Morphodynamic Modeling of Gravel Bar Formation at a Bridge Replacement

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Abstract

Colorado State Highway 14 spans the Cache la Poudre River on the east side of Fort Collins, CO. The Poudre River at this location underwent a substantial realignment in 1949 to accommodate the SH 14 bridge structure, shifting the channel via an engineered meandering section. Design of the replacement bridge began in 2013 and culminated in construction of the replacement bridge in 2015-16, along with a substantial change to the vertical alignment of SH 14 and associated river grading. A tall, largely stable vegetated bank was present on the right overbank area prior to the recent bridge replacement. Only one year after construction, a significant gravel bar with cobble top layer had rapidly developed upstream of, and under, the new bridge footprint. As well, significant sand deposits underlain by gravels and cobbles have accumulated under the bridge in the overbank area.

A morphodynamic model of the fluvial system for this reach has been constructed using SRH-2D. Taking advantage of topographic data and employing SRH-2D's sediment transport capabilities, we have experimented with the predictability of the observed gravel bar formation using this hydraulic model. Towards that end, we utilized a nearby USGS gaging station to run actual flow data through the simulated fluvial system model.

Our preliminary findings suggest that the initial stages of the gravel bar formation could have been expected within a single year of post-construction snowmelt-generated runoff, which matches observation of the site. Further, the morphodynamic model is able to demonstrate approximately correct lateral and vertical locations of the bar's formation.

An important take-away for hydraulic engineering practitioners, as demonstrated by this study, is that design using only large magnitude (small recurrence) peak flows, and assuming a static non-moveable bed, may not provide adequate understanding of the fluvial system when arriving at a proposed condition grading plan for infrastructure improvements. This could lead to diminished hydraulic capacity and performance at a bridge crossing, as well as larger floodplain encroachments than initially expected.

Introduction

Site Orientation

Colorado State Highway 14, also known as Mulberry Street, spans the Cache la Poudre River on the east side of Fort Collins, CO city limits. The Poudre River at this location was re-engineered in 1949, shifting its channel alignment to the north and east, to accommodate the highway bridge crossing as well as the new City water treatment plant. Design of a replacement bridge at this location began in 2013 and culminated in construction of the new crossing in 2015. The construction activities included a substantial change in the vertical alignment of CO 14 as well as associated river grading in the vicinity of the crossing. A tall, largely stable vegetated bank was present on the right overbank area (Figure 1, area of interest outlined in red) prior to the bridge replacement. Only one year after grading activities in the channel (2016), a substantial cobble and gravel bar, underlain by gravelly sands, had formed along and below the right bank – this feature extended well into the bridge footprint (Figure 2). While the bar has largely stabilized and new vegetation is now sprouting along portions of the bar, it is evident that the bar continues to reshape itself, and that the predominately sandy deposits under the bridge footprint continue to aggregate/erode and change elevation and form.

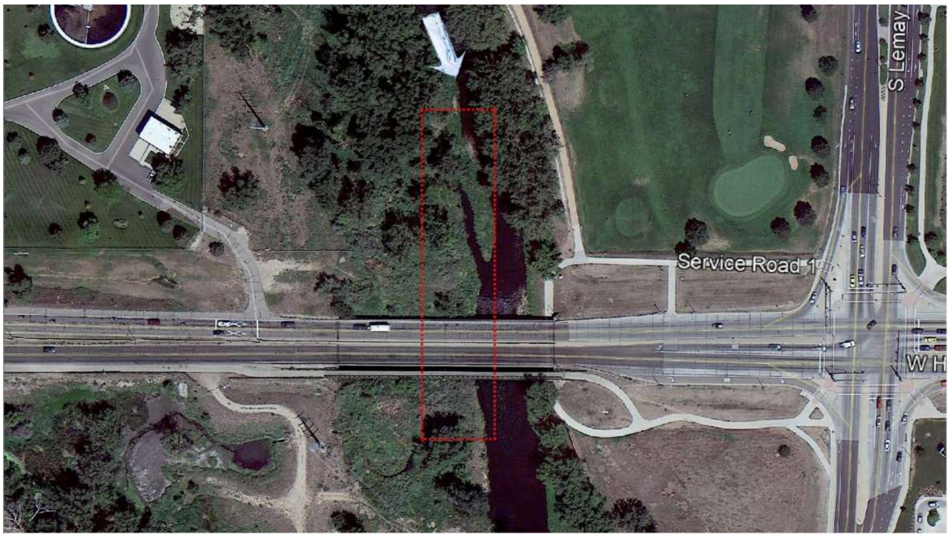

Figure 1. Aerial photo with future gravel bar location outlined in red. August 2012 (pre-project). Retrieved via Google Earth (2020)

