by snowmelt runoff from the mountainous regions of Colorado and Wyoming. In 1889, the journalist and humorist Edgar Nye coined the well-known phrase "a mile wide and an inch deep" to describe the Platte River. The river has undergone major changes in hydrologic regime and morphology since the mid-1860s (Eschner, et al. 1983; Williams, 1978). The changes in morphology primarily result from the changes in flow regime associated with upstream water-development, including construction and operation of storage reservoirs (Figure 5), irrigation diversions and ongoing groundwater development. Islands were a ubiquitous feature in the river, even prior to water development, with many large, timbered islands that were sufficiently high to "...be secure from the annual flood" (Freemont, 1845), and numerous smaller islands, most of which were covered by riparian species such as shrubs, young willows and cottonwoods (Eschner, et al. 1983). The change in flow regime, upstream sediment supply and other factors, including the effects of introduced species such as common reed (Phragmites australis) and encroachment into the river by infrastructure, caused the river to narrow dramatically from the conditions in the mid-1860s, primarily by progressive encroachment of vegetation and consequent vertical and horizontal accretion on sandbars in the channel (Eschner, et al. 1983; Williams, 1978) (Figure 6). As a result, the bed of the Platte River converted from a primarily braided planform characterized by constantly shifting sandbars and numerous braid channels over the bars in the mid-1860s to an island-braided planform with more stable, vegetated bars/islands and less channel shifting by the early- to mid-1900s, and then to an anastomosing planform with stable, vegetated bars/islands and a limited number of relatively stable channels by the late-1990s (Fotherby, 2008; Eschner, 1983; Williams, 1978). Despite the “relatively stable channels” under current conditions, the primarily sand bed remains highly mobile with active bedforms that present challenges for bathymetric surveying and bed load sampling.

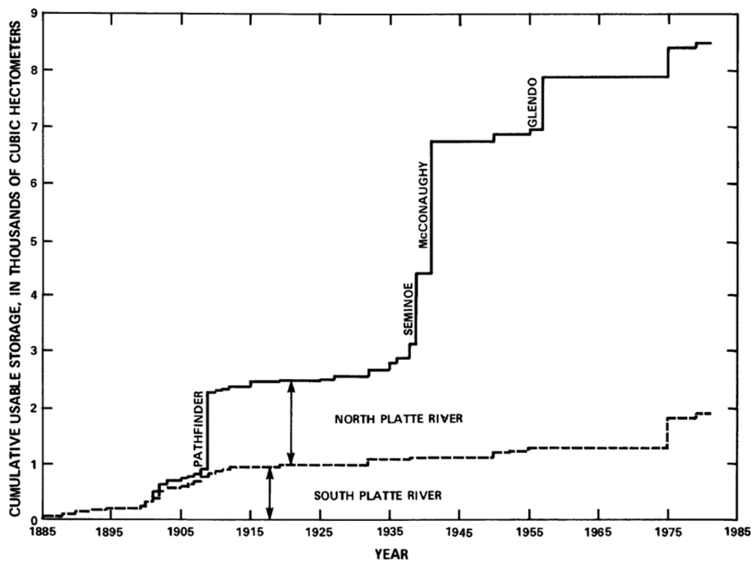

Figure 5. Cumulative usable storage of reservoirs in the Platte River basin (from Eschner, et al. 1983)

