RECLAMATION

Managing Water in the West

Hydraulic Laboratory Report HL-2019-04

Physical Hydraulic Model Study of Debris Management Alternatives for Hogback Diversion Dam

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

August 2019

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE August 14, 2019	**2. REPORT TYPE** Technical	**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE Physical Hydraulic Model Study of Debris Management Alternatives for Hogback Diversion Dam		**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Kent Walker, P.E. Christopher Shupe		**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Department of the Interior, Bureau of Reclamation Technical Service Center, 86-68560 P.O. Box 2,5007 Denver, CO 80225		**8. PERFORMING ORGANIZATION REPORT NUMBER** HL-2019-04
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A 1:60 Froude-scale physical hydraulic model of the Hogback Diversion Dam intake structure on the San Juan River near Farmington, NM was constructed in the Bureau of Reclamation's Denver hydraulics laboratory. The model was used to test alternatives for reducing plugging of the intake structure by large woody debris. Model results showed that the most critical conditions occur at moderate river flows at which debris is capable of being transported, but there is limited lateral spreading of the river over the diversion dam crest and thus more debris in the main river channel. Alternatives studied in the model included log booms, in-channel rock structures, and a combined log boom and rock structure. The greatest debris reduction was obtained with a combined log boom and rock structure.

15. SUBJECT TERMS
Hogback intake, trashrack, debris management, large woody debris, LWD

16. SECURITY CLASSIFICATION OF: Unclassified			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Robert F. Einhellig
U	U	U	U	91	**19b. TELEPHONE NUMBER** *(Include area code)* 303-445-2142

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Hydraulic Laboratory Report HL-2019-04

Physical Hydraulic Model Study of Debris Management Alternatives for Hogback Diversion Dam

KENT WALKER Digitally signed by KENT WALKER Date: 2019.08.16 09:34:04 -06'00'

Prepared: Kent Walker, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services Group, 86-68560

CHRISTOPHER SHUPE Digitally signed by CHRISTOPHER SHUPE Date: 2019.08.20 08:57:13 -06'00'

Checked: Christopher Shupe
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services Group, 86-68560

ROBERT EINHELLIG Digitally signed by ROBERT EINHELLIG Date: 2019.08.19 10:22:28 -06'00'

Technical Approval: Robert F. Einhellig, P.E.
Manager, Hydraulic Investigations and Laboratory Services Group, 86-68560

THOMAS GILL Digitally signed by THOMAS GILL Date: 2019.08.16 17:18:05 -06'00'

Peer Review: Tom Gill, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services Group, 86-68560

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

August 2019

Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Hydraulic Laboratory Reports

The Hydraulic Laboratory Report series is produced by the Bureau of Reclamation's Hydraulic Investigations and Laboratory Services Group (Mail Code 86-68560), PO Box 25007, Denver, CO 80225-0007. At the time of publication, this report was also made available online at **https://www.usbr.gov/tsc/techreferences/hydraulics_lab/reportsdb/reportsearchall.cfm**

Disclaimer

CONTENTS

TABLES

FIGURES

Executive Summary

The Hogback Diversion Dam is planned to be utilized as part of the Navajo Gallup Water Supply Project which will increase the flows diverted into the structure from the San Juan River once implemented. Due to concerns of debris obstruction of the intake trashracks with the increased demands, a 1:60 Froude scale physical model was constructed to compare various alternatives to divert river transported debris away from the intake structure. Other alternatives identified but not tested in the model were bank capture structures and in channel piles.

This report summarized the physical model results of six alternatives and the existing conditions at the structure. During existing conditions testing, moderate river flows between 2,000 and 12,000 cfs were found to have the ability to transport large debris quantities which remained channelized near the intake structure at the diversion dam alignment. Alternatives tested included two log booms, rock structures and a combination of the best performing log boom and rock structure alternatives. While all alternatives were effective at reducing the amount of debris at the intake structure forebay, the greatest reduction was observed while operating the model with the combination of both a log boom and a rock structure. Additionally, it was observed that the closer the debris mitigation alternative was to the intake structure, the better it performed.

Introduction

Project Background

The Hogback Diversion Dam is located on the San Juan River in San Juan County, New Mexico roughly 18 miles west of Farmington, NM. It was originally constructed by the Federal government with Civilian Conservation Corps crews in the 1930's to create a small impoundment and permanent intake facility for the Shiprock Irrigation District canal. This site was selected due to its location where the San Juan River penetrates the Hogback rock formation which reduces the likelihood of channel migration. In 2002 the original boulder and cobble overflow weir was fortified with grouted riprap and sheet pile. In addition, a new trashrack structure was added to reduce the amount of debris entering the canal. Also included with this revision was a fish weir and sluicing structure located approximately 2000 feet downstream. Figure 1-3 show the intake structure that was constructed in 2002 from the left bank and two plan view images with project features identified.

Figure 1. Photo of Hogback Diversion Dam intake structure from left bank of San Juan River, with lower bars of trashrack panels removed to reduce the debris caught along the bars.

Figure 2. Plan view of Hogback Diversion Dam and vicinity.

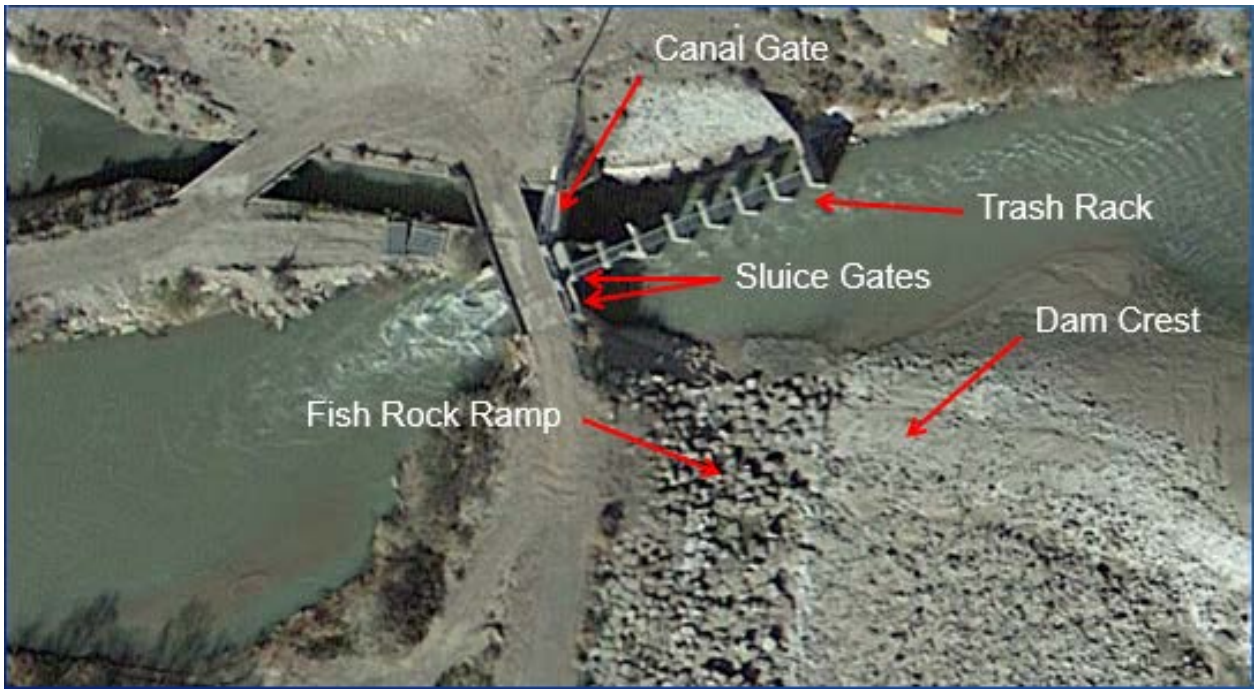

Figure 3. Plan view of the Hogback Intake structure with features labeled.

The diversion structure consists of a 16-foot wide by 4-feet high canal head gate protected upstream by the five-bay trashrack structure. Adjacent to the trashrack structure are two sluice gates, each 10-feet wide by 7-feet high. The bottom sill of the canal head gate is 4 feet higher than the bottom sill of the sluice gates to reduce the amount of bed load sediment that enters the canal. The canal is operated for irrigation from March to October and is controlled by the canal gate opening. More water is usually diverted through the headworks than is delivered downstream to the Hogback Canal. The excess diverted flow is used to sluice sediment and return fish into the river through sluicing dual leaf gates located beyond the fish weir.

The trashrack was designed by Reclamation in 1999, and was developed for design flow of 300 ft^3/s. Its length was determined based on bar spacing of 1½ inches clear and an approach velocity of 1 ft/s. The trashracks were intended to be hand raked for debris removal. The initial bar spacing of 1 ½ inches served dual purposes of limiting both fish and debris entry into the Hogback Canal. The Hogback fish barrier weir was designed in 2009 by Reclamation with substantial construction completion in June 2013. The fish barrier installation downstream changed the dual purpose of the trashrack and no longer required the trashrack to exclude fish. Concurrent with the construction of the fish barrier, bars were removed from the lower portion of the trashrack, resulting in bar spacing clear on the lower portion of the trashrack of 11 ½ inches. During operation, the hand raking of debris caught on the smaller clear spacing had been problematic.

During normal operations of the diversion structure, the canal head gate is opened to divert a portion of the river flow into the Hogback Canal while the sluice gates are in the closed position. River flow passes down the fish rock ramp at lower stages and both down the rock ramp and over the diversion dam crest at higher stages. Periodically, the sluice gates are fully opened to allow sediment deposited in front of the intake structure to be transported downstream. With the sluice gates open, the river stage may drop

below the Hogback Canal stage resulting in flow exiting the canal into the river at the trashrack structure. This flow reversal was observed in October 2018 during the trashrack velocity testing and was very effective at removing captured debris from the trashrack bars. According to operators from Shiprock Irrigation District, the sluice gates are normally opened for approximately one hour, on monthly intervals during irrigation season and more often when needed.

Prior to the modifications at Hogback Diversion Dam, the low flow channel of the San Juan River was migrating away from the intake structure. The channel shift jeopardized the future ability to provide reliable irrigation diversion as shown below in Figure 4. Following the fortification of the diversion dam, the main channel of the San Juan River was constrained to follow the right bank road embankment, as shown in Figure 2, and reduced its ability to spread during low to moderate flows. Sand bed channels such as the San Juan maintain a stable energy balance by their dynamic ability to meander during moderate flows resulting in continuous channel migration throughout the floodplain. The reduction in the river's ability to meander has resulted in a more stable river channel which has allowed vegetation to colonize the large overbank area upstream of the diversion dam.

Figure 4. USGS satellite image of San Juan River at the Hogback Canal Intake, 1997.

While the stabilized river channel has secured the availability of irrigation water to the intake structure, it has also resulted in more debris being encountered at the intake structure. During low flow periods, the diversion into the canal can be a significant portion of the total upstream river flow which results in much of the river debris being drawn into the trashrack structure, even though the debris is typically a smaller size. When flows rise to moderate levels which have enough energy and depth to erode mature trees found along the riverbank, these trees are kept within the channelized river and are carried by the flow into the intake structure as well. High flows in the river will allow lateral spreading which spreads the flow and debris across a portion of the diversion dam's crest, but due to the river bend upstream of the intake, much of the large debris will still follow along the right bank towards the intake structure.

This debris concentration has resulted in operational challenges to the operators and has resulted in expenses in terms of staff time and damage to the intake structure as shown in Figure 5 and Figure 6. Debris removal at the structure of smaller pieces is accomplished by manually dislodging debris

captured along the face of the trashrack with a long pole and allowing it to pass through the sluice gates. Large debris that deposits in front of the structure has required an excavator to extract from the river channel to ensure that debris does not obstruct and prevent closure of the sluice gates. If this were to occur there is potential for loss of the ability to control the water surface elevation which would impact the ability to deliver irrigation water. To investigate alternatives that reduce the likelihood of large debris pieces at the intake structure, a physical model was constructed in the Bureau of Reclamation's Hydraulics Laboratory in Denver, CO.

Figure 5. Debris following a peak flow of 9,000 cfs in May 2007. The log boom was damaged in this event due to the high amount of debris coming down the river.

Figure 6. Photograph of damaged sluice gate skin plate due to debris strike.

During the diversion dam design phase, a crest elevation was selected to allow high flows to pass with a slight concentration towards the intake structure. However, a recent survey indicated that the crest elevation is much more variable than originally designed. The current varied elevation is likely due to sediment aggradation and effects of velocity sheltering from the overbank vegetation in some areas and flow concentration in other areas. This has led to a general increase in flows near the intake structure, and an associated increased debris load. Figure 7 shows the diversion dam design crest elevation along with point and surface data from a 2017 dam crest survey, as well as elevation data from a survey of the physical model dam crest.

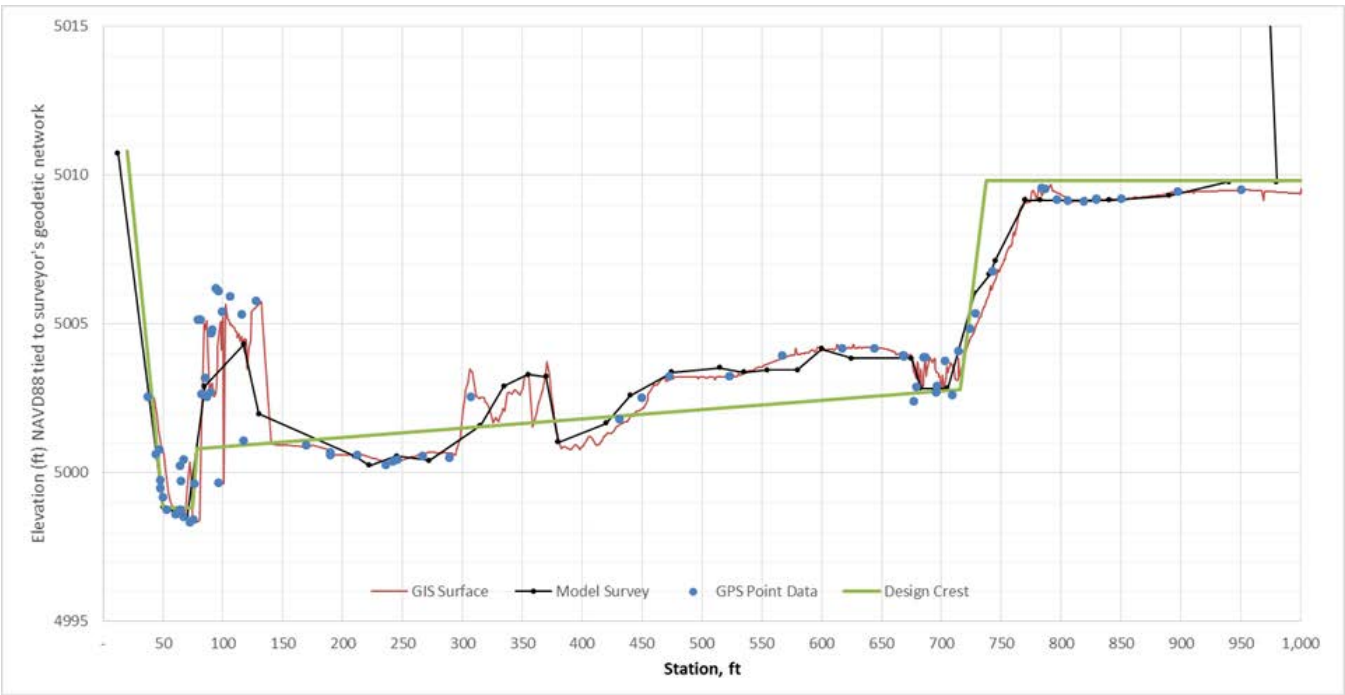

Figure 7. Crest profile as looking upstream (fish rock ramp notch on the left, moving south to the high ground tie in on the right) showing the design elevations, point survey data from 2017, a GIS surface created from all the survey points and elevations adjusted to prototype from the physical model survey.

Physical Model Description

To be able to model debris transport in the river a large area of the river upstream of the Hogback Diversion Dam was needed. Due to the magnitude of area involved and space constraints in the laboratory, the model scale selected was 1:60 (model: prototype) geometric scale which included roughly one mile of river and overbank area upstream of the diversion dam. The entire diversion dam crest and the Hogback intake structure (including sluice gates, canal gate and trashrack piers) were also included within the extent of the model. While sediment is continually transported throughout the San Juan River channel, it was decided to construct the model with a non-mobile bed that represented conditions established by 2013 Light Detection and Ranging (LiDAR) and 2017 bathymetric surveys. Figure 8 shows the model extent overlaid with an aerial image and a flow depth raster created from United States Army Corps Hydrologic Engineering Center's River Analysis System (HEC-RAS) hydraulic modeling.

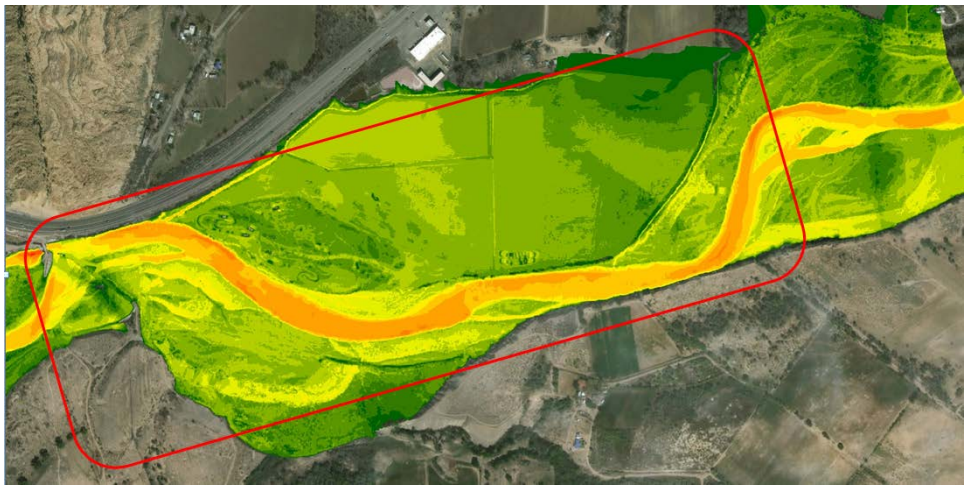

Figure 8. 1:60 scale physical model of the Hogback Diversion Dam, upstream San Juan River Channel and overbank area. The red line is the model extent. The background image shows flow depths during a 20,000 cfs flow event.

Model Design

Model topography was based on LiDAR data obtained from GeoDigital who performed the calibrated LiDAR data products acquisition in November 2013, and was supplemented with information from a 2017 GPS survey of the entire crest length as well as boat-based bathymetry of the San Juan River channel performed by the Sedimentation and River Hydraulics group of Reclamation's Technical Service Center (TSC). The digital terrain model was imported into AutoCAD and converted into contours that were used to lay out cross sections for the physical model. These cross sections were constructed using a template skeleton created from air injected Polyvinyl chloride (PVC) which was impervious to shrink and swell from moisture. This provided a stable elevation basis for the model topography. Figure 9 shows a plan view of the physical model extent and location of the cross sections.

Figure 9. Model cross section layout.

The PVC templates were cut with a water jet which allowed accurate representation of the elevation changes in the topography and were installed using an index location incorporated into the water jet CAD file that allowed consistent survey markers across all the individual template sections. Once each template was installed, the area between templates (typically four feet) was backfilled with moistened concrete sand and compacted. To create the stable bed surface for the model, the top one inch was filled with a roughly 80:20% concrete sand to Portland cement mix. To ensure elevation control for the top one inch, the PVC templates were cut with a removable top section that allowed adjacent material to be screeded level to the top of the PVC and stabilized by curing the cement with water. Once cured, the top piece of the PVC was removed, and material was placed into this void and screeded level with the adjacent stabilized topography. To prevent underflow between cross sections, alternating PVC templates were sealed to the model floor. A photograph of model construction is shown in Figure 10.

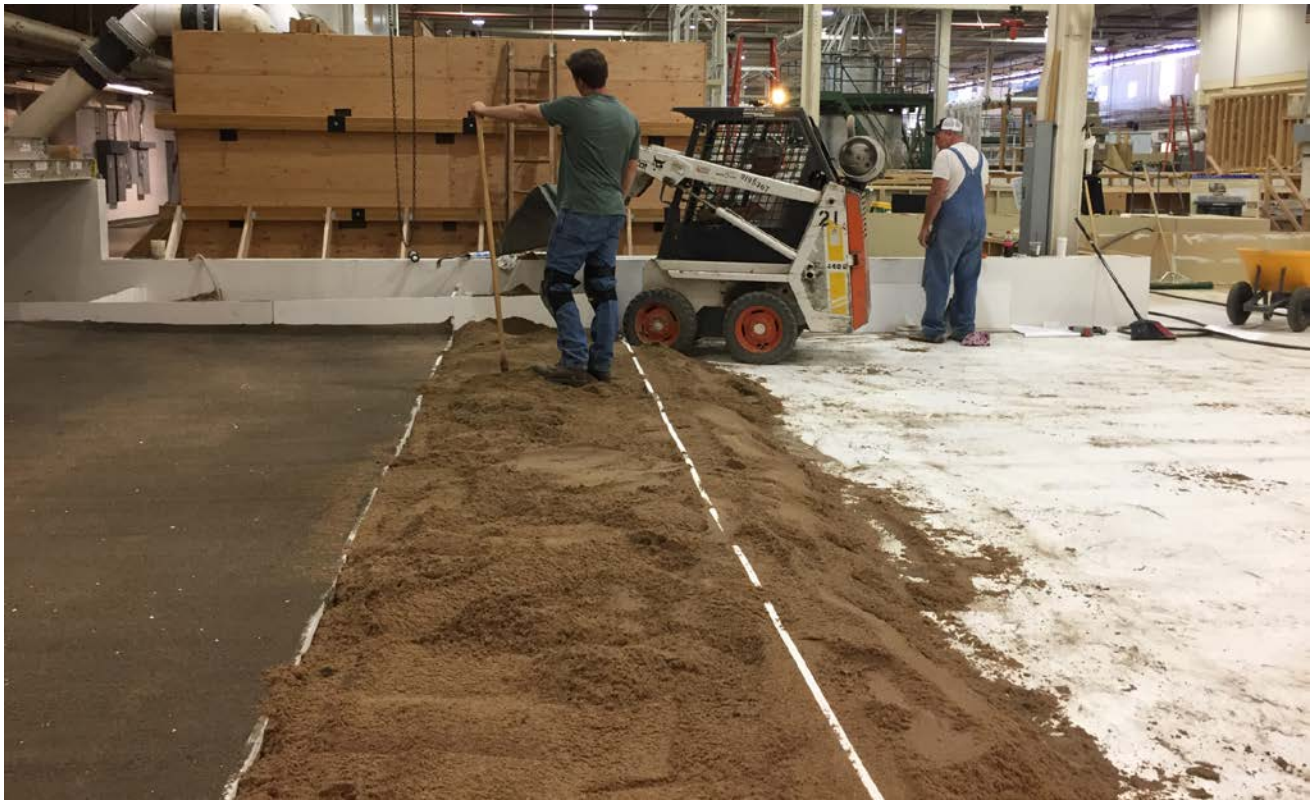

Figure 10. Model construction using PVC templates with concrete sand backfill and a mix of Portland cement and sand for a stabilized bed surface. The section to the left in the photograph has been stabilized with Portland cement, while the center section has just been filled with concrete sand. Both sides of the templates were filled with material to prevent deflection of the template during compaction.

Following construction, the physical model was validated by comparing reference flow depths with the HEC-RAS hydraulic model. To achieve this, 15 depth marker points were identified to compare flow depths between the physical model and the HEC-RAS model. Nine of these points were located within the main flow channel, and six points were in overbank areas. These depth markers were compared for all flows tested in the model. Figure 11 shows the location of these markers and the recorded model depth in inches overlain the HEC-RAS raster for one of the four test flow rates. Table 1 includes the measured physical model flow depths in inches, those physical measurements converted to prototype flow depths in feet, and the flow depth range as estimated by HEC-RAS in feet.

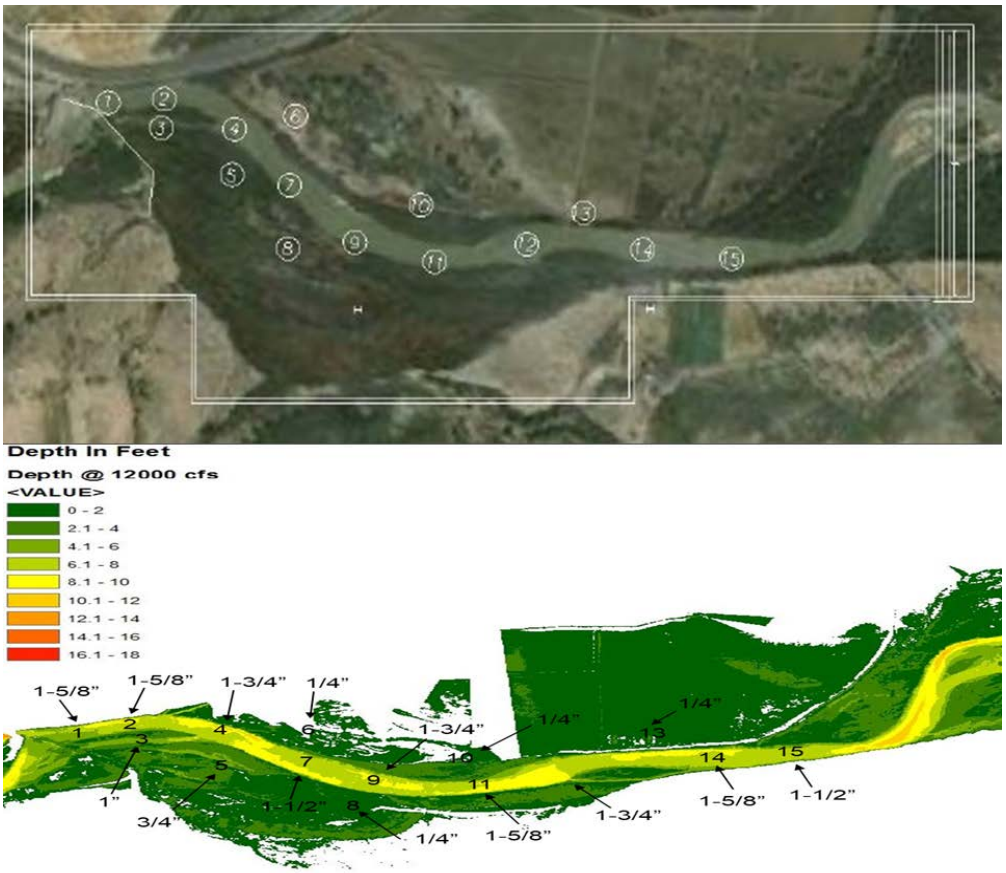

Figure 11. Physical model data verification points (upper image) and HEC-RAS inundation maps for river flow of 12,000 cfs with physical model flow depth measurements shown in inches.

Table 1. HEC-RAS and model flow depths, highlighted cells were found to be outside of HEC-RAS model range.

Flow	River Q= 800 cfs			River Q= 2500 cfs			River Q= 5000 cfs			River Q= 12000 cfs		
Depth Marker Number	Physical Model Depth (in)	Physical Model Depth (ft)	HEC-RAS Model Depth (ft)	Physical Model Depth (in)	Physical Model Depth (ft)	HEC-RAS Model Depth (ft)	Physical Model Depth (in)	Physical Model Depth (ft)	HEC-RAS Model Depth (ft)	Physical Model Depth (in)	Physical Model Depth (ft)	HEC-RAS Model Depth (ft)
1	0.75	3.8	2.1-3	1	5.0	3.1-4	1	5.0	4.1-5	1.625	8.1	4.1-6
2	0.75	3.8	3.1-4	1	5.0	4.1-5	1.25	6.3	5.1-6	1.625	8.1	6.1-8
3	0	0.0	0-1	0.25	1.3	1.1-2	0.75	3.8	3.1-4	1	5.0	4.1-6
4	0.625	3.1	1.1-2	0.75	3.8	3.1-4	0.75	3.8	4.1-5	1.75	8.8	8.1-10
5	0	0.0	0	0	0.0	0	0	0.0	0-1	0.75	3.8	2.1-4
6	0	0.0	0	0	0.0	0	0	0.0	0	0.25	1.3	0-2
7	0.5	2.5	2.1-3	0.75	3.8	2.1-3	1.125	5.6	4.1-5	1.5	7.5	6.1-8
8	0	0.0	0	0	0.0	0	0	0.0	0	0.25	1.3	0-2
9	0.625	3.1	2.1-3	0.875	4.4	3.1-4	1.25	6.3	5.1-6	1.75	8.8	6.1-8
10	0	0.0	0	0	0.0	0	0	0.0	0	0.25	1.3	0-2
11	0.375	1.9	2.1-3	0.75	3.8	3.1-4	1.125	5.6	5.1-6	1.625	8.1	6.1-8
12	0.5	2.5	2.1-3	1	5.0	3.1-4	1.25	6.3	5.1-6	1.75	8.8	8.1-10
13	0	0.0	0	0	0.0	0	0	0.0	0	0.25	1.3	0-2
14	0.375	1.9	2.1-3	1	5.0	3.1-4	1.25	6.3	4.1-5	1.625	8.1	6.1-8
15	0.5	2.5	2.1-3	1	5.0	3.1-4	1.25	6.3	5.1-6	1.5	7.5	6.1-8

Due to the porous topography that potentially could result in seepage losses through the physical model, all flow measurement was situated downstream of the Hogback Intake Structure. The model was designed with two separate flow measurement locations; one location for the combined flow passing over the diversion dam and through the sluice gates and the other location for flows passing into the Hogback Canal. Flow measurement locations utilized v-notch weirs connected to stilling wells, each outfitted with a combination of an ultra-sonic acoustic level sensor for automated reading, and a manual hook-type point gage reading for reference. Due to the sensitivity of the model flow scaling at a 1:60 scale, low flows were also calibrated with manual flow measurement. A photograph of the downstream flow measurement is found in Figure 12. DASYLab V13.0.0 was utilized for automated data acquisition which included the flow measurements of the v-notch weirs as well as the water surface elevation (WSE) in front of the trashrack. Flows to the model were supplied by a Variable Frequency Drive pump with a submerged intake plumbed into the sub-floor reservoir at the hydraulic laboratory.

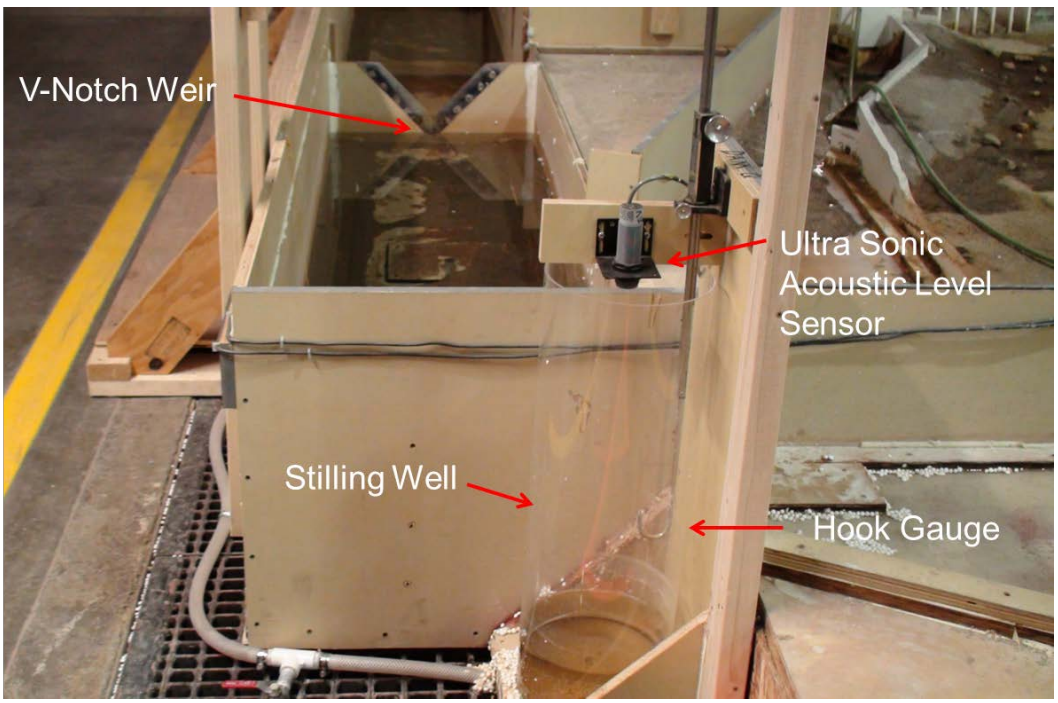

Figure 12. Photograph of physical model flow measurement.

Comparable results between the model and prototype data are achieved when the ratios of the major forces controlling the hydraulic processes are kept equal in the model and the prototype. Since gravitational and inertial forces dominate open channel flow, Froude-scale similitude was used to establish relationships between the model and the prototype parameters. The Froude number is defined as:

$$\mathrm{Fr} = \frac{v}{\sqrt{gd}}$$

where: v = velocity
g = gravitational acceleration
d = flow depth

When Froude-scale modeling is used, the following relationships exist between the model and prototype for the 1:60 geometric scale chosen:

Length ratio: $L_p = L_m * 60$

Velocity ratio: $V_p = V_m * (60)^{1/2}$

Time ratio: $T_p = T_m * (60)^{1/2}$

Discharge ratio: $Q_p = Q_m * (60)^{5/2}$

The 1:60 scale hydraulic model provided an accurate representation of prototype depths, velocities and lateral spreading of flow across the floodplain which will control debris transport in the river channel. Since the physical model topography was constructed using concrete sand stabilized with cement, bed roughness elements were considerably larger than the prototype equivalent, and the physical model topography did not include any bed forms (sand dune, ripples, etc.) that would be expected in the San Juan River. However, these limitations were deemed reasonable and allowed the qualitative assessment of how large debris pieces are transported by the river, and comparison of selected alternatives designed to reduce large debris from approaching the Hogback intake structure.

Test Matrix

To evaluate the impacts of various alternatives on the debris characteristics at the Hogback structure, a test matrix was established to test a variety of flow conditions in the physical model. Following shakedown testing, it was evident in the model that very high flood flow conditions – similar to the expected 1/100 probability (100-year return) flood event occurrence – were not the conditions that brought a majority of debris towards the Hogback structure. While these high flows would be expected to mobilize a significant amount of debris, most of the diversion dam crest and overbank area would be inundated and debris would not be concentrated in the vicinity of the diversion structure. Shakedown testing found that low to intermediate flows during which the river remains channelized near the structure were more likely to transport debris towards the intake structure. Therefore, the test matrix focused on river conditions at low to intermediate flow rates.

In addition to the flow rates in the San Juan River approaching the Hogback diversion structure, operation of both the canal and sluice gates control WSEs along the structure and how flows pass the diversion dam. To incorporate this into the test matrix, two separate scenarios were investigated: sluice gates open with canal gate closed; and canal gate open with sluice gates closed. Following data collection from the listed flow and gate operations in Table 2, river flows below 12,000 cfs were surged up to approximately 12,000 cfs. This allowed debris that had been deposited in the river channel or overbank areas to be recruited with an increasing flow that represented stable debris in the channel that is mobilized by a rapid flow increase from a runoff event.

Table 2. Test matrix of flows and sluice gate operation.

Upstream River Flow, cfs	Flow over Dam, cfs	Hogback Canal Flow, cfs	Sluice Gates Operation
800	550	250	Closed
2,500	2100	400	Closed
5,000	4500	500	Closed
12,000	11400	600	Closed
800	800	0	Open
2,500	2,500	0	Open
5,000	5,000	0	Open
12,000	12,000	0	Open

To compare alternatives, the initial set of data collection from the physical model was performed on the existing conditions topography and without the use of any alternatives. Following the evaluation of existing conditions, one minor change to the model topography was performed. During shakedown testing, it was observed that the sudden river channel contraction that occurs when flows encounter the upstream wall of the trashrack structure produced a very large eddy that increased both flows and velocities entering the most upstream bay of the trashrack. This can also be observed at the prototype when looking at how the flow is forced around the 90-degree corner of the concrete structure as shown below in Figure 13. To remedy this, the right bank immediately upstream of the trashrack structure was filled with the sand & cement mix to create a smoother flow transition. Images of existing and modified upstream right bank can be found in Figure 14.

Figure 13. Screen capture from flow video of the prototype recorded at 600 cfs showing flow separation and eddy at the upstream corner of the trashrack structure, viewed from top.

Figure 14. Photographs of physical model showing the right bank at the upstream corner of the trashrack for existing conditions (left image) and modified to smooth flows (right image).

Debris pieces smaller than 15-inch diameter (prototype) were not considered in the physical model due to the planned trash rake (Hogback Assessment, 2019) that is expected to be incorporated into the trashrack structure. This rake will be able to clear the smaller debris that has been observed and reported to clog the trashrack screens.

For consistency among all tested conditions 20 pieces of debris were selected and used for each model test. Debris pieces were chosen to be representative in size of large cottonwoods and other mature tree species along the San Juan River, but had reduced branch complexity due to availability. Details of the debris pieces used for the physical model tests can be found below in Figure 15 and Table 3. Bands of colored tape were added to the test debris pieces to assist in identification of individual pieces during deposit and post deposit flow surge videos. One important consideration for the physical model tests was the ability to perform numerous iterations of where debris was deposited for a given flow and gate configuration. Due to the extensive test matrix (56 tests), and the duration required to stabilize flow in the model for steady state tests combined with the flow surging to represent flood conditions, only one iteration of each test was performed. Repeating tests would be expected to provide different results for debris accumulation locations, but the flow velocity vectors and hydraulic conditions created by each iteration would be repeatable. Therefore it is unlikely that repeated iterations would have changed the relative ranking of alternative performance.

Figure 15. Debris pieces used for physical model tests in ascending order from left to right. The background is a 1-inch square grid.

Table 3. Debris inventory.

Tree Number	Model Length (in)	Model Diameter (in)	Prototype Length (ft)	Prototype Diameter (ft)	Root Ball Diameter (ft)
1	12	1	60	5.00	13.75
2	8	1	40	5.00	none
3	9	1.00	45	5.00	none
4	6	1.00	30	5.00	none
5	10	1.00	50	5.00	none
6	7	0.75	35	3.75	none
7	8	0.75	40	3.75	none
8	10	0.56	50	2.81	none
9	8	0.75	40	3.75	7.5
10	4	0.56	20	2.81	none
11	6	0.44	30	2.19	none
12	8	0.50	40	2.50	5
13	8	1.00	40	5.00	6.25
14	6	0.75	30	3.75	none
15	7	0.50	35	2.50	none
16	10	1.00	50	5.00	12.5
17	4	0.31	20	1.56	none
18	6	0.25	30	1.25	none
19	7	0.31	35	1.56	none
20	4	0.25	20	1.25	none

Alternatives

To direct debris away from the Hogback intake structure, two types of alternatives were investigated, rock structures and log booms. Rock structures are structures created from large boulders that project into the river channel from the bank and were investigated to assess their effectiveness in directing the flow paths away from the river bank towards the center of the river channel. By directing the flow, any debris in the flow will also be directed towards the center of the channel. Different configurations were investigated to find what worked best for large debris. Log booms are floating barriers that act to either change direction of or capture surface debris in a river or a lake. When installed at an angle to the primary flow direction, a log boom can direct river debris away from key infrastructure and towards an area where debris can pass naturally over the diversion dam.

Timber piles driven into the river bed were also given preliminary consideration as a method to catch debris at low flows in near bank areas, with a top elevation set to release the captured debris at high flows. However due to a shallow depth to bedrock, challenging construction access into the river to drive the piles, and potential river user safety issues, these were not included in the physical model tests.

The rock structure and log boom alternatives that were tested are described below. All reported distances regarding the structures are in prototype scale. The top elevation of the rock structures was set to match the water surface at river flow rate of 9000 cfs, corresponding to the 2-year return flood flow stage, with the sluice gates in the closed position and the canal gate set to pass 550 cfs. The modeled

rock structures were built using available rounded river rock. Since tested model alternatives were being evaluated from a qualitative perspective, no effort was made to attain similitude in the size or angularity of the rock that might be expected for prototype rock structure construction.

Rock Structure 1 (RS1)

RS1, shown in Figure 16, was located along the right bank of the river with the centerline of the bank tie in 80 feet upstream from the corner of the intake structure concrete wall. It was 55 feet in length and oriented downstream approximately 135° from bank tangent.