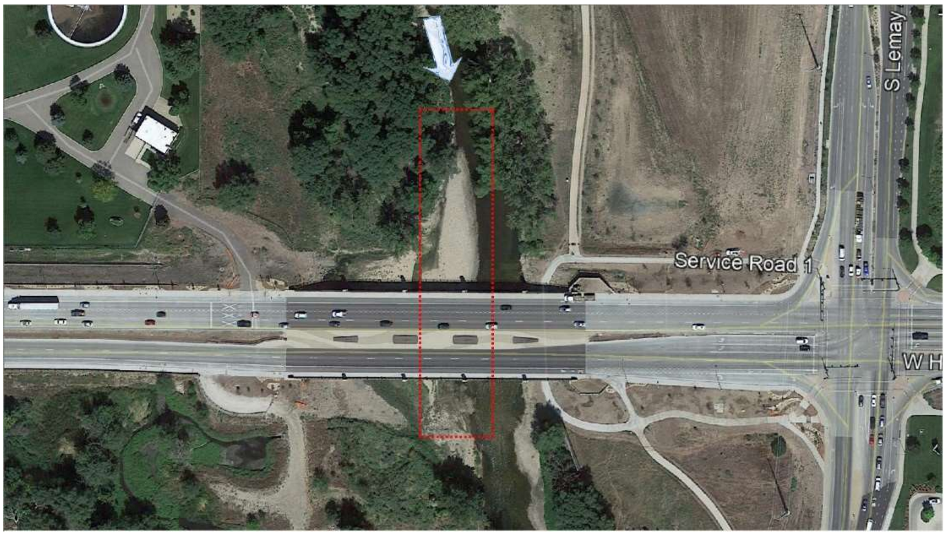

Figure 2. Aerial photo from October 2016 (post-construction) with the same gravel bar outlined. Retrieved via Google Earth (2020)

Literature Review

Much published research on the morphodynamic modeling of bar formation are available to inform the present study. Cordier et al. (2018) finds that the coarseness and granularity of the computational mesh affect the prediction of bar growth, with finer mesh construction resulting in lower perturbation growth and coarser mesh resulting in longer bars than predicted in laboratory experiments. Li and Millar (2010), in analyzing the increased stability provided to straight reaches with bar formation by vegetative growth, predicted bars to form in a 2D morphodynamic model which tended to migrate upstream. By comparing the performance of Delft3D and Mike21 FM morphodynamic models of sample fluvial systems, Parsapour et al. (2018) found that both 2D models were able to replicate the morphodynamic effects of the 2013 flooding of the Bow and Elbow Rivers through Calgary, though both models were also susceptible to the horizontal eddy viscosity and Manning roughness, and emphasize the need for good calibration of the modeling. They found that mesh/grid resolution plays an important role in accurate simulation of the developing gravel bars. Mosselman (2012) advocates for setting of international standards for model validation in fluvial morphodynamic simulations, and notes that these kinds of predictive models are becoming more widely used as decision-making tools on river projects, including those with multiple stakeholders that may not be versed in fluvial morphodynamics.

Of course, recent advancements in the understanding of the mechanics of bar formation continue to inform the interpretation of morphodynamic models and their predictions. Tubino (1991) demonstrates that bar development is mostly controlled by nonlinear effects in unsteady flow regimes. Bar growth is more concentrated in the falling (as opposed to rising) river stage as the flow recedes. The final amplitude of a developing gravel bar is strongly affected by the unsteady character of the flow. Cordier et al. (2020) examines bar morphodynamics in sand/gravel bed rivers subject to unsteady flow with contraction and expansion areas present. They find, in part, that these bars advance by the propagation of steep fronts and that bedload magnitude is higher by 3 to 5x over submerged bars and in the main channel than in pools and lee sides. Submergence of the bars is an important factor when considering the potential expansion or movement of a bar. Jaballah et al. (2015) report on a site-specific case study of an engineered alpine river system, which had an artificially flattened river bed into a trapezoidal section. Within just a few years, a new system of alternate bars had already developed. The new bar system exhibited fewer bars, but longer. The authors estimate the total time for bar growth to reach a steady state to be on the order of 10 years. Nelson and Morgan (2018), via flume studies, find that changes in sediment transport rates via unsteady flow regimes are reflected by corresponding increases or decreases in bar amplitude, though not reflected in bar migration patterns. They acknowledge the formation of alternate bars at lower width-to-depth ratios than would typically be predicted under current theories.

Methodology

Morphodynamic Modeling via SRH-2D – Overview and Goals

The original hydraulic design for the Poudre River bridge crossing was completed in 2013-14 using HEC-RAS 1D modeling (CDOT, 2014). At that time, the choice of modeling approach was made primarily to facilitate the CLOMR/LOMR effective floodplain permitting process.[1] Though a geomorphic assessment was conducted of the reach, morphodynamic modeling was not a part of that exercise. Now that the technology has advanced and sediment transport simulation is ever-more accessible at the practitioner level, and given the rapid formation of an unexpected bar upstream of the bridge crossing post-construction, an ideal situation has presented itself to construct a morphodynamic model of the post-construction system in an attempt to replicate the bar formation. If today's technology and tools were accessible in 2013-14 during the design phase of the project, could the bar formation and sedimentation under the new bridge opening have been predicted?

To that end, SRH-2D version 3.5.0, developed by the US Bureau of Reclamation, is employed as the hydraulic model and sediment transport simulator. SMS (Surface-water Modeling System) version 13.2.14, produced by Aquaveo LLC, is utilized as the pre-processor and setup for SRH-2D to prepare the simulation mesh, hydraulic roughness layout, model boundary conditions, and sediment transport parameters. SRH-2D is a depth-averaged solution of the St. Venant equations, and provides a flexible mesh approach to mesh generation (FHWA, 2019).

SRH-2D currently does not have the capability to simulate lateral (bank) erosion, according to USBR (2020). However, the morphodynamic changes observed in this reach since 2016 are not largely influenced by lateral erosion, and the areas (particularly along the left river bank, upstream of the bridge crossing) exhibiting bank erosion appear to be mostly in stasis – thus, their predictability is not of particular concern in this present study.