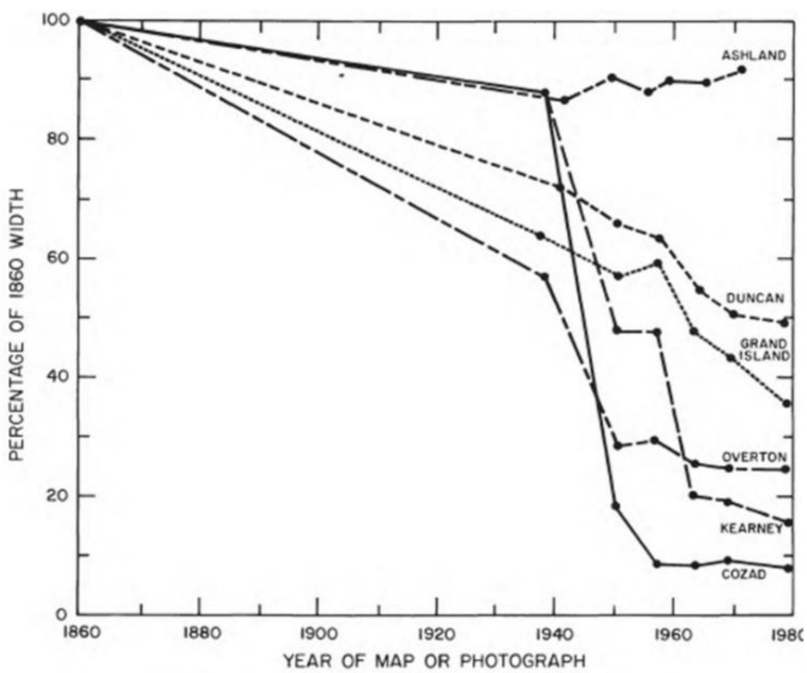

FIGURE 11.—At-a-station changes of channel width of the Platte River, Nebraska, with time.

Figure 6. At-a-station changes of channel width of the Platte River with time (from Eschner, et al. 1983)

Sediment Transport Balance Estimates

Bed and Suspended-Bed Material Load Measurements

The sediment transport measurements were made from the 6 bridges following USGS protocols (Edwards, et al. 1999) using a crane-mounted, 3" Helley-Smith bed load sampler and a crane-mounted D-74 suspended sediment load sampler. The data collection protocol envisioned up to 6 sampling events per year, including 3 samples at flows between 1,000 cfs to 3,000 cfs, 2 samples at flows between 3,000 cfs and 5,000 cfs and 1 sample at a flow greater than 5,000 cfs. Because of limitations caused by the timing and magnitude of the flows that occurred during the data collection period and access issues caused by road and bridge re-construction, 11 to 23 individual samples were ultimately collected at each of the bridges over the 7-year data collection period. As is typical with bed load measurements, in general, and those in a wide, shallow, sand-bed rivers, in particular, there was considerable scatter in the data. Correlation coefficients (R^2) for power-function rating curves for the bed load data ranged from 0.29 to 0.62 at the individual sampling locations. Less, but still substantial, scatter occurred in the suspended sand load measurements, with R^2 values ranging from 0.68 to 0.77.

Annual bed material sediment loads (i.e., sand and larger sizes) passing each bridge were estimated for each year of the data collection period using the above-described datasets and the recorded mean daily flows at each location. The estimates were made by developing bias-corrected rating curves using the Maintenance of Variance Unbiased Estimator (MVUE) method (Cohn and Gilroy, 1991) that is recommended by the U.S. Geological Survey (USGS, 1992), and integrating those rating curves over the mean daily flow records. The bed load and suspended bed material (primarily sand) load were treated separately and added together to provide the total load to maximize the number of data points, since there were some cases where a suspended sediment load sample was not collected in conjunction with a bed load measurement. An example curve for bed load transport resulting from least-squares regression and the corresponding bias-corrected curve are shown in Figure 4. The proportion of the total annual bed material load represented in the bed load ranged from 23% to 68% and averaged about 37% over all sites and years. In general, the percentage of bed load decreases with increasing discharge (Figure 7). The proportion bed load from this data set is consistent with those reported by Turowski, et al (2010) for large sand bed rivers.

Annual flow volume during the survey period varied widely from about 500,000 acre-feet (af) at Overton between the 2012 and 2013 surveys (exceeded in about 90 percent of the years between 1943 and 2017) to nearly 2.5M af during 2011 (exceeded in only about 6 percent of the years) (Figure 8). Maximum discharge also varied widely from about 4,070 cfs in 2013 (exceeded in about 60 percent of the years) to 15,900 cfs in 2015 (exceeded in only 4 percent of the years). Consistent with the flow variability, the estimated annual bed material loads also varied widely from year to year, with the loads in the dry year of 2013 typically in the range of 150,000 tons, increasing to about 1.5M tons during the wet years in 2011 and 2015.

Uncertainty in the annual loads was quantified using the bootstrap method (Efron, 1979; Efron and Tibshirani, 1986; Chernick, 1999). Bootstrap is a technique that involves resampling the original data set to develop empirical distributions of the key regression parameters, and from those distributions, nonparametric, Monte Carlo estimates of the uncertainty parameters (Chernick, 1999). The method is implemented by repeatedly generating new data sets equal in size to the original data set, but consisting of randomly selected values from the original data set.