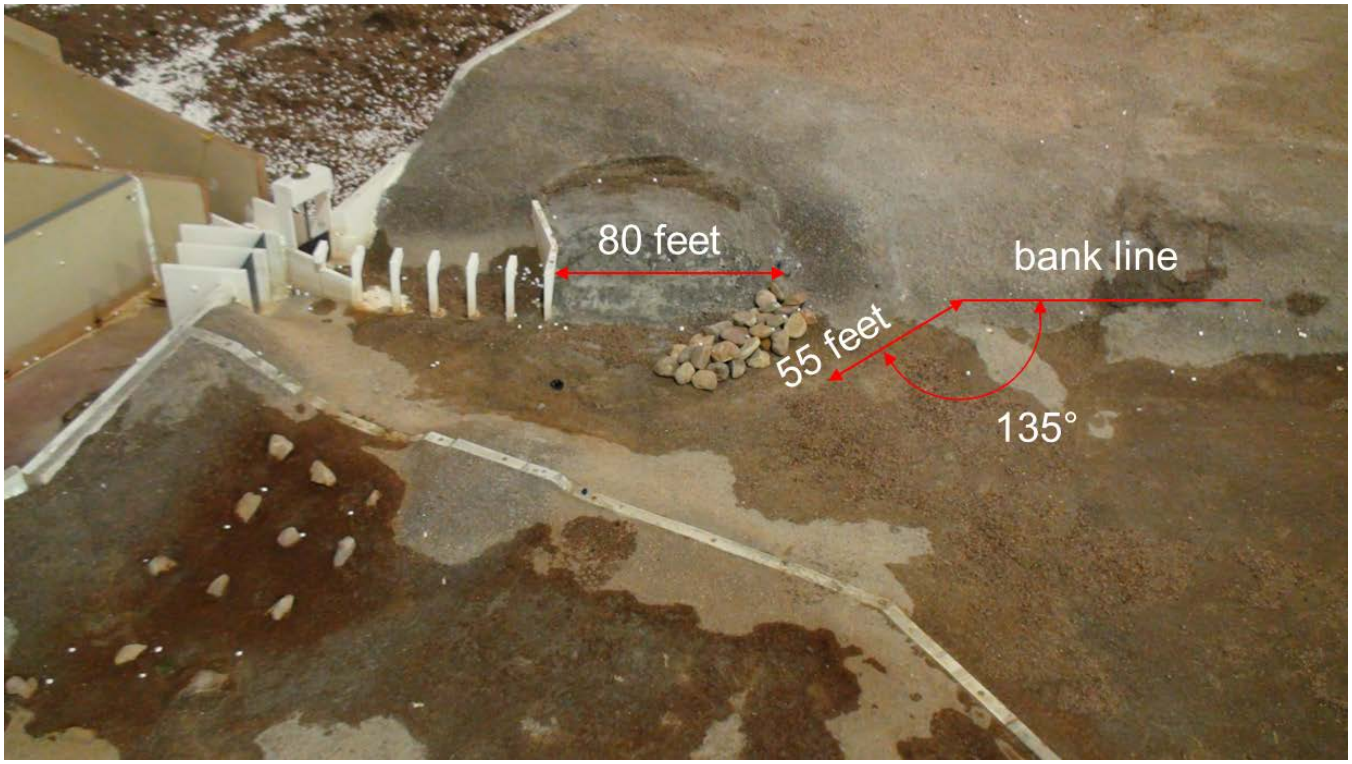

Figure 16. Photograph of Rock Structure 1 from downstream of the diversion dam.

Rock Structure 2 (RS2)

RS2 was a combination of three structures as shown in Figure 17. RS2 incorporated RS1 with two additional structures tied into the right bank line upstream at 355 feet and 465 feet from the corner of the trashrack structure. The upstream structures were also 55 feet in length but were oriented upstream into the river flow each at angles of 60° from bank tangent.

Rock Structure 3 (RS3)

RS3 was a 90-foot-long structure constructed by adding 35 feet of material to the end of RS1 in an arc shape with the edge pointed toward the tie in point of the dam at the right abutment, it is shown in Figure 18.

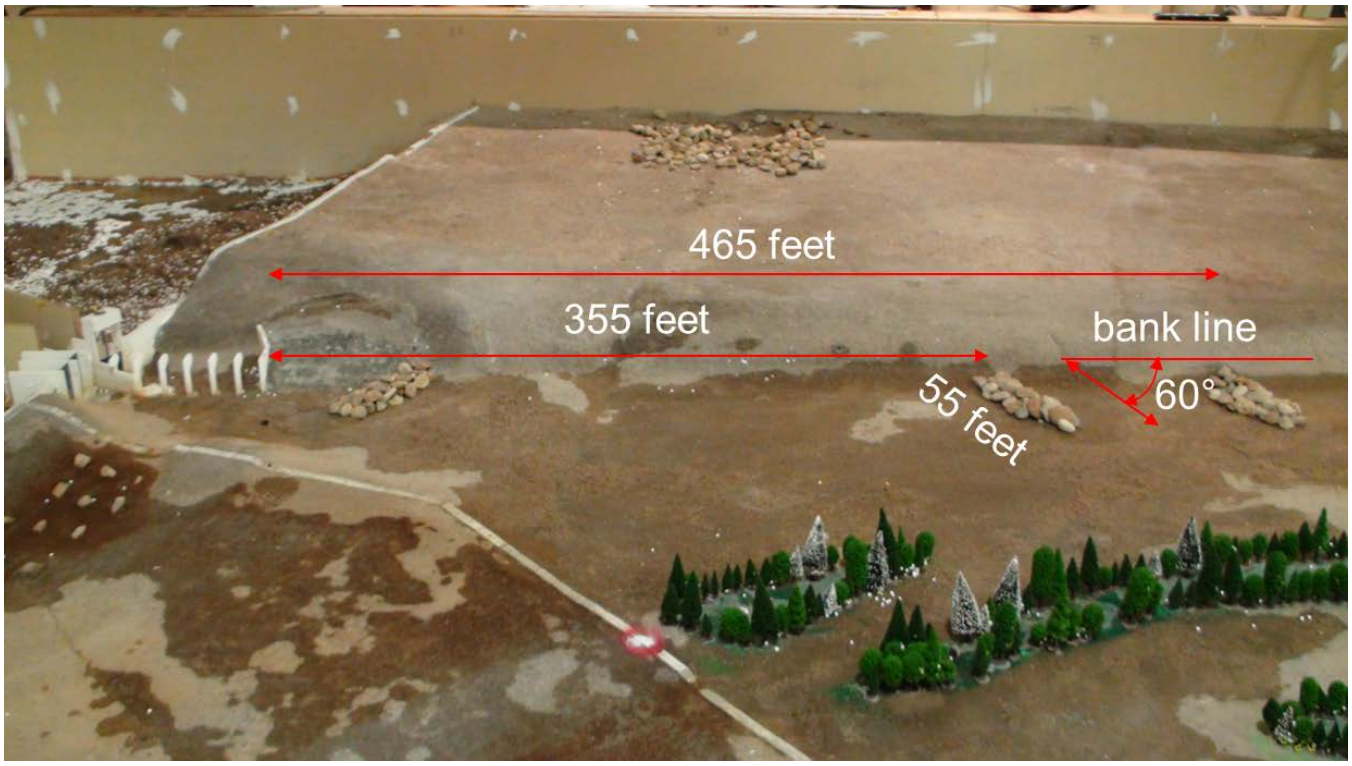

Figure 17. Photograph of Rock Structure 2 viewed from downstream of diversion dam.

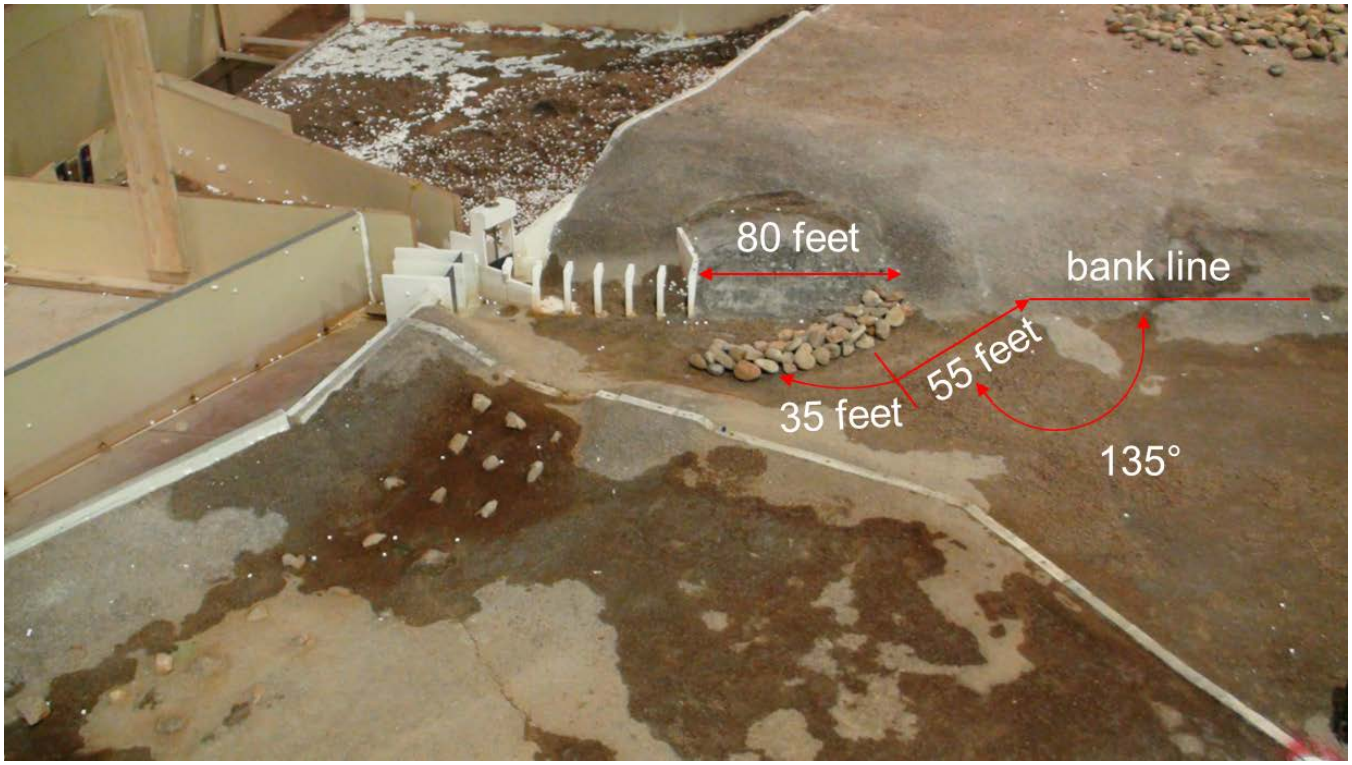

Figure 18. Photograph of Rock Structure 3 viewed from downstream of the diversion dam.

Log Boom 1 (LB1)

LB1 was a 126-foot-long boom that spanned the river's width from 70 feet upstream of the intake structure on the right bank to right side of the fish rock ramp, when viewed from upstream shown in Figure 19. The downstream connection point was located 30 feet from the top of the slope on the right most extent of the dam crest. The orientation of the log boom was angled approximately 150° from the right bank line. It consisted of three 42-foot sections of boom, 22 ½ inch diameter, connected to a cable that extended past the boom 24 feet on the upstream and 9 feet on the downstream end. In the model the log boom was made of three sections of (3/8" OD) plastic tubing that were fitted over nylon string and injected with expanding foam to assist with buoyancy.

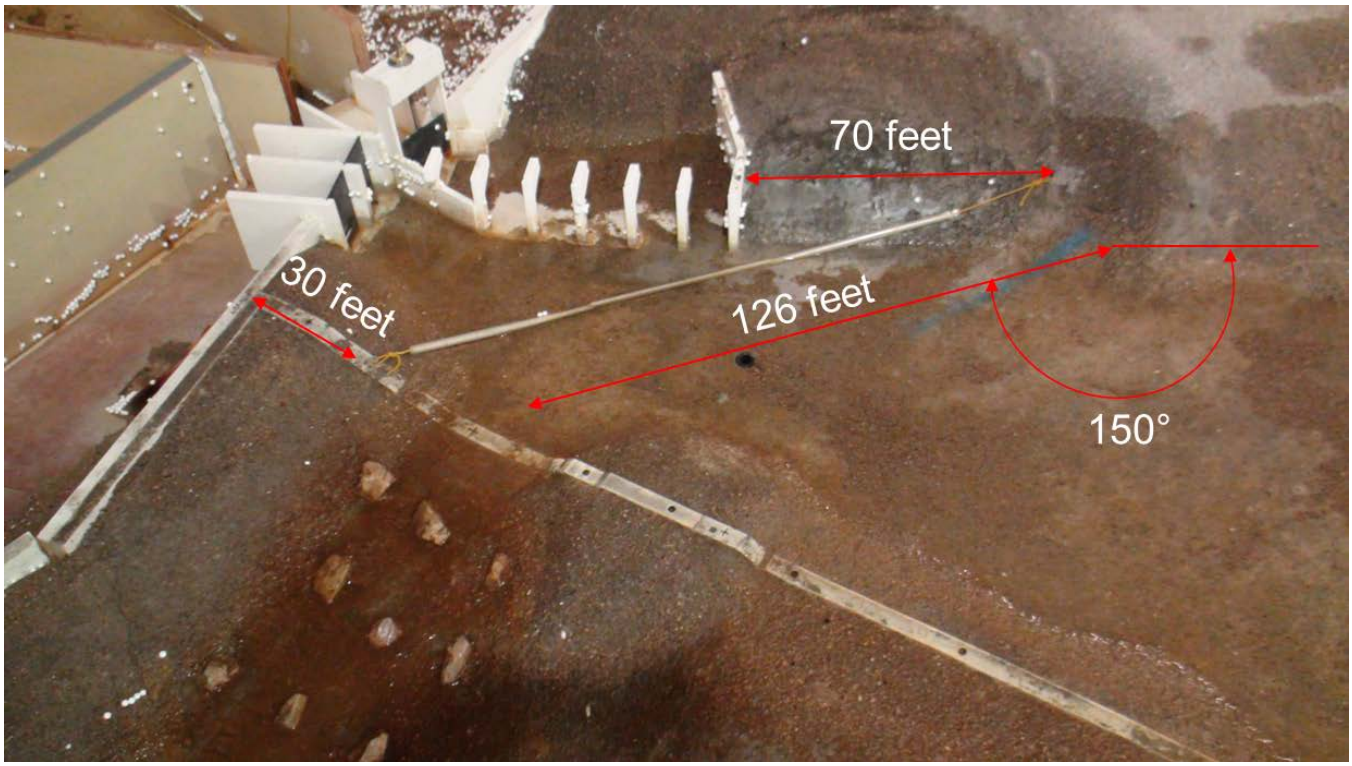

Figure 19. Photograph of LB1 viewed from downstream of the diversion dam.

Log Boom 2

LB2 was a 252-foot-long boom that spanned from the right bank upstream of the intake structure (viewed from upstream) to the dam crest on the left side of the fish rock ramp shown in Figure 20. The orientation of the log boom was angled approximately 160° from the right bank line. The boom consisted of six 42-foot sections attached with a cable that extended past the boom 24 feet on the upstream and 9 feet on the downstream end. The upstream connection point was on the right bank 280 feet upstream of the intake structure. The downstream connection point was located on the dam crest, 130 feet from the top of the slope at the right most extent, when viewed from upstream. In the model the log boom was made of six sections of (3/8" OD) plastic tubing that were fitted over nylon string and injected with expanding foam to assist with buoyancy.

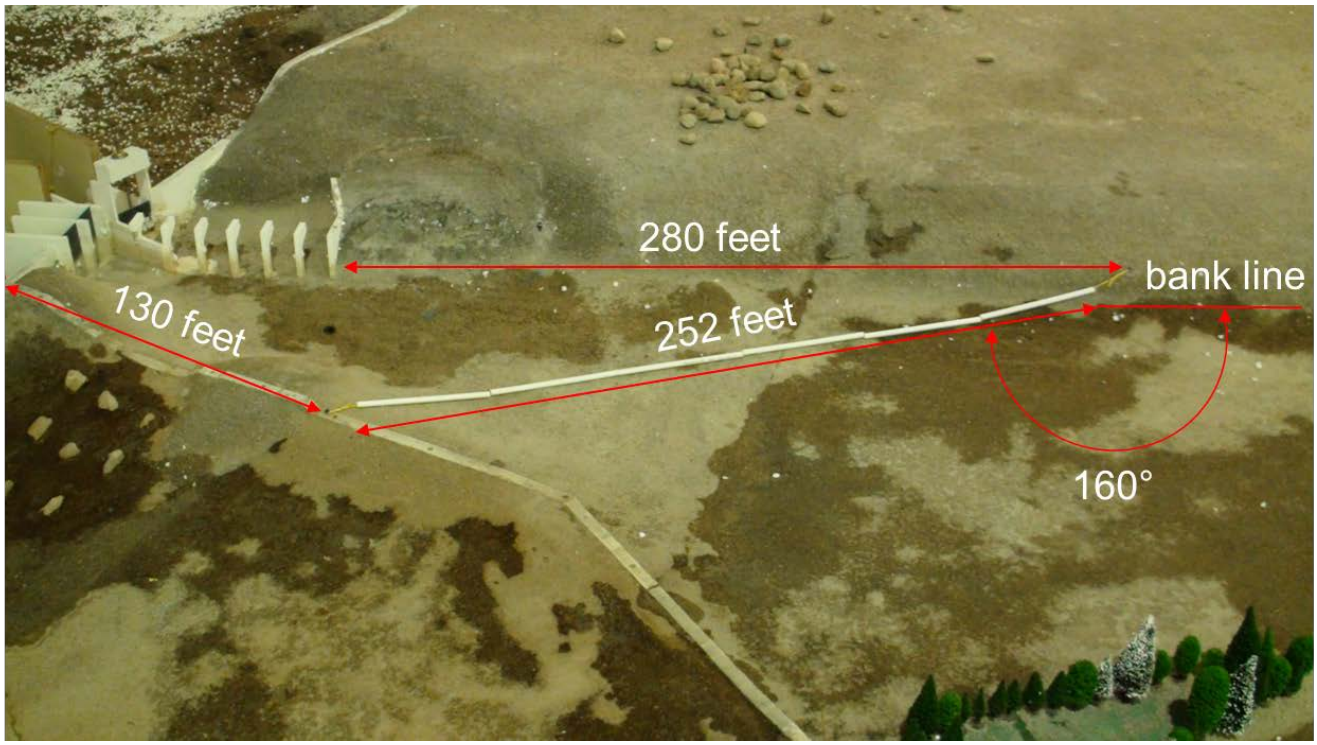

Figure 20. Photograph of LB2 viewed from downstream of the diversion dam.

Rock Structure 1 & Log Boom 1 (RS1LB1)

RS1LB1 was a combination of alternatives RS1 and LB1 which were the best performing individual rock structure and log boom alternatives. The combination is shown in Figure 21.

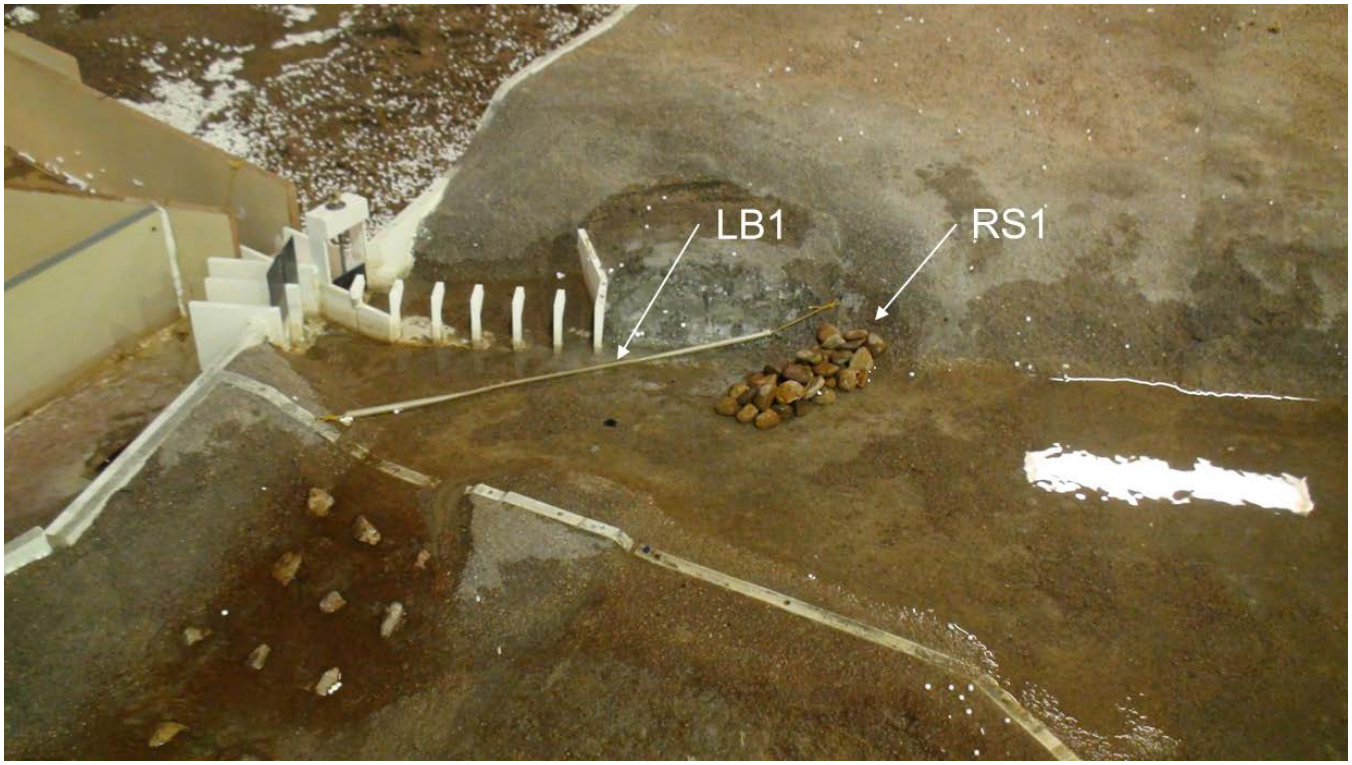

Figure 21. Photograph of RS1LB1 viewed from downstream of the diversion dam.

Results

Data recorded during physical model tests to compare the alternatives included Particle Image Velocimetry (PIV) that used video recorded while seed material was introduced into the model. Rectification of Image Velocity Results (RIVeR, V2.2) was used to extract paired images from 10 seconds of trimmed video. PIVlab V1.41 was used to create average surface velocity vectors of individual particle movements from the paired extracted images. This process was repeated for all flow conditions in the test matrix. Examples of PIV output images are shown in Figure 22 for RS1LB1 at 5,000 cfs for both the sluice gates open and closed. All other PIV images can be found in Appendix A. The orange vectors indicate that more than half of the original vectors at that spot were interpolated while the green vectors show individual particle movement.

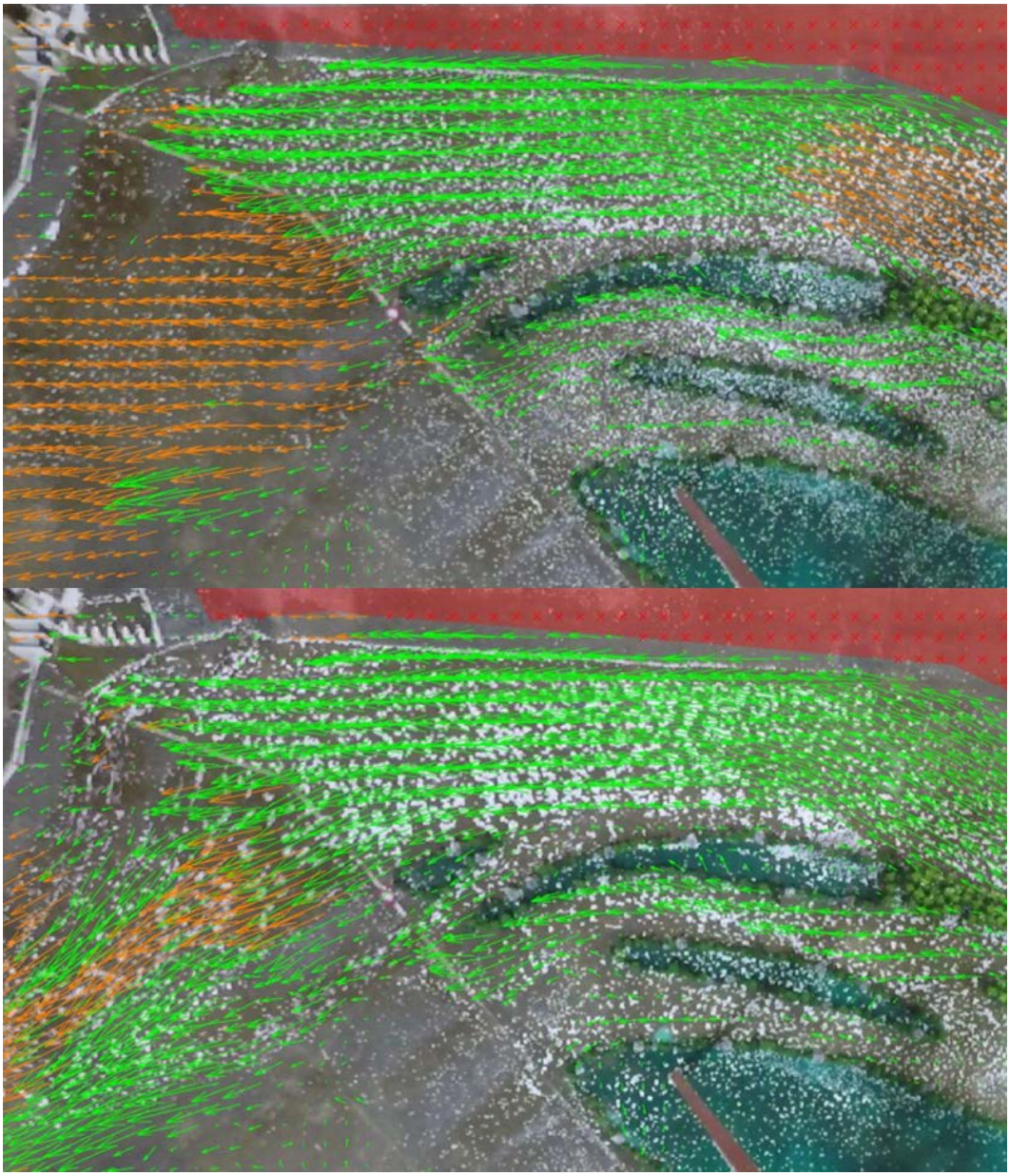

Figure 22. PIV velocity vectors for the RS1LB1 at 5,000 cfs for sluice gates open (top) and canal gate open with sluice gates closed (bottom).

To assess where debris was deposited in the physical model tests, debris capture locations were recorded following each model test combination of flow and gate configuration. In addition to the steady state flow deposition, the debris locations were also recorded following the flow surge to simulate how captured debris at lower river flows would mobilize when high flows were encountered. Figure 23 shows debris capture locations for RS1LB1 at 5,000 cfs for both the sluice open and closed. Debris capture locations for all other alternatives and flow conditions are included in Appendix A.

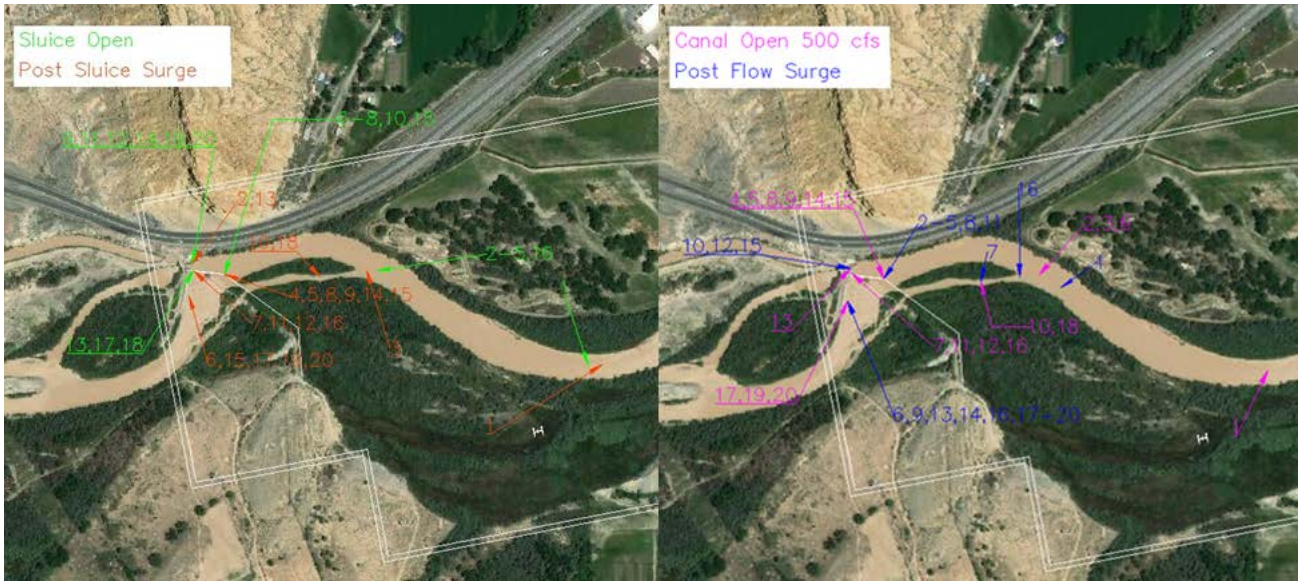

Figure 23. Debris capture locations for RS1LB1 at 5,000 cfs with sluice gates open and canal gate closed (left) and sluice gates closed and canal gate open to pass 500 cfs(right). The two text colors indicate debris deposit locations with steady flow (green and fuchsia) and following the flow surge (orange and blue).

The only quantitative data collected in the model was a rating curve of the river WSE in front of the trashrack structure, shown in Figure 24. Two curves were created, one for river WSE when the canal gate was closed and sluice gates open, and one for when the canal gate was open and sluice gates were closed. Data points taken with the canal gate open were based on a canal diversion flow of 250, 400, 500, and 600 cfs with river flow rates at 800, 2,500, 5,000, and 12,000 cfs, respectively.

Existing Condition

Typical streamlines identified in the mean surface velocity PIV images, show the flow approaching the diversion structure nearly parallel to the right bank with highest velocities near the center of the river channel. The effect of the open sluice gates being open results in both a higher velocity magnitude and a greater concentration of velocity vectors towards the sluice gates for flow rates up to 2,500 cfs than with the sluice gate closed. Flows below 2,500 cfs are concentrated towards the intake structure and as a result bring any river debris close to the intake structure. When the model was tested at the lowest flow rate with the canal gate open (800 cfs river flow, 250 cfs canal), the trashrack was observed to have a larger amount of debris then with many of the other scenarios. This is primarily due to the high percentage of flow entering the canal in relation to the total river flow. As more flow enters the canal, especially during low river flows, more debris will be caught on the trashrack structure. Fortunately, most of the debris in the river at low flows is smaller and would be expected to be handled by the planned trash rake addition. From an operation perspective, if the flows entering the canal are limited to

the minimum amount necessary for irrigation, less debris will be caught on the trashrack. At flow rates in the river above 2,500 cfs the effect of sluice gates is diminished and the flow patterns of the two operations conditions become similar as more of the diversion dam crest becomes inundated to pass the higher river flows.

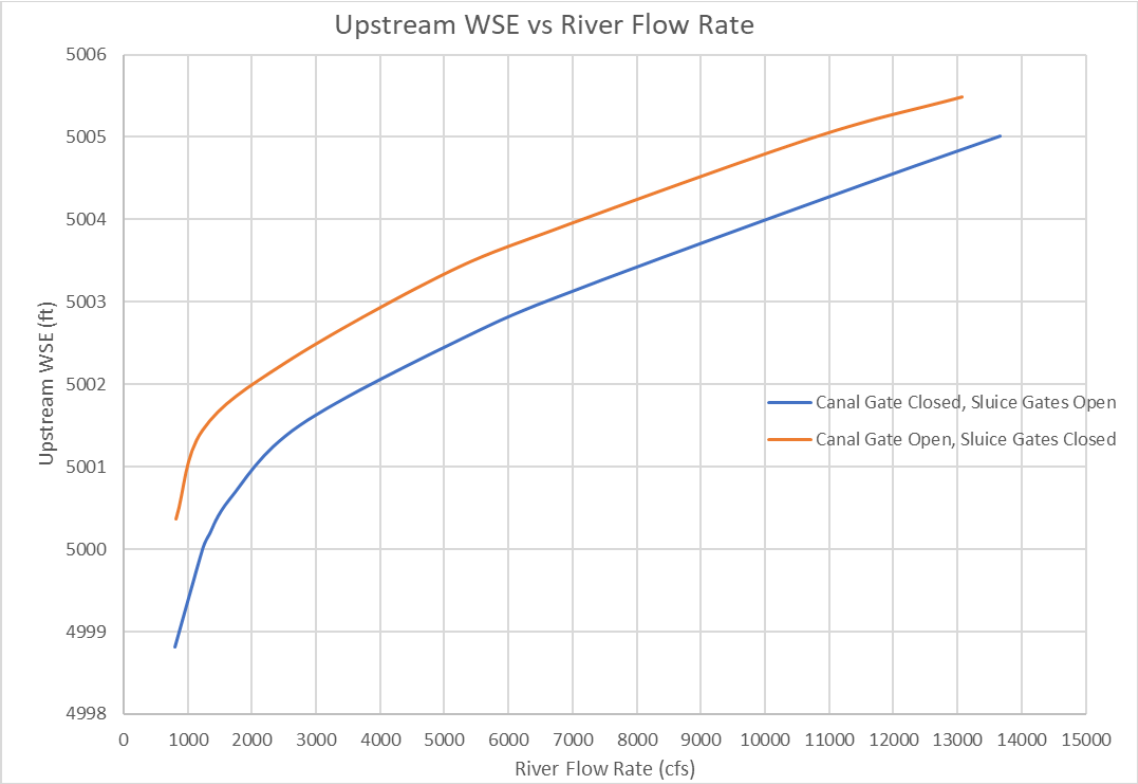

Figure 24. Rating curve for the San Juan River water surface elevation in front of the Hogback Intake trashrack structure.

Comparison of Alternatives

Each of the alternatives tested resulted in some improvement over existing conditions by generally either altering the river flow path (rock structures) or directing debris away from the intake structure (log booms). However, while improvements were observed, nearly all alternatives still had large debris pieces that passed through or around the alternative and approached the intake structure. In all tests, operating the structure with the sluice gate opened created higher velocities and a greater concentration of flow which is more likely to bring floating debris closer to the intake structure. A qualitative ranking of the alternatives' performance is presented below, and a detailed description of each is following.

1. Combined rock structure 1 and log boom 1
2. Rock structure 1
3. Log boom 1
4. Rock structure 3
5. Log boom 2
6. Rock structure 2

Before discussing the performance of any of the rock structures, it should be stated that any rock structure placed in the San Juan River has a high likelihood of causing bed scour that could potentially

contribute to undermining of the structure. Access for construction of these rock structures along the right bank of the river would also be challenging due to the adjacent road embankment and right of way. An additional consideration is the lack of competent rock locally available that match the size of the rock used in the physical model (D_{50} of approximately 7 feet). A more feasible solution might be to substitute another material (i.e. pre-formed concrete jacks, a concrete wall, or other designed structure) sized to match the tested rock structure placement. Access and scour issues would still remain, scour protection could be designed if this type of flow redirecting alternative is selected.

Combined Rock Structure 1 & Log Boom 1 (RS1LB1)

RS1LB1 was very effective at keeping debris away from the trashrack and sluicing bays when the sluice gates were closed, as no debris made it past LB1. When the sluice gates were open, some pieces of debris slid under LB1 and floated toward the sluice bays. The pieces accelerated toward the sluice bays with some passing through and some colliding with the walls of the sluice gates. Due to the proximity of LB1 to the sluice gates, the debris did not have the same violent collisions that were observed when debris made it under LB2 and impacted the sluice gate structure. RS1 did a good job of directing high velocity flows away from the right bank toward the center of the river which was evident by its ability to direct larger debris pieces at a flow rate of 2,500 cfs away from the structure. RS1 would serve to protect LB1 for river flow rates between 2,500 and 9000 cfs, while LB1 would be capable of directing smaller debris that made it past RS1, down the fish rock ramp. For flows greater than 9000 cfs most flow is directed over the dam crest or down the fish rock ramp.

At river flow rate 800 cfs with the sluice gate open to pass 250 cfs three pieces of mobilized debris made it past RS1, two passed down the fish rock ramp and the third settled against LB1 near the fish rock ramp exit. When the flow was surged the two pieces slid down RS1 and passed down the fish rock ramp. As flow rates and the larger debris moved toward RS1LB1 all the debris was guided over the dam crest or down the fish rock ramp. At the same river flow rate with the sluice gates open one piece of smaller debris made it past RS1 and settled against LB1 near the upstream corner of the trashrack structure. When the flow was surged the piece was knocked under LB1 by an incoming piece of larger debris, both floated toward the sluice gates but became lodged between the trashrack and the right bank adjacent to the fish rock ramp exit. At river flow rate of 2,500 cfs most of the mobilized debris turned down the fish rock ramp with one piece becoming stuck up against the upstream side of RS1 and one piece settling against LB1 near the fish rock ramp exit. During the flow surge, the piece against RS1 floated away down the fish rock ramp and the piece against LB1 slid down its length to the fish rock ramp. Larger debris became stuck in the fish rock ramp and caused the debris to pile up, but none passed under LB1.

At 2,500 cfs river flow rate and with the sluice gates open, the debris either passed over the dam crest, turned down the rock ramp, or one piece hit the right bank, at the fish rock ramp exit, spun and slid partially under LB1. When the flow surged the piece slid the rest of the way under LB1 and passed through a sluice bay. A second piece later settled against LB1, slid under it and then accelerated toward the sluice structure colliding with the wall between the gates. Most of the other debris was caught up in vegetation, passed the dam crest, or went down the fish rock ramp. One piece settled half down the fish rock ramp and half under LB1. The PIV mean surface velocity vectors show the high velocity approach flow along the right bank upstream of RS1 is directed toward the dam crest and fish rock ramp for river flow rates of 2,500 cfs and greater for either operation of the sluice gate.

At river flow rate 5,000 cfs and during the flow surge up to 12,000 cfs, with the canal gate open to pass 500 cfs, the mobilized debris either passed over the dam crest or turned down the fish rock ramp. When the sluice gates were opened at river flow rate 5,000 cfs one piece temporarily settled against LB1 and was knocked under it by a debris collision and subsequently collided with the sluice bay structure. During the flow surge none of the remaining debris made it past LB1. All debris either was caught up in vegetation, passed over the dam crest or down the fish rock ramp when the river flow rate was 12,000 cfs with the canal gate open to pass 600 cfs. When the sluice gates were open, one piece of debris passed beneath LB1 and through a sluice bay.

Rock Structure 1(RS1)

At river flow rates below 2,500 cfs material 1.5 foot in diameter and less was able to float past RS1 and either get caught on the trashrack (with sluice gates closed) or move toward the sluice bays (with sluice gates open). When the river flow rate exceeded 2,500 cfs, RS1 was very effective at directing debris toward the dam crest either or passing down the fish rock ramp. Surface velocity vectors from the PIV analysis showed decreasing velocities along the right bank leading up to RS1 and increasing in the direction of the dam crest and fish rock ramp.

While operating at river flow rate 800 cfs with the canal gate open to 250 cfs, most of the debris 1.5 foot in diameter and less moved past RS1 toward the center of the river and then was caught in an eddy in front of the closed sluice gates and became lodged against the trashrack. The surface velocities were highest between the dam crest and the upstream corner of the fish rock ramp. As larger material began to mobilize with the rising flow rates of the post debris deposit surge, RS1 was very effective at guiding the larger debris toward the dam crest either overtopping it or passing down the fish rock ramp. With the sluice gates open at river flow rate 800 cfs, the river stage dropped enough to prevent the 15 inch diameter smooth logs, the smallest used during testing, from being transported in the flow. The surface velocities showed most the flow accelerating toward and passing through the sluice gates. During the post deposit flow surge the first few pieces of debris floated past RS1 and directly toward the open sluice gate. As the flows increased to approximately 2,500 cfs and higher, the mobilized debris was directed by RS1 over the dam crest or down the fish rock ramp.

At the river flow rate of 2,500 cfs and during the post deposit flow surge with the canal gate open to pass 400 cfs, all pieces of debris but one was either guided over the dam crest or down the fish rock ramp, with the one exception being deflected into the trashrack. The PIV surface velocity image shows slowing velocities upstream of RS1 along the right bank and very low velocities directly downstream of RS1. Velocity vectors show a recirculation behind the trashrack and flow exiting through the upstream most bay of the trashrack. The highest velocities are overtopping the dam, just upstream of the turn in the dam crest. Large velocities are also directed into the right bank adjacent to the fish rock ramp exit, as the flow turns to the left down the fish rock ramp. While with the canal gate closed and the sluice gates open and the river flow rate at 2,500 cfs most of the smaller diameter debris that floated past RS1 went directly toward the sluice gate. A cluster of debris became lodged between the toe of RS1 and the crest topographic high spot on river left of the fish rock ramp. The PIV analysis shows increasing velocities across the width of the river from the toe of RS1 to the dam crest in the direction of the open sluice gates. During the post deposit surge, the lodged cluster broke up and floated down the fish rock ramp. The remaining debris overtopped the dam crest or went down the fish rock ramp except for one very

large piece of debris that deflected off the high spot on the crest near the rock ramp, spun and slammed into the debris caught in the sluice bay.