Topographic Sources and Timeline

Survey data from the post-construction LOMR submittal for the crossing has been merged together from two independent sources. The first is the 2015 survey for the CDOT Mulberry bridge replacement and Woodward development site upstream (north) of the crossing. This source contains the bridge structural details, roadway embankment, trail system, and associated stream grading. The second, supplemental, source is the 2015 LiDAR topographic survey (resampled at a 3 foot point interval) provided by the Colorado Water Conservation Board. The combined surface contains the final post-construction configuration of the replacement bridge and the associated grading.

Aerial photos from October 2016 indicate that the gravel and cobble bar has already substantially formed. Construction activities commenced in September of 2014, and structural work along with much of the grading upstream and downstream of the new crossing took place throughout winter of 2014 and spring of 2015. Localized inundation of the site was experienced in mid-2015 as a result of high flows on the Poudre River. Construction was completed in November of 2015. The baseline, combined survey, captures the condition wherein the construction activities have been completed, but bar formation has not substantially commenced.

[1] A LOMR is a Letter of Map Revision through FEMA and the local Floodplain Administrator. Similarly, a CLOMR is a pre-construction, Conditional Letter of Map Revision.

Volumetric Flow Rates for Unsteady Simulation

On the basis of the site history and timeline presented above, we chose to route flows representative of the 2015 river flow season capable of transporting gravels and cobbles through the fluvial system and morphodynamic model. We downloaded water data from USGS gage 06752260, a gage is located approximately 4700 feet upstream of the bridge crossing, and has no significant inflows (aside from a storm sewer outfall) between the gage and the bridge. A 17-day (420 hour) period of the flow record, from May 7 to May 24, 2015, has been chosen in which to simulate the hydraulic conditions and associated bed movement.

An item for consideration in an unsteady sediment simulation is equilibrium – the amount of time necessary at a given flow rate for stable solutions to be achieved. Though 15-minute intervals of flow record are available, we did not wish to use such rapid transitions between flow rates with the risk of lack of convergence of a solution at a given flow rate. For this reason, and after analyzing the available flow data for this time period, we have elected to input the highest volumetric flow rate over a 12-hour span, and to run this same flow rate for 12 hours of simulated time, before advancing to the next 12-hour span. Figure 3 depicts the original flow record per 15 minute span, and Figure 4 depicts the simplified flow record per 12 hour span.