This is accomplished by resampling with replacement, and then repeating the basic analysis of the parameters of interest for each new data set. The statistical parameters (e.g., mean, median, variance, skewness, etc.) of the resulting bootstrap-derived data sets represent estimates of the population parameters and their uncertainty, free of assumptions regarding the statistical distribution the variability about the mean, as is necessary using most analytical techniques for quantifying uncertainty. For purposes of this analysis, the bootstrap technique was used to generate 1,000 resampled data sets for each component, bed load and suspended bed material load, of the sediment load at each sampling location. The upper and lower 95% confidence limits on the estimates (whiskers in Figure 9) averaged about 34% and 26%, respectively, of the mean values from the Monte Carlo simulations.

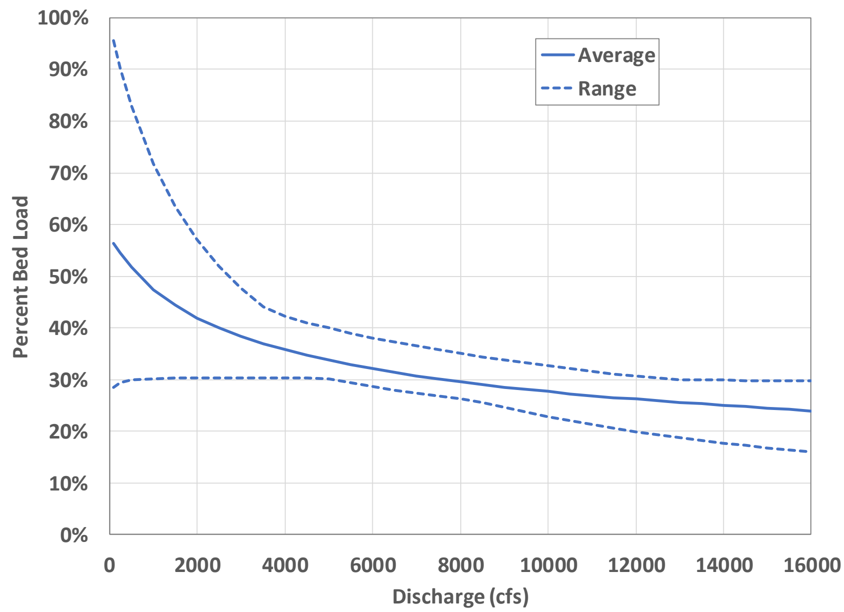

Figure 7. Percent of bed load in the total bed material load.

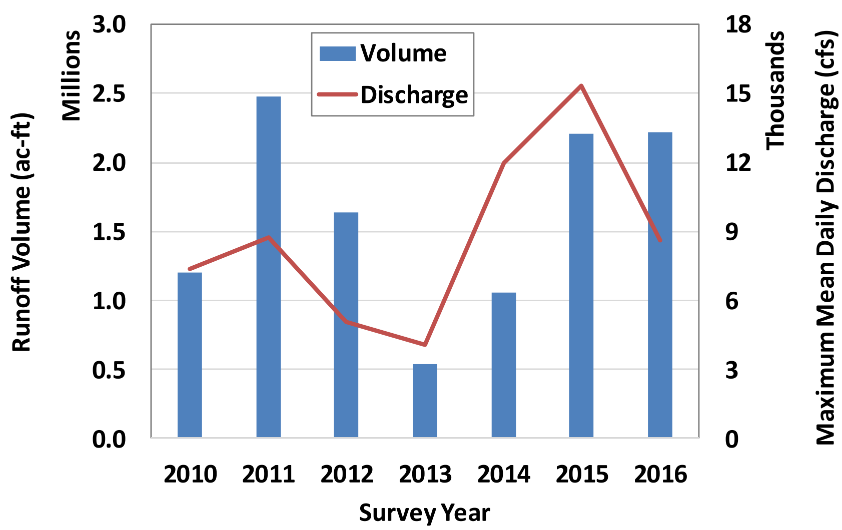

Figure 8. Annual runoff volume and maximum mean daily discharge at Overton during the 7-year survey period (initial survey conducted in 2009)