With the canal gate open to pass 500 cfs, during both river flow rate of 5,000 cfs and the post deposit surge to 12,000 cfs, all the debris that floated past RS1 either overtopped the dam crest or was guided down the fish rock ramp. At a river flow rate of 5,000 cfs with the sluice gates was open and canal gate closed some of the smaller diameter debris again floated past RS1 directly toward the sluice gates. Surface velocity images show the effects of the open sluice gates most prominently at the fish rock ramp exit and downstream of RS1. At the fish rock ramp, the direction of the highest velocities was split between directed at the sluice gates or down the fish rock ramp. Downstream of RS1 the surface velocities are very small with the sluice gates closed and larger with the gates open, but the velocities are significantly smaller than the velocities directed toward the dam crest and fish rock ramp at 5,000 cfs. During the post deposit flow surge some larger debris did overtop the dam crest or pass down the fish rock ramp while other pieces were drawn toward the open sluice gate.

When the canal gate was open to pass 600 cfs and the river flow rate was 11400 cfs one piece of debris was headed down the fish rock ramp where it had a collision and spun into the trashrack. All other debris pieces near the intake structure were either caught on RS1, overtopped the dam crest, or passed down the fish rock ramp.

Log Boom 1 (LB1)

The LB1 alternative was effective at catching and directing debris down the fish rock ramp at river flow rate of 800 cfs and as the flow surged to 12,000 cfs while the canal gate was open to pass 250 cfs. The mean surface velocity image shows most of the velocity vectors parallel to the right bank up to LB1 and upon contact are being directed toward the fish rock ramp. At river flow rate 800 cfs with the sluice gates in the open position, LB1 was effective at catching and directing the mobilized debris. During the post deposit flow surge, two pieces of debris that had been caught on the log boom became dislodged at impact of incoming debris and passed underneath the boom making their way through the sluice bays. With the river flow rate at 2,500 cfs and the canal gate open to pass 400 cfs, all but one piece of debris overtopped the dam crest or passed down the fish rock ramp, the single piece of debris being caught up on the downstream length of the boom near the connection point. During the post deposit flow surge, the piece of debris caught on LB1 was dislodged and passed down the fish rock ramp. One large piece of debris became lodged between the log boom, just in front of the upstream corner of the trashrack structure, and a pile of debris that had deposited on the gravel/sand bar to the left of the fish rock ramp exit.

At river flow rate of 5,000 cfs and the sluice gate open to pass 500 cfs, all the mobilized debris passed over the dam crest or down the fish rock ramp except for one piece which impacted debris deposited at the exit of the fish rock ramp which swung to rest against LB1. During the post deposit flow surge the debris piece was swept down the fish rock ramp. One piece of debris slid under LB1 at river flow rate 5,000 cfs with the sluice gates open while a second piece partially slid under LB1 and remained there through the post deposit flow surge. All other debris either passed over the dam crest or down the fish rock ramp. At river flow rate of 12,000 cfs and with the canal gate open, all debris was either caught on vegetation, passed over the dam crest or down the fish rock ramp. With the sluice gates open one piece of the debris, that approached along the right bank, slid under LB1 and passed through the sluice bays.

Due to the light weight and small particle size of the seeding material, the PIV surface velocities were not effective at capturing the velocity vectors in close proximity upstream or downstream of LB1.

Rock Structure 3 (RS3)

With the RS3 installed and river flow rate of 800 cfs the maximum flow possible through the canal gate was 200 cfs. Due to the lower flow depths, no debris mobilized past RS3. When the flow was surged the debris was directed toward the dam crest. A debris jam occurred between the toe of RS3 and the gravel/sand bar on the dam crest just upstream of the fish rock ramp exit. The mean velocity vector image showed the flow effectively directed toward the center of the river at RS3 with a few small velocity vectors downstream of RS3 pointed toward the sluice bays. At river flow rate 800 cfs with the sluice gates open no debris mobilized past RS3. When the flow was surged after the debris deposit, the first two pieces of debris that floated past RS3 accelerated quickly and collided into the right bank, adjacent to the fish rock ramp while the third piece accelerated to the sluice bays. The remaining debris either was caught in vegetation, overtopped the dam, or became part of a debris jam between the toe of RS3 and the gravel/sand bar on the dam crest just upstream of the fish rock ramp. With the sluice gates open a few medium sized debris pieces floated past RS3 and accelerated through the sluice bays, a few passed down the fish rock ramp, but most debris became part of a debris load lodged between the toe of RS3 and the gravel/sand bar at the dam crest.

With the canal gate open to 400 cfs and the river flow rate of 2,500 cfs, multiple pieces of smaller debris floated past RS3 and down the fish rock ramp while one piece attached to the toe of RS3 and another became lodged between the RS3 toe and the gravel/sand bar at the crest. During the flow surge, the piece that was attached to the side of the toe floated free and came to rest against the trashrack. The piece that was lodged between the RS3 toe and dam crest caused a small debris jam that broke up and sent another piece into the trashrack. All other debris was caught up in vegetation, overtopped the dam, or went down the fish rock ramp. The PIV mean surface velocity image shows the flow directed toward the middle of the river with the highest velocities were located in the contracted flow between the toe of RS3 and the gravel/sand bar on the dam crest. At river flow rate 2,500 cfs with the sluice gates open, all of the smaller diameter debris that floated past the RS3 went down the sluice bays. When the flows were surged a large piece of debris floated past RS3 and accelerated through the sluice bays while the piece behind it became lodged between the trashrack and right bank, adjacent to the fish rock ramp exit. All other debris was caught in vegetation, overtopped the dam, went down the fish rock ramp or became part of the debris jam at the mouth of the fish rock ramp exit. The surface velocity vectors are primarily directed over the dam crest with a small number of shorter vectors pointed toward the sluice bays, very similar to the PIV image with the sluice gates closed.

At the river flow rate of 5,000 cfs and during the post deposit flow surge, with the canal gate set to pass 500 cfs, the debris either was caught in vegetation, overtopped the dam crest, or that which floated past RS3 turned down the fish rock ramp. With the river flow at 5,000 cfs and the sluice gates open, a piece of debris floated past RS3 and continued through the sluice gate. A couple pieces of debris became lodged on the upstream side of RS3 while the remaining mobilized debris passed down the fish rock ramp or overtopped the dam crest. Debris mobilized during the flow surge either overtopped the dam crest or passed down the fish rock ramp. The surface mean velocity shows the flow effectively directed over the dam crest upstream of RS3 and down the fish rock ramp downstream both with the sluice gates open and closed. When the river flow rate was 12,000 cfs RS3 was effective at either guiding the debris over the dam crest or down the fish rock ramp regardless of sluice gate operation.

The shape and proximity of RS3 to the gravel/sand bar on the dam crest, just upstream of the fish rock ramp, contracted the flow and caused passing debris to accelerate before the flow carried it in one of many different paths. Due to the acceleration, many of the impacts were forceful and could result in damage to concrete, sluice gates, trashrack or dislodge grouted rock in the fish rock ramp. Other times debris would become lodged perpendicularly to the flow, between the toe of RS3 and the gravel/sand bar at the dam crest, which would often cause a debris jam. As flows increased the debris jam would dislodge from the rock and move closer to the intake structure and sluice gates.

Log Boom 2 (LB2)

The alternative LB2 created a debris collection area between the dam crest and LB2 near the downstream connection. Most of the debris dislodged from this zone would continue over the dam crest or down the fish rock ramp but some would float toward the sluice structure when the sluice gates were open. During some tests, debris jams in this area applied significant load on LB2 and the downstream connection as witnessed by a large bow in the log boom due to its long length. Occasionally debris would settle against LB2 near midspan and was likely to slide under LB2 when impacted by oncoming debris. When this occurred, if the sluice gates were open, some dislodged debris was observed to accelerate toward the sluice bays and have violent collisions with the sluice gate structure or gates. When the sluice gates were closed, the dislodged debris from LB2 more often turned down the fish rock ramp.

The small diameter debris that mobilized, at river flow rate 800cfs and with the canal open to pass 250 cfs, collected between the dam crest and LB2 near the downstream connection point. During the post deposit flow surge most of the debris collected in the same zone. One small piece slid under LB2 upon impact from a larger piece and then passed down the fish rock ramp. With the sluice gates open, the river stage dropped and only one piece floated to LB2 and became lodged against LB2 at near midspan. During the post flow surge, four pieces of debris slid under LB2, two of which passed down the fish rock ramp and the other two pieces impacted the sluice gate structure. At river flow rate 2,500 cfs and with the canal gate open to pass 400 cfs most of the mobilized debris again deposited between the dam crest and LB2 near the downstream connection. One piece passed over the dam a little further upstream. The flow surge saw similar results with most debris collecting between the dam crest and LB2 at its downstream connection point and a piece sliding under LB2 and again passing down the fish rock ramp. The debris deposit was similar, when the sluice gates were open and the canal gate closed, at river flow rate 2,500 cfs with most of the debris collecting in the same zone. During the post deposit flow surge, a debris jam occurred at the same zone pushing some debris under LB2, and again causing a large bow in the log boom. A few pieces slid under LB2 and passed down the fish rock ramp.

At river flow rate 5,000 cfs with the canal gate open to 500 cfs, all of the mobilized debris that floated to LB2 collected in the same zone between the dam crest and LB2 near the downstream connection point. During the post deposit flow surge additional debris collected in the same zone pushing some of the initial debris down past the dam crest. The debris load on LB2 as the flow rate was returned to 5,000 cfs left LB2 bowed in the downstream direction showing the significant load that was being applied. With the sluice gates open, debris was caught on LB2 near midspan, with one piece sliding under LB2 and passing through the sluice gates while one piece slid partially under LB2. Throughout the flow surge this piece stayed partially under LB2 and moved to the downstream connection point. During the flow surge a large piece of debris collided with three pieces of debris caught on the midspan of LB2 pushing

all four pieces under LB2. Two debris pieces turned down the fish rock ramp, one collided violently with the sluice gate structure and the fourth lodged between the stuck debris and the right bank of the fish rock ramp exit.

At river flow rate 12,000 cfs with the canal open to pass 600 cfs debris was either caught up on vegetation along the left bank, passed over the dam crest, or collected in between the dam crest and LB2 near its connection point. With the sluice gates open debris patterns were similar, however the higher velocities allowed three pieces to pass beneath LB2.

Rock Structure 2 (RS2)

Rock Structure 2 is the combination of RS1 with two additional rock structures located further upstream. With a river flow rate of 800 cfs the maximum flow possible through the canal gate was 200 cfs. Due to the lower flow depths, no debris mobilized past the upstream rock structures. PIV surface velocities show the flow being directed toward the middle of the river at the furthest upstream rock structure and low velocities between it and RS1 but increasing velocities downstream of RS1. The highest velocities were directed into the slope between the fish rock ramp and sluice bays. When the flow was surged, a few pieces of debris became lodged against the trashrack. At river flow rate 800 cfs with the sluice gates open the flow depth was again too shallow to transport debris. With the flow surge, RS2 was effective at either collecting debris against the upstream rock structures, guiding the debris over the dam or down the fish rock ramp with only a couple of debris pieces approaching the sluice bays. In the PIV analysis, high velocities were observed along the right bank upstream of RS1 which were directed at the structure. Flows accelerated around the upstream structures and generally stayed towards the center of the river channel until passing RS1 and finally accelerating toward the sluice gates.

With the canal gate open to 400 cfs and the river flow rate of 2,500 cfs, multiple pieces of smaller debris floated to the trashrack. Surface velocity vectors show most flow is directed toward the center of the river by the upstream rock structures, but large velocities occurred downstream of RS1 with a noticeable draw toward the diversion structure. When the flow was surged with the 400 cfs canal gate opening, one large piece of debris came to rest against the trashrack. In addition, a log jam formed between the debris on the trashrack and the right bank of the fish rock ramp (looking downstream). The log jam broke up and all except the piece of debris resting against the trashrack moved down or toward the fish rock ramp. With the river flow rate at 2,500 cfs and the sluice gates open, all the smaller diameter debris that floated past the RS1 structure went through the sluice bays. When the flows were surged, two additional pieces of larger debris became lodged in front of the sluice bays.

At the river flow rate of 5,000 cfs and the canal gate set to pass 500 cfs the debris that floated past the RS1 component was guided over the dam crest or down the fish rock ramp with the exception of two pieces that impacted the right bank of the fish rock ramp exit and were deposited between the right bank and the trashrack, nearly perpendicular to the sluice bay openings where they remained through the post deposit flow surge. The surface velocity vectors show the flow directed toward the center of the river between the upstream rock structures and RS1 and downstream of RS1 either accelerating down the fish rock ramp or into the bank between the rock ramp and sluice gates. Some larger vectors point toward the downstream end of the trashrack. With the river flow at 5,000 cfs and the sluice gates open, a handful of debris pieces that floated past the RS1 component continued through or impacted into the sluice bays structure. A few more large pieces of debris had high speed direct impacts to the sluice

structure during the flow surge. The surface velocity vector image looked similar to the image with the canal gate open but with slightly larger velocities pointed toward the sluice bays.

When the river flow rate was 12,000 cfs and the canal gate was open to pass 600 cfs, RS2 was effective at either catching the large debris or guiding it over the dam crest or down the fish rock ramp. The PIV image shows all large velocity vectors directed toward the dam crest or fish rock ramp. At the same river flow rate but with the sluice gates open a large piece of debris floated toward the RS1 component from the dam crest, impacted the toe of the RS1 structure, then spun and collided violently headlong into the trashrack. At various flow rates, with the sluice gates open, numerous pieces of debris would either become lodged against the side of, or impact the toe of, the RS1 structure and subsequently spin off and float toward the open sluice bays. The surface velocity image shows a line of very high velocity flow along the right bank which flowed over the rock structure tie in and continued directly to the open sluice bays.

Recommendations

While 100% debris removal is not feasible across the entire range of flow rates regardless of any combination of alternatives examined, the physical model results show the capability for significant reduction of debris issues at the Hogback intake structure. The best performing alternative was RS1LB1 which was the combination of RS1 and LB1. Individually, these were the two best performing alternatives. When combined this resulted in greater debris reduction than either RS1 or LB1 provided separately.

1. Filling of the right bank which removes the sudden flow contraction at the upstream trashrack concrete wall produced much smoother flow patterns in the physical model and would reduce high approach velocities into the trashrack at the upstream most panel. This was also observed to reduce flow exiting the trashrack at the downstream bay in the physical model.
2. Log Boom 1 – This is a relatively low effort installation and can either be completed fully through contractors that specialize in log boom installations, or in house. A log boom with a debris screen underneath the boom sections is recommended. If the design is done in-house, anchor points and connections should be verified for design loads using velocities from the *Hogback Diversion Dam & Canal Intake Structure Velocity Sampling* trip report. Since the originally installed log boom survived many water years before becoming damaged, existing bank anchor points may be sufficient and discoverable. If the right bank is filled as recommended above, an upstream anchor can be installed as part of this process. A potential design consideration would be to incorporate a smaller size shackle (or a “shear pin” shackle connection) to connect to the downstream bank anchor. This would act as an overload relief mechanism to prevent damage to the log boom during very high runoff periods. Once the downstream connection had failed, the log boom should sweep across the river and float parallel to the trashrack structure which would prevent additional debris from accumulating on the trashrack.
3. While the model tested a rock structure, the availability of competent large rocks (the model used 1.5 inch D_{50} gravel which corresponds to 7.5 foot D_{50} boulders in prototype scale) does not exist in close proximity to Farmington, NM. Therefore, the cost for sourcing and transporting large boulders should be investigated as well as other design alternative such as a concrete wall or pre-formed concrete jacks that matches the elevation, bank angle and extent of the rock structure tested. With any structure at this location, scour of the river bed will be a concern and will need

to be planned for in the design. Velocities in this region of the riverbed have not been measured, but would not be expected to exceed those in front of the trashrack panels as measured during sluicing operations.

Conclusions

Physical hydraulic model experiments were conducted on the Hogback intake structure of the San Juan River to reduce the likelihood of floating woody debris near the structure. Numerous rock and log boom alternatives were investigated, and results were compared using a qualitative assessment on the impact to the debris carried towards the Hogback Intake structure. The key lessons learned from the physical model were:

- When the diversion dam sluice gates are opened, considerably more debris is drawn towards the intake structure and trashrack. The velocity vectors are much larger and oriented towards the structure compared to when the sluice gates are closed and the velocity vectors orient towards the diversion dam crest (away from the structure). The impact of this on the floating debris was that more pieces would be captured in front of the trashrack structure and sluice gates which requires removal with heavy equipment.
- The highest performing alternative tested in the physical model was the combination of Rock Structure 1 and Log Boom 1. This combination resulted from adding the flow direction impacts of the rock structure with the ability to catch surface debris from the log boom. Both alternatives were located nearest the intake structure and resulted in the greatest benefit due to their proximity. A log boom located at this location would also reduce impacts to public safety as any boaters would need to exit the river further upstream to portage around the diversion dam. A brightly colored log boom would also aid in identification of a hazard in the river.
- No alternative or combination of alternatives can be guaranteed to eliminate debris approaching the structure, however all alternatives tested were found to reduce the likelihood of debris near the structure compared with existing conditions (assuming matching flow and gate operations)
- Many tests were observed to have debris that was able to pass beneath the 22.5” prototype diameter boom sections. River debris observed at this location can be either well branched or cylindrical, and would likely change its ability to pass beneath the log boom. Many commercially available log booms can be specified with a screen beneath the log boom to prevent debris from passing beneath.
- The range of flows that create debris management challenges at the Hogback structure appear to be between 2,000 and 12,000 cfs where flows are biased towards the diversion side of the dam due to the fish ladder. Below approximately 2,000 cfs insufficient energy is available for bank erosion (which reduces trees falling into the river) and transport of woody debris. At flows higher than about 12,000 cfs there is woody debris being recruited and transported towards the Hogback Diversion Dam, but at these high flow rates a majority of flow and debris goes over the dam crest rather than being channelized near the Hogback structure. This study did not assess bank erosion explicitly so specific flow values for erosion are approximate.
- The dam crest survey performed in 2017 recorded elevations that vary from the design elevations. This has resulted in some areas that are higher than design likely due to sediment deposition and velocity sheltering from overbank vegetated areas, and other that are lower due to flow concentration and scour. In general, lower areas of the crest are closer to the intake structure and areas further away are slightly higher. This results in a greater flow concentration near the intake structure and with it, increased debris load.

- The diversion dam has stabilized the channel which will facilitate future irrigation deliveries, but has also resulted in overbank area stabilization and a deeper, more permanent river channel that with bring any floating debris toward the structure.
- The location of the structure on the right bank, immediately downstream of a left bend in the river channel will always tend to concentrate debris at or near the structure.
- Large debris removal operation at the Hogback intake structure requires heavy equipment and considerable effort.
- Smaller debris that is caught on the trashrack structure is removed with a long pole to push debris away from the rack. A trash rake system is planned for the structure which will be able to remove debris from the rack.

References

Bureau of Reclamation. (2016). *Design Summary - Hogback Diversion Dam and Fish Barrier Weir*, U.S. Dept. of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Bureau of Reclamation. (2017). *Feature Assessments - Hogback Diversion Dam to Fish Facility*, TM No. 1695-NGWSP-8150-DD-2017-8. U.S. Dept. of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Bureau of Reclamation. (2019). *Hogback Headworks Assessment Recommendations*, TM No. 1695-NGWSP-8150-AR-2018-13. U.S. Dept. of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Glaser, Leah. (1998) "Navajo Indian Irrigation Project," U.S. Dept. of the Interior, Bureau of Reclamation. https://www.usbr.gov/projects/pdf.php?id=141

Varyu, David. (2018). *100-year Inundation Mapping for the NGWSP Intake.* SRH-2018-33. Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Walker, Kent. (2019). *Hogback Diversion Dam and Canal Intake Structure Velocity Sampling.* Draft Report. Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Appendix

Existing Condition

Image of LSPIV mean velocity vectors of the river modeled at the existing condition with River Q 800 cfs, Dam Q 550 cfs, Canal Q 250 cfs, and sluice gates closed.

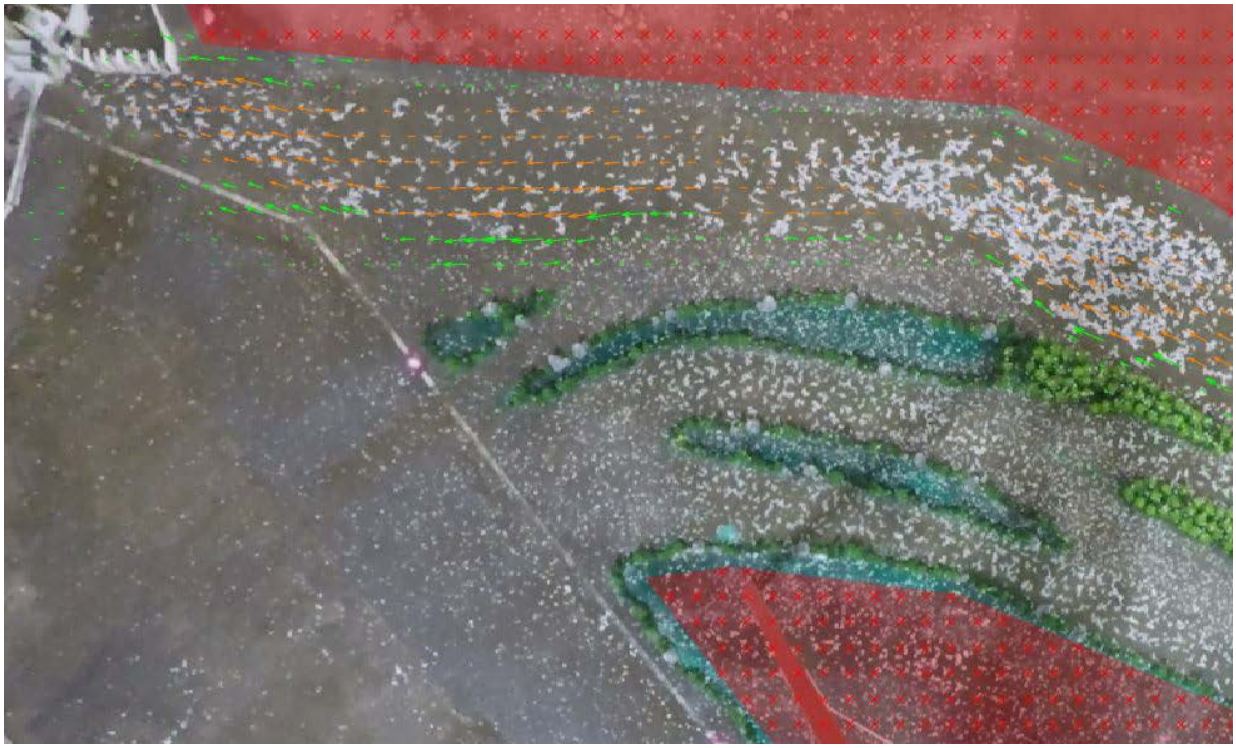

Image of LSPIV mean velocity vectors of the river modeled at the existing condition with River Q 800 cfs, Dam Q 800 cfs, Canal Q 0 cfs, and sluice gates open.

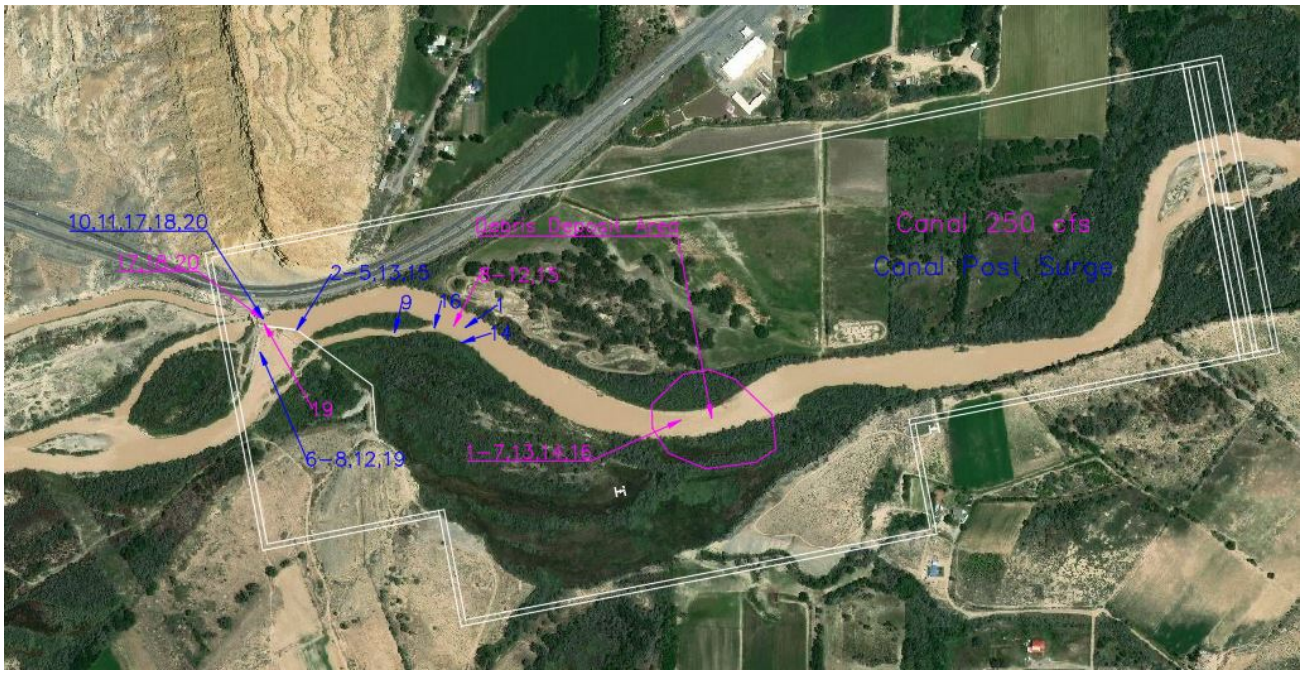

Image of debris capture location of the river modeled at the existing condition with River Q 800 cfs and Canal Q 250 cfs, with sluice gates closed.

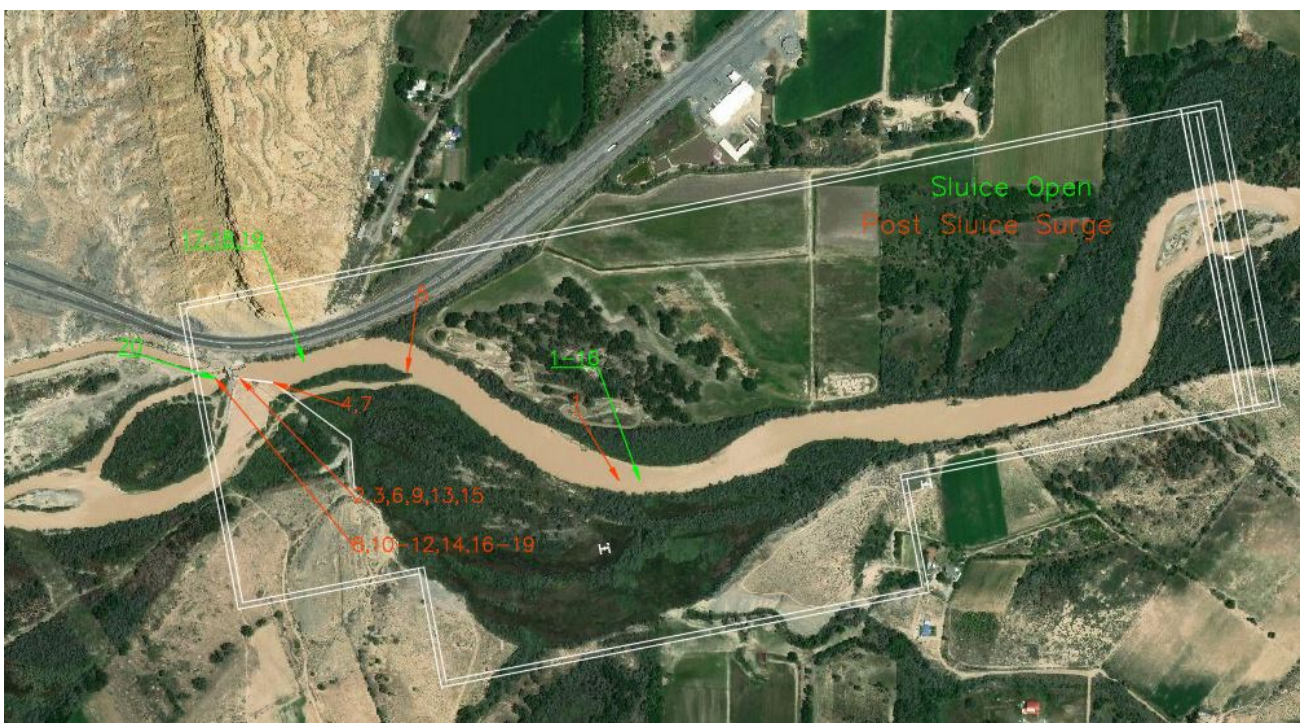

Image of debris capture location of the river modeled at the existing condition with River Q 800 cfs and Canal Q 0 cfs, with sluice gates open.

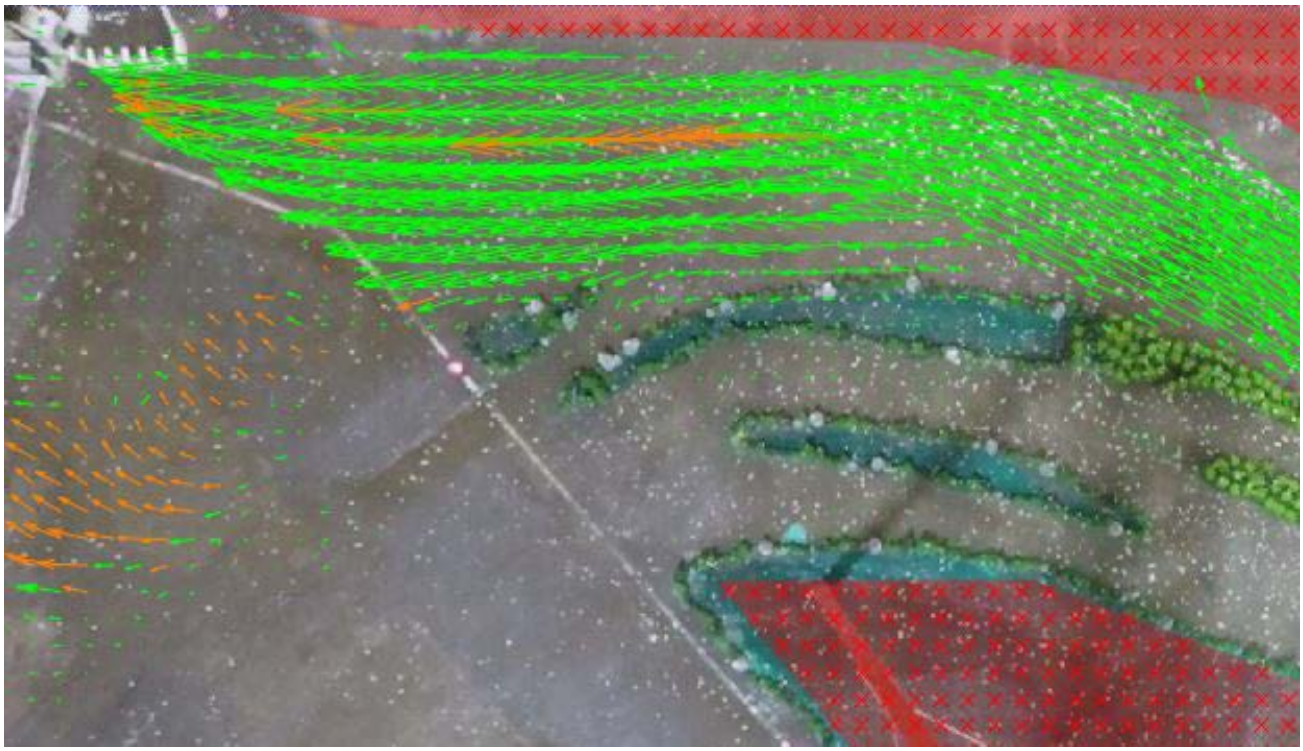

Image of LSPIV mean velocity vectors of the river modeled at the existing condition with River Q 2,500 cfs, Dam Q 2,500 cfs, Canal Q 0 cfs, with sluice gates open.

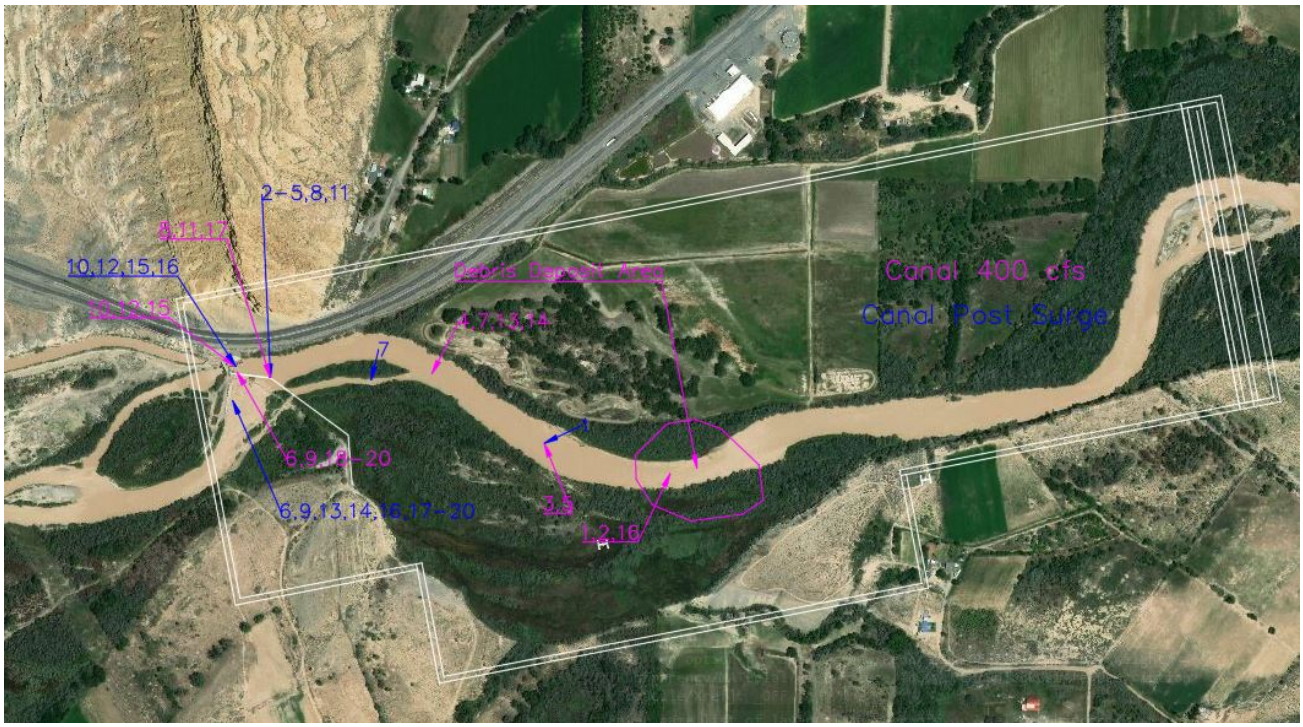

Image of debris capture location of the river modeled at the existing condition with River Q 2500 cfs and Canal Q 400 cfs, with sluice gates closed.

Image of debris capture location of the river modeled at the existing condition with River Q 2500 cfs and Canal Q 0 cfs, with sluice gates open.

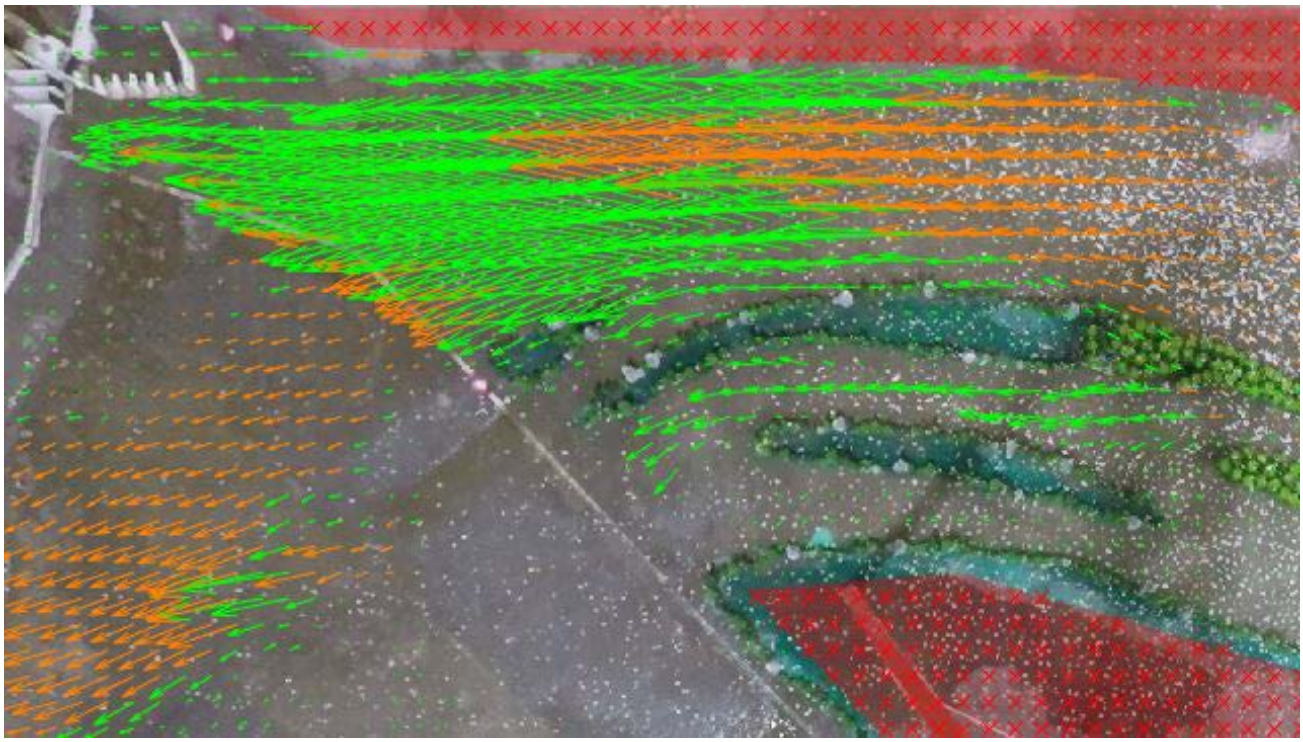

Image of LSPIV mean velocity vectors of the river modeled at the existing condition with River Q 5,000 cfs, Dam Q 4500 cfs, Canal Q 500 cfs, and sluice gates closed.

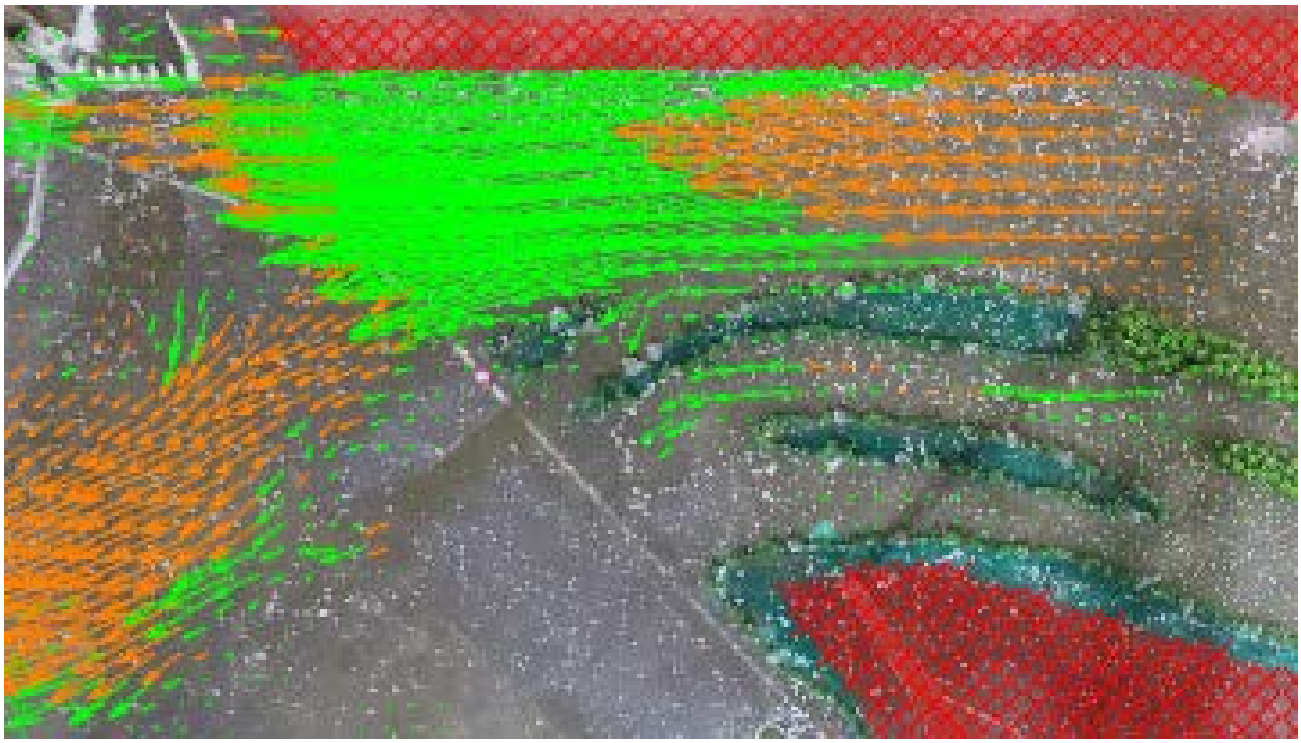

Image of LSPIV mean velocity vectors of the river modeled at the existing condition with River Q 5,000 cfs, Dam Q 5,000 cfs, Canal Q 0 cfs, with sluice gates open.