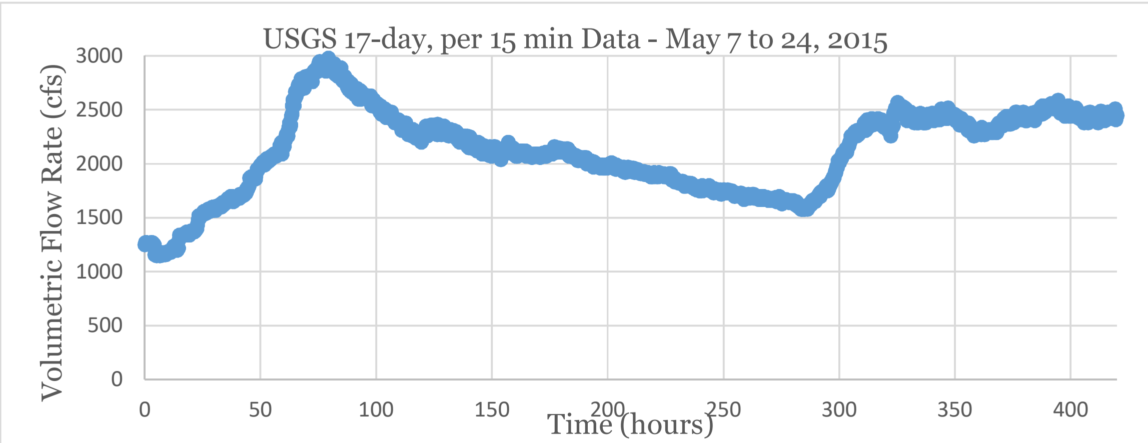

Figure 3. USGS volumetric flow at 15-minute intervals

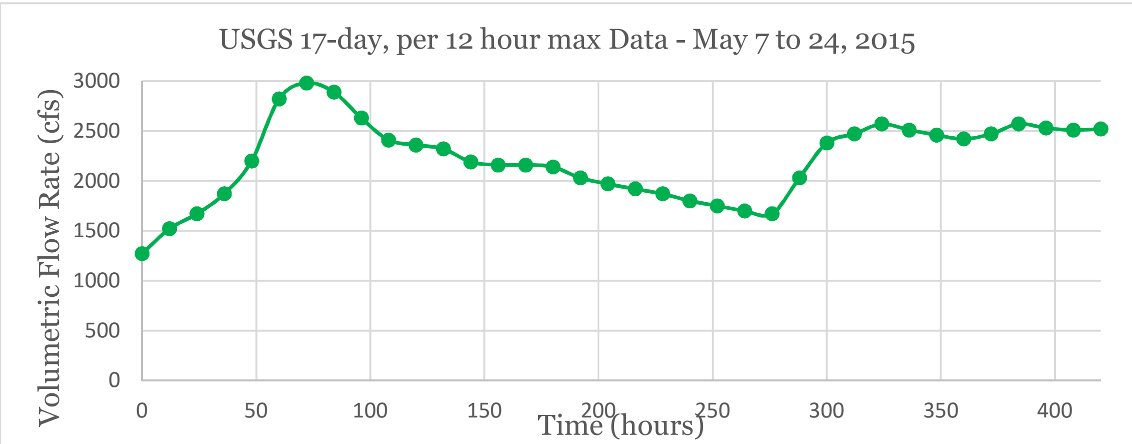

Figure 4. USGS volumetric flow, with highest flow per 12-hour period of record

The upstream boundary condition for the unsteady morphodynamic model is populated with the data from Figure 4. For the initial downstream boundary condition, a rating curve has been established using normal depth calculations. For the sake of comparison, the current FEMA Effective 1% annual chance flood on the Poudre River at this location is 16,600 cfs, which was also the Design Flood used for the 1D hydraulic model for the bridge replacement. This flow is given in the most recent version of the Flood Insurance Study (FEMA, 2021). Finally, it should be noted that the 2015 water year at this location was higher than typical, as recorded by the USGS gage. The annual mean flow for that year was 481 cfs, whereas the 1975 to 2015 annual mean flow was just 171 cfs. Thus, the speed of the bar's formation may be partially accountable to the higher than typical flow rates in 2015.

Hydraulic Roughness and Steady Flow Calibration

Prior to the 2022 runoff season, we installed a static stream gage at the toe of the cobble/gravel bar. We also installed a timelapse camera upstream of the gage, programmed to take still photos of the gage at intervals of 5 minutes, as shown in Figure 5. In this way, static flow depth may be read up to a flow depth of roughly 3.3 feet. By also associating the recorded flow rate at the upstream USGS gage with the depth measurement, and by surveying in the absolute elevation at the base of the static gage ruler, we arrived at a reading of the water surface elevation (WSE) at the time of various USGS gage flow measurements.

Figure 5. Static stream gage and timelapse camera at the right bank edge of the gravel/cobble bar.

Four steady flow rates, as recorded at the USGS gage throughout the runoff season, have been simulated in the SRH-2D model. We began with assumed, initial values of hydraulic roughness, then compared the WSE measured at the static gage with the WSE predicted by the steady hydraulic model. To improve accuracy and reduce discrepancies, the pertinent hydraulic roughness values would then be adjusted and the steady model re-run in an iterative process. The results of these investigations appear in Table 1.

Table 1. Results of Manning Roughness calibration exercise

Date	Time (hrs)	USGS Flow (cfs)	Static Gage WSE Reading (ft)	SRH-2D Steady Model WSE (ft)	Difference (Actual – Model, ft)
22.6.2022	1630	174	4929.1	4928.5	0.6
25.6.2022	1100	426	4929.8	4929.7	0.1
17.5.2022	0923	892	4930.9	4930.9	0.0
10.6.2022	1035	1820	4931.9	4932.3	-0.4

These results have been used to help refine the Manning roughness values for the overall simulation as seen below in Table 2. As we have a continuous record of static gage readings throughout the spring runoff season, future improvements to this study may involve additional steady flow runs in the hydraulic model and adjustments to various material properties to reduce the error between the measured WSE and USGS gage reading. However, there are other potential reasons for the discrepancy, particularly at the higher flow rate of 1820 cfs. For one, there is considerable turbulence in the water surface at this flow rate, including standing waves and complex surface variations not present at lower flows – thus, the static photo of the gage reading almost certainly has substantial error in the reading (on the order of 0.2 or 0.3 feet, based on the site conditions of the photo at 1035 hrs and those taken at 1030 and 1040 hrs). Further, the higher flow rates introduce flow over the gravel/cobble bar and into the overbank area, which encounters additional layers of vegetative and surface roughness that may not be accounted for in the 2D hydraulic model roughness layer.

As should be expected, the in-stream roughness is higher at lower flows for this cobble and gravel reach, and decreases as flow rates increase and flow depths decrease.

Table 2. Manning hydraulic roughness values for the hydraulic model

Land Use	Depth of Flow (ft)	Manning Roughness
Paved	All	0.012
Pond (filled)	All	0.020
Solar Panel Farm	All	0.028
Rocky Overbank with Trees and Brush	All	0.060
Bare Overbank (sands and gravels)	All	0.040
Short Grasses	All	0.024
Cobble and Gravel Main Channel	0.0 – 1.0	0.060
	1.0 – 2.0	0.060
	1.5 – 2.5	0.055
	2.5 and above	0.047

Mobile Bed Unsteady Simulation

We are able to take advantage of the boring logs taken during the preconstruction phase of the project, as well as Wolman counts of the top surface layer of sediment. Based on these data, seven particle diameter "bins" have been supplied to SRH-2D, per Table 3. These size breakouts and associated size classifications are obtained from FHWA's HDS-6 (2001).

Table 3. Sediment classification "bins" supplied to SRH-2D

Particle Diameter Threshold (mm)	Size Classification
0.031 – 0.062	Coarse silt
0.062 – 0.25	Fine sands
0.25 – 2.0	Medium to coarse sands
2.0 – 15	Very fine to medium gravels
15 – 33	Coarse gravels
33 – 127	Very coarse gravel to small cobbles
127 - 254	Large cobbles

The sediment transport equation we chose for the model is the Meyer-Peter-Müller, as modified by Wong and Parker (2006). This is the version of MPM pre-programmed into the SRH-2D model, according to USBR (2020). In the model setup, we chose no hiding factor activation, and a water temperature of 20 degrees centigrade. The sediment composition layers were delineated based on the boring log information (location of borings as well as stratification of sediment per boring) and the Wolman count of the surface layer of sediment. The layer is as appears in Figure 6 for the sediment, and the layer thicknesses and composition are as appears in Table 4.