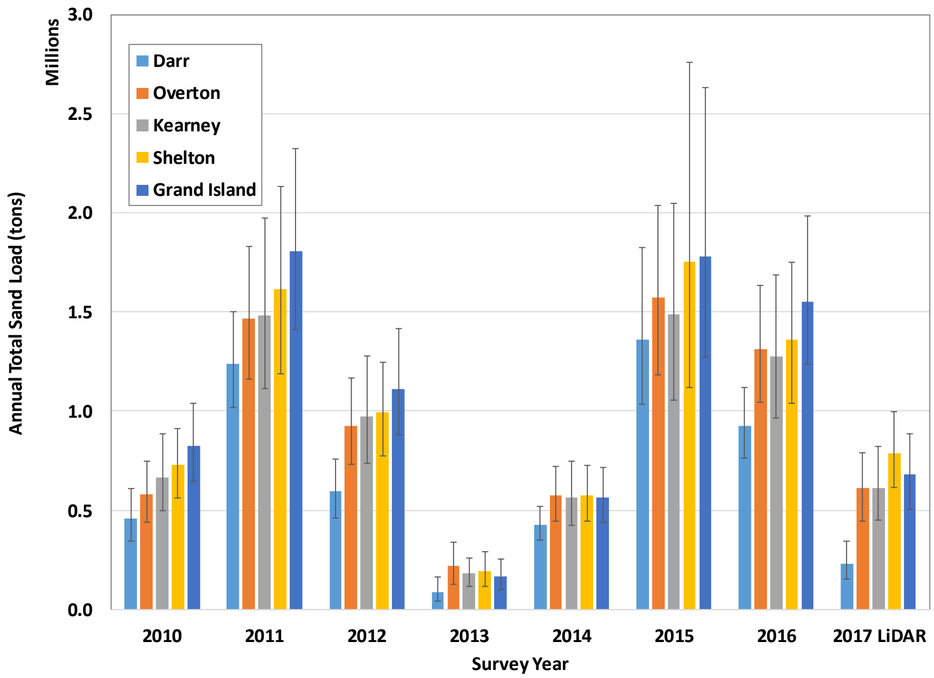

Figure 9. Estimated annual total bed material (sand) load at 5 measurement locations. Whisker represent upper and lower 95% confidence limits on the estimates. Also shown are the values for the period between the 2016 and 2017 LiDAR surveys.

Based on the best-estimate values of the annual loads from the rating curves, the reach from Darr to Overton was degradational in all years, with average deficit of about 215,000 tons per year over the period (Figure 10). The Overton to Kearney reach was mildly degradational during the first 3 years and then mildly aggradational during the last 4 years, with an overall average aggradation for the period of about 8,000 tons. The Kearney to Shelton reach was also degradational in all years, averaging about 89,000 tons per year over the period, and the Shelton to Grand Island reach was degradational during the first 3 years and the last year and aggradational during the 2014 and 2016, with overall average degradation over the 7-year period of 77,000 tons. Based on the error bands from the bootstrap analysis, however, the only result that is statistically significant at the 95% level is 2012, 2013 and 2016 in the Darr to Overton reach. For this analysis, the null hypothesis is that the reach is in sediment-transport balance. Since the error bands (whiskers in Figure 10) cross zero for all other cases, the null hypothesis cannot be rejected at the 5% (one-sided) level, and it must be concluded that the inferred aggradation/degradation trend is not statistically significant. Integration of the bias-corrected rating curves over the recorded flows for all years from 1984 through 2016 indicates that the portion of the overall reach between Overton and Kearney is approximately in-balance with no trend with annual runoff volume, while the portion of the reach from Kearney to Grand Island is net degradational with a strong trend of increasing degradation with increasing flow volume. (Figure 11).