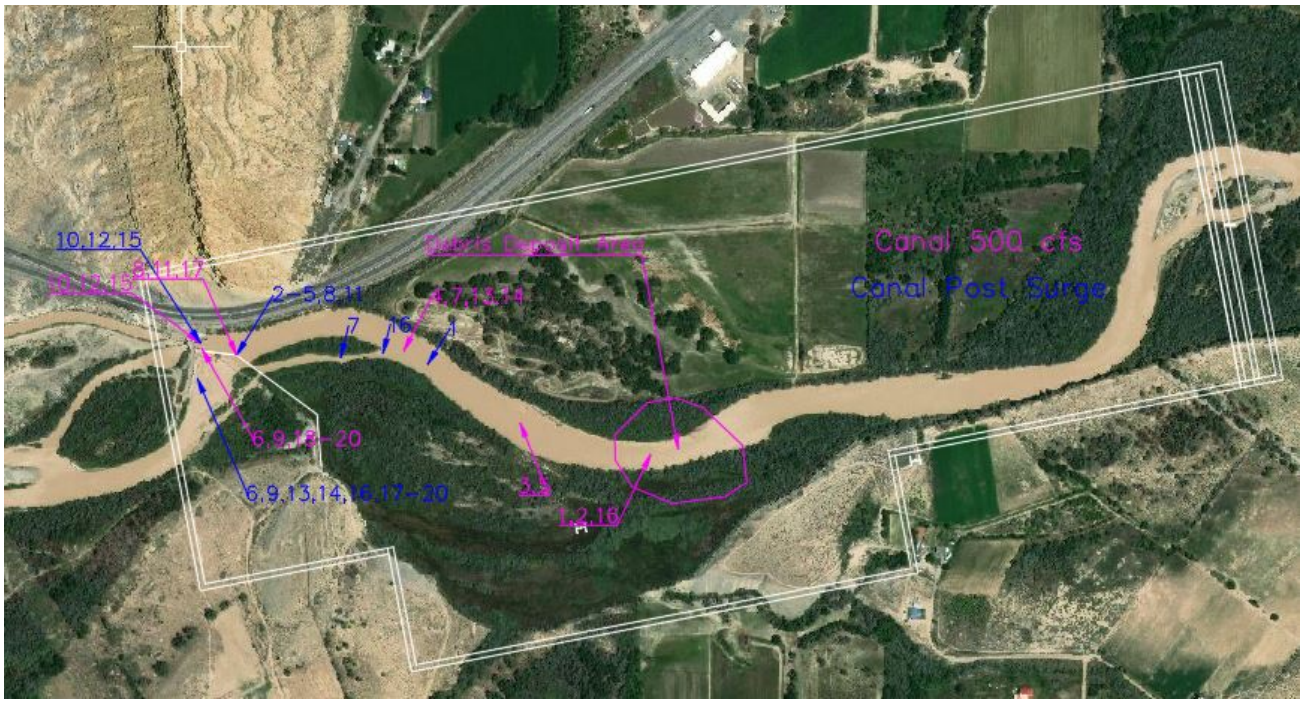

Image of debris capture location of the river modeled at the existing condition with River Q 5000 cfs and Canal Q 500 cfs, with sluice gates closed.

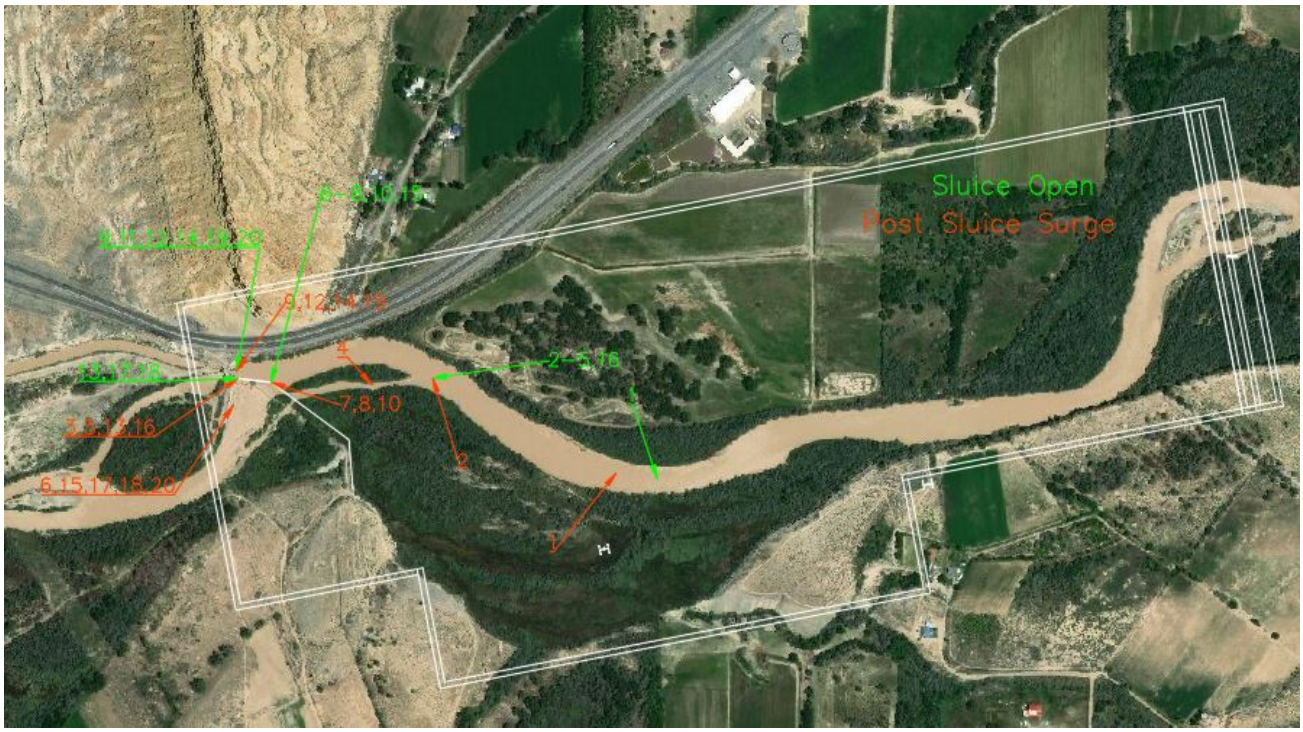

Image of debris capture location of the river modeled at the existing condition with River Q 5000 cfs and Canal Q 0 cfs, with sluice gates open.

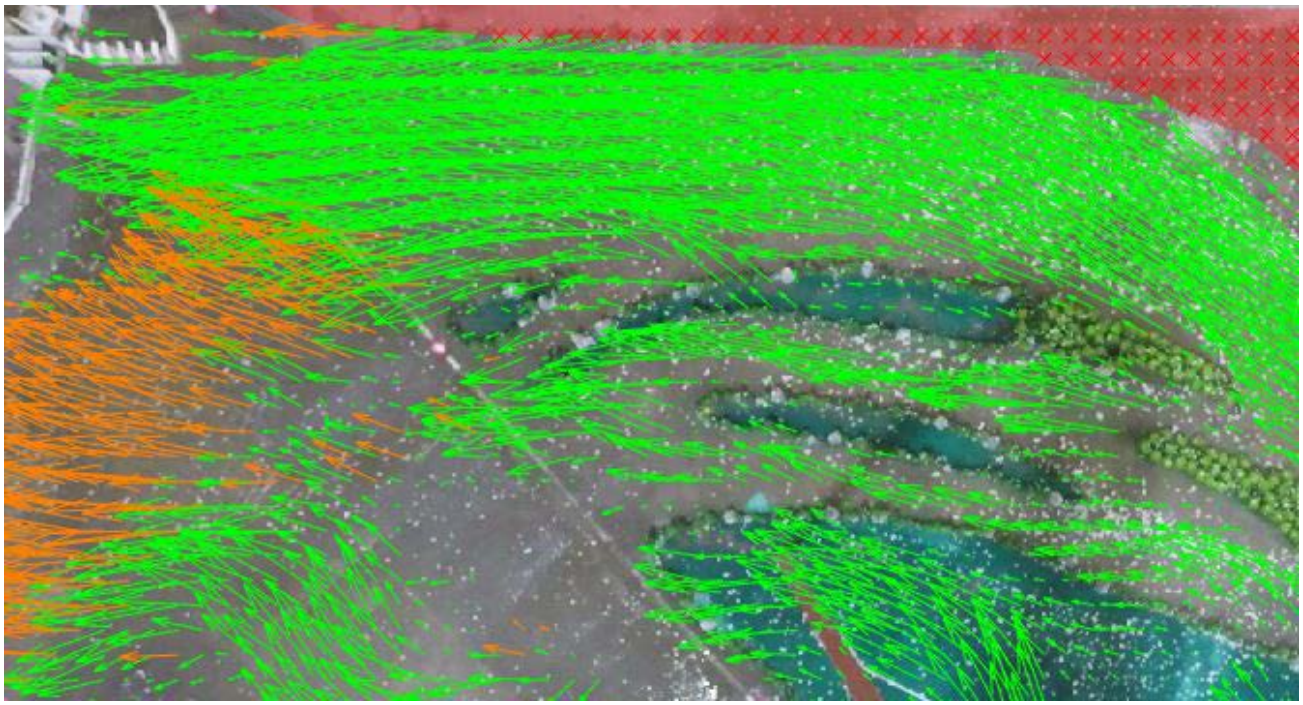

Image of LSPIV mean velocity vector of the river modeled at the existing condition with River Q 12,000 cfs, Dam Q 11400 cfs, Canal Q 600 cfs, with sluice gates closed.

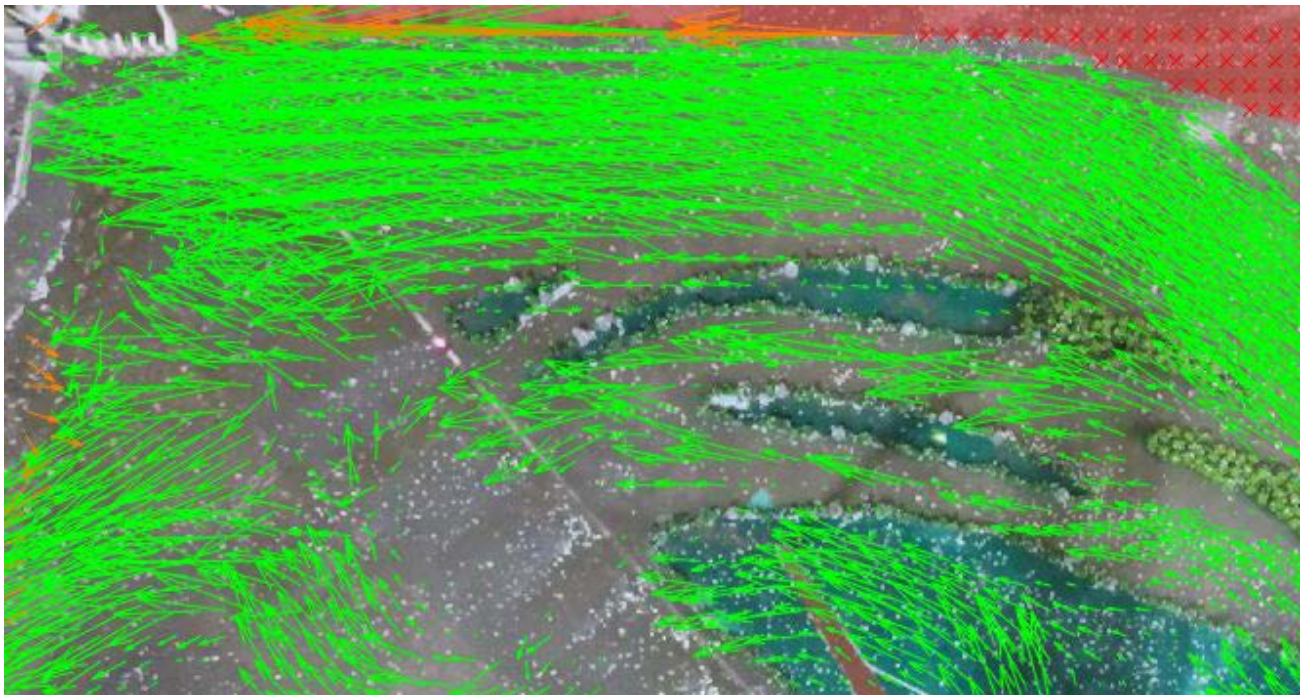

Image of LSPIV mean velocity vector of the river modeled at the existing condition with River Q 12,000 cfs, Dam Q 12,000 cfs, Canal Q 0 cfs, with sluice gates open.

Combined Rock Structure 1 & Log Boom 1 (RS1LB1)

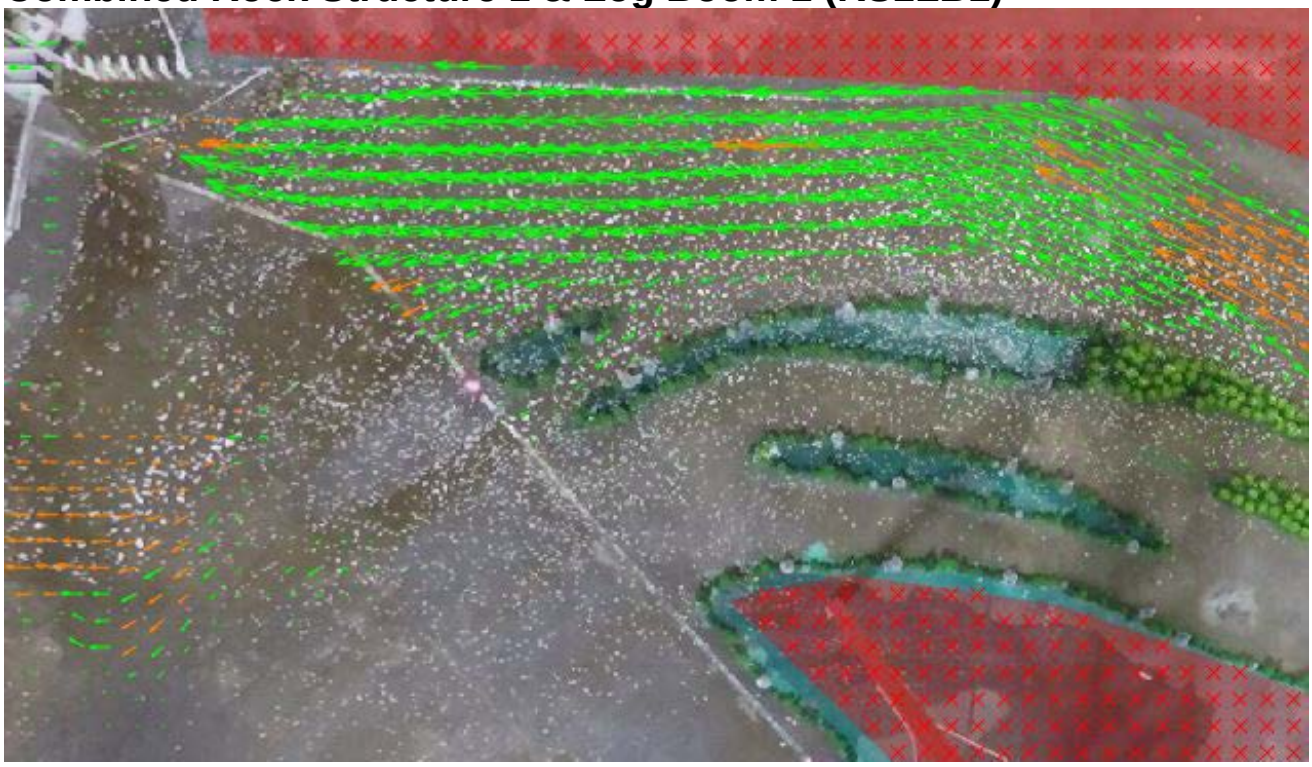

Image of RS1LB1 with LSPIV mean velocity vector at River Q 800 cfs, Dam Q 550 cfs, Canal Q 250 cfs, with sluice gates closed.

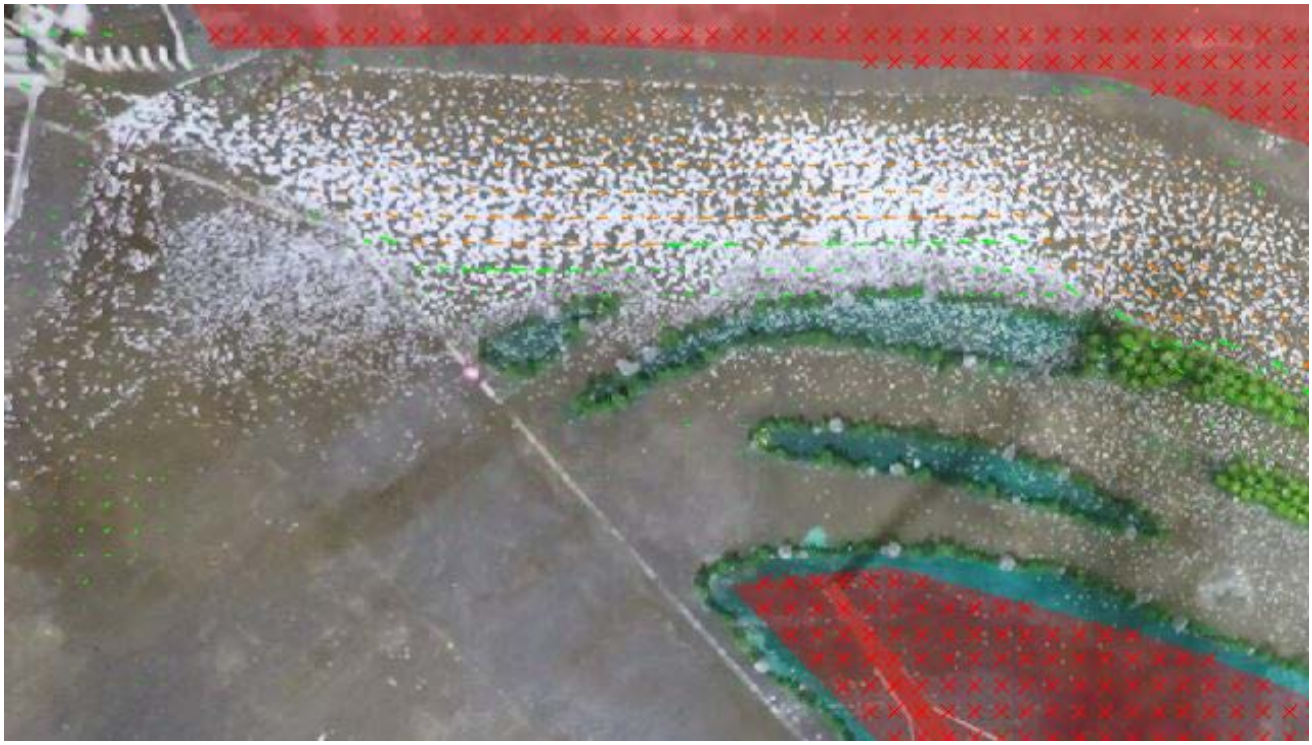

Image of RS1LB1 with LSPIV mean velocity vector at River Q 800 cfs, Dam Q 800 cfs, Canal Q 0 cfs, with sluice gates open.

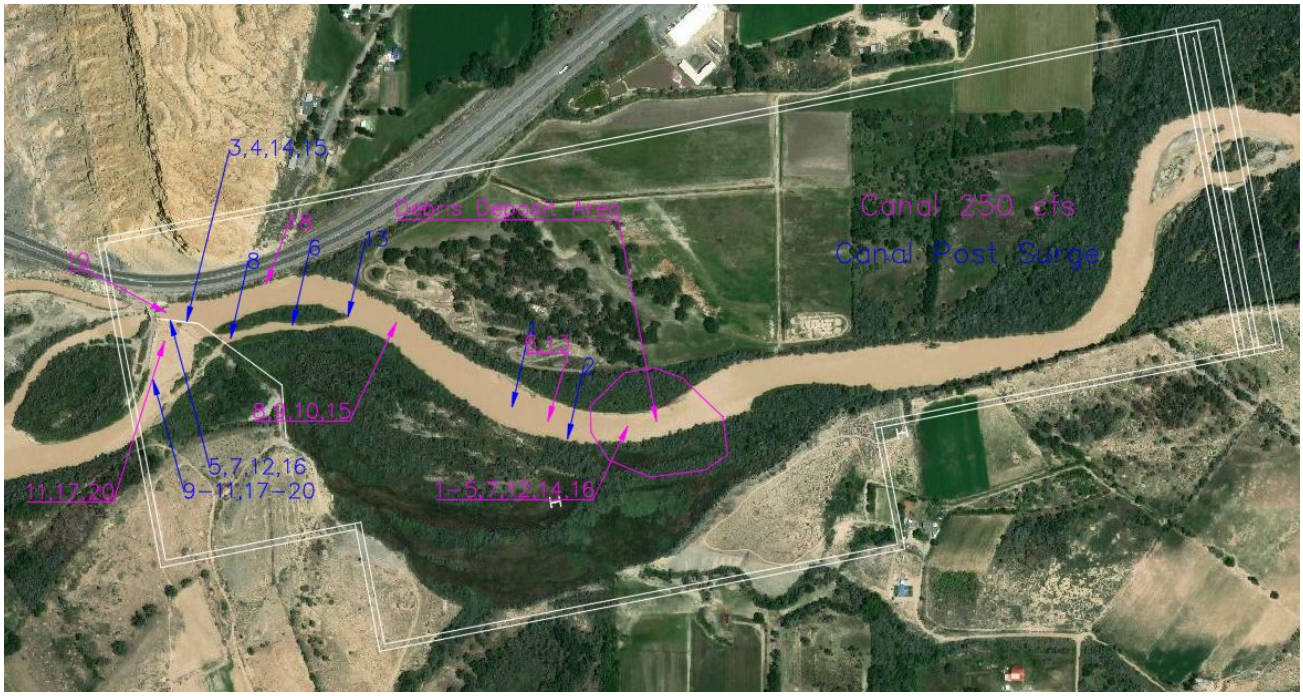

Image of debris capture location of the river modeled at the RS1LB1 condition with River Q 800 cfs and Canal Q 250 cfs, with sluice gates closed.

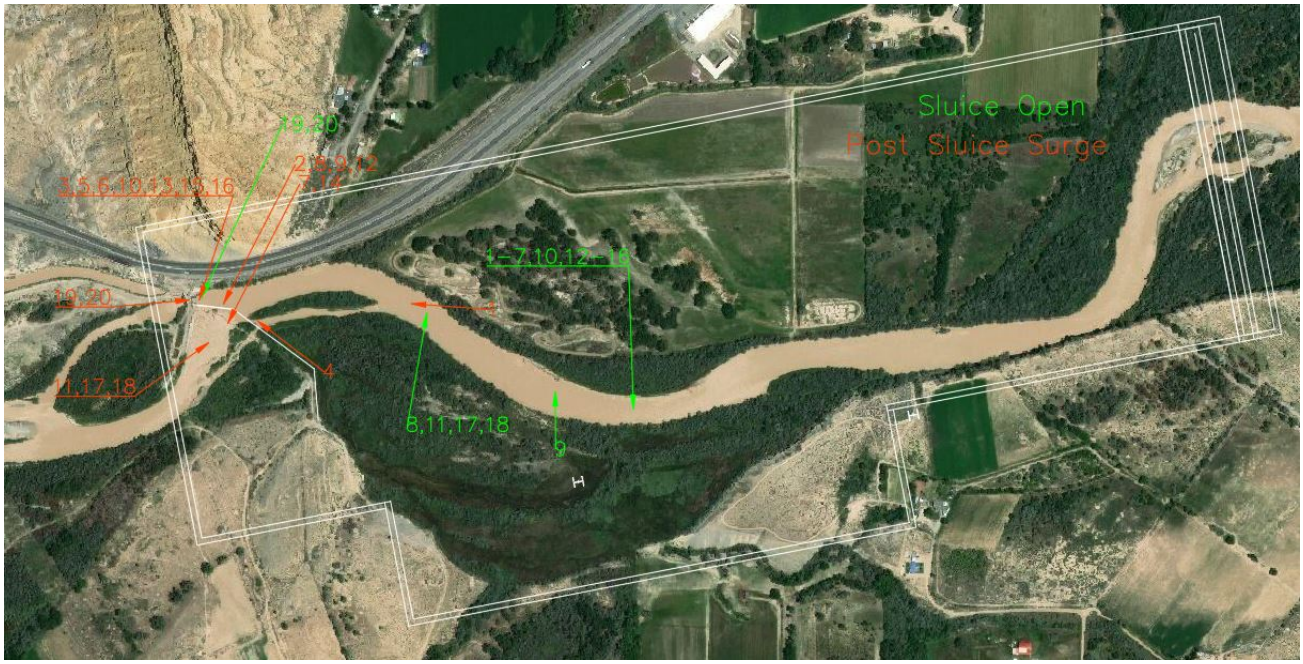

Image of debris capture location of the river modeled at the RS1LB1 condition with River Q 800 cfs and Canal Q 0 cfs, with sluice gates open.

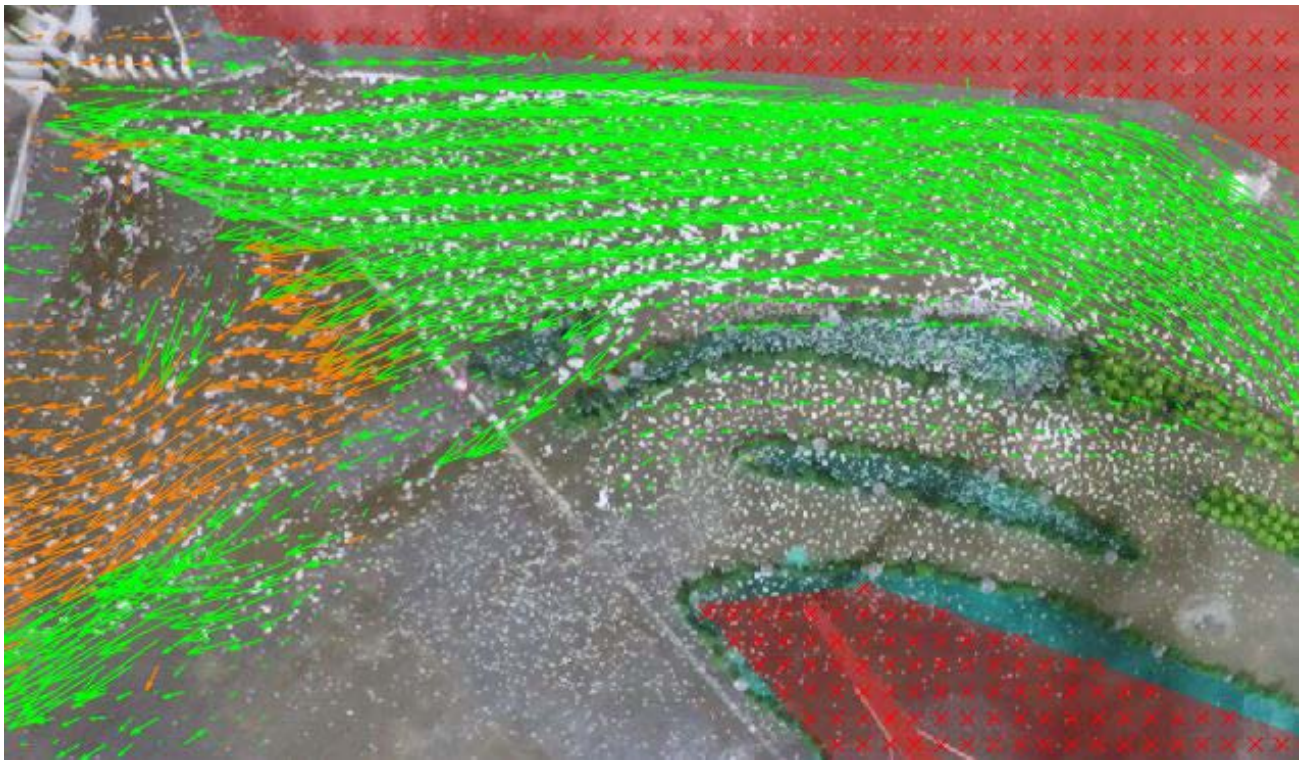

Image of RS1LB1 with LSPIV mean velocity vector at River Q 2,500 cfs, Dam Q 2100 cfs, Canal Q 400 cfs, with sluice gates closed.

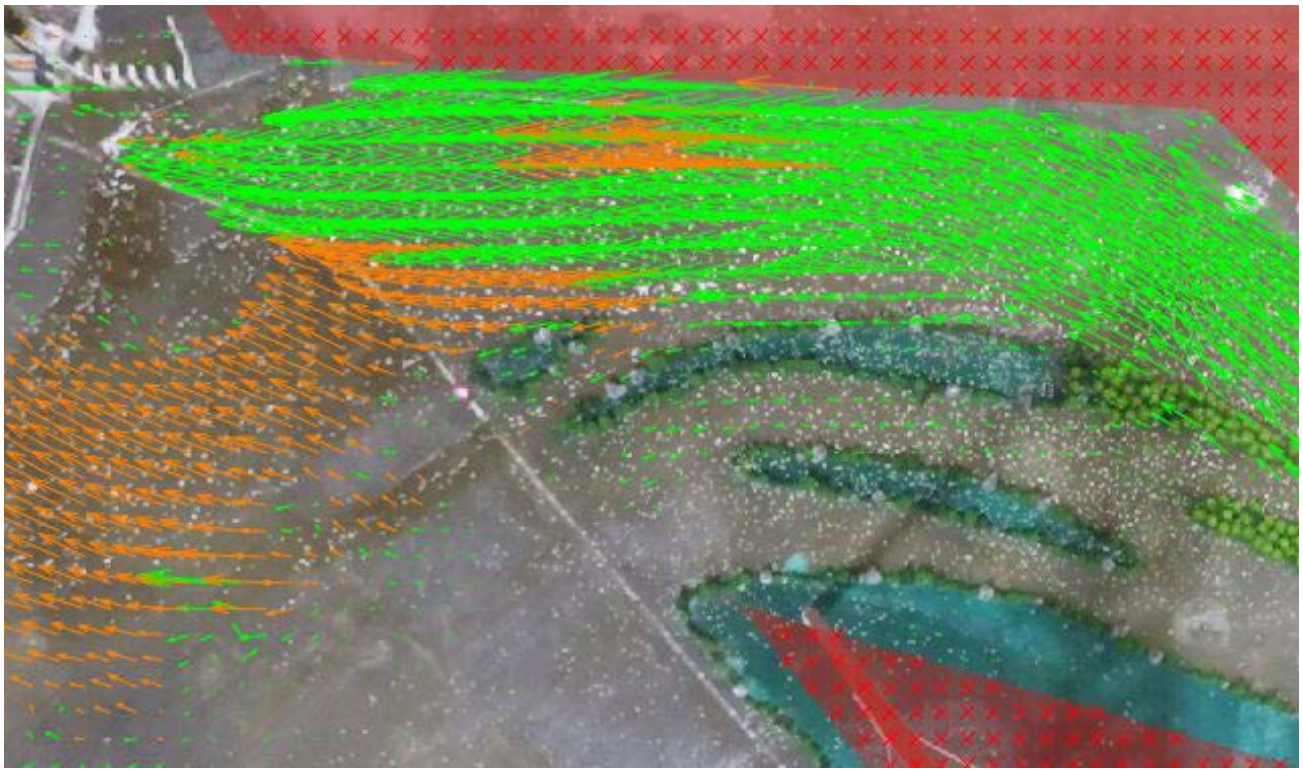

Image of RS1LB1 with LSPIV mean velocity vector at River Q 2,500 cfs, Dam Q 2,500 cfs, Canal Q 0 cfs, with sluice gates open.

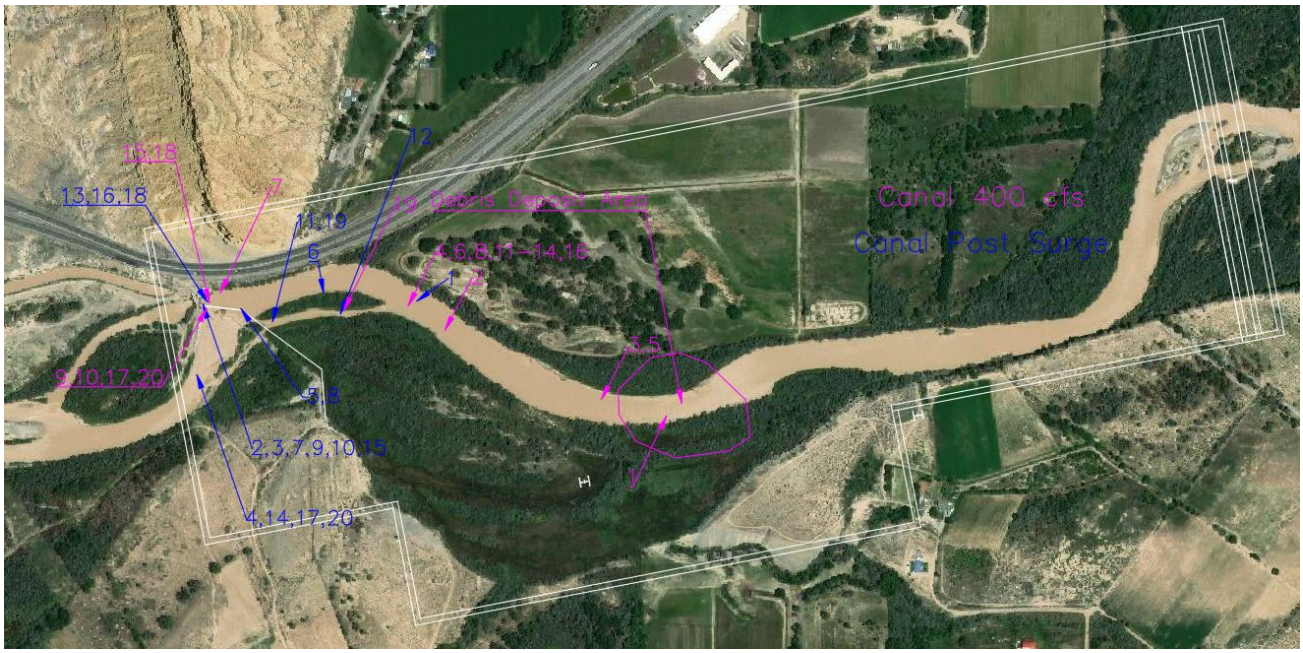

Image of debris capture location of the river modeled at the RS1LB1 condition with River Q 2500 cfs and Canal Q 400 cfs, with sluice gates closed.

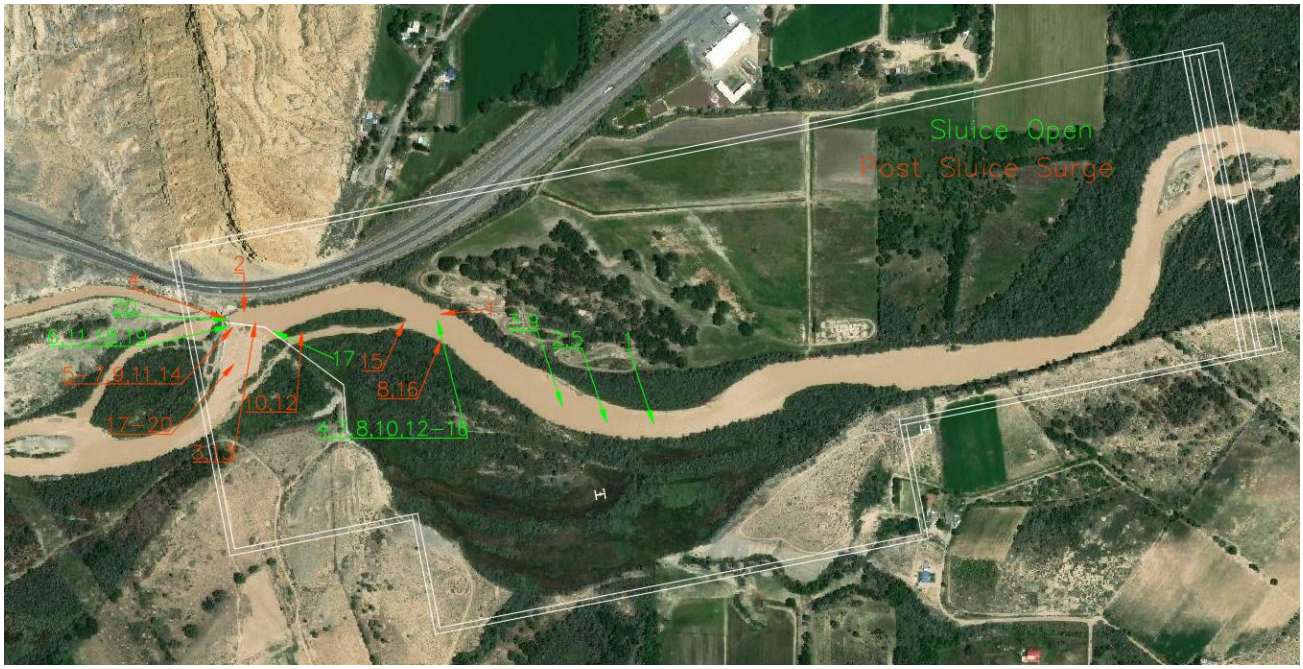

Image of debris capture location of the river modeled at the RS1LB1 condition with River Q 2500 cfs and Canal Q 0 cfs, with sluice gates open.

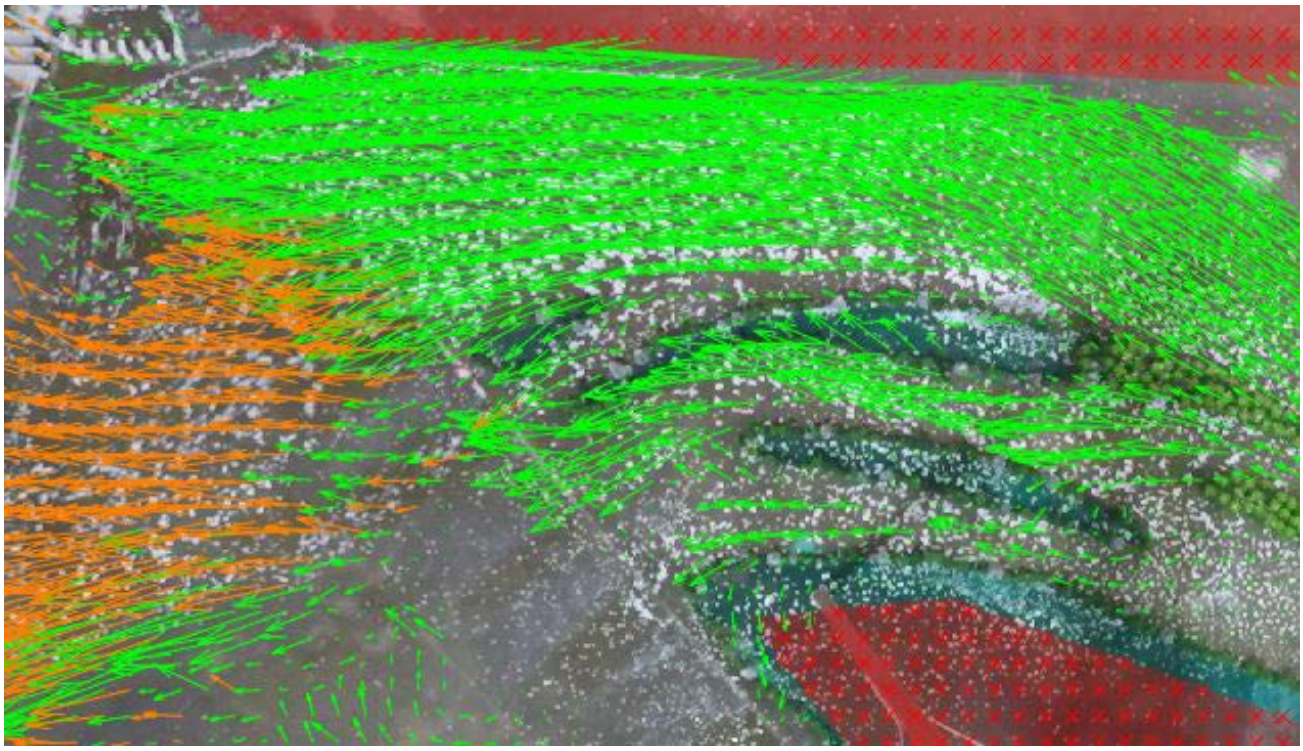

Image of RS1LB1 with LSPIV mean velocity vector at River Q 5,000 cfs, Dam Q 4500 cfs, Canal Q 500 cfs, with sluice gates closed.