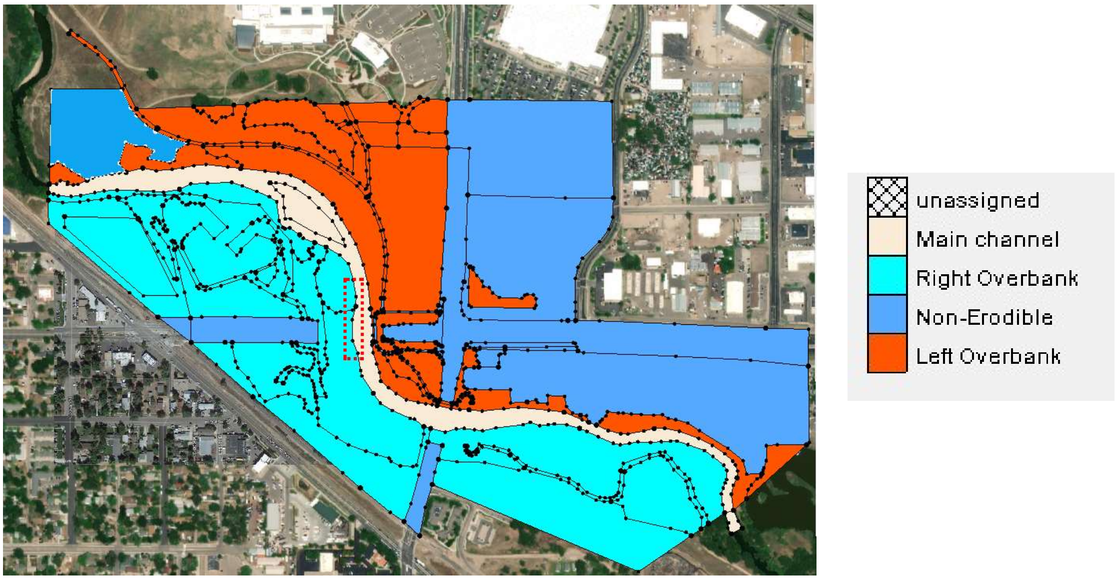

Figure 6. Sediment layers for the morphodynamic model

Table 4. Sediment Thicknesses and Distribution for the Sediment Layers in SRH-2D

Zone	Thickness (ft)	Particle Size (mm)	% finer		Zone	Thickness (ft)	Particle Size (mm)	% finer
Main Channel	2	0.062	0.0		***Left Overbank***	1	0.062	0.0
		2.0	14				2.0	14
		20.0	31				20.0	31
		40.0	39				40.0	39
		50.0	47				50.0	47
		65.0	59				65.0	59
		120.0	84				120.0	84
		170.0	98				170.0	98
Right Overbank	1	0.062	0.0			7	0.062	0.0
		2.0	14				0.125	20
		20.0	31				0.25	40
		40.0	39				0.5	60
		50.0	47				1.0	80
		65.0	59				2.0	100
		120.0	84					
		170.0	98					
	7	0.062	0.0					
		0.125	20					
		0.25	40					
		0.5	60					
		1.0	80					
		2.0	100					

The morphodynamic model controls were set to run the initial flow rate as a steady flow for 3.0 hours of simulation time, after which the unsteady run would initialize based on the USGS gage data boundary condition as described above, for a total simulation of 420 hours. We chose a time step of 1.0 seconds, as this time step preserved the Courant criteria for most mesh elements and also provided stable solutions at each of the steady runs during the calibration stage. The simulation runs to completion over a real-time processing time of about 9 hours.

Results

Comparison of Baseline Post-Construction Surface vs. 17-day MPM Sediment Transport Predicted Surface vs. 2022 Supplemental Survey for the Bar

To compare the predicted 17-day duration spring runoff sedimentation/erosion to the baseline post-construction condition, and to the late 2022 supplemental survey for the bar, three representative cross-sections have been cut in the area of noticeable sediment aggradation, Figure 7. The upstream XS is cut approximately 22 feet upstream of the bridge face; the bridge XS is approximately concurrent with the centerline of the bridge structure underneath the footprint; and the downstream XS is cut approximately 20 feet downstream of the bridge face.