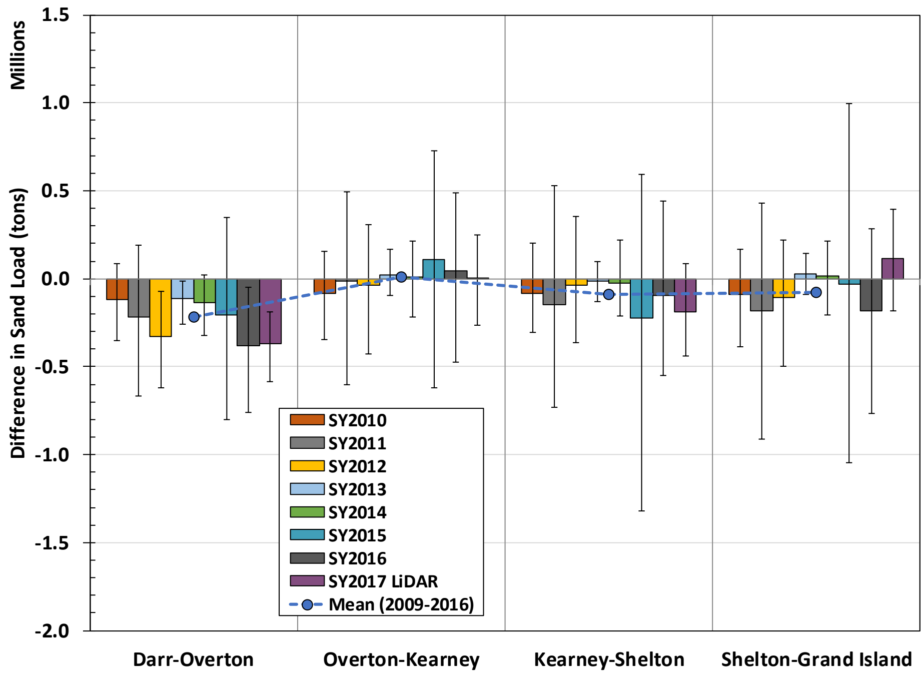

Figure 10. Estimated sediment deficit (-) or excess (+) in 4 reaches of the Platte River between 2009 and 2016, based on integration of the MVUE-based sediment load regression equations. Also shown are the values for the period between the 2016 and 2017 LiDAR surveys. Whiskers represent the upper and lower 95% confidence bands on the estimates.

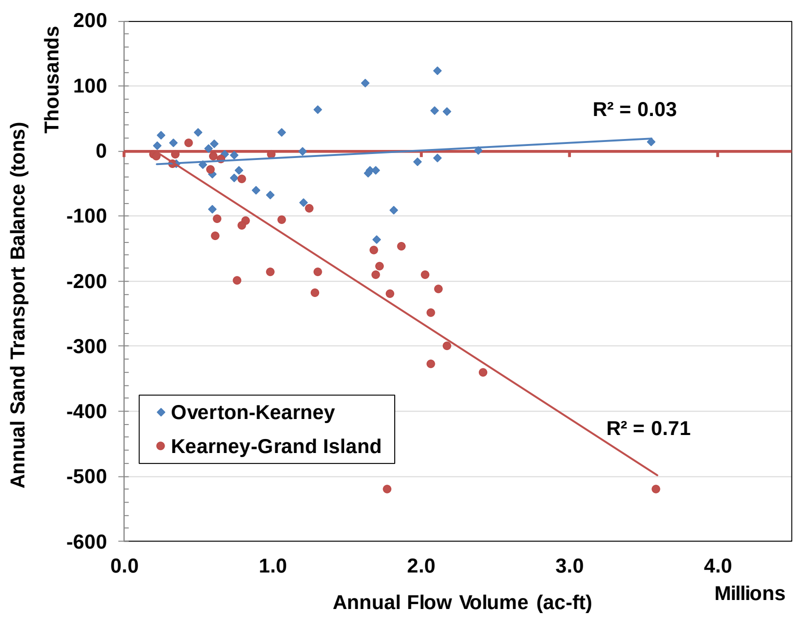

Figure 11. Annual sand transport balance based on integration of the bias-corrected rating curves over the flow record for the period from Water-year (WY) 1984 through WY2016.

Although there is considerable scatter in the data, the large uncertainty in the rating curve-based estimates stems in large part from the small size of the data sets. A reasonable question is, how much data would actually be necessary to reduce the uncertainty sufficiently to allow statistically-valid conclusions to be drawn regarding at least the direction of change (i.e., aggradation or degradation tendency) in a system like the Platte River? An approximate answer to this question can be obtained by repeating the bootstrap analysis using larger data sets developed by resampling the original data sets. A key assumption in this approach is that the magnitudes and variability in the data from a longer-term, systematic sampling program would be the same as that obtained from the limited sampling program on which the above analysis was based. This approach will provide the same best-estimate aggradation/degradation values, but the about uncertainty bands will diminish with increasing size of the data set due the reduced variability in the rating curves among the Monte Carlo trials. The upper and lower 95% uncertainty limits on the estimates for the Darr to Overton reach are 1.3 and 1.5 times greater than the best-estimate value for the overall 7-year monitoring period based on the approximately 20-sample dataset; thus, the upper band indicates aggradation while the best-estimate and lower band values indicate degradation (Figure 12). The trend is, therefore, not statistically significant. If the dataset included an additional approximately 30 points (for a total of 50), the upper uncertainty limit indicates slight degradation, and at least the direction of the trend would be statistically significant. Increasing the dataset size to 100 and 200 points results in a substantial reduction in the width of the width of the uncertainty band. However, for the other 3 reaches considered in this evaluation, even 200 data points would not reduce the uncertainty bands sufficiently to make the best-estimate trend statistically significant.

