Repeat Bathymetric Surveys and Model Simulation of Sedimentation Processes Near Fish Spawning Placements, Detroit and St. Clair Rivers, Michigan

Paul Kinzel, U.S. Geological Survey, Hydrologist, Golden, CO, pjkinzel@usgs.gov
Greg Kennedy, U.S. Geological Survey, Fisheries Biologist, Ann Arbor, MI, gkennedy@usgs.gov
Taylor Dudunake, U.S. Geological Survey, Hydrologist, Boise, ID, tdudunake@usgs.gov

Abstract

Nine rock-rubble fish spawning placements, or artificial reef complexes, constructed in the Detroit and St. Clair Rivers between 2004 to 2018 were surveyed periodically with multibeam sonar. These serial bathymetric surveys, conducted in 2015, 2018, 2021, and 2022, identified active sand bedform fields impinging two reef complexes: Fighting Island in the Detroit River and Middle Channel in the St. Clair River delta. The spatial extent over which the bedforms interacted with these reef complexes differed. The Fighting Island reef complex, which was comprised of twelve reef beds oriented across the river channel, experienced partial sedimentation that can be attributed to the streamwise translation and lateral encroachment of a bedform field on several of the eastern reef beds. The Middle Channel reef complex was comprised of nine reef beds also oriented across the river channel. Sedimentation of the Middle Channel reef complex was more comprehensive compared to the Fighting Island reef complex as most of the beds in the Middle Channel reef complex were within a translating bedform field. We simulated the temporal evolution of reef sedimentation at the Middle Channel reef complex using the Wilcock-Kenworthy (WK) two-fraction sediment transport model. In the WK simulation, sand available upstream of the reef migrated into the 36-meter-long gravel reef beds over 10 days of model simulation. The rate of sediment infill predicted by the model was more rapid than the speed of bedform slip face translation measured in the field, approximately 0.3 meters per day. Further, as the supply of sediment from upstream is continuous, once a reef bed fills with sediment it generally remains in place, although some small variations (+/- 0.2 m) in the elevation of the sand overlying the reef beds were observed. Taken together, bathymetric surveys and modeling could be used to identify, monitor, and simulate potential sources of bedload sediment that could impair the longevity of future spawning reef placements. Efforts directed toward enhancement and/or maintenance of reefs impaired by sedimentation could benefit from continued monitoring through periodic high-resolution bathymetric surveys, detailed inspection by diving, and collection of underwater imagery.

Introduction

In the late 1800s and early 1900s, overfishing and habitat loss reduced populations of lake sturgeon (*Acipenser fulvescens*) throughout the Great Lakes (Houston 1987; The Nature

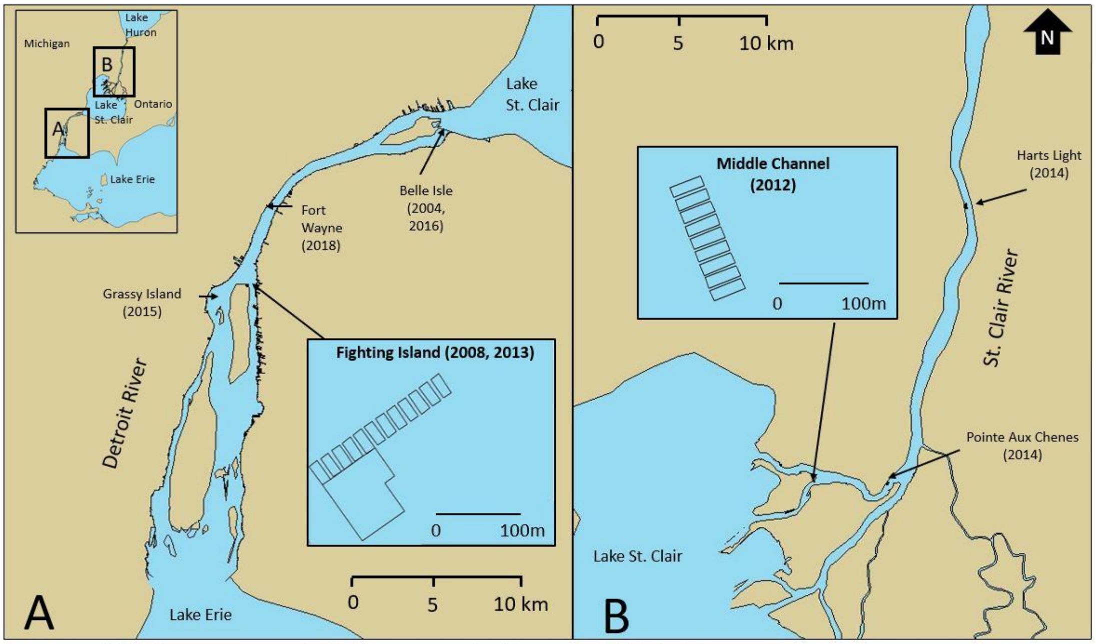
Conservancy 1994; Manny and Kennedy 2002; Caswell et al. 2004). By the end of the 20th century, concern over the diminished population of lake sturgeon, estimated to be one percent of historical abundance (Tody 1974), and low recruitment prompted their listing as threatened or endangered in all but one of the states along the Great Lakes and adjacent Canadian provinces (Pollock et al. 2015). The Detroit River, which once supported a significant population of lake sturgeon in the Great Lakes, was the focus of investigations in the early 2000s by Caswell et al. (2004) to identify lake sturgeon home range and spawning sites. In the years that followed these initial surveys in the Detroit River, considerable effort was directed toward identifying additional spawning locations in the broader St. Clair River Detroit River system (SCDRS). When surveys for egg deposition and larval production proved unsuccessful, consensus began to form among scientists and managers that the quantity and quality of suitable spawning habitat was a factor limiting lake sturgeon recruitment (Manny, 2003).