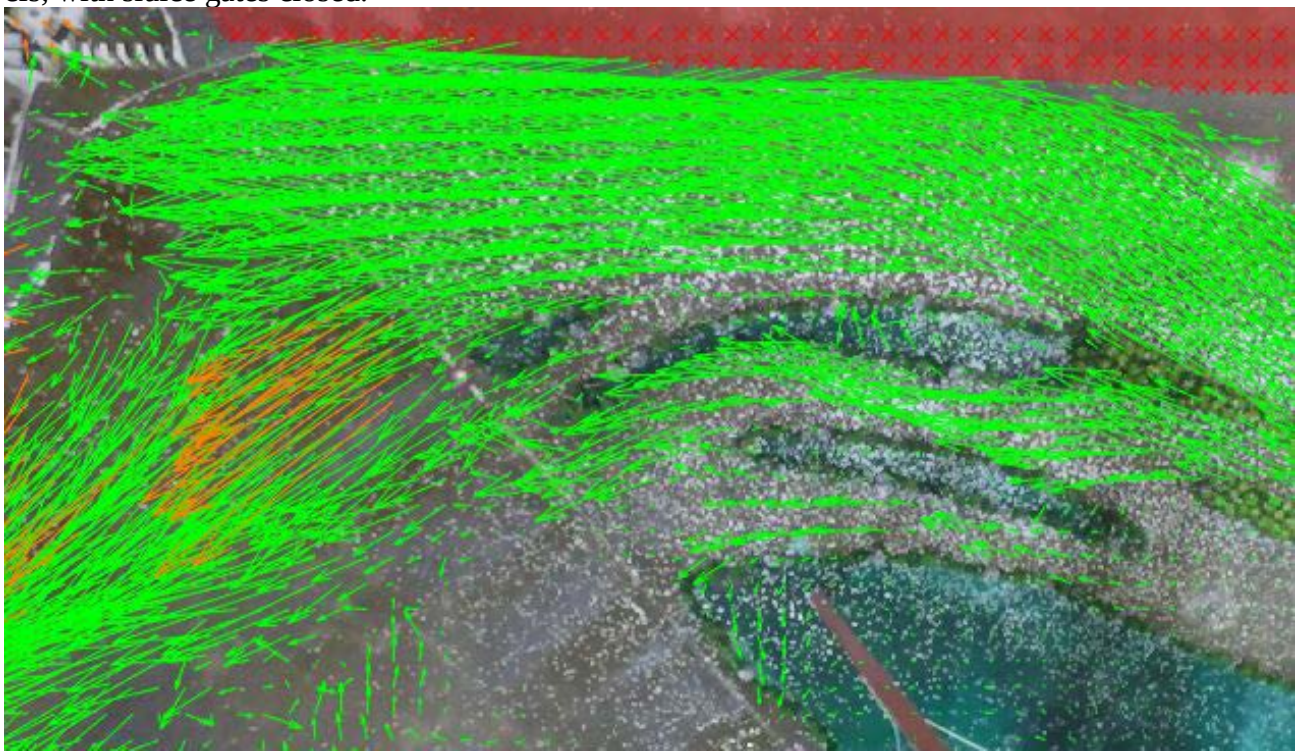

Image of RS1LB1with LSPIV mean velocity vector at River Q 5,000 cfs, Dam Q 5,000 cfs, Canal Q 0 cfs, with sluice gates open.

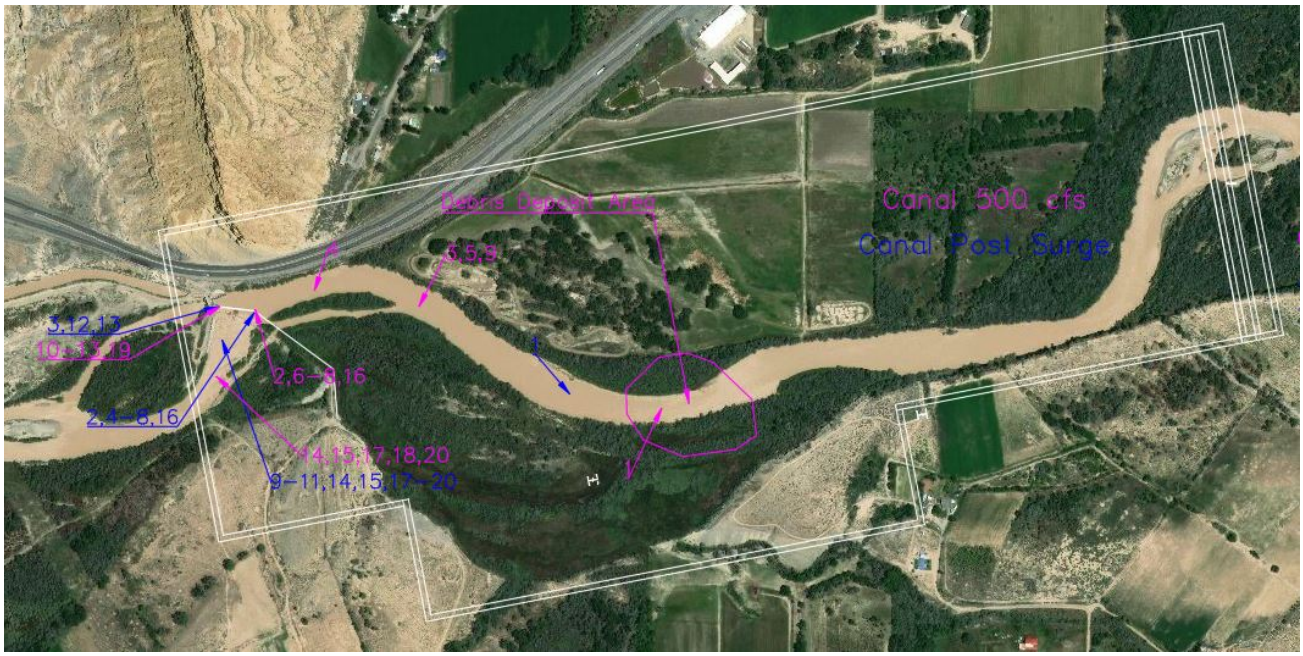

Image of debris capture location of the river modeled at the RS1LB1 condition with River Q 5000 cfs and Canal Q 500 cfs, with sluice gates closed.

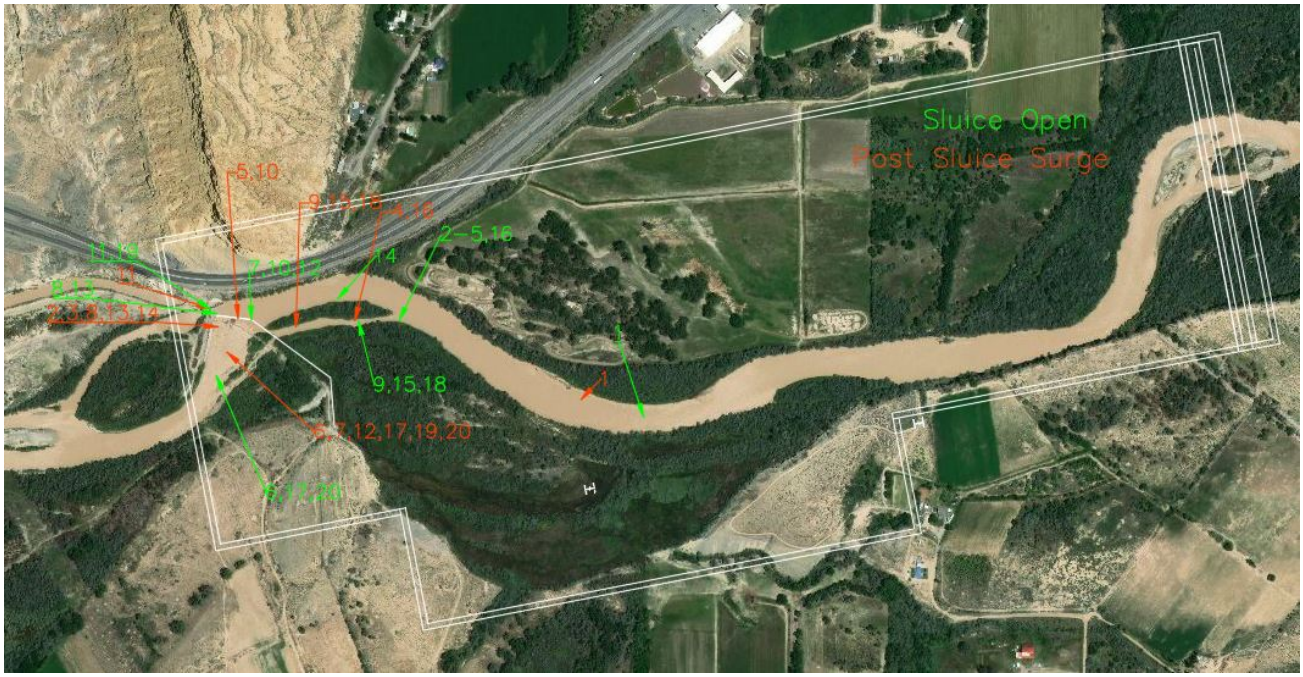

Image of debris capture location of the river modeled at the RS1LB1 condition with River Q 5000 cfs and Canal Q 0 cfs, with sluice gates open.

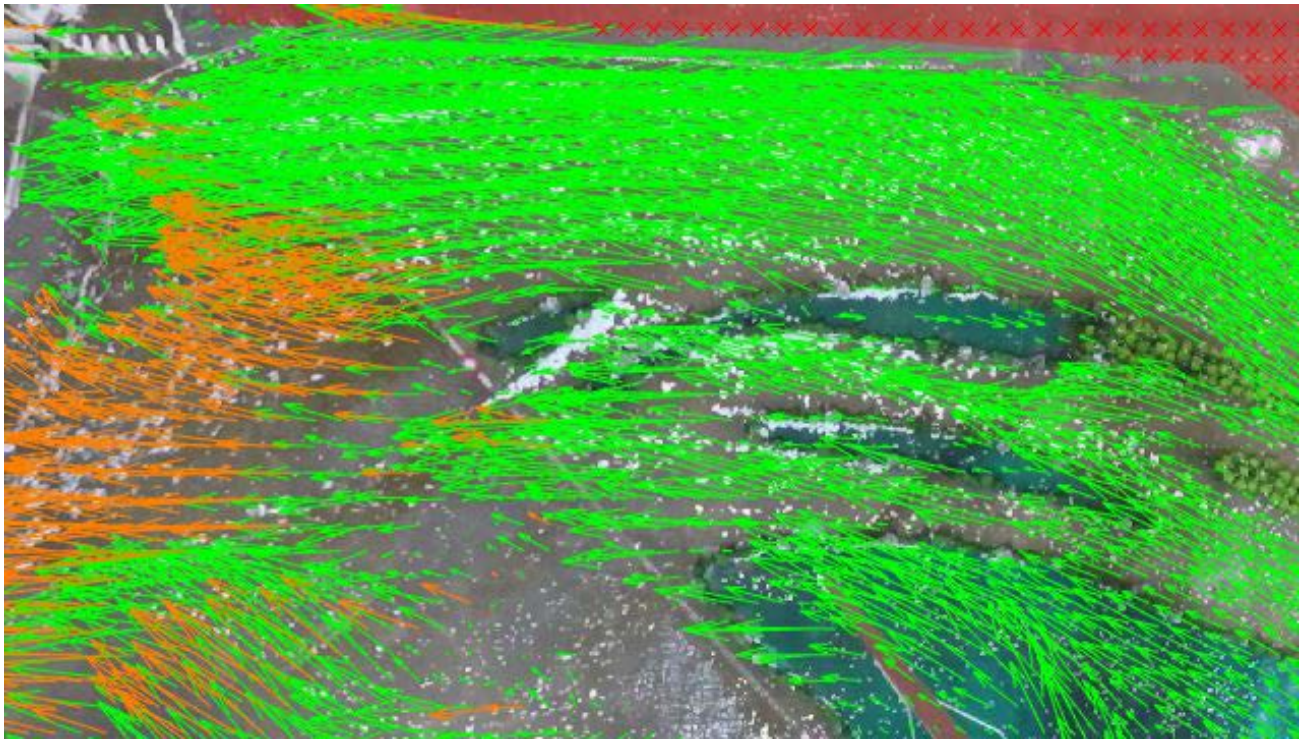

Image of RS1LB1 with LSPIV mean velocity vector at River Q 12,000 cfs, Dam Q 11400 cfs, Canal Q 600 cfs, with sluice gates closed.

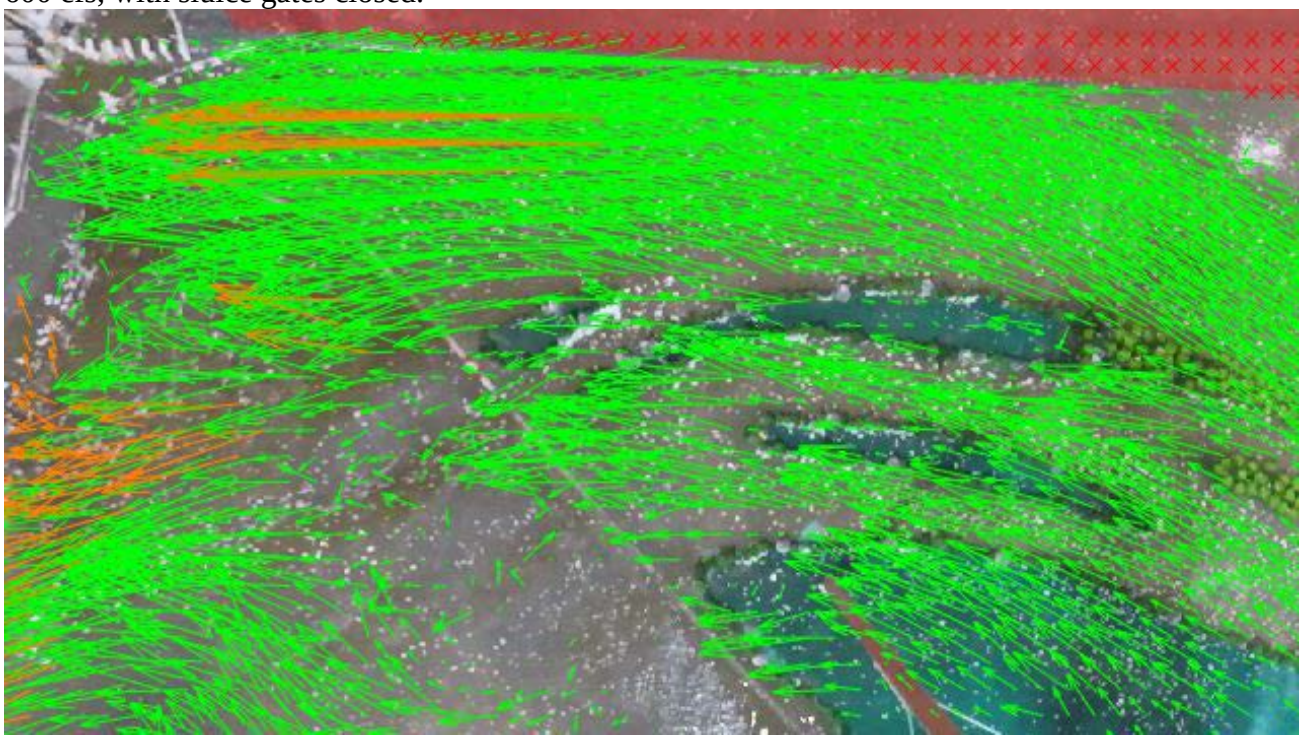

Image of RS1LB1 with LSPIV mean velocity vector at River Q 12,000 cfs, Dam Q 12,000 cfs, Canal Q 0 cfs, with sluice gates open.

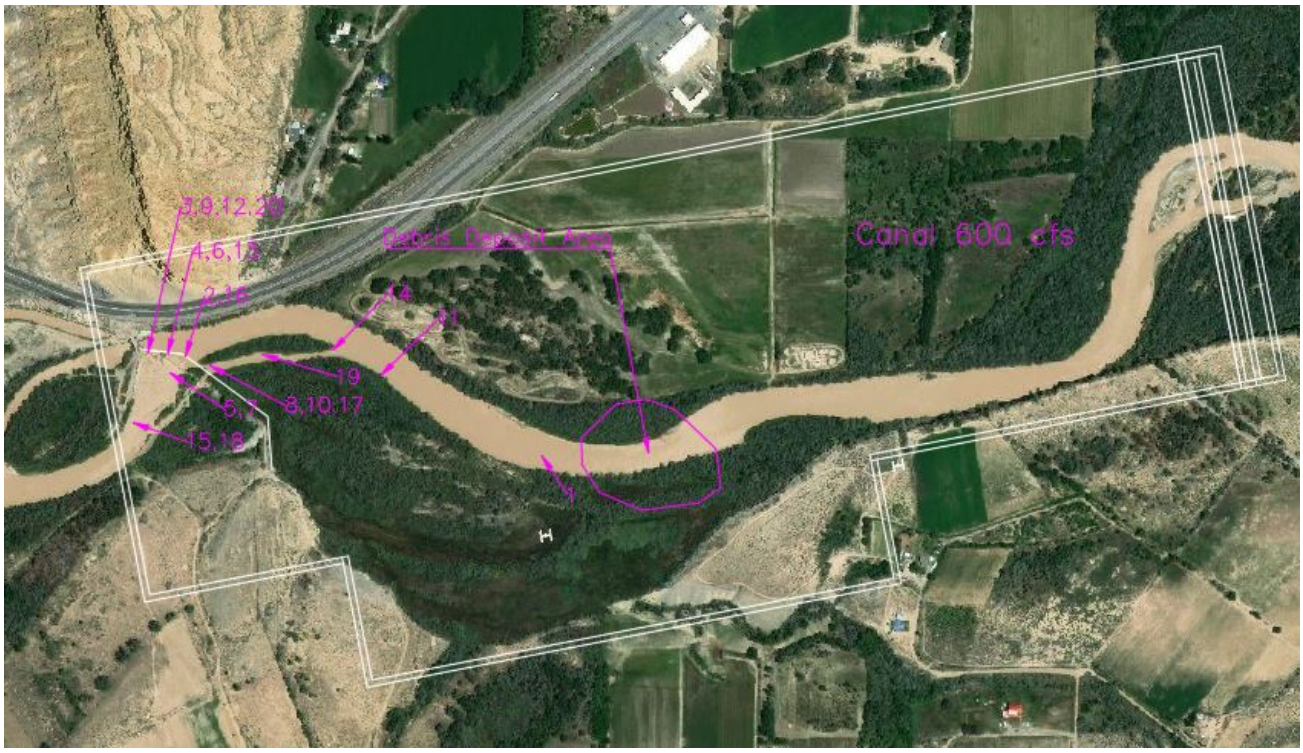

Image of debris capture location of the river modeled at the RS1LB1 condition with River Q 12000 cfs and Canal Q 600 cfs, with sluice gates closed.

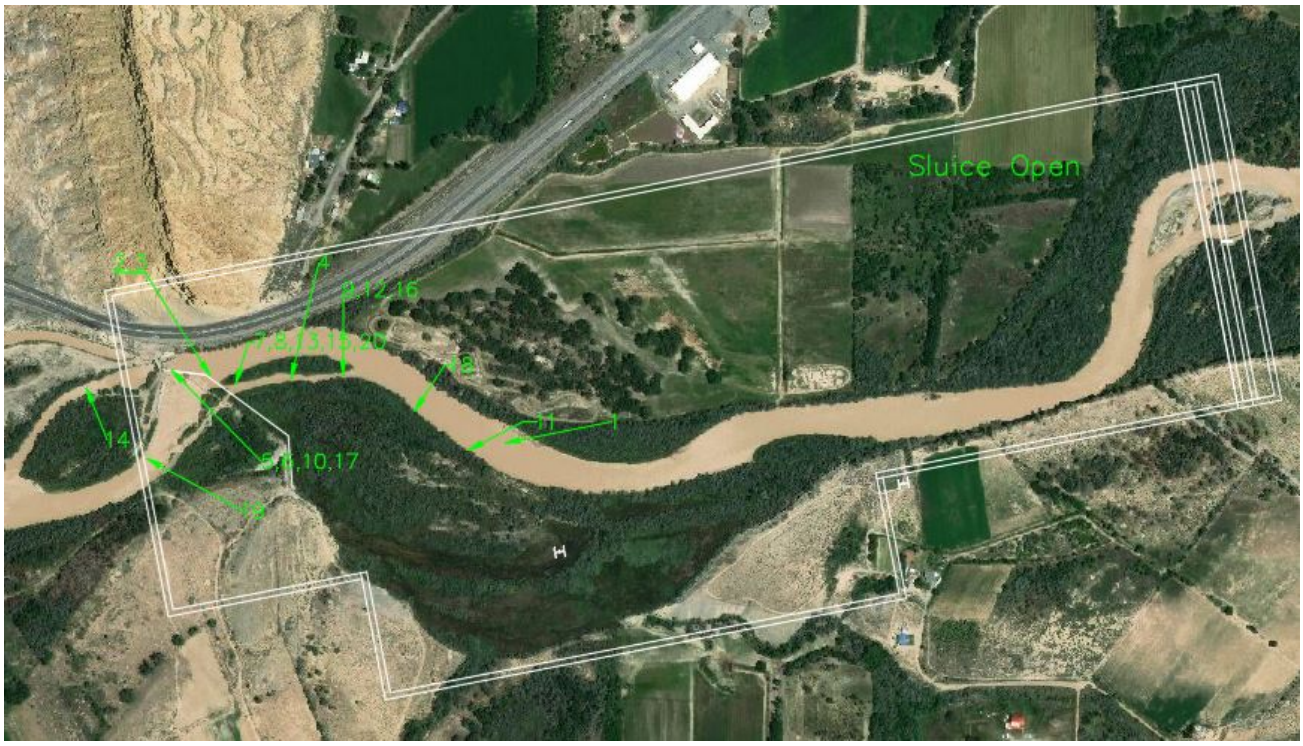

Image of debris capture location of the river modeled at the RS1LB1 condition with River Q 12000 cfs and Canal Q 0 cfs, with sluice gates open.

Rock Structure 1 (RS1)

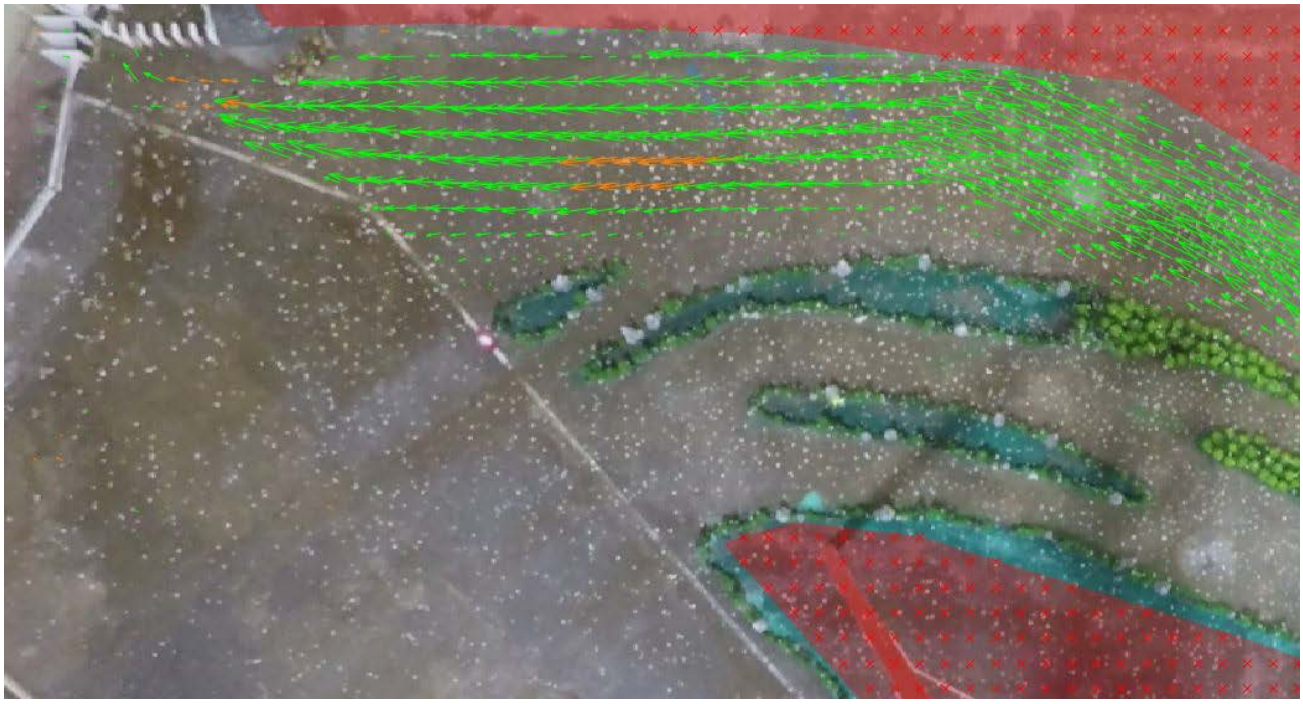

Image of RS1 with LSPIV mean velocity vector at River Q 800 cfs, Dam Q 650 cfs, Canal Q 250 cfs, with sluice gates closed.

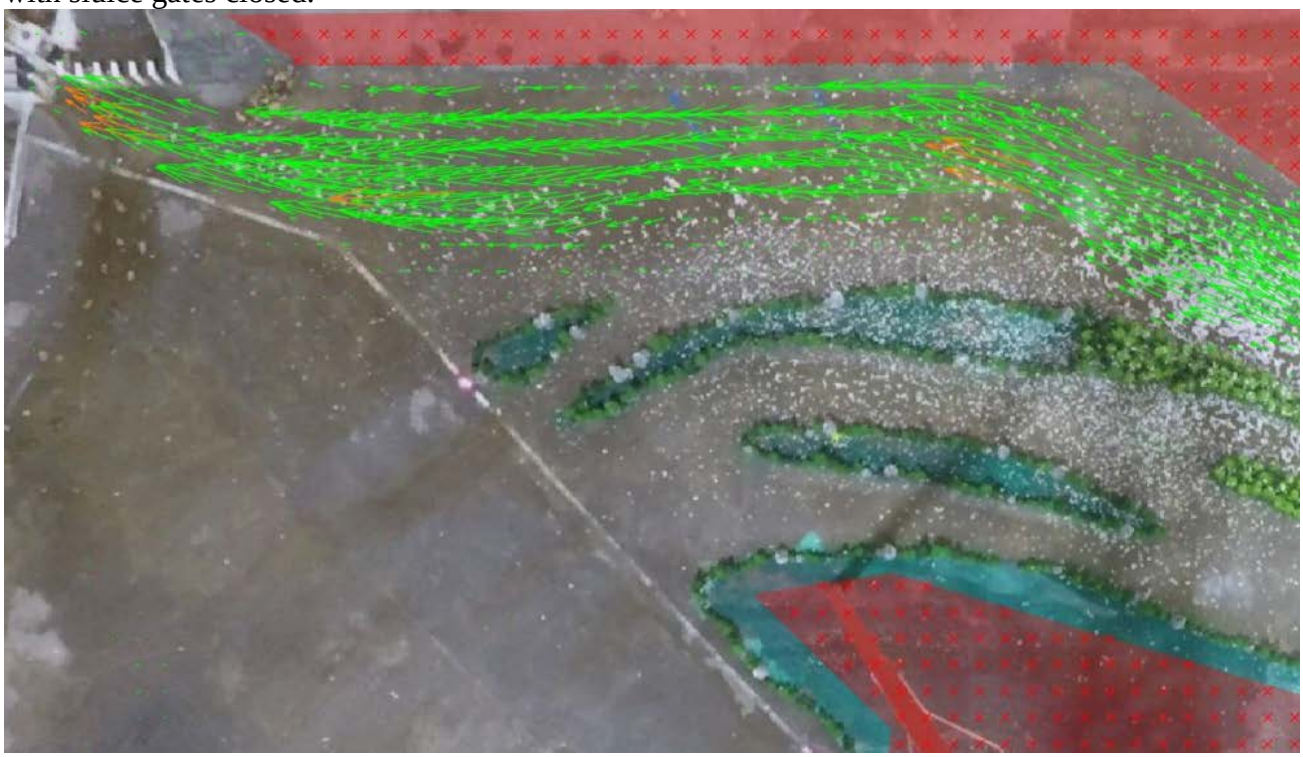

Image of RS1 with LSPIV mean velocity vector at River Q 800 cfs, Dam Q 800 cfs, Canal Q 0 cfs, with sluice gates open.

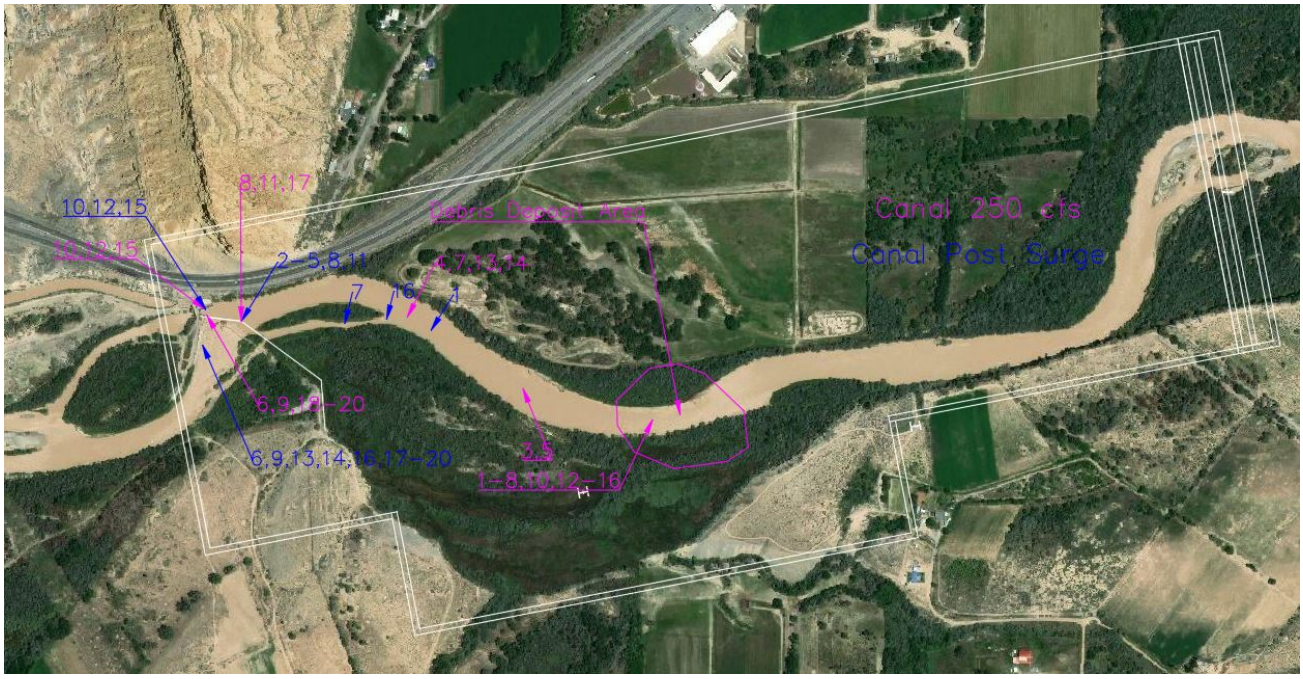

Image of debris capture location of the river modeled at the RS1 condition with River Q 800 cfs and Canal Q 250 cfs, with sluice gates closed.

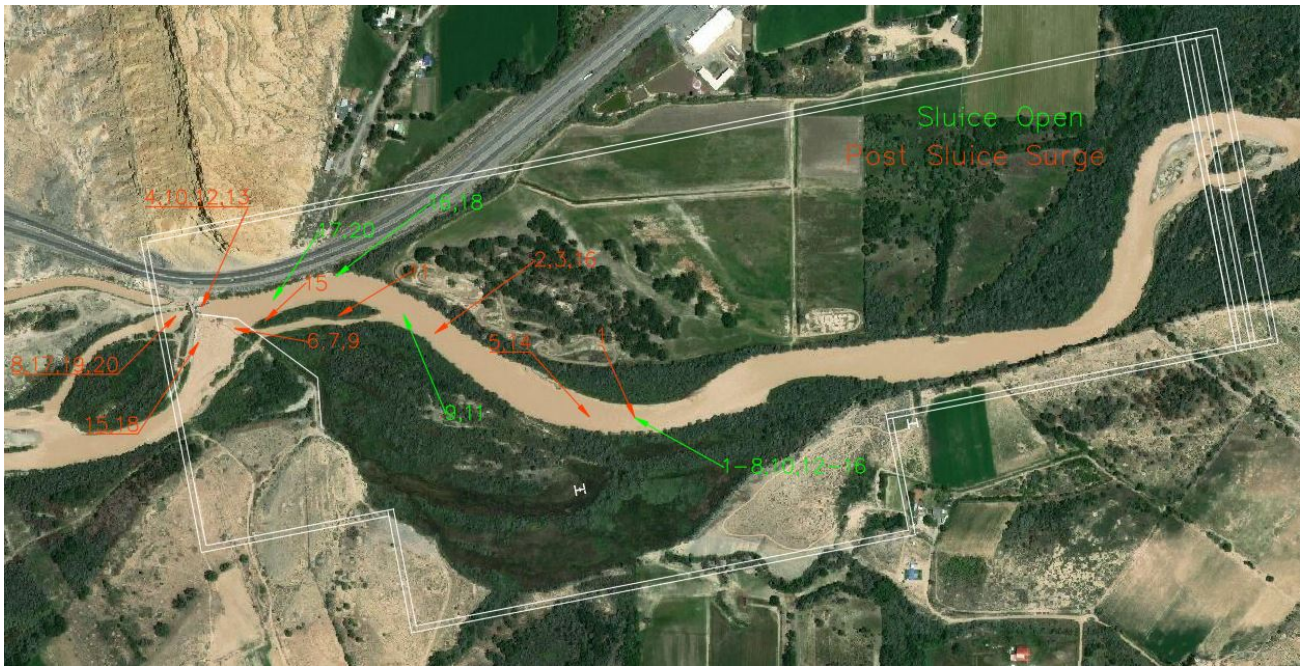

Image of debris capture location of the river modeled at the RS1 condition with River Q 800 cfs and Canal Q 0 cfs, with sluice gates open.

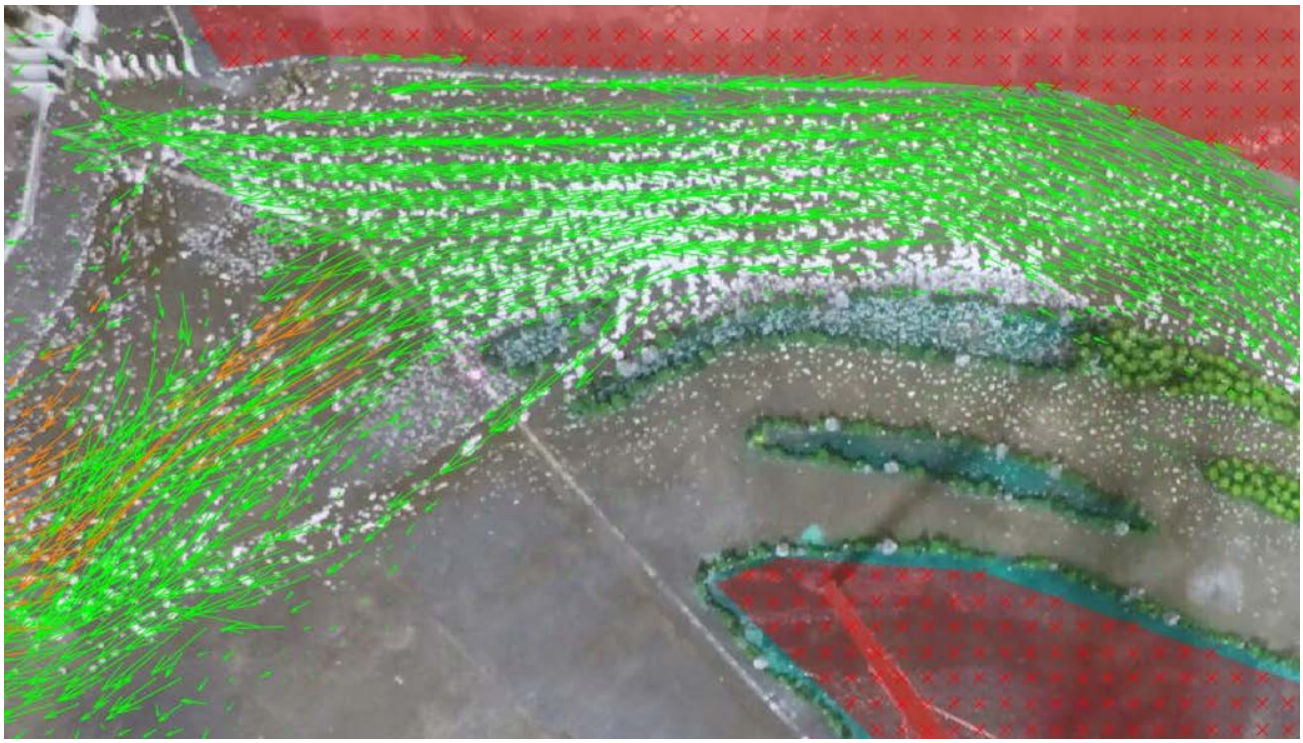

Image of RS1 with LSPIV mean velocity vector at River Q 2,500 cfs, Dam Q 2100 cfs, Canal Q 400 cfs, with sluice gates closed. Notice recirculation behind trashrack and velocities exiting upstream end of trashrack.

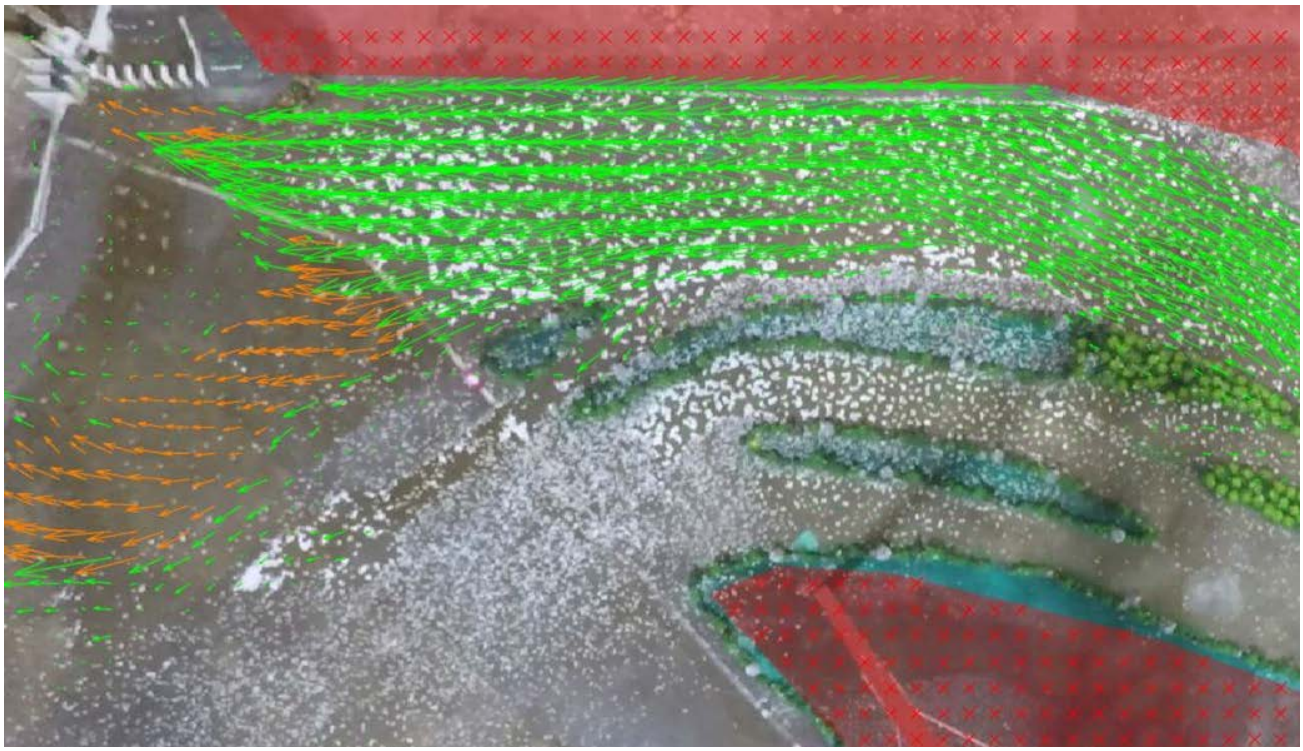

Image of RS1 with LSPIV mean velocity vector at River Q 2,500 cfs, Dam Q 2,500 cfs, Canal Q 0 cfs, with sluice gates open.