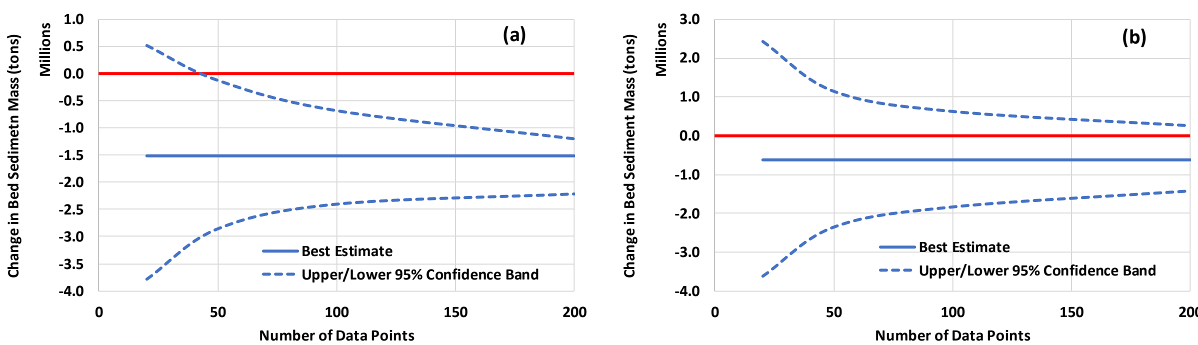

Figure 12. Effects of the size of the sediment transport data set on uncertainty bands on the estimated change in bed sediment mass over the 7-year monitoring period: (a) Darr to Overton (b) Kearney to Shelton. Curves for Overton to Kearney and Shelton to Grand Island similar to (b).

Transect Surveys

The transect data indicated considerable variability from year-to-year at the individual survey sites, in terms of both the magnitude and direction of changes, and this translated to large variability in the estimates for the reaches encompassed by the sediment transport measurement sites (Figure 13). The total bed sediment mass lost or gained in some of the reaches exceeded the rating-curve based estimates by an order of magnitude or more in some cases (compare equivalent bars in Figure 10 and 13 – note difference in scale). In addition, the direction of changes was different. For example, net aggradation occurred at the transects in the Darr to Overton reach during 3 of the years and significant aggradation occurred in the Kearney to Shelton reach during one of the years, while estimates based on the sediment transport data showed a net sediment deficit (i.e., degradation) in all years in both reaches. The rating-curve based result also showed degradation in 4 of the 6 years in the Kearney to Shelton reach, with net degradation over the 7-year period, while the transects indicated aggradation in 4 of the 6 years, with net aggradation over the period.

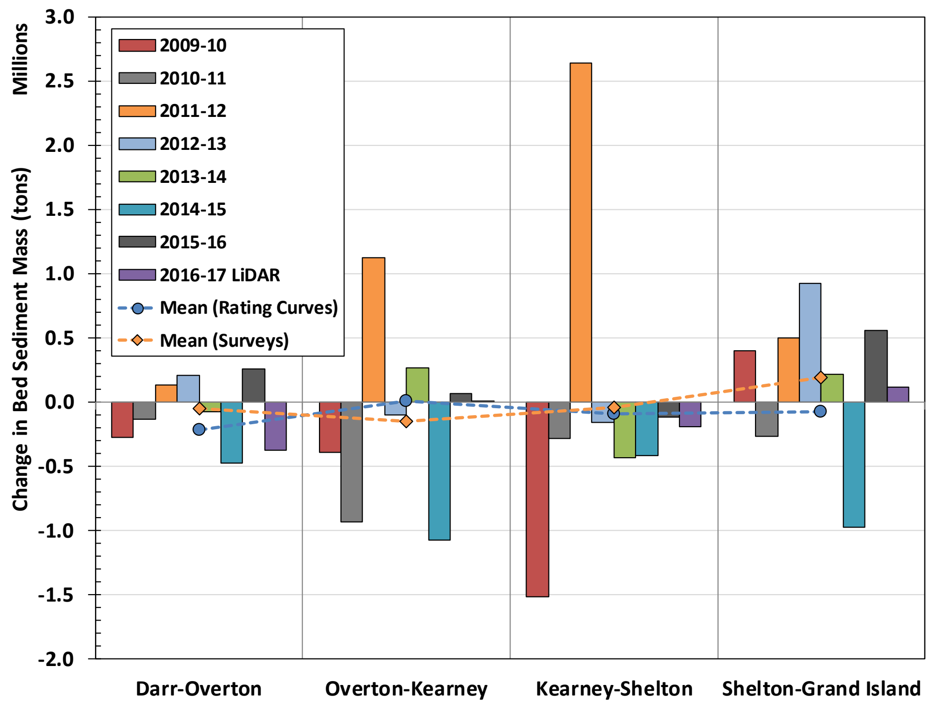

Figure 13. Estimate sediment deficit (-) or excess (+) in 4 reaches of the Platte River between 2009 and 2016, based on the transect data. Also shown are the values for the period between the 2016 and 2017 LiDAR surveys.