Artificial Spawning Habitat Site Selection and Construction

In 2001, a team of scientists was formed with the goal of increasing spawning habitat that had been historically lost in the SCDRS. The team considered aspects of several projects in other rivers with impaired habitat. Introduction of rock-rubble substrate had been used as a habitat enhancement strategy in other systems; structures were constructed in Thunder Bay, Michigan in 2010 as well as in the Milwaukee River (Vacarro et al. 2016; Roseman et al. 2017). Therefore, placement of rock-rubble structures, or reefs, on the river bottom was a strategy that was adopted by stakeholders in the SCDRS to increase lake sturgeon spawning and recruitment (Vaccaro et al. 2016).

Spawning habitat enhancements can incur significant costs including those related to planning, permitting, and construction. Therefore, it was crucial in the site selection process that substrate be placed in locations that benefited the fish species of concern in the SCDRS and, to the extent possible, ensure its longevity and ecological function. To identify optimal sites for spawning reef construction, early work primarily involved use of a spatial model for identifying velocities that were suitable for lake sturgeon habitat (Bennion and Manny 2014). In their site selection criteria, the team chose locations with velocities greater than 0.5 meters/second. Other physical attributes of potential sites included deep water, between approximately 7 to 15 meters. Telemetry was used to determine sturgeon movements and identify locations where the fish frequent and/or were known to spawn. The team also consulted with the commercial shipping industry to avoid locations where freighter traffic would have the potential of disturbing the spawning reefs. In addition to selecting optimal locations, the type of substrate material was also thought to be critical to the success of the reef structures. Early reef designs incorporated a variety of materials to identify an optimal spawning substrate (Roseman et al. 2011; Manny et al. 2015). The Fighting Island and Middle Channel reef complexes were designed to span the entire width of river channel to maximize encounters between adult lake sturgeon and reef substrate. Reefs were also located in areas where river processes were believed to be sufficient to maintain the reef substrate through time. In other words, locations where depositional features such as bedforms were not observed on the river bottom during pre-construction surveys. Numerical modeling simulations (Kinzel et al. 2016; Fischer et al. 2020a) were also used to examine flow hydraulics near the pre- and post-construction reefs.

The locations of the SCDRS reef complexes monitored during this study are shown in Figure 1A and B. A comprehensive discussion of the construction of all reefs in the SCDRS is provided by Vaccaro et al. (2016). The history of two projects where river sedimentation buried reef beds, and central to the topic of this paper, are discussed below.



Base modified from U.S. Geological Survey and other Federal digital data.

Figure 1. Location of spawning reefs in the SCDRS with the year(s) of construction in parentheses. Inset maps show the Fighting Island reef complex in the Detroit River (A) and the Middle Channel reef complex in the St. Clair River delta (B).