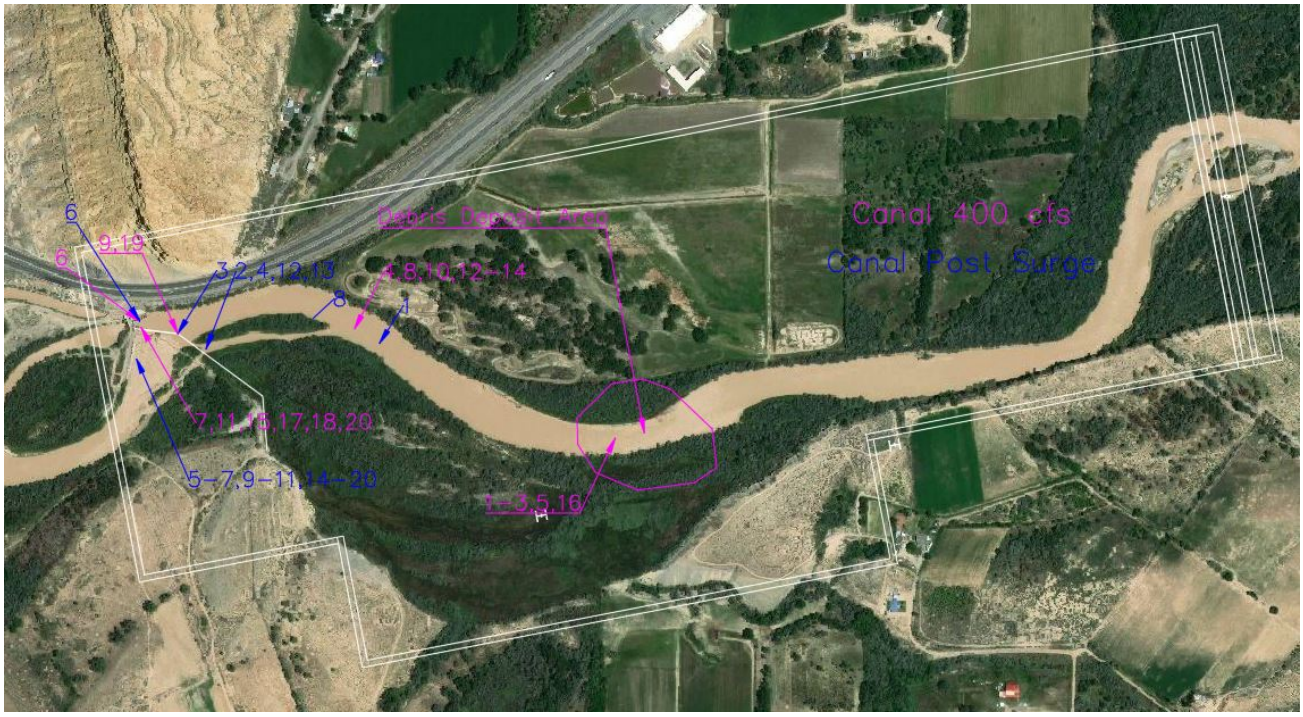

Image of debris capture location of the river modeled at the RS1 condition with River Q 2500 cfs and Canal Q 400 cfs, with sluice gates closed.

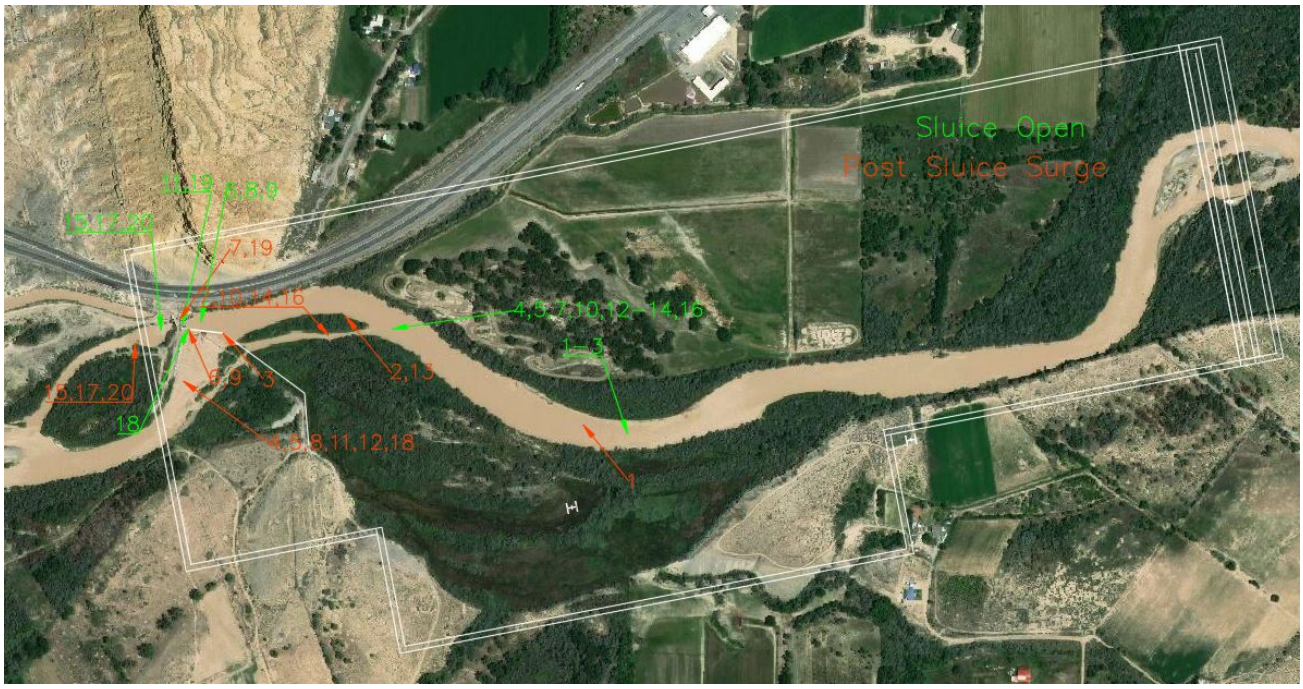

Image of debris capture location of the river modeled at the RS1 condition with River Q 2500 cfs and Canal Q 0 cfs, with sluice gates open.

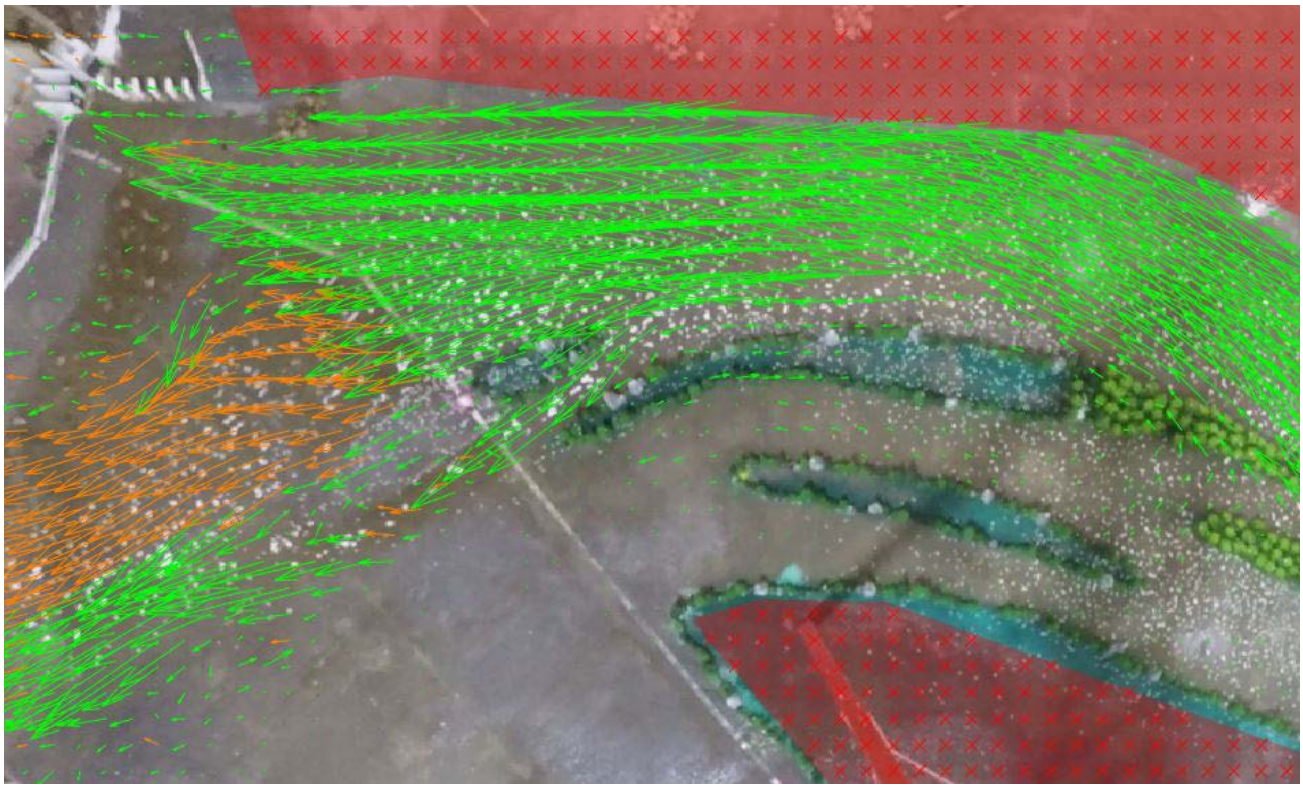

Image of RS1 with LSPIV mean velocity vector at River Q 5,000 cfs, Dam Q 4500 cfs, Canal Q 500 cfs, with sluice gates closed.

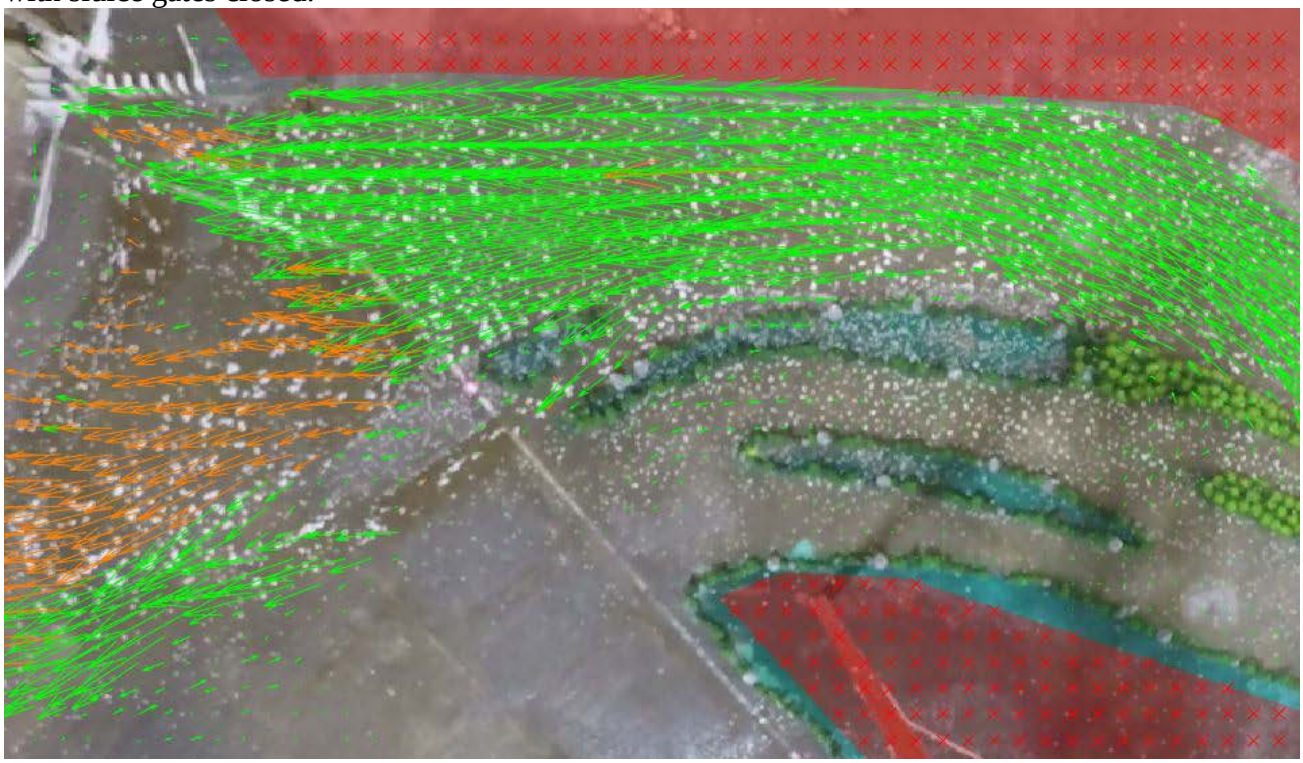

Image of RS1 with LSPIV mean velocity vector at River Q 5,000 cfs, Dam Q 5,000 cfs, Canal Q 0 cfs, with sluice gates open.

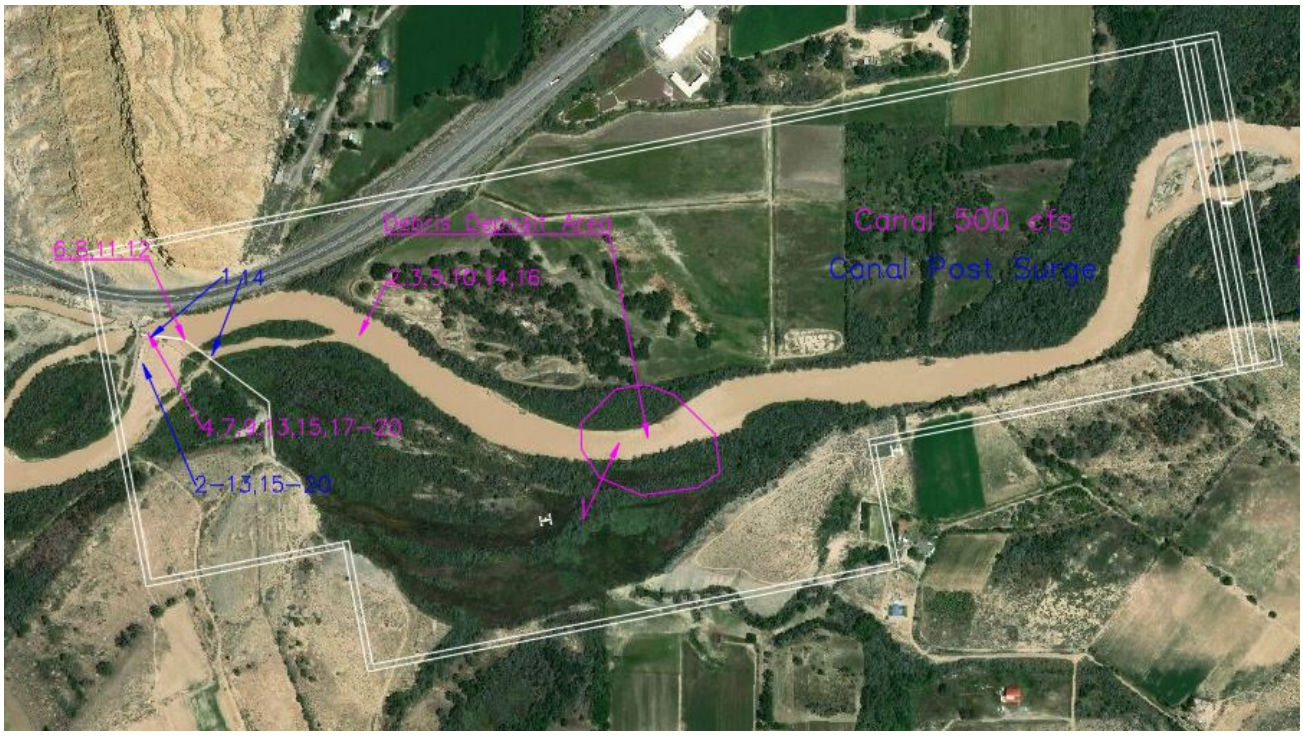

Image of debris capture location of the river modeled at the RS1 condition with River Q 5000 cfs and Canal Q 500 cfs, with sluice gates closed.

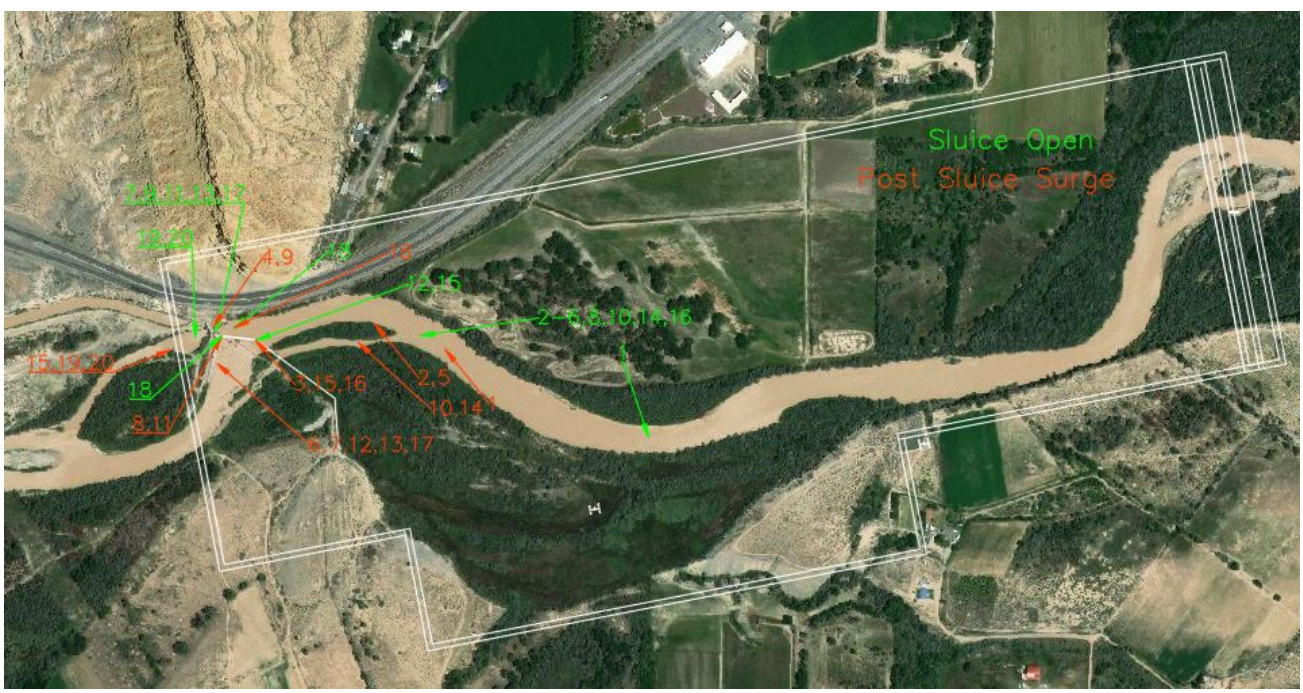

Image of debris capture location of the river modeled at the RS1 condition with River Q 5000 cfs and Canal Q 0 cfs, with sluice gates open.

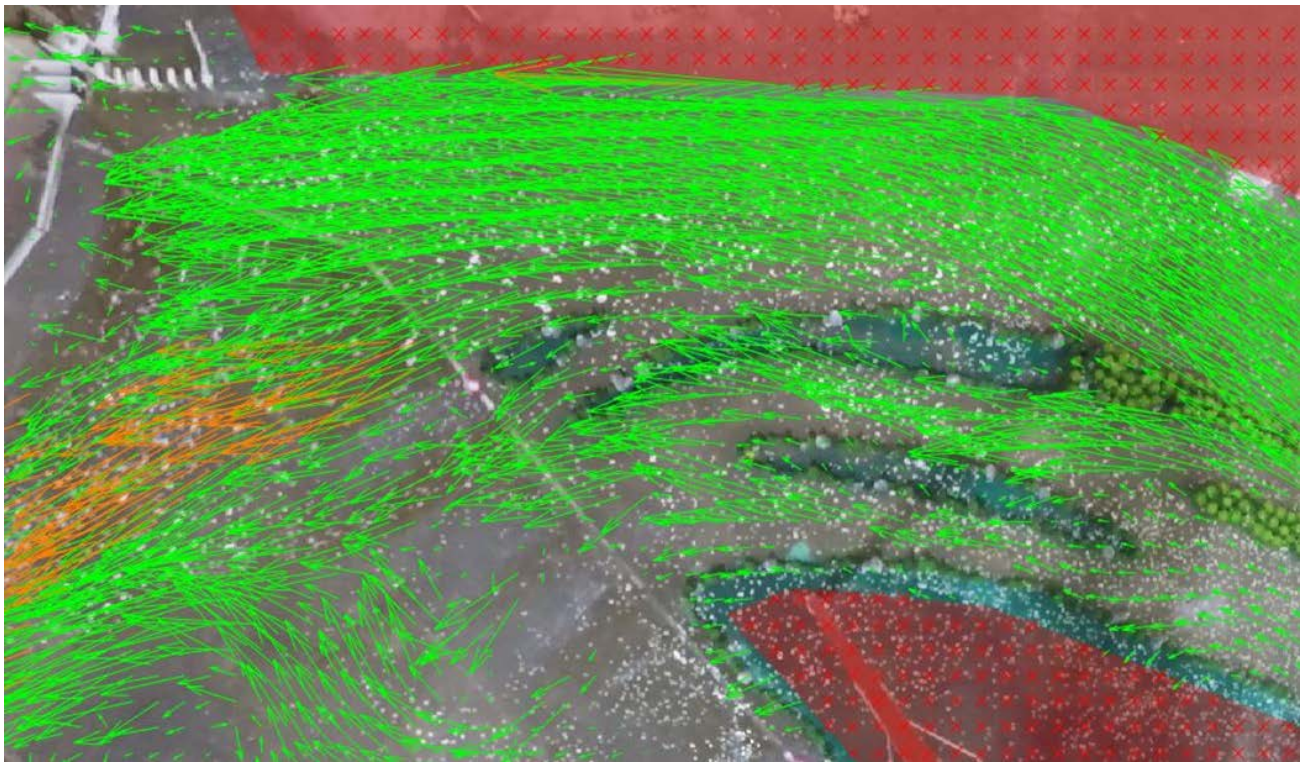

Image of RS1 with LSPIV mean velocity vector at River Q 12,000 cfs, Dam Q 11400 cfs, Canal Q 600 cfs, with sluice gates closed.

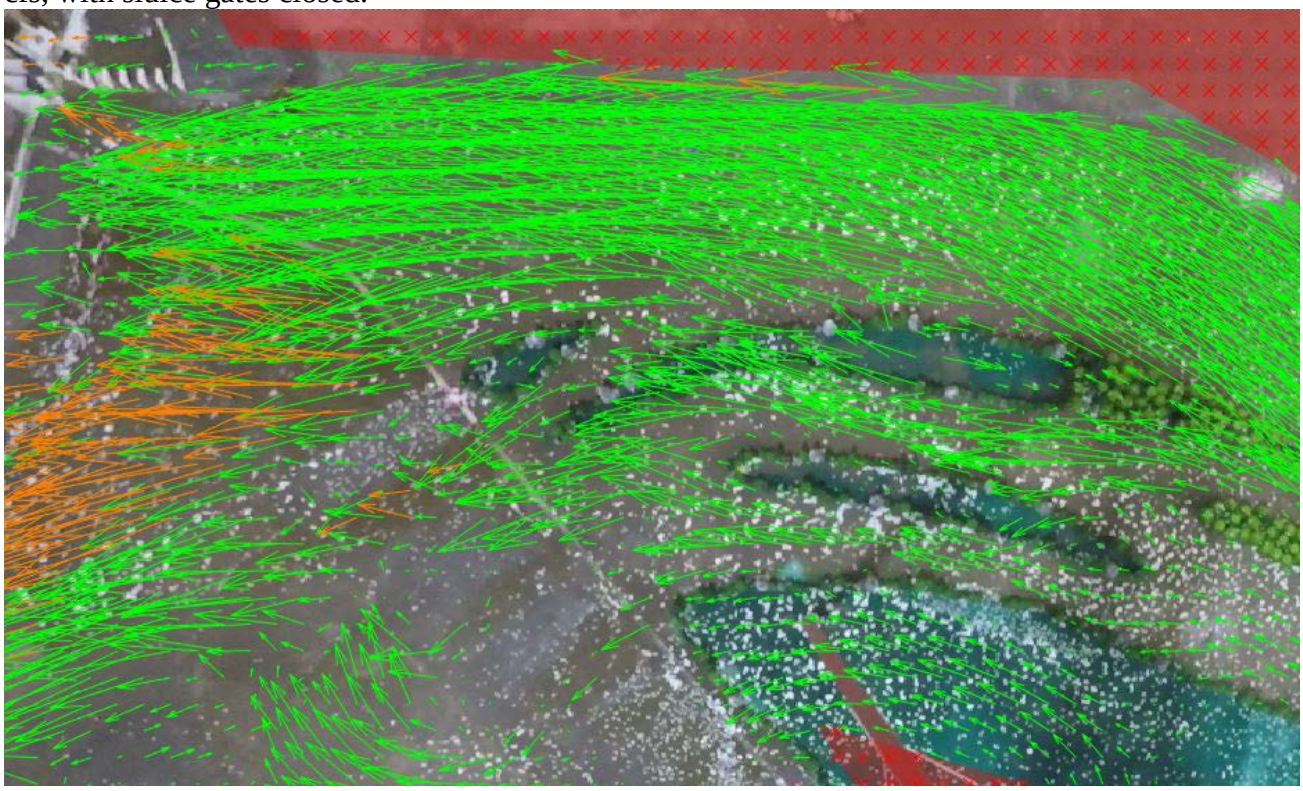

Image of RS1 with LSPIV mean velocity vector at River Q 12,000 cfs, Dam Q 12,000 cfs, Canal Q 0 cfs, with sluice gates open.

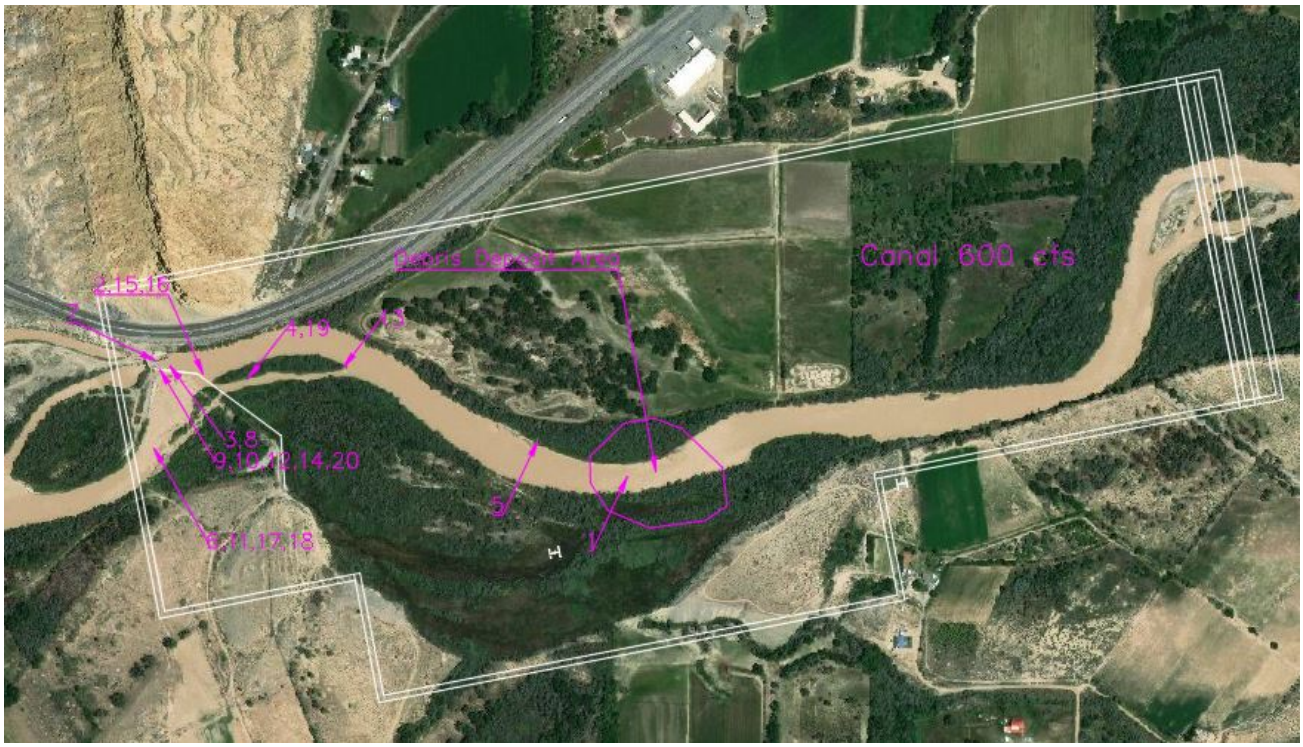

Image of debris capture location of the river modeled at the RS1 condition with River Q 12000 cfs and Canal Q 600 cfs, with sluice gates closed.

Image of debris capture location of the river modeled at the RS1 condition with River Q 12000 cfs and Canal Q 0 cfs, with sluice gates open.

Log Boom 1 (LB1)

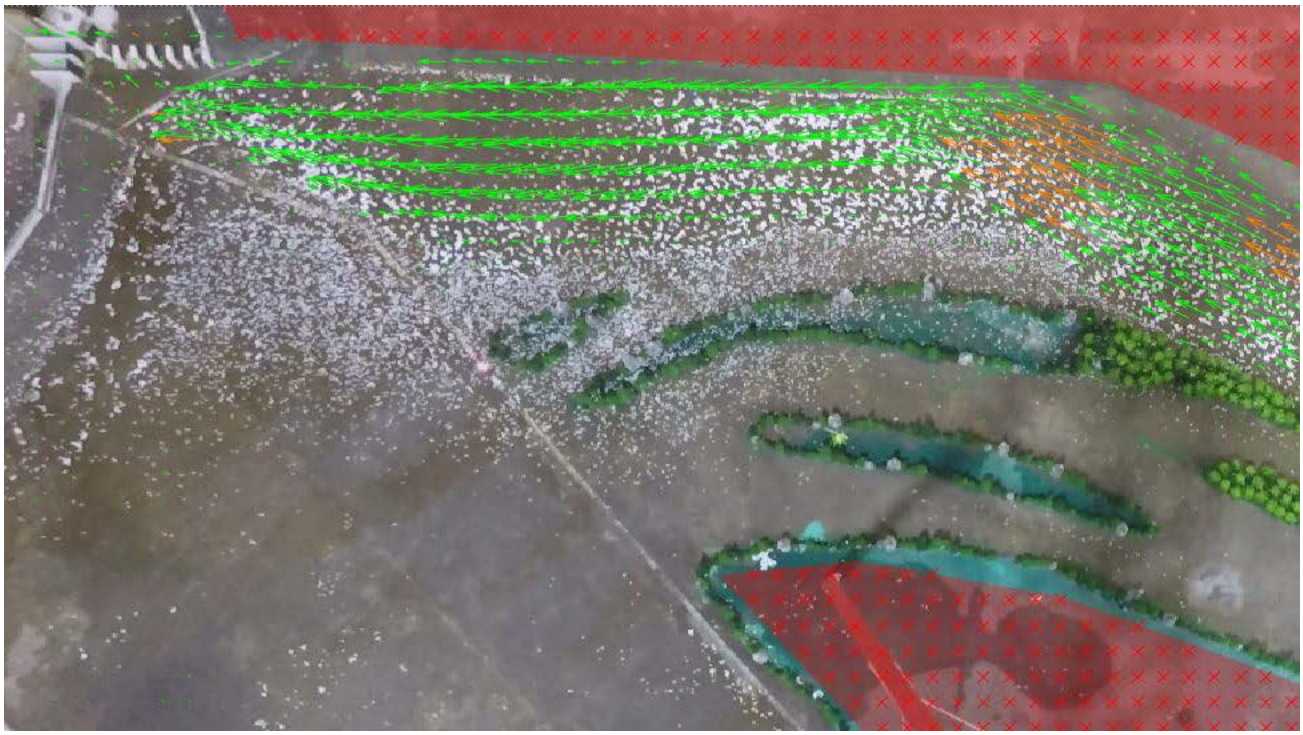

Image of LB1 with LSPIV mean velocity vector at River Q 800 cfs, Dam Q 550 cfs, Canal Q 250 cfs, with sluice gates closed.

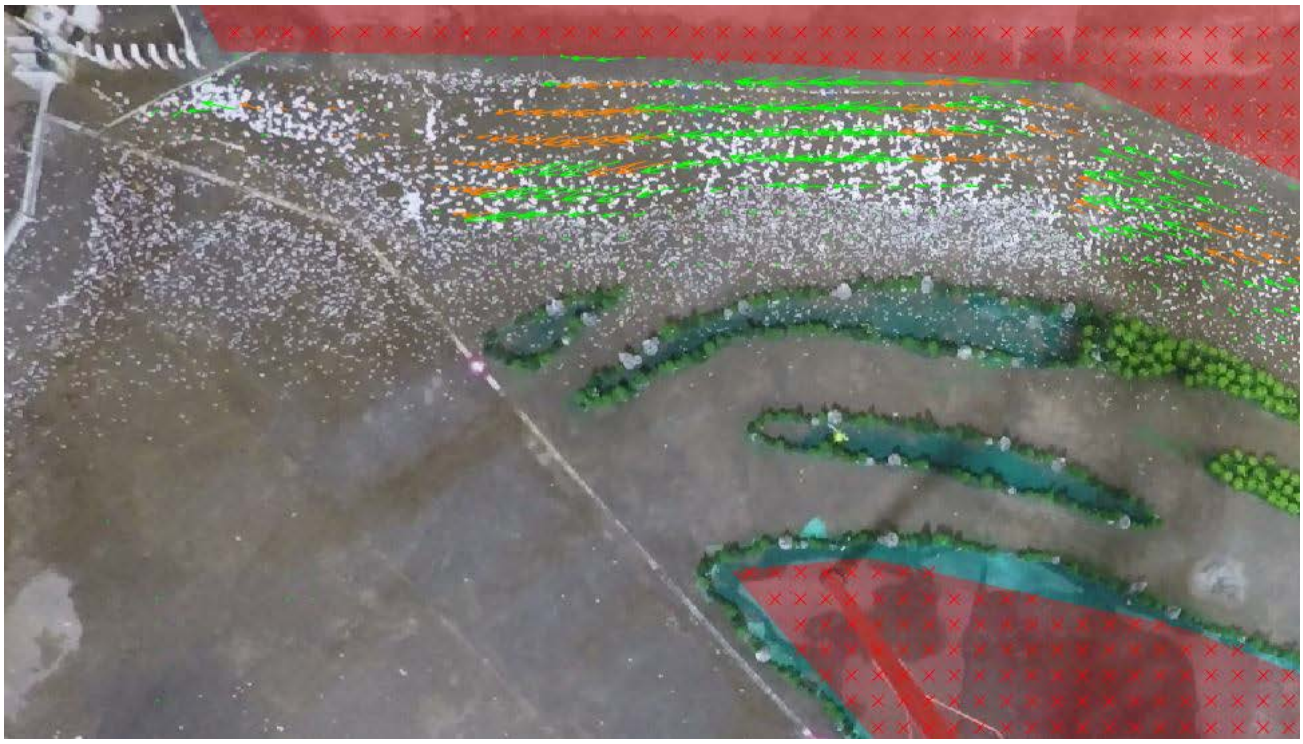

Image of LB1 with LSPIV mean velocity vector at River Q 800 cfs, Dam Q 800 cfs, Canal Q 0 cfs, with sluice gates open.

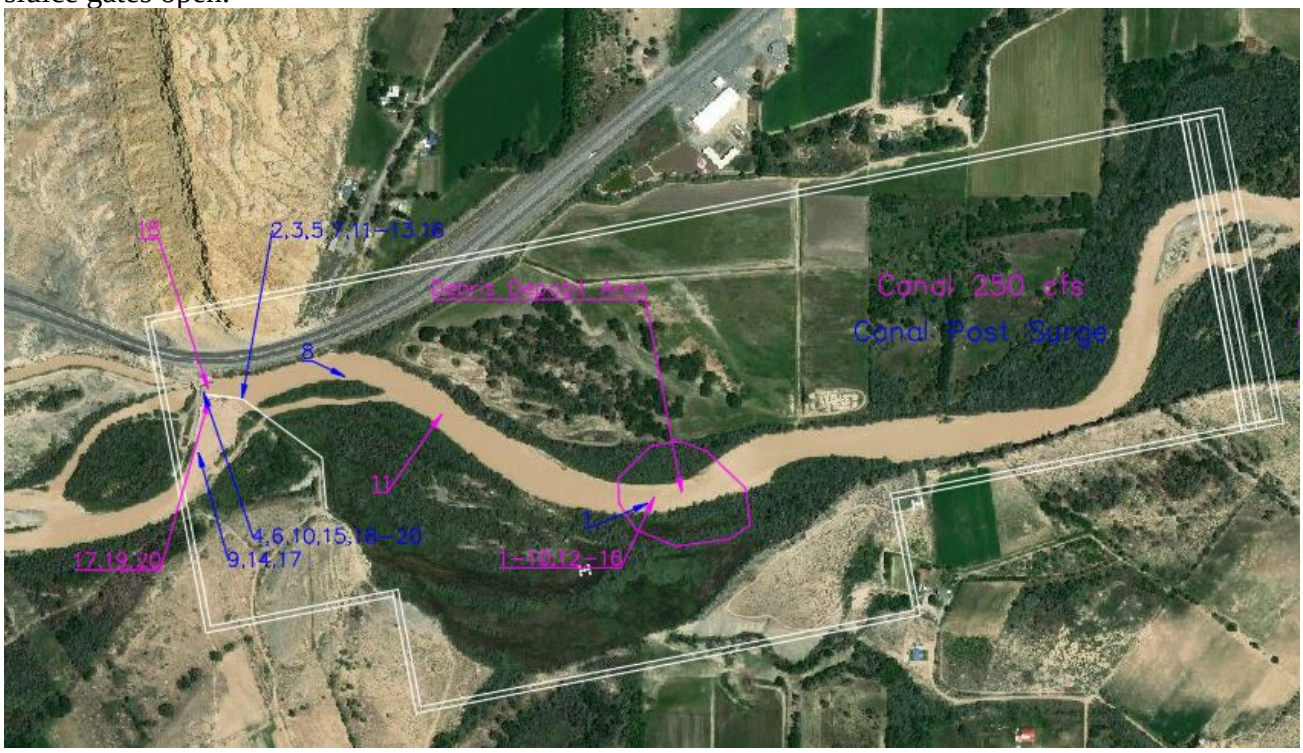

Image of debris capture location of the river modeled at the LB1 condition with River Q 800 cfs and Canal Q 250 cfs, with sluice gates closed.

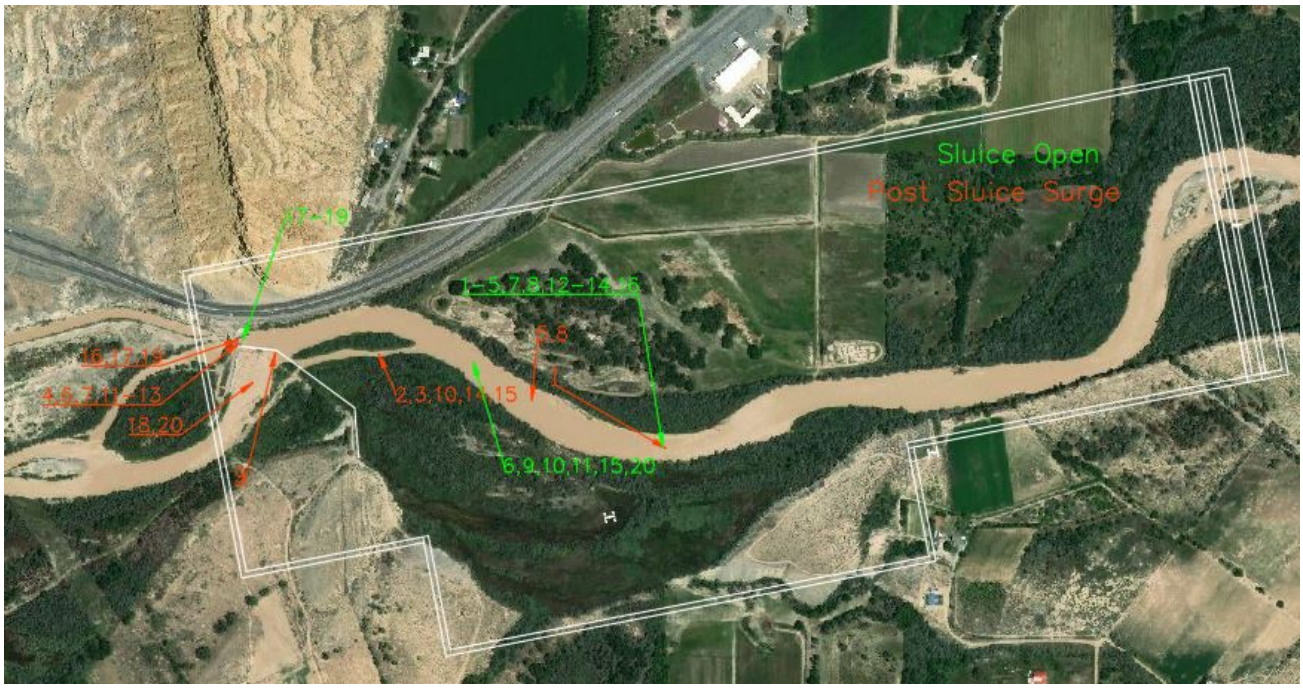

Image of debris capture location of the river modeled at the LB1 condition with River Q 800 cfs and Canal Q 0 cfs, with sluice gates open.