Unfortunately, data with which to directly quantify the uncertainty in the transect-based estimates over the 7-year monitoring period are not available. The detailed topo/bathymetric surfaces from the 2016 and 2017 LiDAR data do, however, provide a limited means of evaluating the uncertainty. The analysis was performed by cutting transects from the 2 LiDAR surfaces at the same locations at which the transect surveys were performed, and the aggradation/degradations volumes estimated using the same procedure that was used for the transect surveys. These results should be equivalent to those from the transect surveys. The surfaces were also used to develop volume estimates for each of the survey sites that consisted of 3 transects spaced at approximately 500-foot intervals to evaluate how well the transects represent the changes at the individual sites. The estimates were then repeated using the entire surface within each reach to evaluate how well the both transect- and rating-curve based estimates represent the actual bed changes that occurred between the two LiDAR surveys.

The correlation coefficient (R^2) between the estimates from the transect lines and the LiDAR surfaces at the individual study sites was 0.97, indicating excellent agreement (Figure 14). The estimates for this single year of data obtained by extrapolating the transect- and local LiDAR-based estimates to the longer reaches between the sediment transport measurement sites show the same aggradation/degradation trends as both the complete LiDAR- and the sediment transport rating curve-based estimates, however, the magnitudes of change are quite different (Figure 15). In general, the estimates from the rating curves suggest the smallest amount of change in bed sediment mass, the local estimates from the transects and local LiDAR surfaces indicate the largest overall changes, and the values from the complete LiDAR surface fall about midway between the two for all but the most downstream part of the study reach between helton and Grand Island. In that reach, the complete LiDAR surface actually shows the largest change.

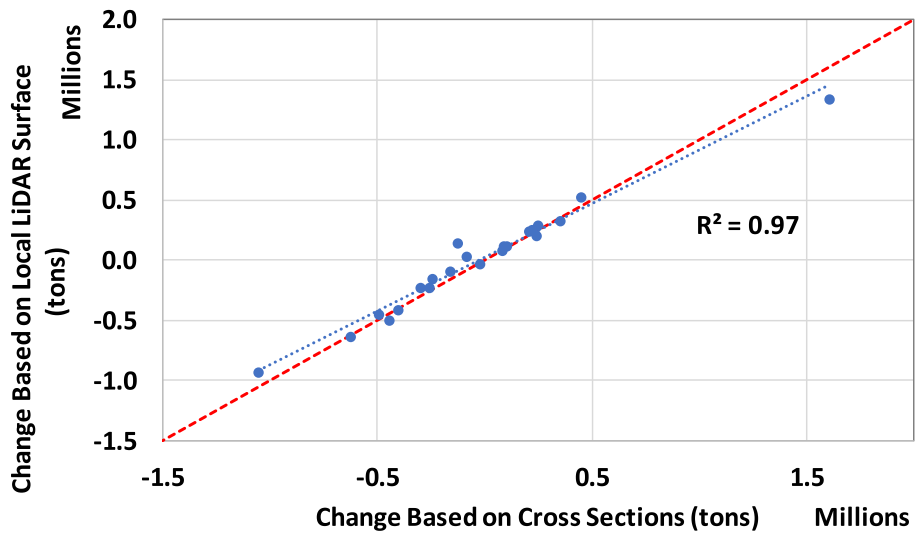

Figure 14. Comparison of change in bed sediment mass between the Fall 2016 and Fall 2017 LiDAR surveys based on the individual transects and the local LiDAR surfaces