Fighting Island:

The Fighting Island reef complex was initially constructed in 2008 (Figure 1A). It consisted of 12 reef beds that were distributed across the channel. Each reef bed was 11 meters by 25 meters and was comprised of one of four rock types: 10-to-51-centimeter limestone; 5-to-10-centimeter limestone; natural rounded stone; and a mixture of the three materials (Roseman et al. 2011; Manny et al. 2015). Additionally, boulders were positioned downstream of the reef beds to provide a location for fish to aggregate and escape the river current. In 2013, the reef complex was expanded downstream of the five western beds using 15 to 30 cm broken limestone, adding an area of 3,300 m^2 and doubling the size of the reef complex. This downstream extension was built upon hard-pan clay substrate found along the western half of the channel.

Middle Channel:

The Middle Channel reef complex (Figure 1B) was constructed in 2012 and is comprised of nine reef beds that are 12 meters wide by 36 meters long and sloped from 0.5 meters thick at the upstream end to 0.76 meters at the downstream end. The reef beds, like those used in Fighting Island, were distributed across the channel. The beds are comprised of one of three rock types: 10-to-20-centimeter angular limestone, 10-to-15-centimeter rounded field stone, and a mixture of the two. In a manner similar to Fighting Island, boulders (approximately 200) were distributed at the downstream end of the reef complex (Vaccaro et al. 2016). The river bottom is comprised of fine to medium sand in this area and bedforms can be observed with sonar upstream and downstream of the reef beds. The bedforms are approximately 0.6 meters in amplitude, roughly equivalent to the upstream thickness of the reef beds. The bedform wavelength is irregular and ranges between 8 to 80 meters between crests.

Vaccaro et al. (2016) discussed the sedimentation at the Middle Channel reef complex. The site pre-assessment underwater video surveys conducted prior to reef construction failed to notice the bedforms. They noted that sand started infiltrating into the gravel beds in the year after the reef complex was constructed, with roughly half of the complex appearing covered in sand by the time of their writing. The authors speculated that sediment transport near the reef could be continuous based on the presence of sand dunes. However, they also suggested it could be episodic based on observations of elevated erosion and turbidity in the region caused by Superstorm Sandy which followed the construction. Fisher et al. (2020b) used annual side scan sonar surveys to determine the bottom hardness and visible area of the reef complex. Both hardness and visible area declined between 2012 to 2018 at the Middle Channel as fine sediments intruded to the complex. The visible area decreased by 70% in the first year. The authors also used underwater video to assess surficial sediment composition. However, these observations began four years after reef complex construction and showed that fine sediment was dominant by this time.

Methods

Bathymetric Surveys

Bathymetric surveys were collected at the reef complexes to characterize the spatial and temporal dynamics in sedimentation patterns. Similarly, the structure of the reef beds was monitored to identify any potential destabilization in the reef planform. Surveys were conducted on June 23-24, 2015, and on July 23-25, 2018 with a Bathyswath interferometric sonar (ITER Systems, La Motte-Servolex, France) operating at 468 kHz. These surveys were processed using the Bathyswath Swath Processor and Grid Processor software at a spatial resolution of 1 meter and are provided in Universal Transverse Mercator (UTM) Zone 17, in meters (Kinzel et al. 2019a, b).

Subsequent bathymetric surveys were collected in 2021 and 2022 with a Norbit iWBMS, 400kHz with an Applanix WaveMaster inertial measurement unit (Kinzel et al. 2022). Real-time kinematic differential corrections came from cellular communication with the Michigan Department of Transportation Real Time Network (RTN) to correct positions in real-time and ensure sonar data coverage of the reef complexes was sufficient during the survey. The Applanix trajectory file was post-processed in the POS-PAC software to provide precise horizontal positioning in UTM Zone 17 meters and elevation relative to NAVD88 using GEOID18 (Kinzel et al. 2022). Positioning precisions are expected to be at the centimeter level with this system. Survey data were saved in LAS format and included sonar intensity information. In 2022, the Middle Channel reef complex was intensively surveyed over four successive days, May 2 to 5, 2022. This was to evaluate if sequential surveys could detect changes in the bedforms and, if so, if a bedform migration rate could be estimated.

Bed Sediment Collection and Processing

In November of 2021, a Ponar sampler (Edwards and Glysson 1999) was used to collect three bed material samples above and two on the Middle Channel reef beds. The samples were dried and sieved at ½ phi increments to determine the grain-size distribution (Kinzel and Kennedy 2022). The median grain size or d_{50}, the size for which 50% of the sample is finer by mass as well as the d_{16} and d_{84} sizes in millimeters are shown in Table 1.