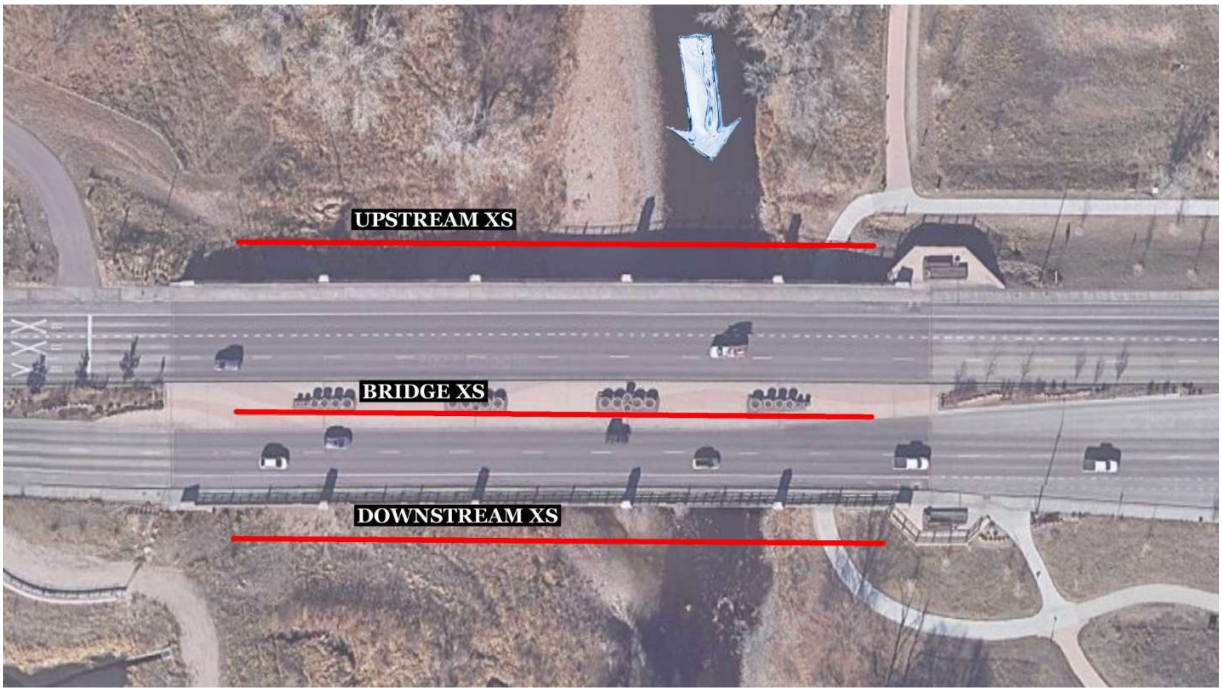

Figure 7. Representative Cross-Section Locations

At the upstream section (Figure 8), the MPM simulation does indeed predict aggradation throughout the section, with about 2 feet of increased bed height at the location of the observed bar (STAs 100 to 175 at this section). We also observe that the original low-flow channel, which was graded in as a trapezoidal section, is predicted to smooth into more of a rounded shape, giving up some capacity on the right bank. Further, as Figure 8 and Table 5 demonstrate, there is very good agreement between the MPM predicted elevations and the recently surveyed ground topography at the bar. The vertical growth of the bar, by 2022, may have stabilized, as also evidenced by the beginnings of vegetative growth establishing on this portion of the bar. It may be that the majority of the bar growth transpired during the first year or two of runoff.

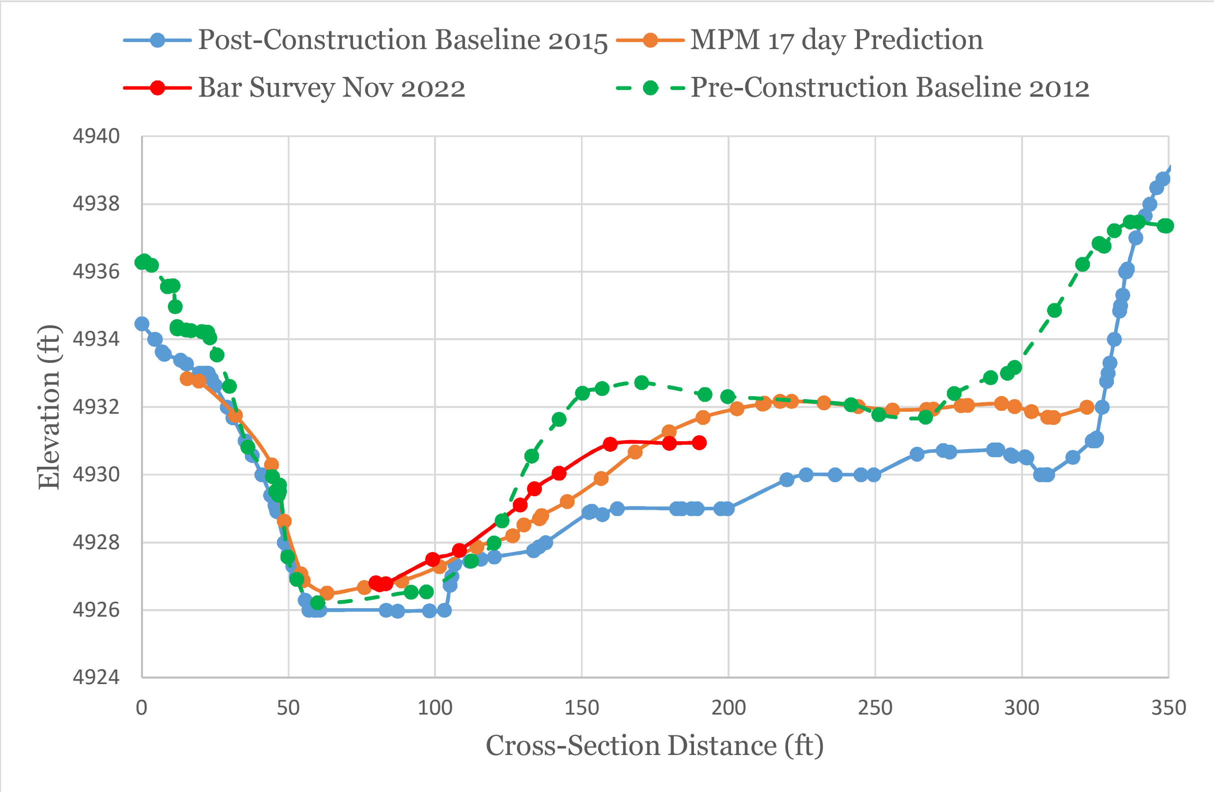

Figure 8. Upstream cross-section at post-construction baseline vs. MPM predicted bed elevation after 17-day run vs. Nov. 2022 bar survey data

Figure 9 displays the same data under the bridge footprint. First, we observe from site visits that the characteristic of the sedimentation under the bridge is much more fine gravels and sands, underlain by larger gravels and small cobbles. Next, we observe that the sedimentation extends throughout the footprint of the bridge all the way to the east toe of abutment slope, indicating that the low recurrence flood flows that have expanded into the full bridge opening have reliably deposited significant amounts of sands and gravels throughout.