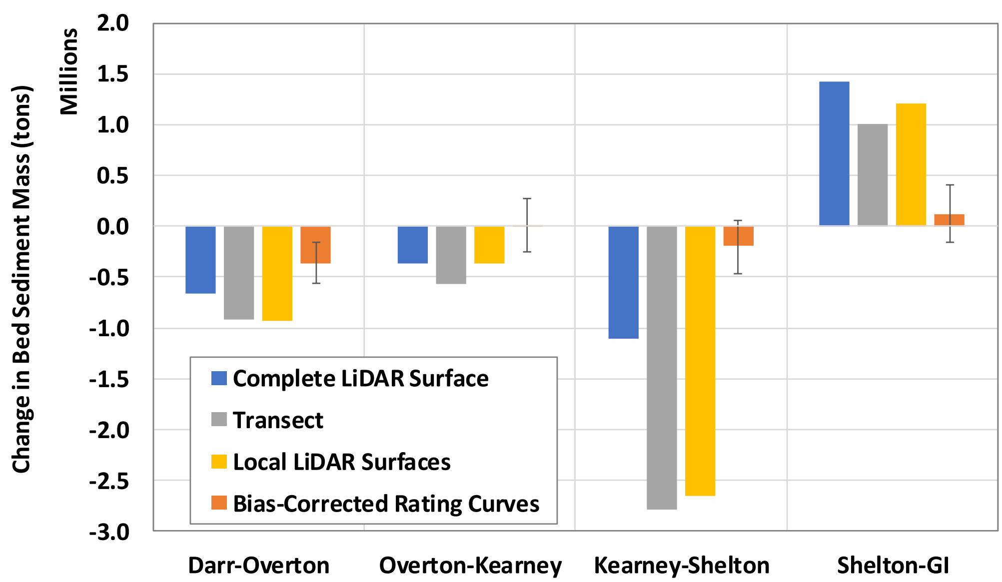

Figure 15. Change in bed sediment mass between the Fall 2016 and Fall 2017 LiDAR surveys based on 4 estimation methods

Error statistics from the LiDAR mapping contractor indicate that the Root Mean Square Error (RMSE) for the two flights in the range of 0.08 feet for dry areas and about 0.15 feet for subaqueous areas. A bootstrap test of the potential error in the LiDAR surfaces in an approximately 0.8-mile segment within the Overton to Kearney reach using these values statistics indicates that the potential error in the estimates from the LiDAR surface is less than 1%. Since the complete LiDAR surface represents the overall bed surface along the reach, and the error in the volume estimates from the surface are quite small, the estimates based on the complete LiDAR surface should accurately represent the changes that occurred in the reach over the year between the flights. The fact that the estimates from the complete LiDAR surface fall outside the 95% confidence bands on the rating curve-based estimates in Figure 14 suggests that the rating curve-based estimates may be in error, probably because of the limited size of the data sets. To put these changes into perspective, however, the total bed elevation change, averaged over the length and width of the channel, over the 7-year survey period associated with the estimated volumes is only about -0.6 feet foot in the Darr to Overton reach, and the total changes in the other reaches are in the range of +/-0.1 foot. Except in the Darr to Overton reach, the indicated changes from either method is probably not statistically significant.

Conclusions

Data from an 8-year monitoring program on the Central Platte River in Nebraska provides a means of assessing the uncertainty in estimates of the sediment transport balance in a wide, sand-bed river based on sediment transport measurements and transect surveys, both methods of which are commonly used in geomorphic studies. Analysis of the sediment transport data, that included a relatively limited set of bed and suspended sediment samples (~20 samples at each location), indicates that the uncertainty in annual aggradation/degradation estimates from these data are quite large, and in most cases, even the direction of change (i.e., aggradation or degradation) is not statistically significant. For one of the reaches analyzed, increasing the size of the dataset to 50 samples would reduce the uncertainty sufficiently to make at least the direction of change statistically significant. In the other 3 reaches between the measurement locations, increasing the dataset to even 200 samples would not be sufficient to provide statistically significant estimates of the trends. For these reaches, the magnitudes of the annual differences are actually quite small compared to the total bed material load passing through the system; thus, the lack of statistical-significance is likely an indication that these reaches are approximately in sediment-transport balance.

Data from transect surveys collected over a 7-year period at 20 locations, each of which consisted of 3 transects spaced at approximately 500-foot intervals resulted in estimated aggradation/degradation trends that, in many cases, were quite different from those indicated by the sediment transport-based estimates. LiDAR surface created from a combination of the near-infrared and green wavelengths, and thus capable of sampling the bed through the shallow water, indicates that the transect-based estimates represent the magnitude and direction of the changes at the local study sites very well, but significant error is introduced when these values are extrapolated to the overall reach between the study sites. Since uncertainty in estimates from the complete LiDAR surfaces are probably quite small, LiDAR mapping is probably the most effective means of making accurate aggradation estimates. This is especially true in systems like the Platte River where the data can be collected during periods when the water is relatively clear and shallow, and the green LiDAR can penetrate to the river bed.

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