Table 1. Middle Channel reef bed sediment size characteristics. Samples 1, 2, and 3 were collected upstream of the reef beds and samples 4 and 5 were collected on the reef beds.

Sample	d_{16} (mm)	d_{50} (mm)	d_{84} (mm)
1	0.22	0.3	0.48
2	0.25	0.25	0.35
3	0.09	0.15	0.22
4	0.2	0.26	0.32
5	0.21	0.28	0.35

Acoustic Doppler Current Profiler Measurements

On May 2-4, 2022, a SonTek M9 acoustic Doppler current profiler (ADCP) was used to measure the streamflow in the Middle Channel of the St. Clair River delta (Table 2). A series of transects perpendicular to the river flow were collected downstream of the Middle Channel reef complex. The mean of the streamflow measurement made on a given day was compared to the mean daily streamflow reported at the upstream U.S. Geological Survey (USGS) gage 04159130, St. Clair River at Port Huron, Michigan (U.S. Geological Survey, 2022). These measurements indicated that the flow in the Middle Channel is approximately 17 % of that in the St. Clair River, not accounting for travel time from the gage to the reef complex. The ADCP also collected velocity measurements. The streamflow on May 4, 2022, and associated velocity measurements were used to set boundary conditions and provide calibration data for hydrodynamic modeling (Kinzel 2022).

Table 2. Mean streamflow measured by an acoustic Doppler current profiler in the Middle Channel of the St. Clair River delta.

Date	Streamflow (cubic meters per second)
5/2/2022	1,032
5/3/2022	1,042
5/4/2022	1,059

Flow and Sediment Transport Modeling

Flow and Sediment Transport with Morphological Evolution of Channels (FaSTMECH) is a multi-dimensional flow and sediment transport model included in the International River Interface Cooperative (iRIC) software suite (Nelson et al. 2015). The version of iRIC used for the simulation reported in this paper was 3.0.19 revision 6748 released on 3/2/22. FaSTMECH assumes that the flow modeled is incompressible, hydrostatic, primarily two-dimensional, not affected strongly by secondary flows and is quasi-steady. Sediment transport in FaSTMECH can be computed using equations developed by Meyer-Peter and Müller (1948), Yalin (1963), Engelund and Hansen (1967) and Wilcock and Kenworthy (2002). Time evolution of the channel morphology can also be simulated. An iterative process is used, wherein the flow solution is used to compute bed stress, a sediment transport equation is used to compute the sediment flux, the erosion equation determines the rate of change of the bed elevation, and a new flow solution calculated. All modeling performed to support this study is included in a model archive available from Kinzel (2022).

Wilcock-Kenworthy (WK) is a two fraction, sand and gravel, transport model that can account for sediment flux in mixtures (Wilcock and Kenworthy 2002). The WK model was used within FaSTMECH. The WK model has been used to simulate the downstream depth and fractions of sand in a gravel bed after the introduction of a pulse or chronic supply of sand (Maturana et al. 2013). The WK implementation has several assumptions:

1) The bed material can be divided into a coarse and fine faction.
2) The coarse fraction is immobile, and the fine fraction is mobile.
3) Fine sediment may deposit within the inter-particle void spaces of the streambed.
4) Once the gravel is entirely covered by sand, bed elevation at each cell is updated as sand deposits over the gravel.
5) Fine sediment may penetrate instantaneously within the gravel pores up to a specified depth.
6) Fine sediment may be removed from the substratum up to specified depth.

Because this model was not designed specifically for our study, further assumptions were made to apply the model for simulating sedimentation of the Middle Channel reef beds. The model assumes that gravel underlies the entire model domain and not just the reef beds (Figure 2). While this is not completely accurate, we assume that areas of active sand bedforms can be modeled as a “sand/gravel matrix”. Conceptually, this is analogous to a situation where sand has already filled a portion of the upstream end of the reef bed and the progression of that sand through the downstream clean gravel is tracked through time. The gravel size was set to 0.15 m, based on the average size of the reef materials described above, and the sand size is set to the average value in Table 1, 0.25 mm. We also set both the thickness of the underlying sublayer of gravel across the entire domain, and the initial depth of sand in this layer, to 1 m. The sand depth was set to zero in the reef beds and was assumed to be absent in the interstices (i.e. zero sand fraction). The sand depth was set to 0.6 m and the sand fraction to 1, filling the gravel interstices in all other locations in the model domain. This 0.6 m depth of sand includes the 0.6 m maximum height of sediment protrusion, a variable called H_{max}. This value was based on the average height of the gravel reef beds. Although the model could account for an additional layer of pure sand over the gravel, this parameterization would require an assumption of average depth of sand in the complex/variable bedform morphology and therefore was not implemented herein.