Once again, we find very good agreement between the predicted 17-day MPM results from the recorded 2015 May flows and the 2022 partial ground survey.

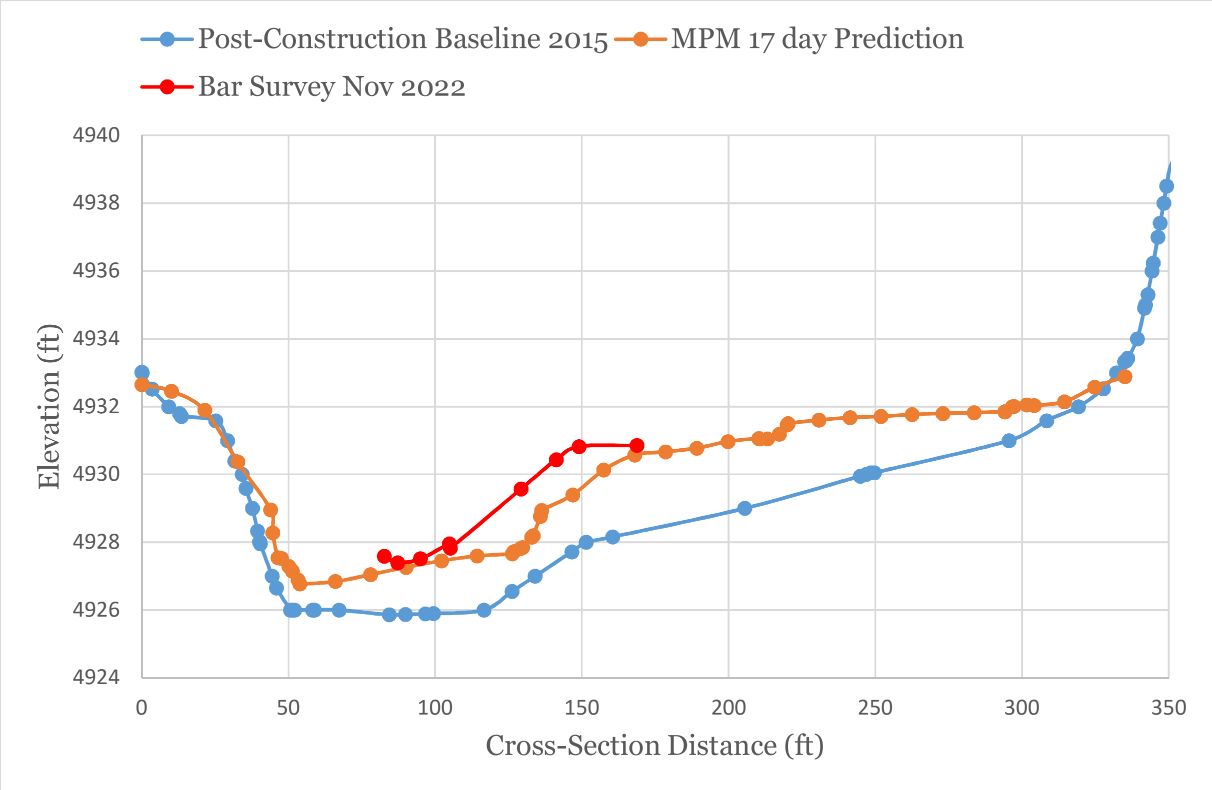

Figure 9. Bridge cross-section at post-construction baseline vs. MPM predicted bed elevation after 17-day run vs. Nov. 2022 bar survey data

Sedimentation between 2-3 feet is predicted under the bridge at the main channel and under the bridge footprint, which is verified by the ground survey that has been obtained thus far.

Figure 10, again cross-referencing with Table 5, also depicts a predicted sedimentation of up to 2 feet when compared with the as-built initial conditions. As contrasted with the previous two cross-sections, the ground survey is showing an additional ~1 foot increase in actual ground elevation against the 17-day MPM result; this is likely indicating continued sedimentation of the right overbank area beyond the 2016 runoff season.