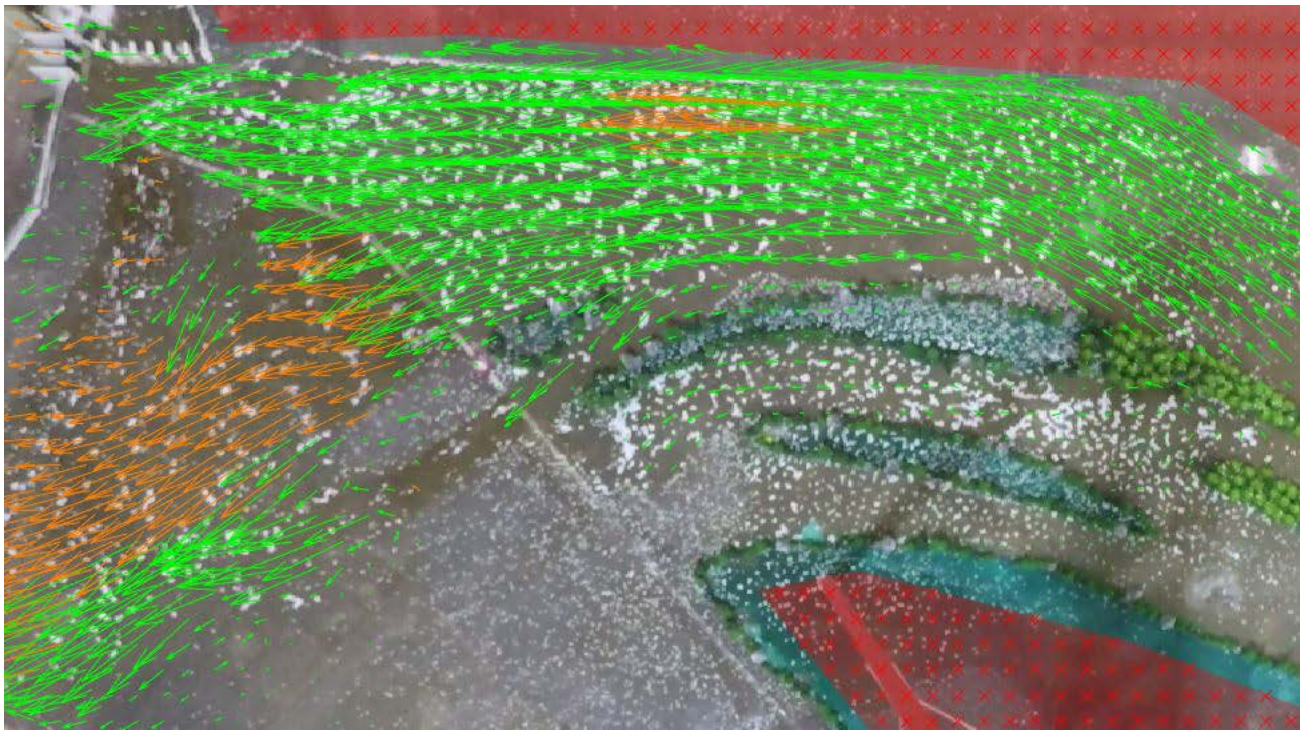

Image of LB1 with LSPIV mean velocity vector at River Q 2,500 cfs, Dam Q 2100 cfs, Canal Q 400 cfs, with sluice gates closed.

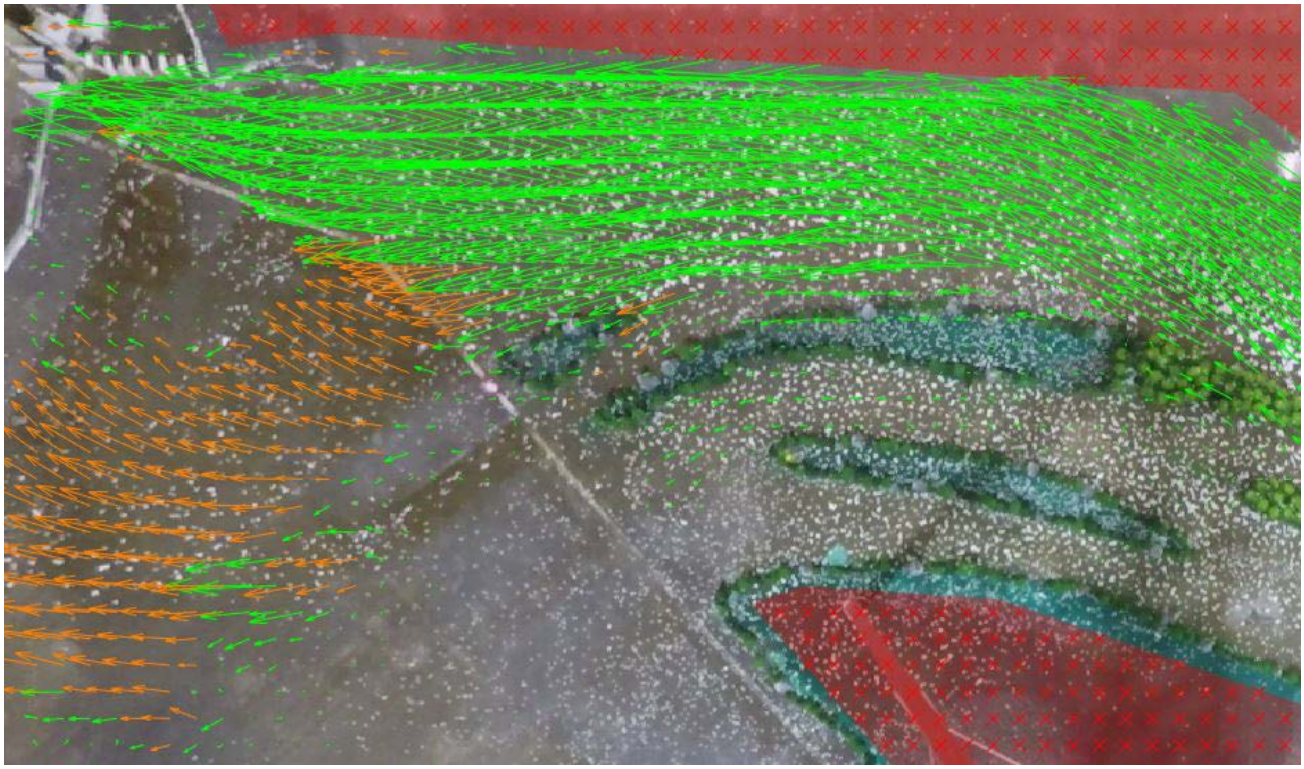

Image of LB1 with LSPIV mean velocity vector at River Q 2,500 cfs, Dam Q 2,500 cfs, Canal Q 0 cfs, with sluice gates open.

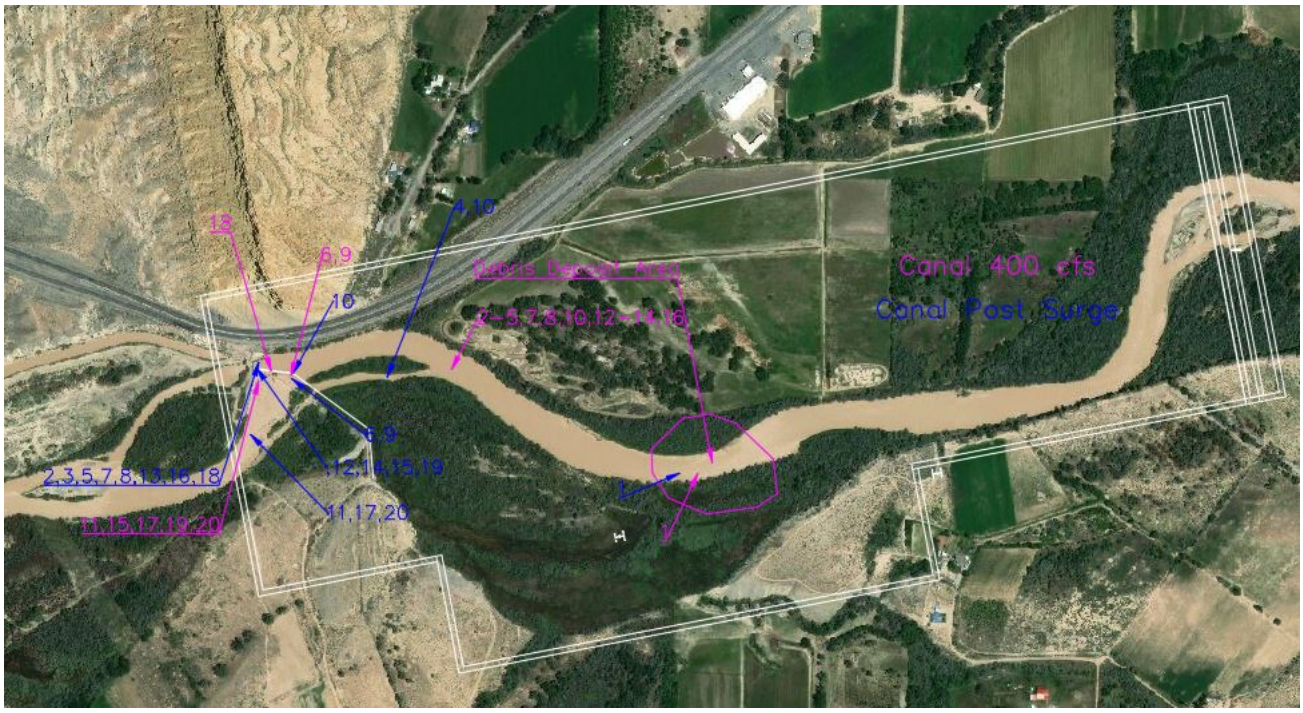

Image of debris capture location of the river modeled at the LB1 condition with River Q 2500 cfs and Canal Q 400 cfs, with sluice gates closed.

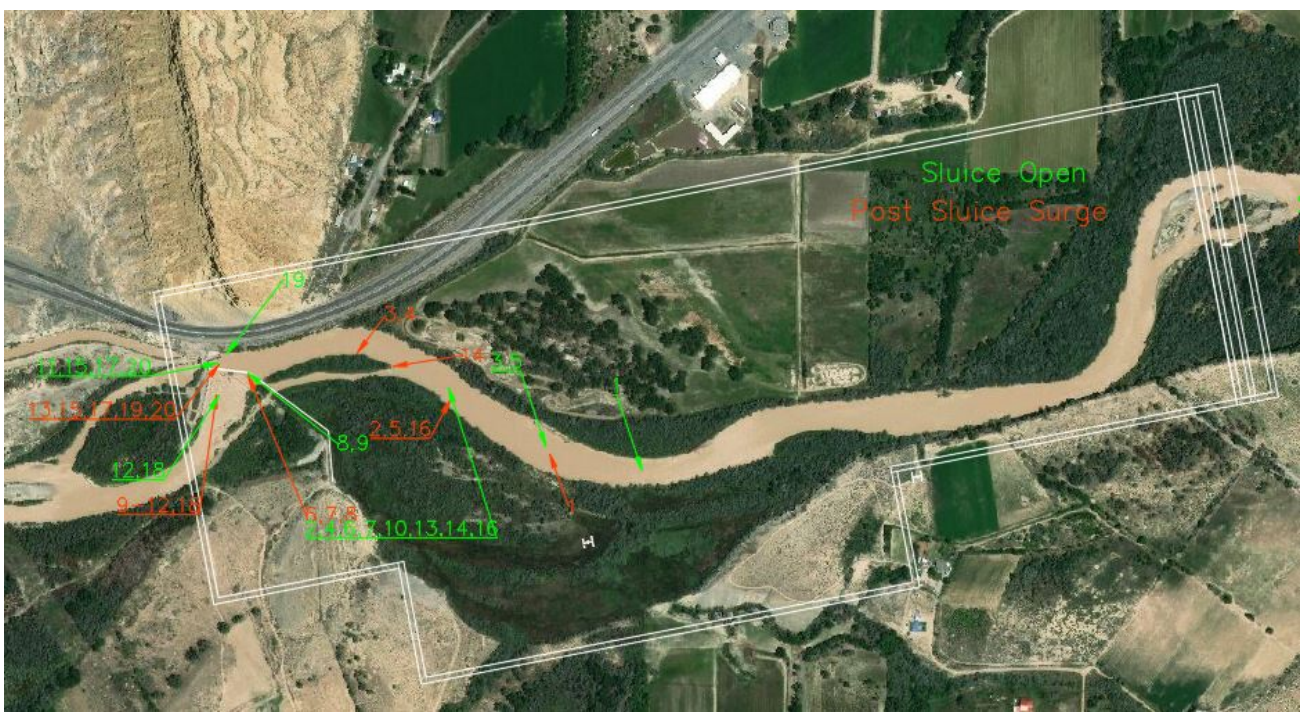

Image of debris capture location of the river modeled at the LB1 condition with River Q 2500 cfs and Canal Q 0 cfs, with sluice gates open.

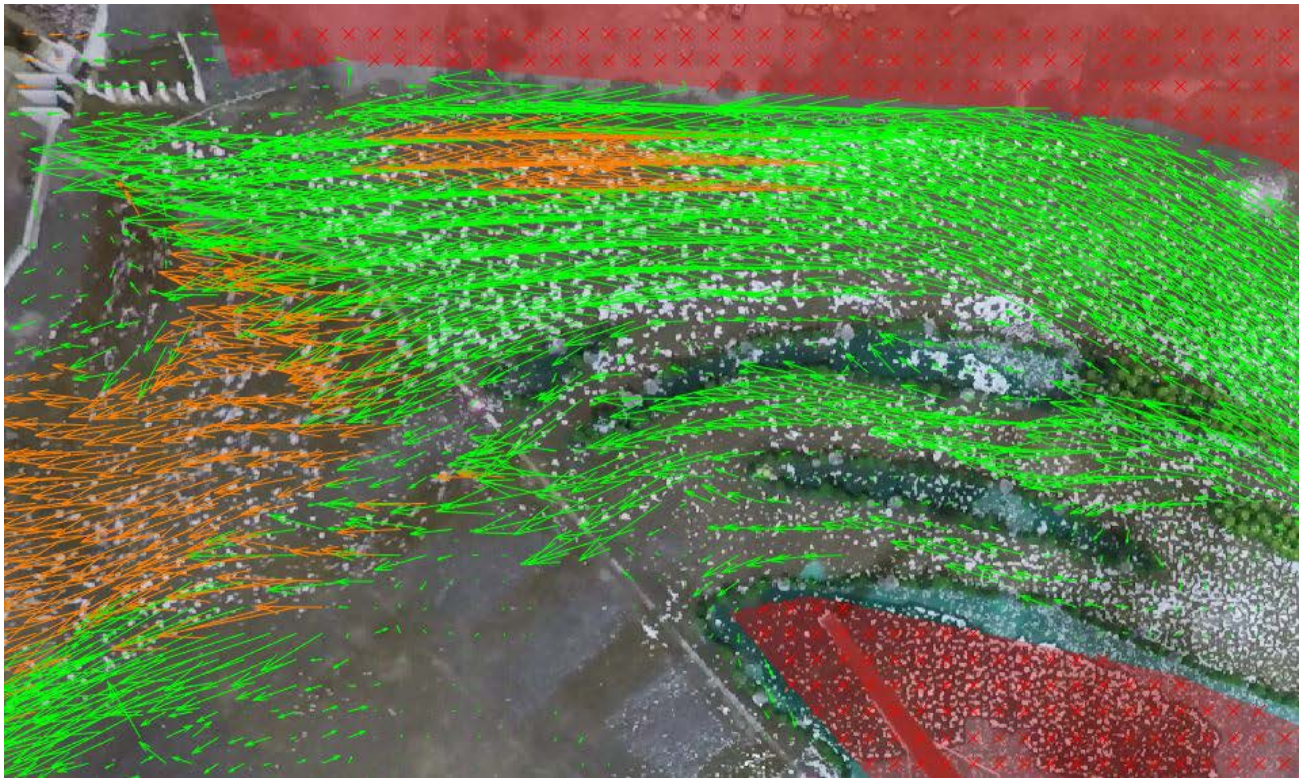

Image of LB1 with LSPIV mean velocity vector at River Q 5,000 cfs, Dam Q 4500 cfs, Canal Q 500 cfs, with sluice gates closed.

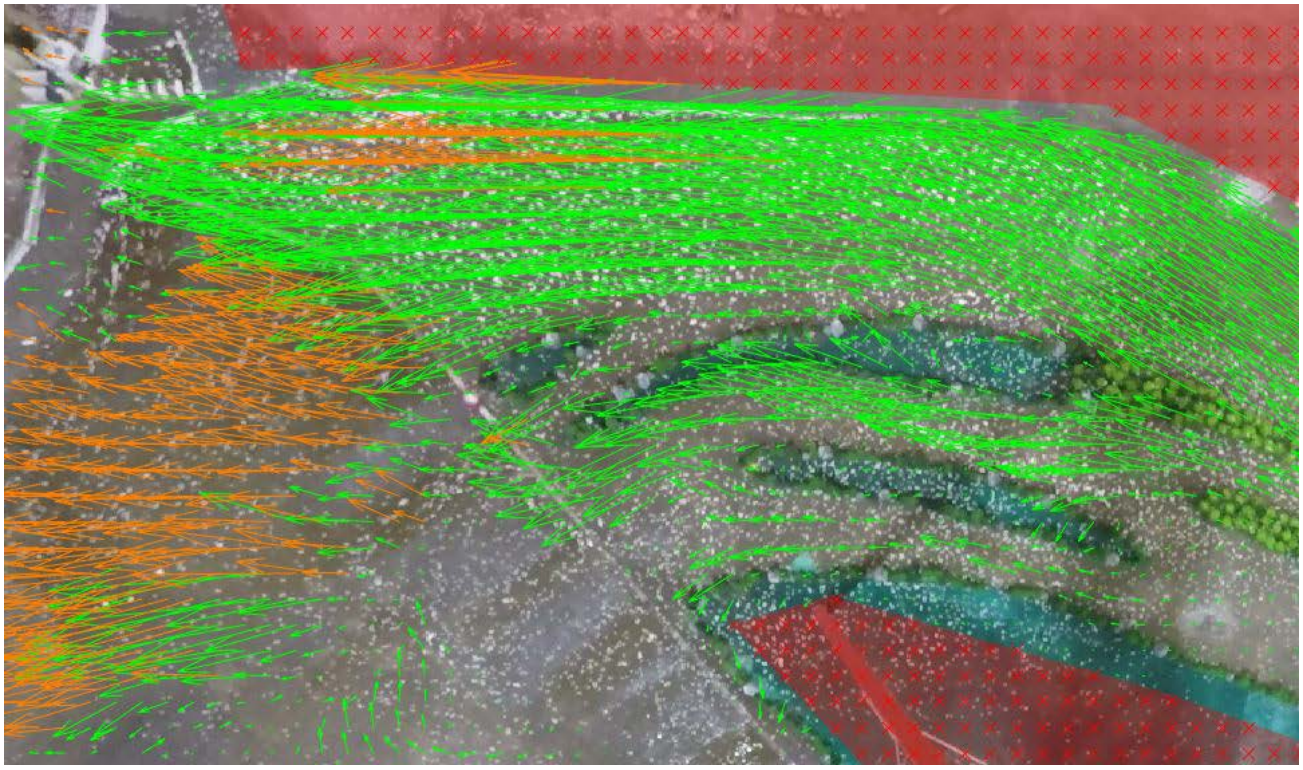

Image of LB1with LSPIV mean velocity vector at River Q 5,000 cfs, Dam Q 5,000 cfs, Canal Q 0 cfs, with sluice gates open.

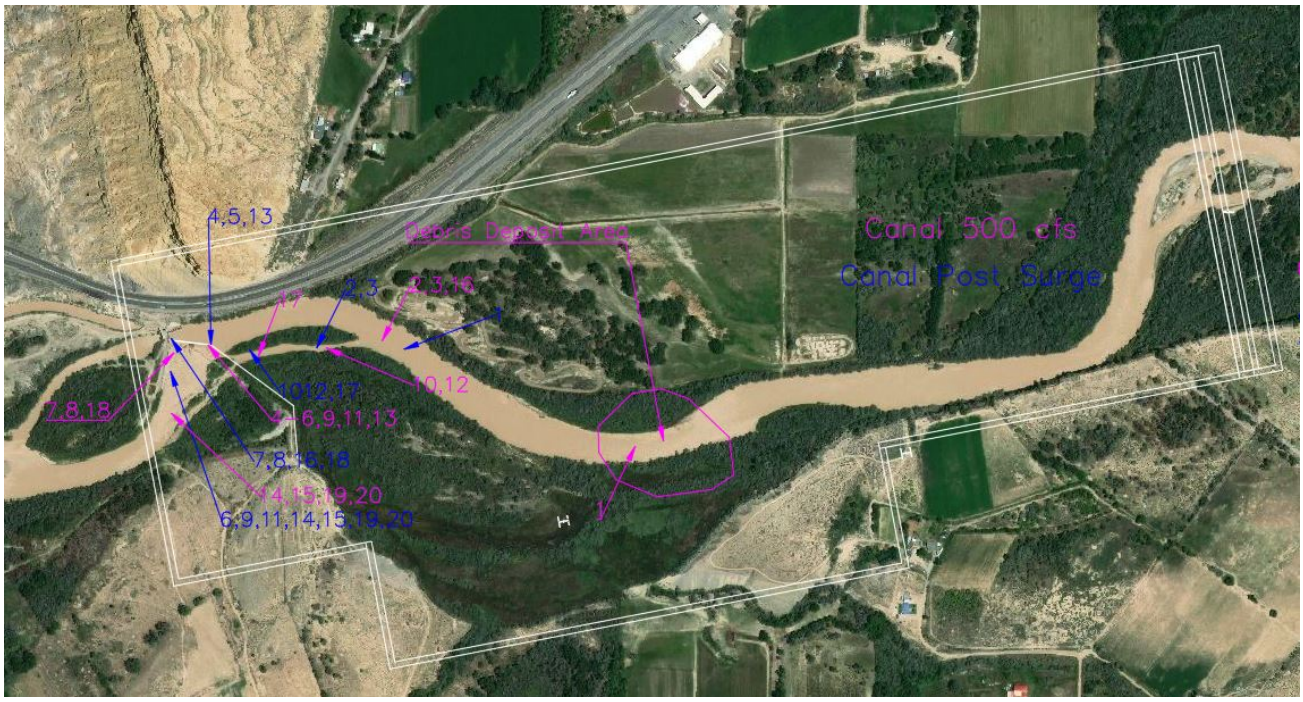

Image of debris capture location of the river modeled at the LB1 condition with River Q 5000 cfs and Canal Q 500 cfs, with sluice gates closed.

Image of debris capture location of the river modeled at the LB1 condition with River Q 5000 cfs and Canal Q 0 cfs, with sluice gates open.

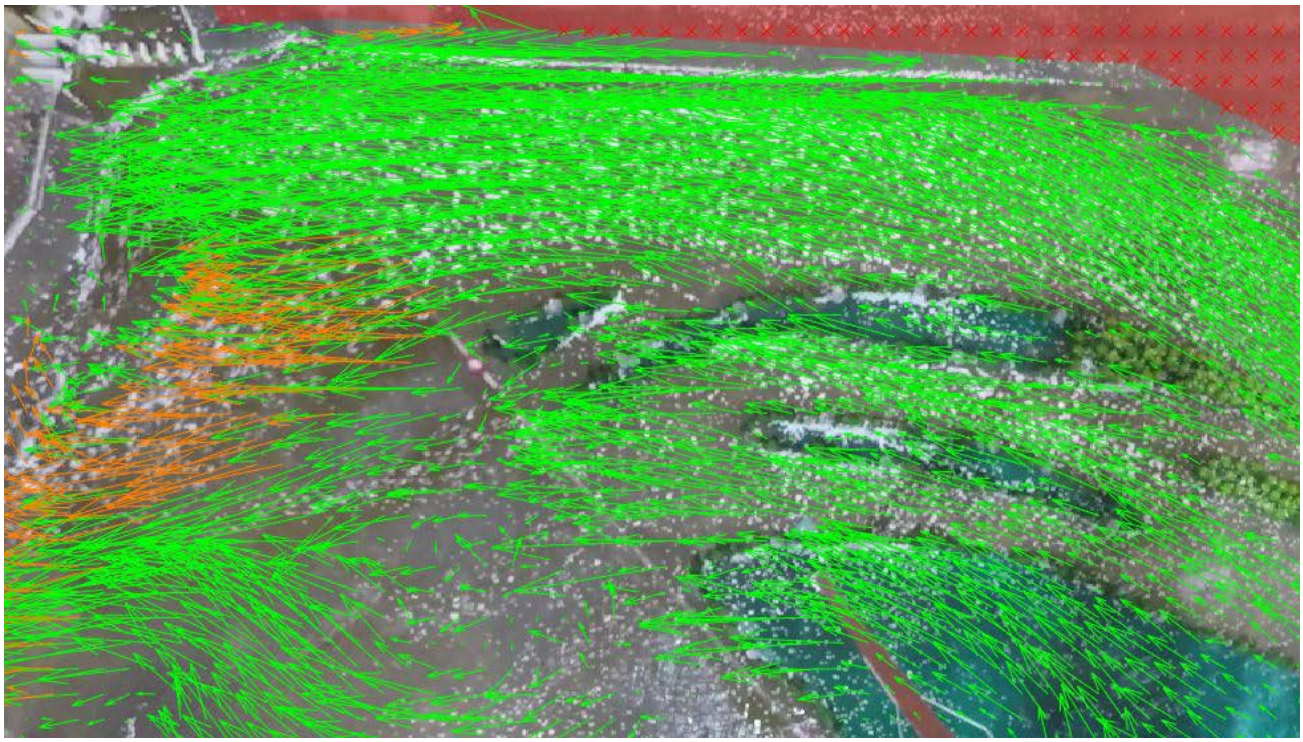

Image of LB1 with LSPIV mean velocity vector at River Q 12,000 cfs, Dam Q 11400 cfs, Canal Q 600 cfs, with sluice gates closed.

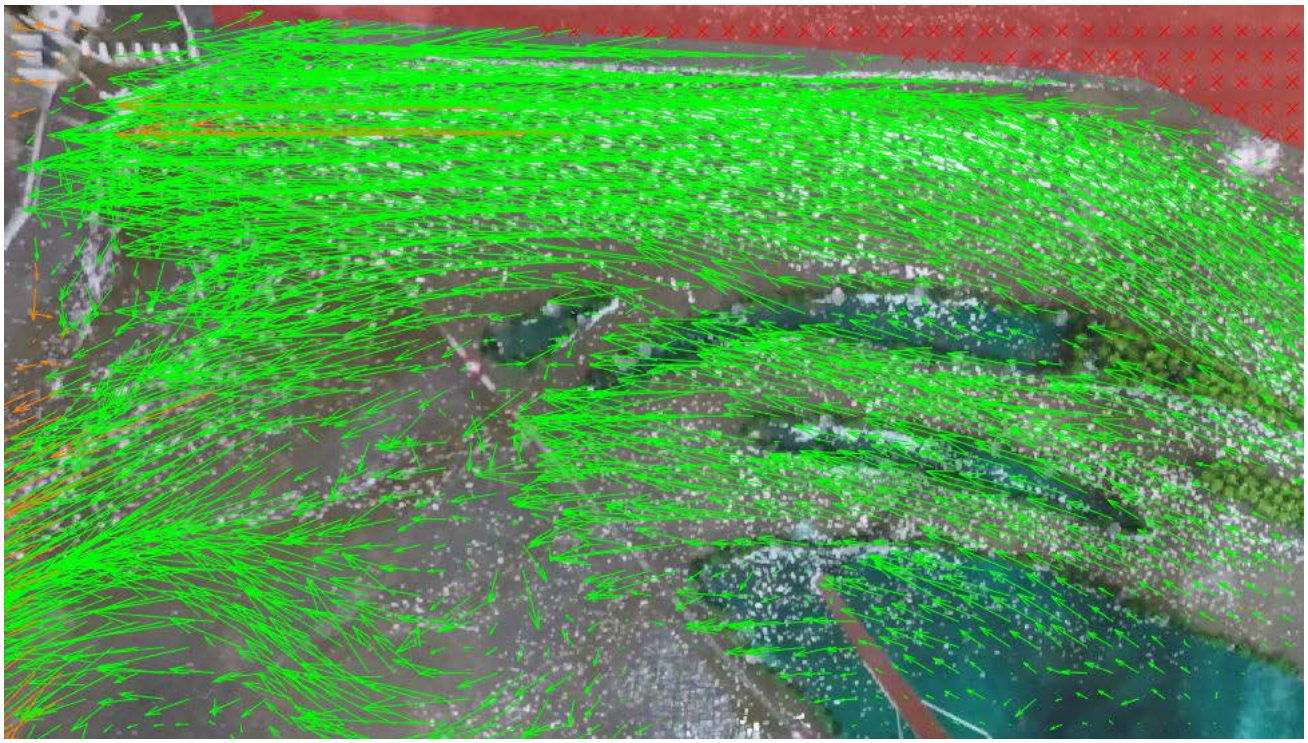

Image of LB1 with LSPIV mean velocity vector at River Q 12,000 cfs, Dam Q 12,000 cfs, Canal Q 0 cfs, with sluice gates open.

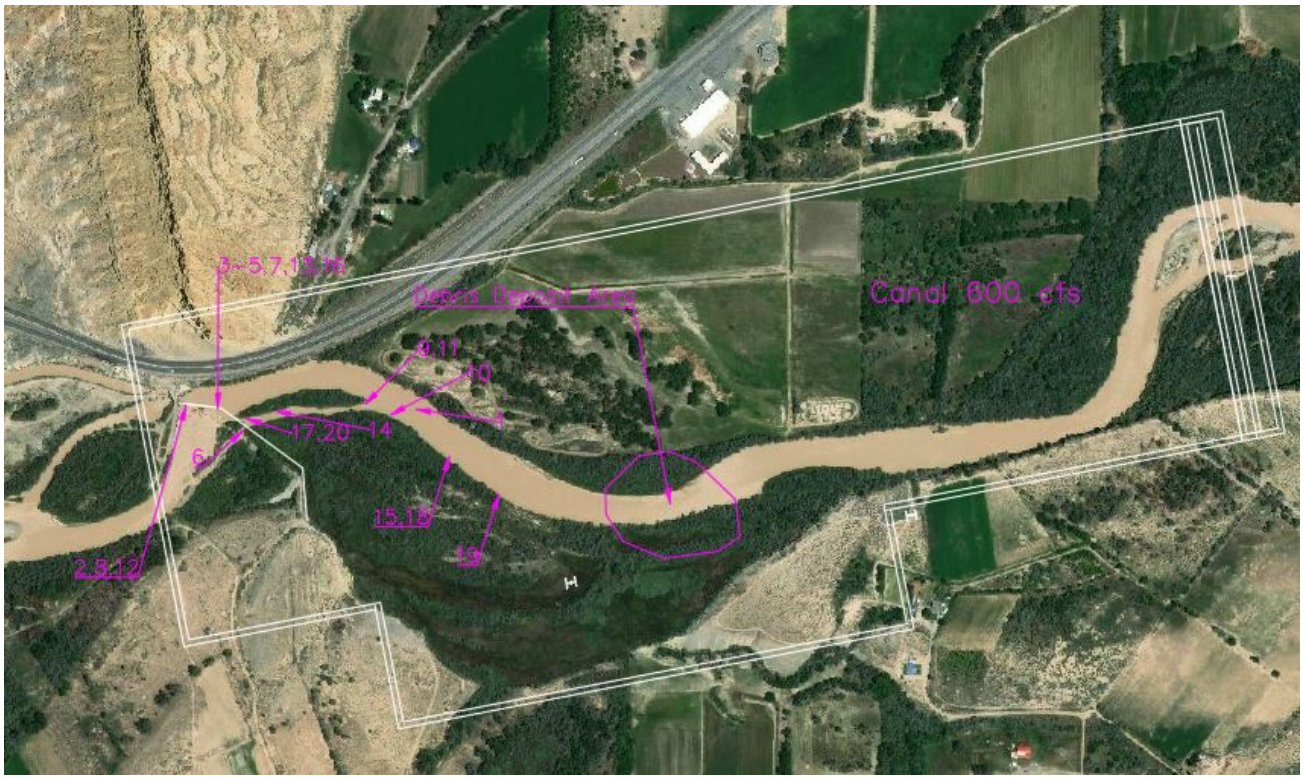

Image of debris capture location of the river modeled at the LB1 condition with River Q 12000 cfs and Canal Q 600 cfs, with sluice gates closed.

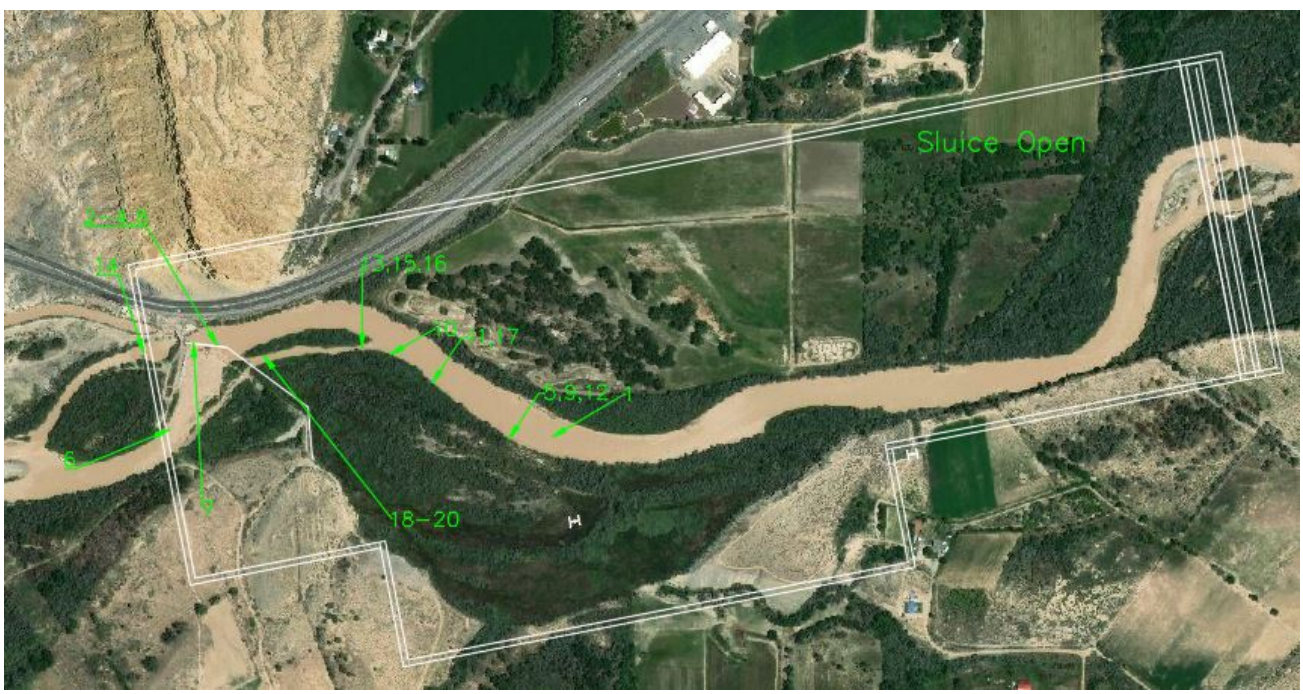

Image of debris capture location of the river modeled at the LB1 condition with River Q 12000 cfs and Canal Q 0 cfs, with sluice gates open.

Rock Structure 3 (RS3)

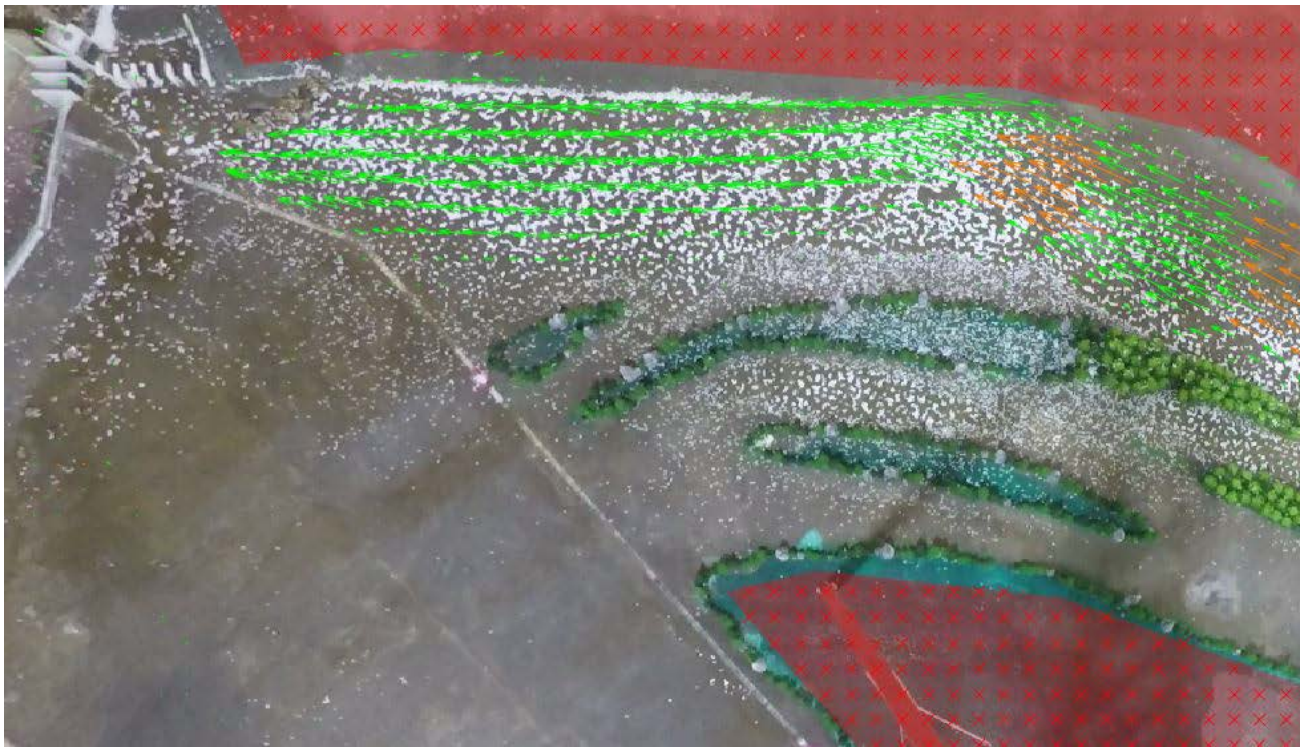

Image of RS3 with LSPIV mean velocity vector at River Q 800 cfs, Dam Q 600 cfs, Canal Q 200 cfs, with sluice gates closed.

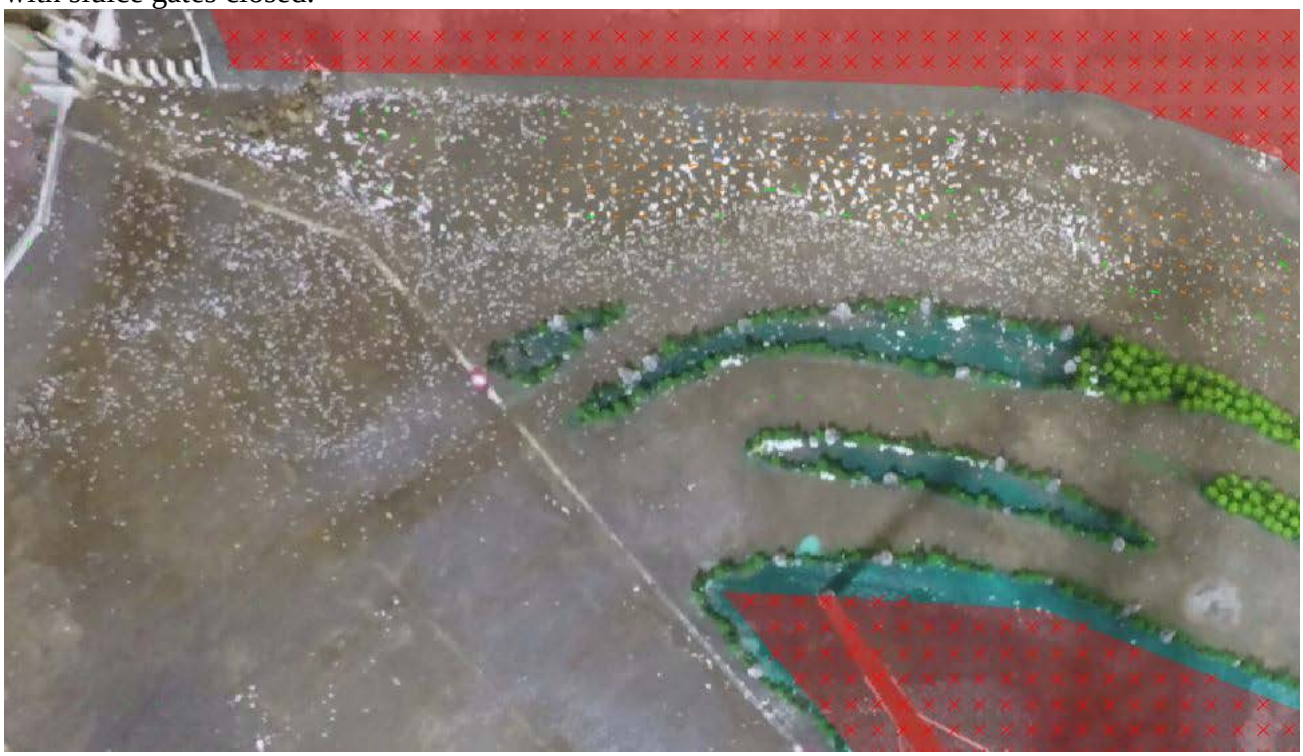

Image of RS3 with LSPIV mean velocity vector at River Q 800 cfs, Dam Q 800 cfs, Canal Q 0 cfs, with sluice gates open.