When the model is executed, sand is made available to move from the areas where the sand fraction is set to 1 to areas where the sand fraction is set to zero. The amount of infilling to the gravel by the sand is dependent upon the porosity of the gravel. A mass balance model allocates the fine sediment within the inter particle void space in the coarser subsurface layer until the void space is filled. After filling the void space up to a depth of H_{max}, the fine sediment can be added in layers which further increases the sand depth and updates the bed elevation.

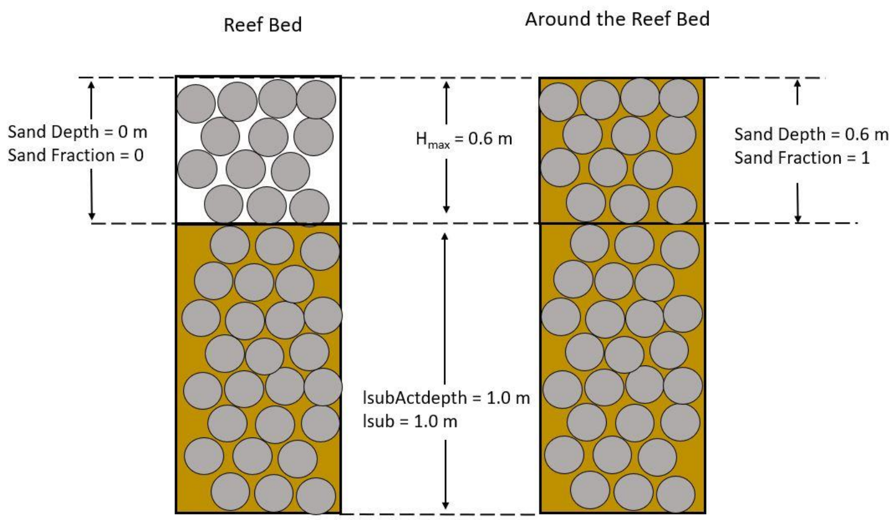


Figure 2. Illustration of input condition at time = 0 of the reef bed (left panel) and all other locations (right panel). The left panel shows a gravel matrix unfilled (sand depth and fraction = 0). The right panel, shows a sand/gravel matrix (sand fraction = 1) with a sand depth of 0.6 m and the maximum height of the sediment protrusion H_{max} of 0.6 m.

Results

Bathymetric Surveys

Surveys of the Fighting Island reef complex collected in 2015 and 2022 are shown in Figure 3. The eastern reef beds became covered in sediment a few years after their construction in 2008 (Vaccaro et al. 2016). A profile drawn over the six eastern reef beds is shown in panel A. The elevations across these beds are relatively consistent between the 2015 and 2022 surveys, only varying on the order of +/-0.2 m over the five reef beds within the bedform field. A second profile drawn 50 meters downstream of the reef bed is shown in panel B. This profile indicates the edge of the bedform field retreated up to seven meters from 2015 to 2022. Future monitoring could focus on this dynamic zone and on the maturation of these eastern reef beds.

Bathymetric maps of the Middle Channel reef beds collected in September 2021 and May 2022 are shown in the left panels of Figure 4. Notice the change in bedform pattern in the eight months between the surveys. An elevation profile across the fifth reef pad from the top is shown in the right two panels. Panel A shows the reef pad and the region just upstream where in 2021 a bedform has approached but not yet impinged on the upstream extent of the reef bed located at approximately 36 meters along the profile. In 2022, a bedform has impinged on the reef bed and two additional bedforms are present immediately upstream. A close-up view of those two bedforms is shown in panel B and shows the translation between May 2 and 5, 2022. The slip face of the bedforms moved approximately 1 m or 0.3 m per day. Although serial surveys showed the bedforms in this area changed from year to year, capturing this relatively slow migration speed was only possible with a precise bathymetric mapping system.