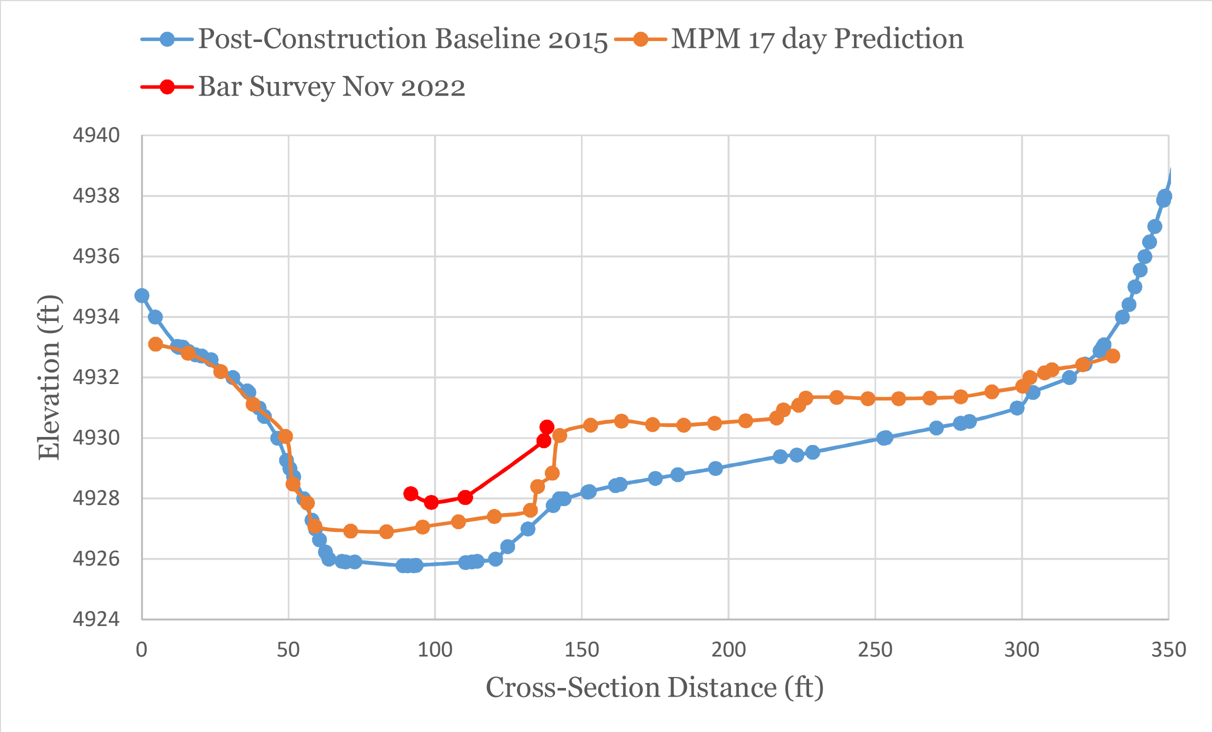

Figure 10. Downstream cross-section at post-construction baseline vs. MPM predicted bed elevation after 17-day run vs. Nov. 2022 bar survey data

Table 5. Elevation Comparisons

XS ID	XS STA (ft)	PREDICTED MPM ELEVATION (ft)	2022 SURVEYED ELEVATION (ft)	DIFFERENCE (SURVEYED – MPM), ft
Upstream	81.0	4926.8	4926.8	0.0
	99.1	4927.0	4927.5	0.5
	108.2	4927.6	4927.8	0.2
	128.9	4928.2	4929.1	0.9
	142.2	4929.1	4930.1	1.0
	159.6	4930.0	4930.9	0.9
	190.0	4931.6	4930.9	-0.7
Bridge	82.7	4927.1	4927.6	0.5
	95.0	4927.4	4927.5	0.1
	105.1	4927.5	4927.8	0.3
	129.2	4927.8	4929.6	1.8
	149.0	4929.5	4930.8	1.3
	168.8	4930.6	4930.9	0.3
Downstream	91.7	4927.0	4928.2	1.2
	98.7	4927.1	4927.9	0.8
	110.4	4927.3	4928.0	0.7
	137.0	4928.7	4929.9	1.2
	138.1	4928.8	4930.4	1.6

Discussion and Conclusion

The present study demonstrates that, in a moderately steep natural river channel whose flow regime is heavily influenced by spring runoff, and has been disturbed via grading activities, prediction of a gravel/cobble bar formation may be possible during the design stage utilizing a 2D morphodynamic model. We establish that the engineered grading plan enacted by the contractor during the bridge replacement could have been predicted to aggrade upstream and through the bridge opening, had a more complex morphodynamic model utilizing an appropriate sediment transport relationship (such as MPM) been available during design. While this prediction may not necessarily have influenced the sizing or design of the bridge (due to other constraints, such as the fixed location of the eastern/left bank abutment and pedestrian trail system; and the required tie-in to the railroad crossing to the west), it almost certainly could have influenced the development of the grading plan upstream and downstream of the bridge to more accurately account for the morphology of the river channel and the loss of hydraulic capacity under the bridge in future years due to sedimentation.

Items needed for a good-quality predictive model in similar systems include: a) measured water surface elevation to calibrate roughness at different flow rates; b) good quality topographic data both before and after construction/disturbance of the fluvial system; c) a good grasp of the geomorphic assessment of the reaches upstream and downstream of the area of interest, which in this case reveals the presence of alternating gravel/cobble bars that eventually vegetate and establish in straight reaches; d) surface bed material data and underlying sediment stratigraphy and size; and e) good quality channel discharge measurements. Future work at this site may involve additional timelapse and aerial footage of the bar, to determine if it has reached a stable state of growth or if it will continue to morph during future flow events. The study may eventually be expanded to determine the quality of the MPM predictions for additional years of data.

An important take-away for hydraulic engineering practitioners, is that design using primarily large, low-recurrence floods (like the 1% annual chance event) and assuming a static bed may not provide adequate understanding of the fluvial system when arriving at a proposed condition grading plan for infrastructure improvements. The flow rates transporting and depositing sediment are often much less than the peak flow rates used for design of the infrastructure, and thus the design team and hydraulic engineer may wish to examine a range of more typical flows within the system when considering sedimentation and erosional predictions.

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