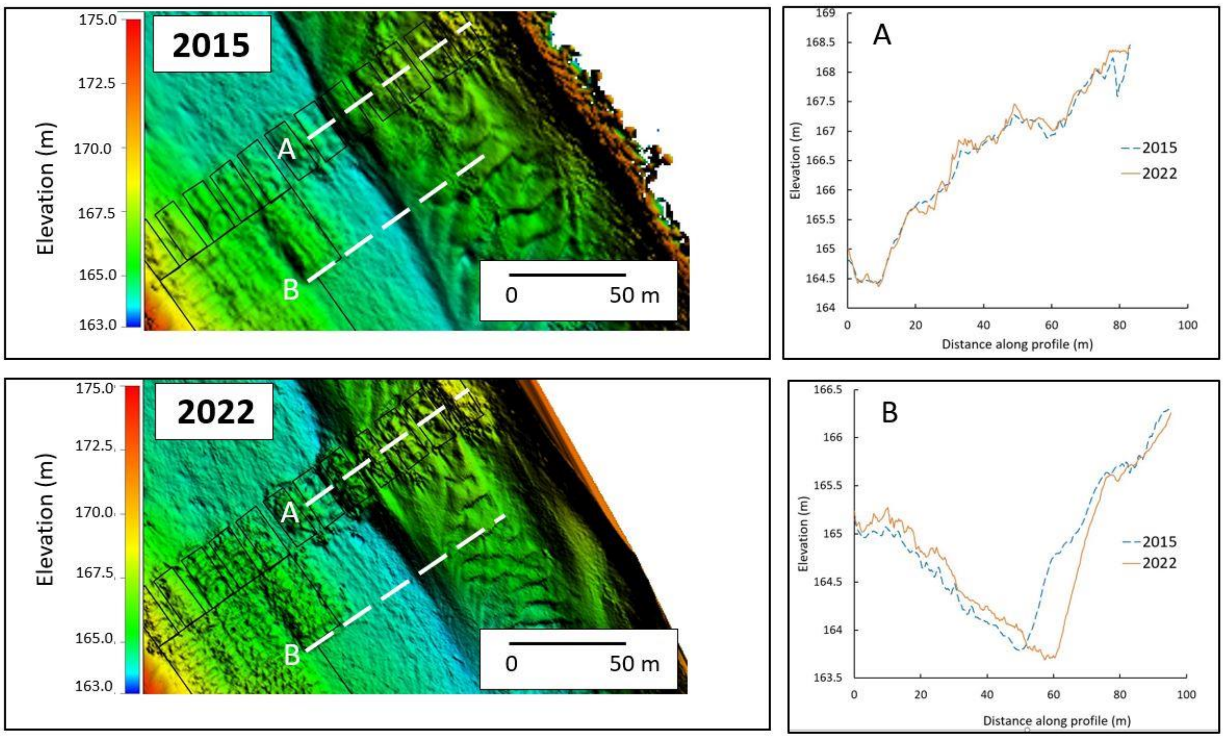


Figure 3. The left panels are surveys of the Fighting Island reef complex collected in 2015 (top) and 2022 (bottom). Elevation profile A is drawn across the reef complex and elevation profile B is drawn 50 meters downstream of A. In the right panels, the blue dashed lines represent the elevations of the 2015 survey across profiles A and B and the solid orange lines represent the elevations of the 2022 survey across profiles A and B. Flow is from upper left to lower right in the left panels.

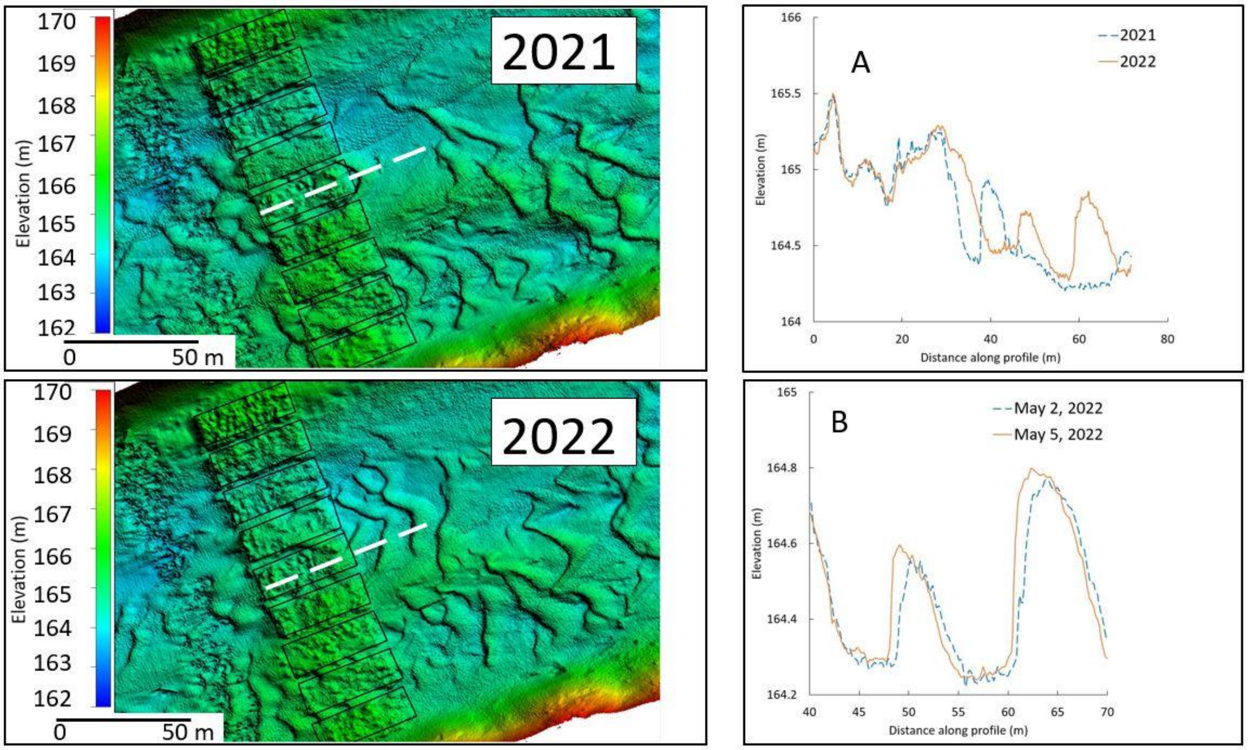


Figure 4. The left panels are surveys of the Middle Channel reef complex collected September 2021 (top) and May 2022 (bottom). The dotted line is a stream-wise elevation profile drawn along and upstream of reef bed 5. Right panel A shows a comparison between the 2021 survey shown with a blue dashed line and the 2022 survey shown with a solid orange line. Right panel B is a subset of A showing the bedforms measured on May 2, 2022, with a dashed blue line and May 5, 2022, shown with a solid orange line. Flow is from upper right to lower left in the left panels.

Flow and Sediment Transport Modeling

Prior to running the WK model to simulate infiltration of fines to the reef beds, a hydraulic model for the Middle Channel was calibrated. As mentioned above, the ADCP measurements were used to specify the streamflow used in the simulations as well as provide measurements of depth-averaged velocity that could be used to calibrate the model. Two plausible lateral eddy viscosity values (0.05 and 0.005) were run over a range of drag coefficients (0.001 -0.05) to find a set of both values that provided the best agreement with the field data (Kinzel 2022). Figure 5 shows a WK sediment transport simulation starting at the initial condition when the reef beds are comprised of clean gravel (sediment depth and fraction are zero) to a time 10 days later. The sand fraction in the reef beds ranges between approximately 0 to 1 with large areas in the reef comprised of between 40 to 50% sand and some filled with sand, 100% after only 10 days. The response of the sand depth is similar, with reef beds accumulating a depth of 0.25 to 0.4 meters of sand in this relatively short period of time. As sediment moves into the reef complex at the upstream end and fills, an opposite process occurs downstream of the reef complex. The initially clean gravels at the downstream end of the complex propagate as this empty volume erodes the contents of down gradient grid cells. Our assumption that a layer of sand is not present above the gravels causes sand to erode from the “sand/gravel matrix” in the channel and reduces the sand fraction and decreases the sand depth in higher shear areas. This is particularly acute upstream of the sixth reef bed from the top where the sand fraction and depth go to nearly zero and upstream sand is not replacing the contents of the matrix. Resolution of the model grid is relatively coarse (2 by 2 meters) and the model is not capable of resolving the complex three-dimensional flow fields around the reef beds or modeling the translation of the bedform slip faces. Although this model simulation has assumptions and limitations, it does provide an accounting of the fine sediment movement through gravel in a reef bed.

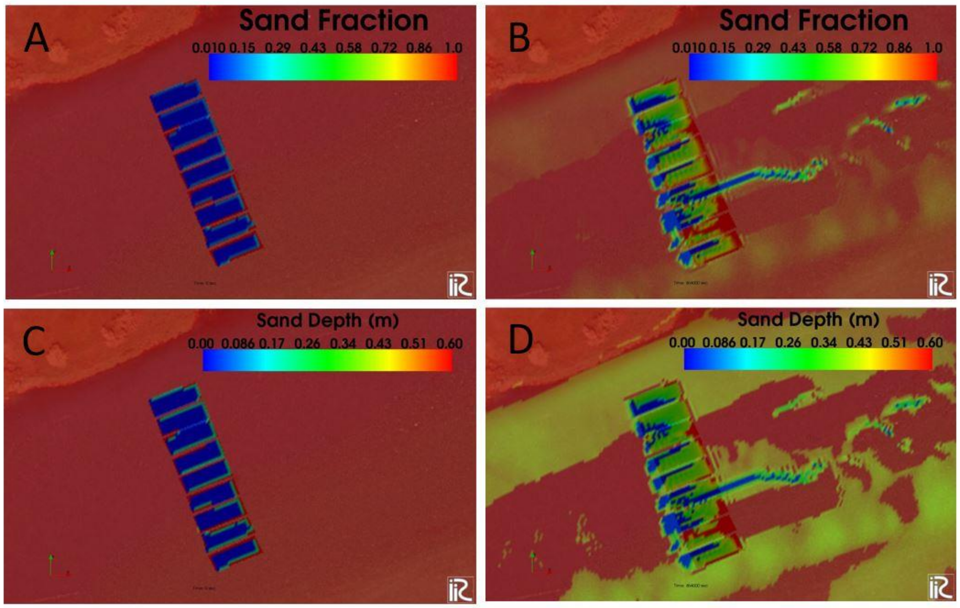


Figure 5. Simulation at time zero and at 10 days for the sand fraction (A, B) and sand depth (C, D) for the Middle Channel reef beds. Flow is from right to left in each panel.

Conclusions

Serial bathymetric surveys were used to document spatial and temporal patterns of sedimentation near nine spawning reef complexes in the Detroit and St. Clair Rivers, Michigan. Two reef complexes, Fighting Island and Middle Channel have dynamic bedform fields that impinge on the reef beds. At the Fighting Island reef complex, surveys collected in 2015 and 2022 showed that the lateral extent of a bedform field changed by seven meters over this time scale. At the Middle Channel reef complex, a bedform migration rate was computed over a few days and was of the order of 0.3 m/day.

A coupled flow and sediment transport model was constructed for a reach of the Middle Channel of the St. Clair River delta to simulate the process of infilling initially clean immobile gravel with sand. This simulation has biological implications, as when reef beds fill with sediment their value as spawning habitat can be reduced (Baetz et al. 2020). Although the sediment transport model was developed for gravel beds, we reasoned that sand supplied from the "sand/gravel matrix" immediately upstream would infiltrate into the clean spawning beds downstream. A 10-day simulation showed the evolution of the sand fraction and sand depth in the reef beds.

The rate of infilling predicted by the model was greater than the bedform migration rate. However, we would not expect them to be the same. The bedform migration rate does not account for a bypass fraction or sand that passes over the bedform and does not deposit on the lee side. In other words, the observed translation rate underestimates the actual transport rate. Similarly, the model assumes that at time zero sand from the "sand/gravel matrix" is instantly available to enter the reef bed. The time required for a bedform to move to and intercept the reef beds is not simulated or accounted for in the model. Also not considered are periods when a bedform is not actively supplying sand to the reef bed.

Detailed field measurements of the rate of colmation at the Middle Channel reef complex during the first year following construction were not available for comparison. Thus, the observed migration rate and the model simulation provide best estimates to characterize the complex process of bedform translation and sediment infiltration. Unless the upstream supply of sediment is intercepted, river processes alone cannot be expected to flush sediment through the reefs and reset them to their post-construction state. Future efforts directed toward potential enhancement and/or maintenance of reefs impaired by sedimentation could benefit from continued monitoring. This could be accomplished through a combination of periodic high-resolution bathymetric surveys, detailed inspection by diving, and collection of detailed underwater imagery.

Disclaimer: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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