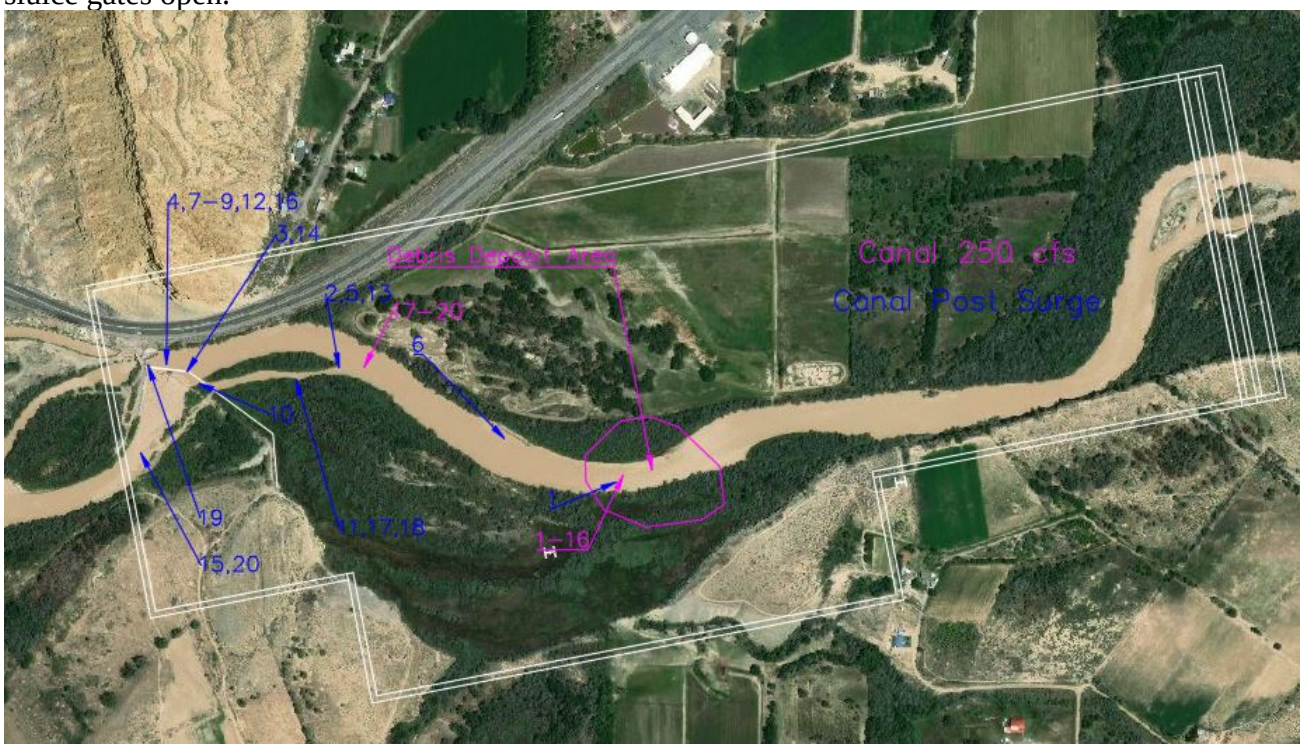

Image of debris capture location of the river modeled at the RS3 condition with River Q 800 cfs and Canal Q 250 cfs, with sluice gates closed.

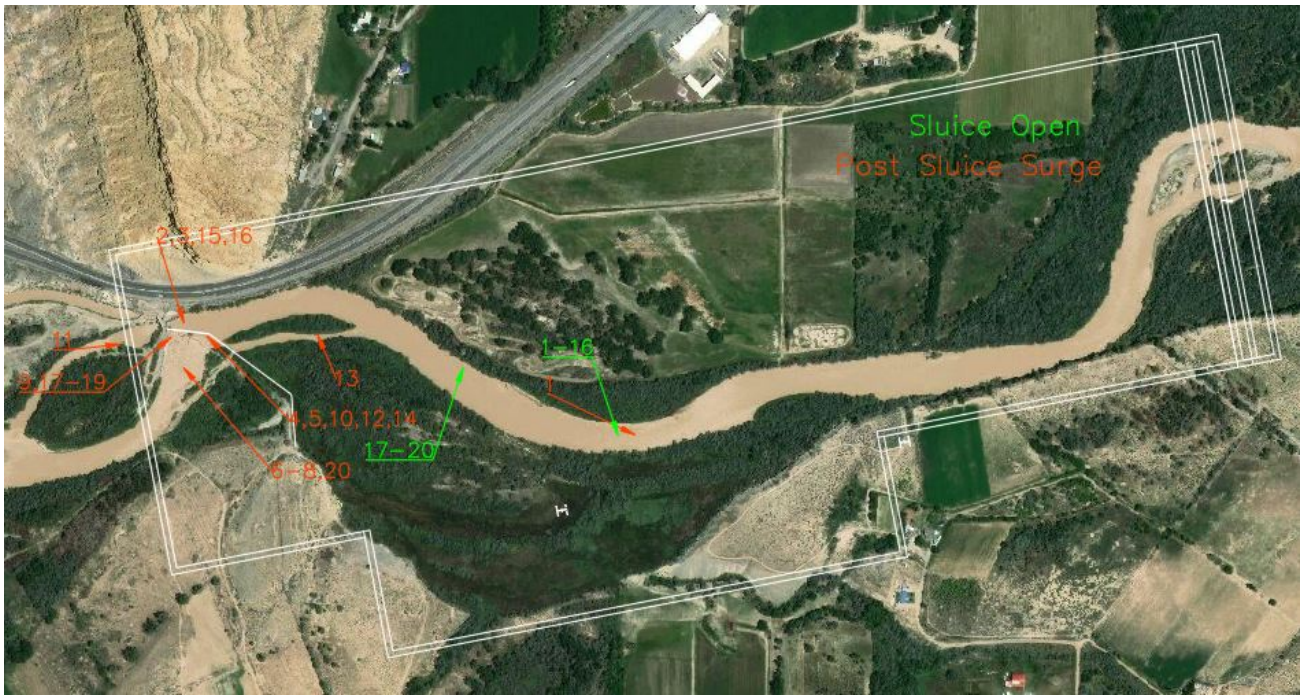

Image of debris capture location of the river modeled at the RS3 condition with River Q 800 cfs and Canal Q 0 cfs, with sluice gates open.

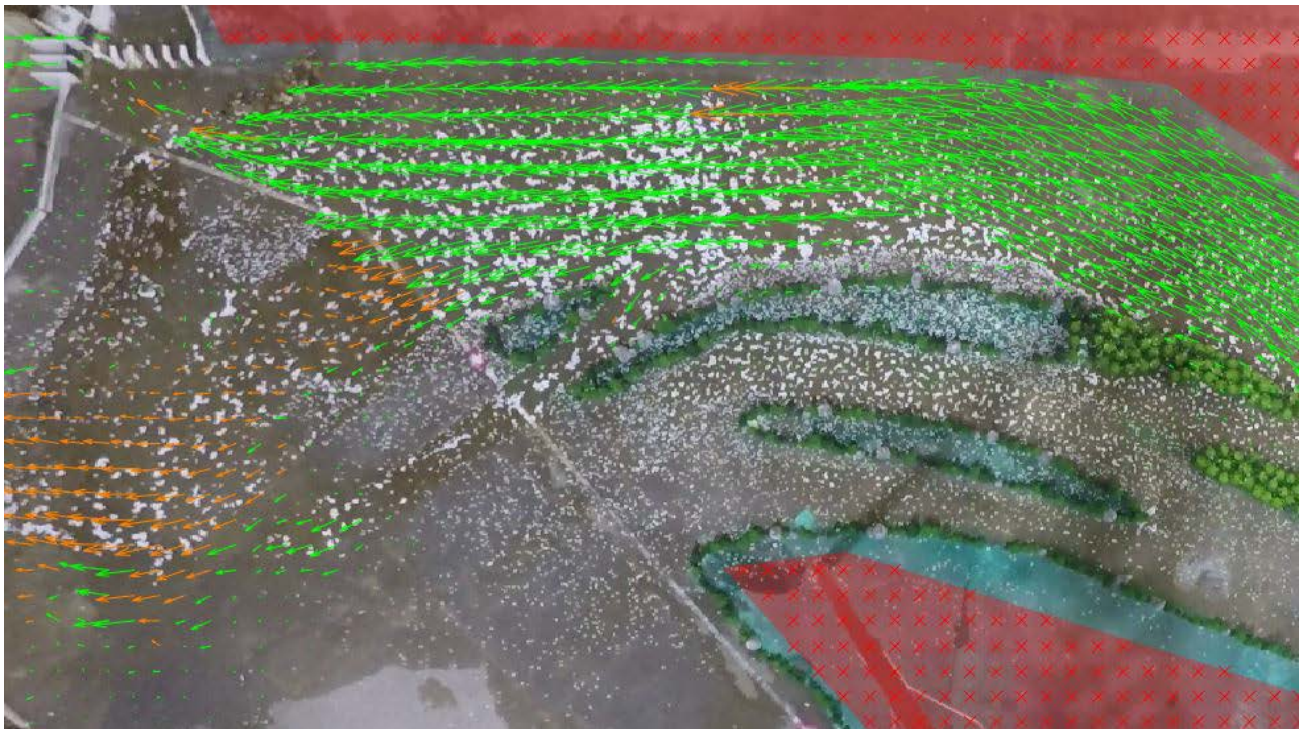

Image of RS3 with LSPIV mean velocity vector at River Q 2,500 cfs, Dam Q 2100 cfs, Canal Q 400 cfs, with sluice gates closed.

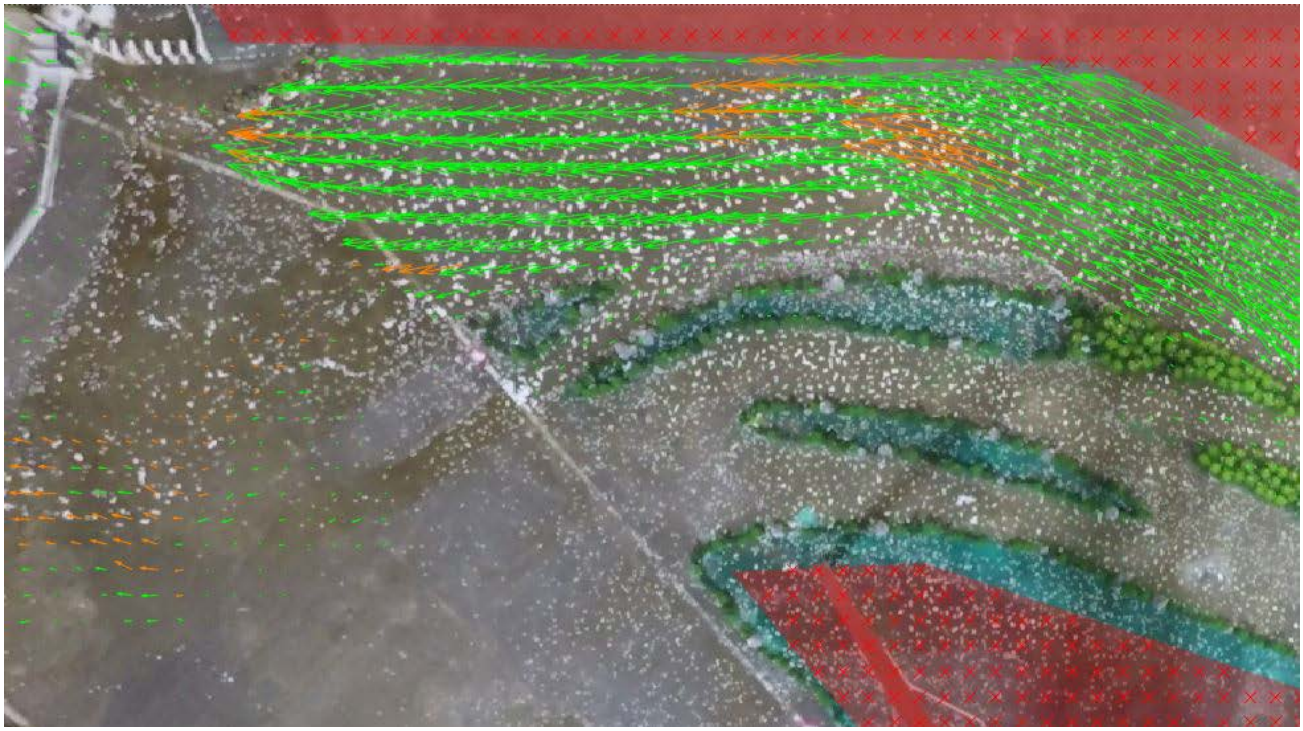

Image of RS3 with LSPIV mean velocity vector at River Q 2,500 cfs, Dam Q 2,500 cfs, Canal Q 0 cfs, with sluice gates open.

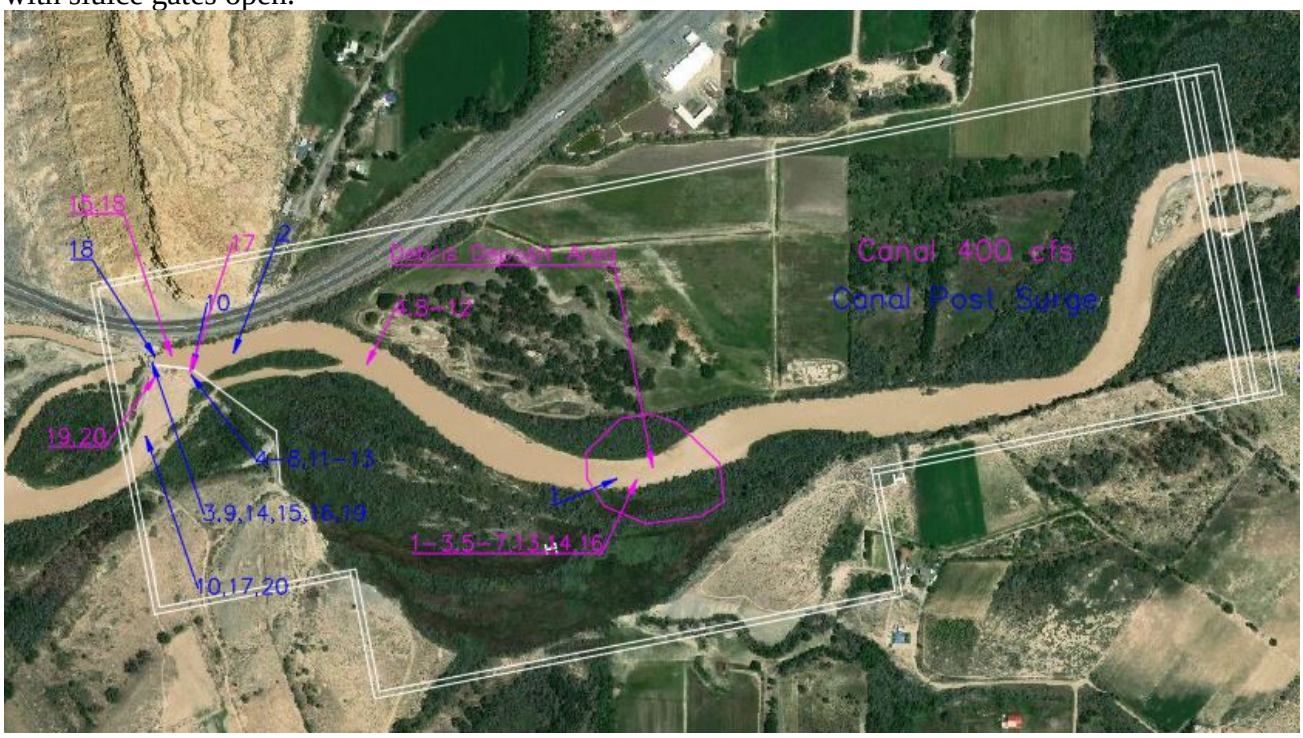

Image of debris capture location of the river modeled at the RS3 condition with River Q 2500 cfs and Canal Q 400 cfs, with sluice gates closed.

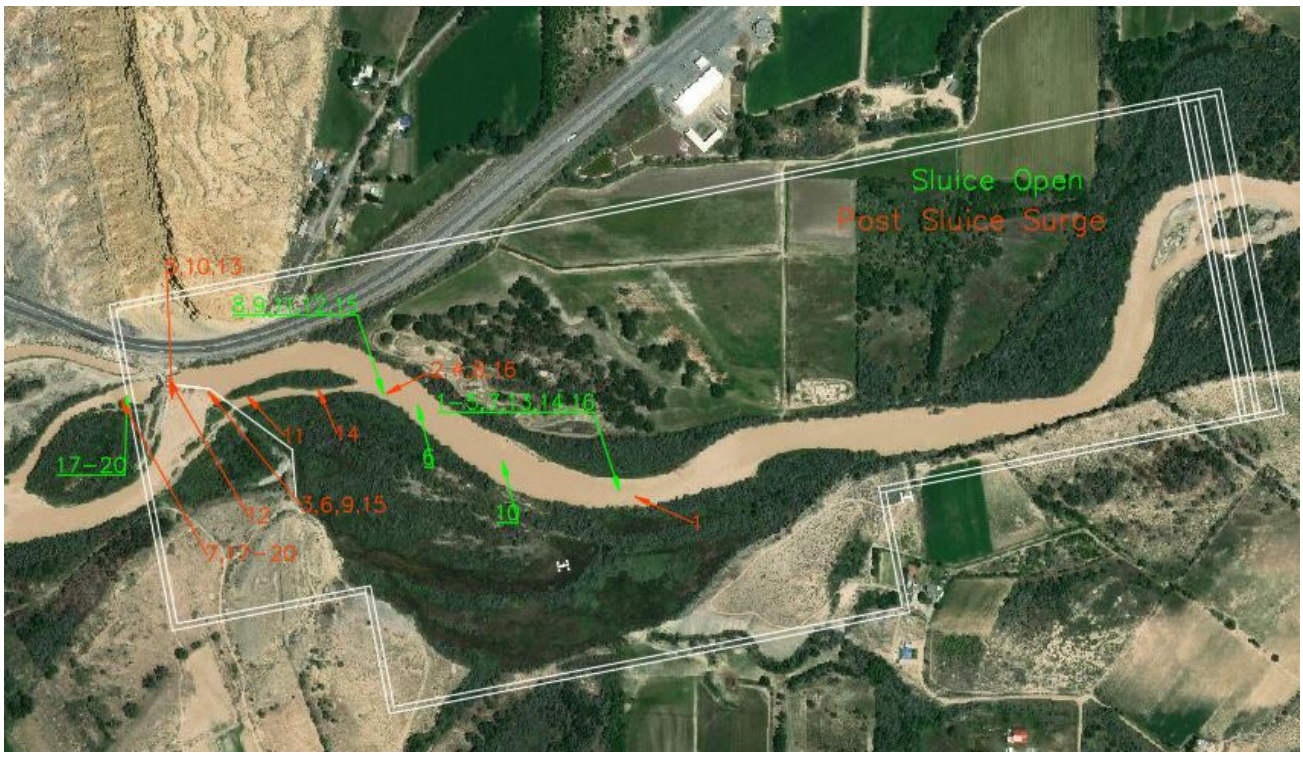

Image of debris capture location of the river modeled at the RS3 condition with River Q 2500 cfs and Canal Q 0 cfs, with sluice gates open.

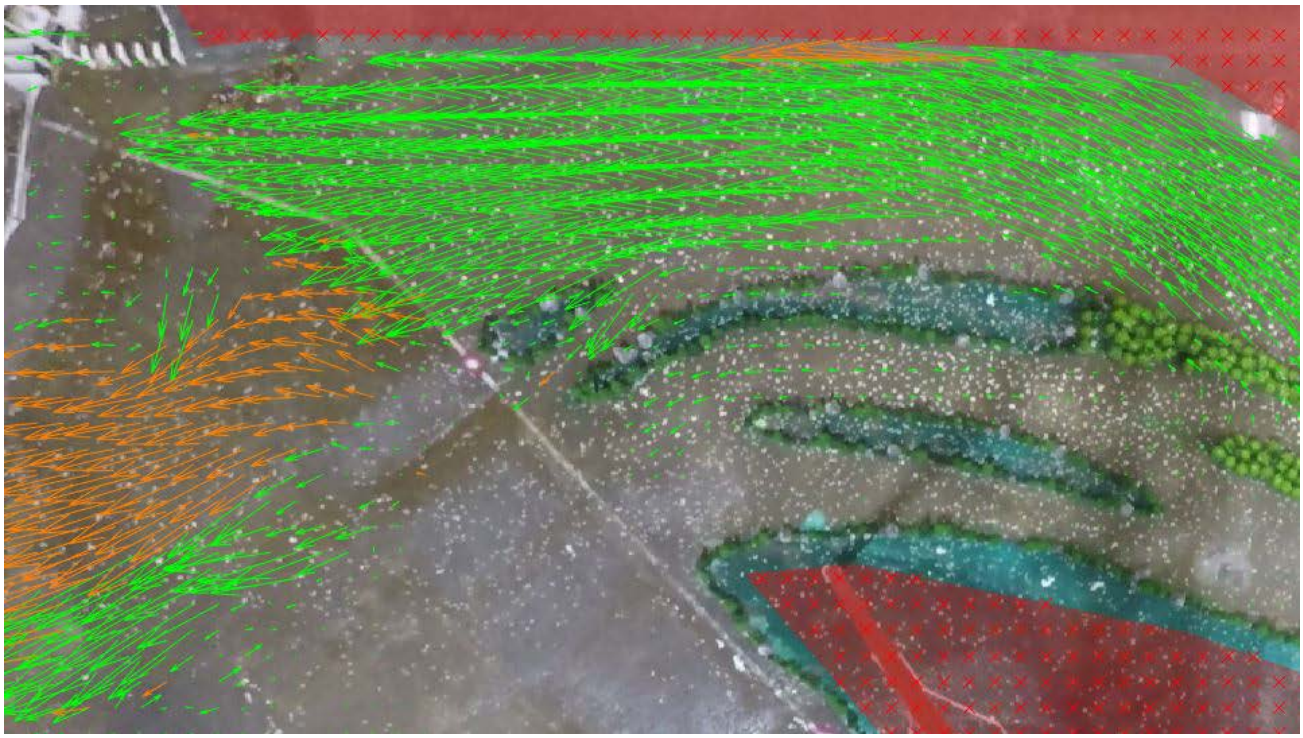

Image of RS3 with LSPIV mean velocity vector at River Q 5,000 cfs, Dam Q 4500 cfs, Canal Q 500 cfs, with sluice gates closed.

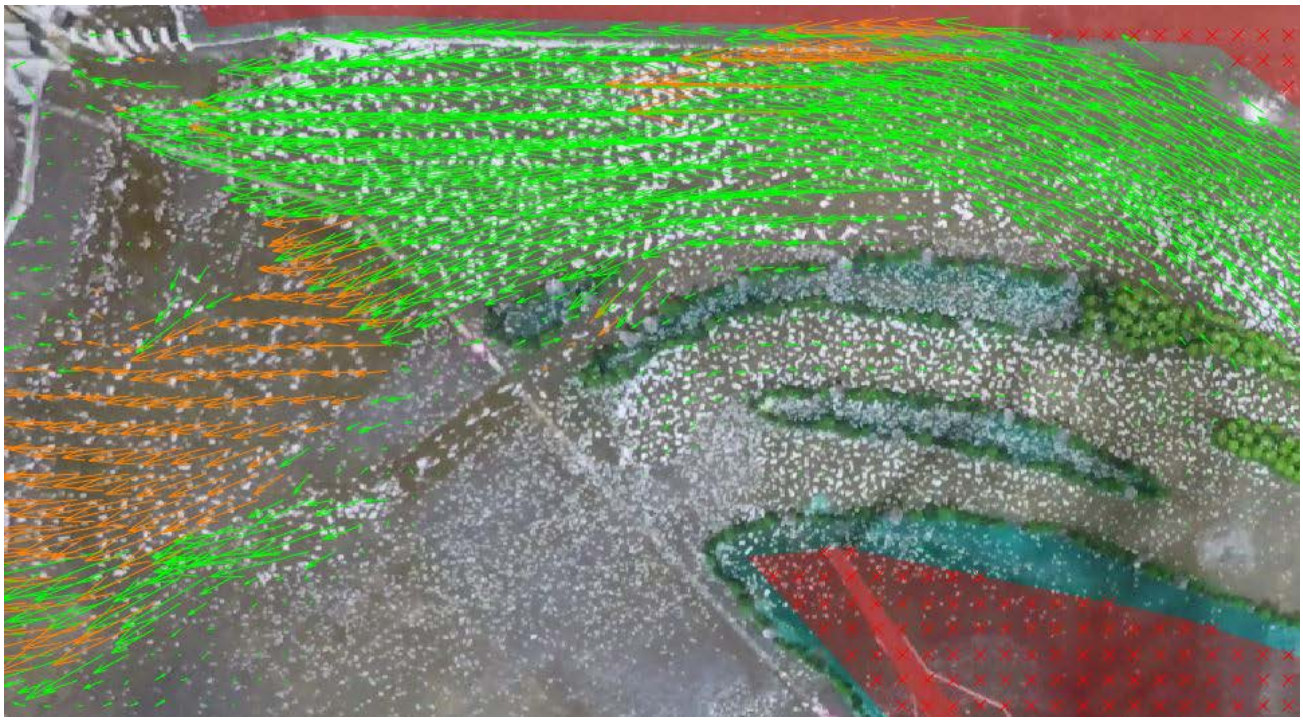

Image of RS3 with LSPIV mean velocity vector at River Q 5,000 cfs, Dam Q 5,000 cfs, Canal Q 0 cfs, with sluice gates open.

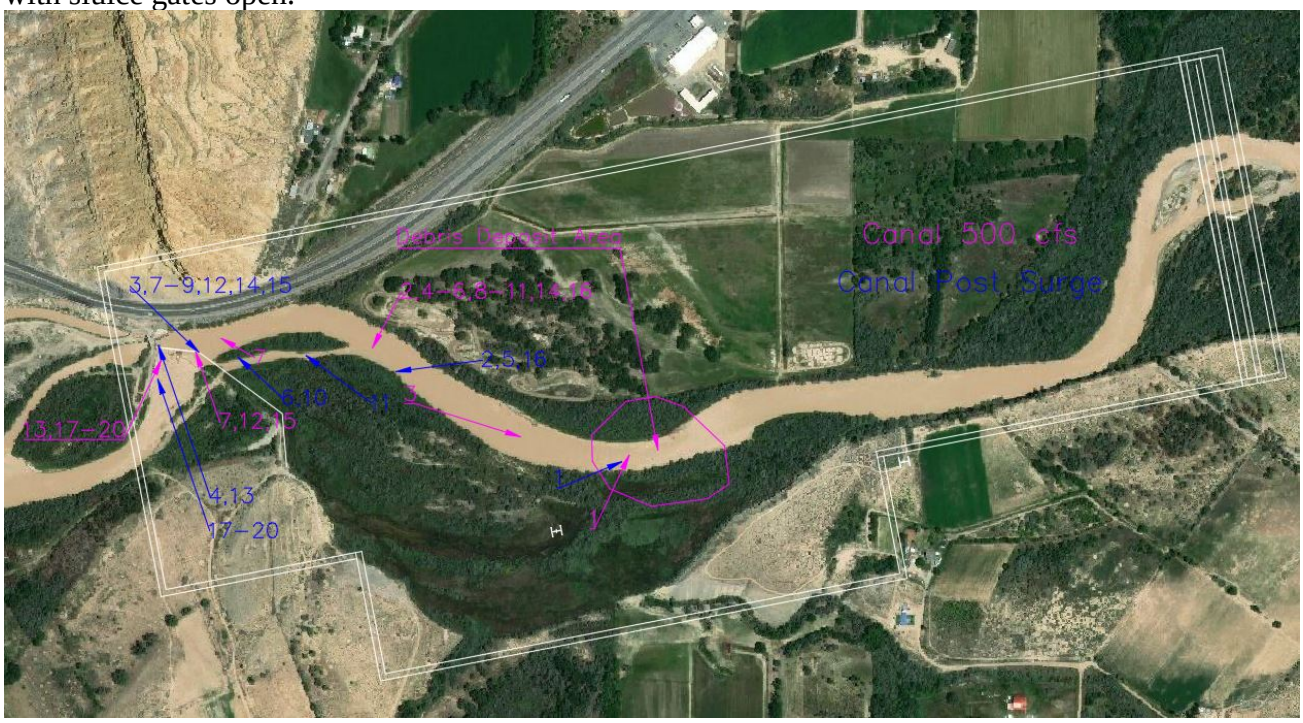

Image of debris capture location of the river modeled at the RS3 condition with River Q 5000 cfs and Canal Q 500 cfs, with sluice gates closed.

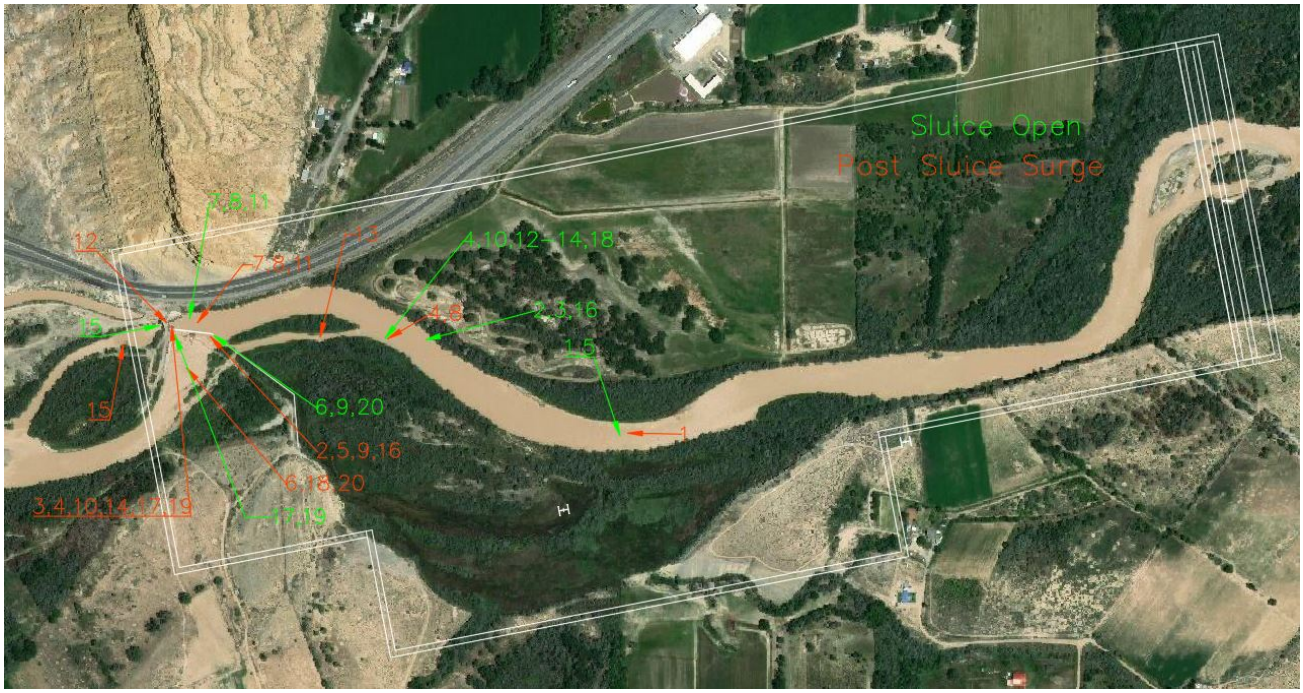

Image of debris capture location of the river modeled at the RS3 condition with River Q 5000 cfs and Canal Q 0 cfs, with sluice gates open.

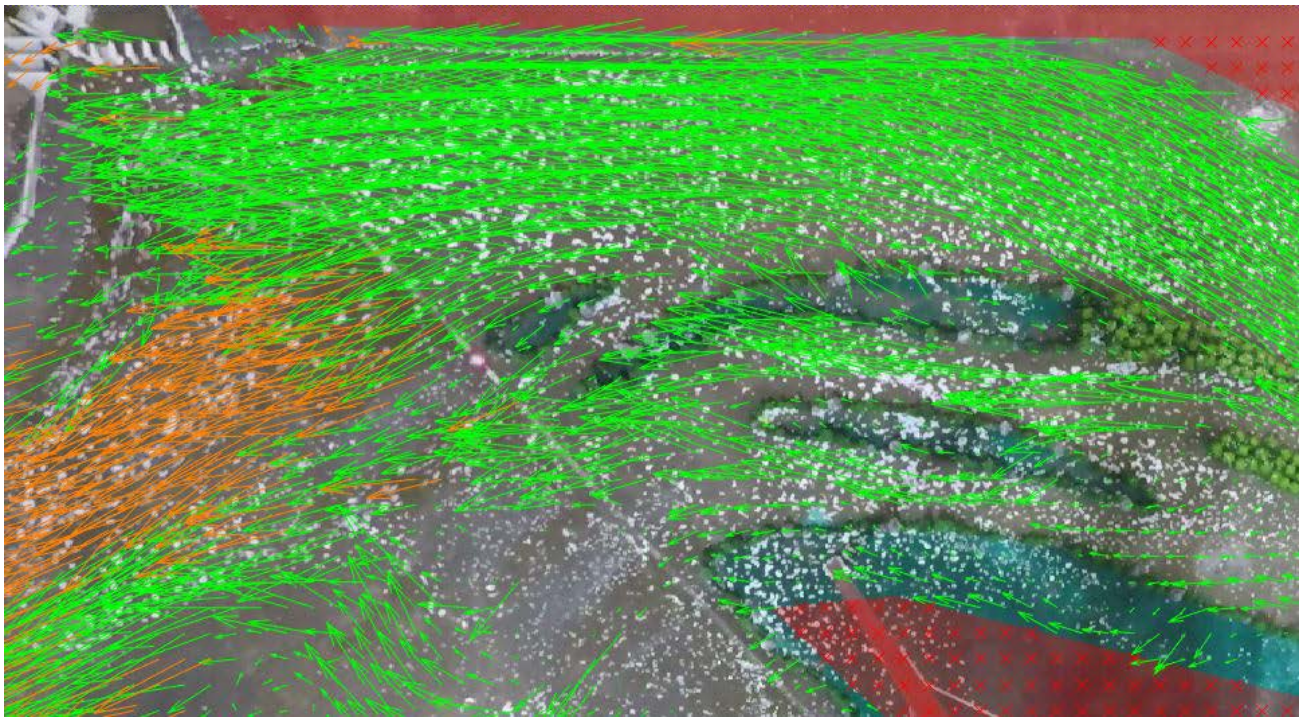

Image of RS3 with LSPIV mean velocity vector at River Q 12,000 cfs, Dam Q 11400 cfs, Canal Q 600 cfs, with sluice gates closed.

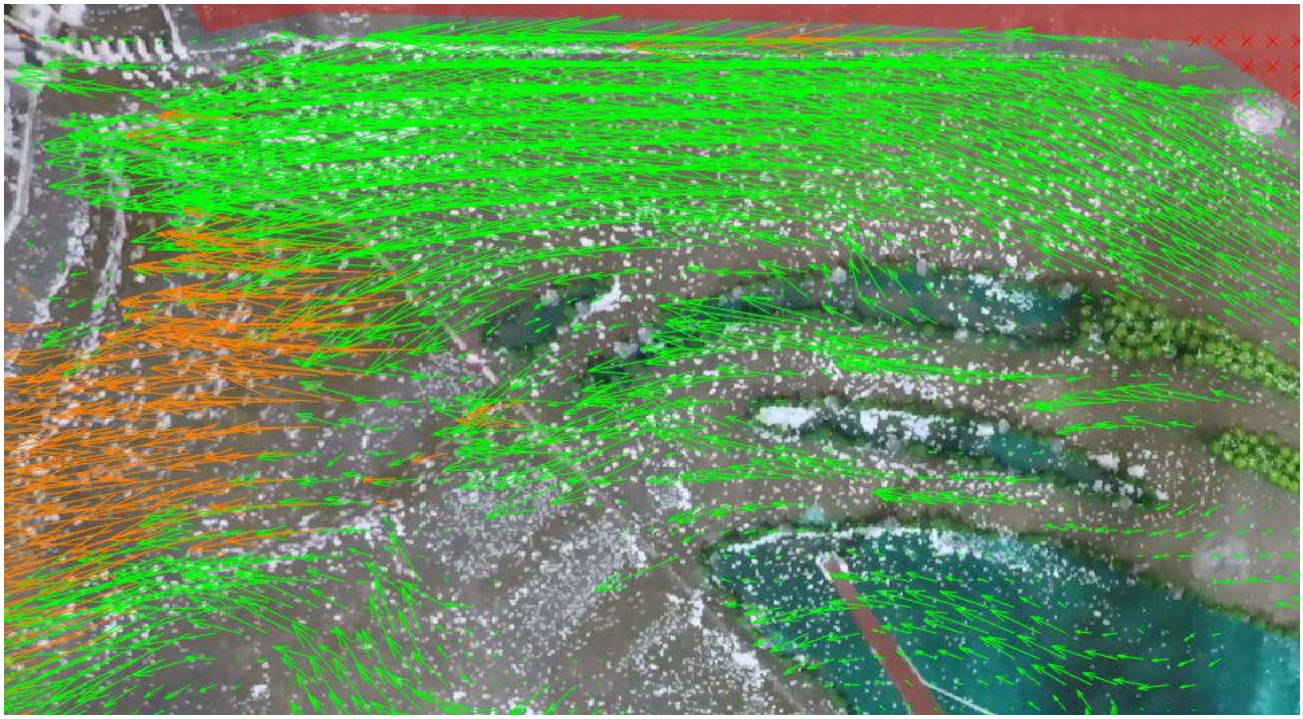

Image of RS3 with LSPIV mean velocity vector at River Q 12,000 cfs, Dam Q 12,000 cfs, Canal Q 0 cfs, with sluice gates open.

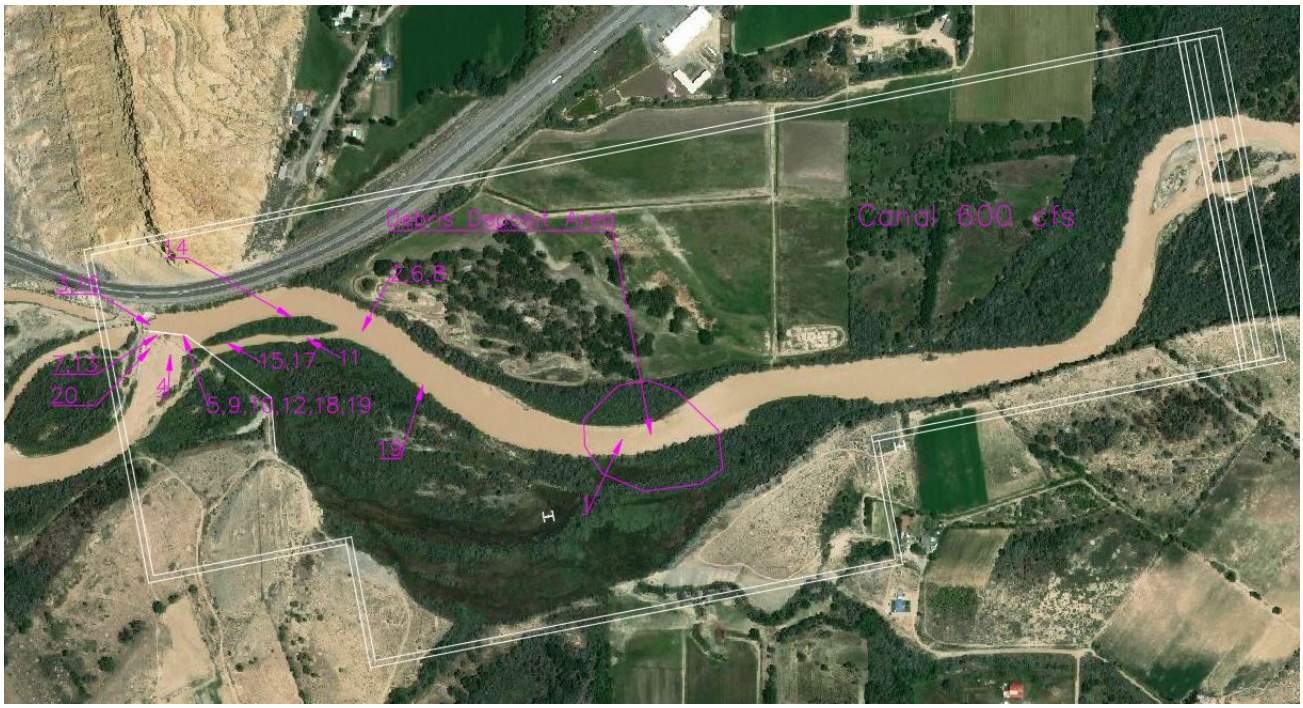

Image of debris capture location of the river modeled at the RS3 condition with River Q 12000 cfs and Canal Q 600 cfs, with sluice gates closed.

Image of debris capture location of the river modeled at the RS3 condition with River Q 12000 cfs and Canal Q 0 cfs, with sluice gates open.

Log Boom 2 (LB2)

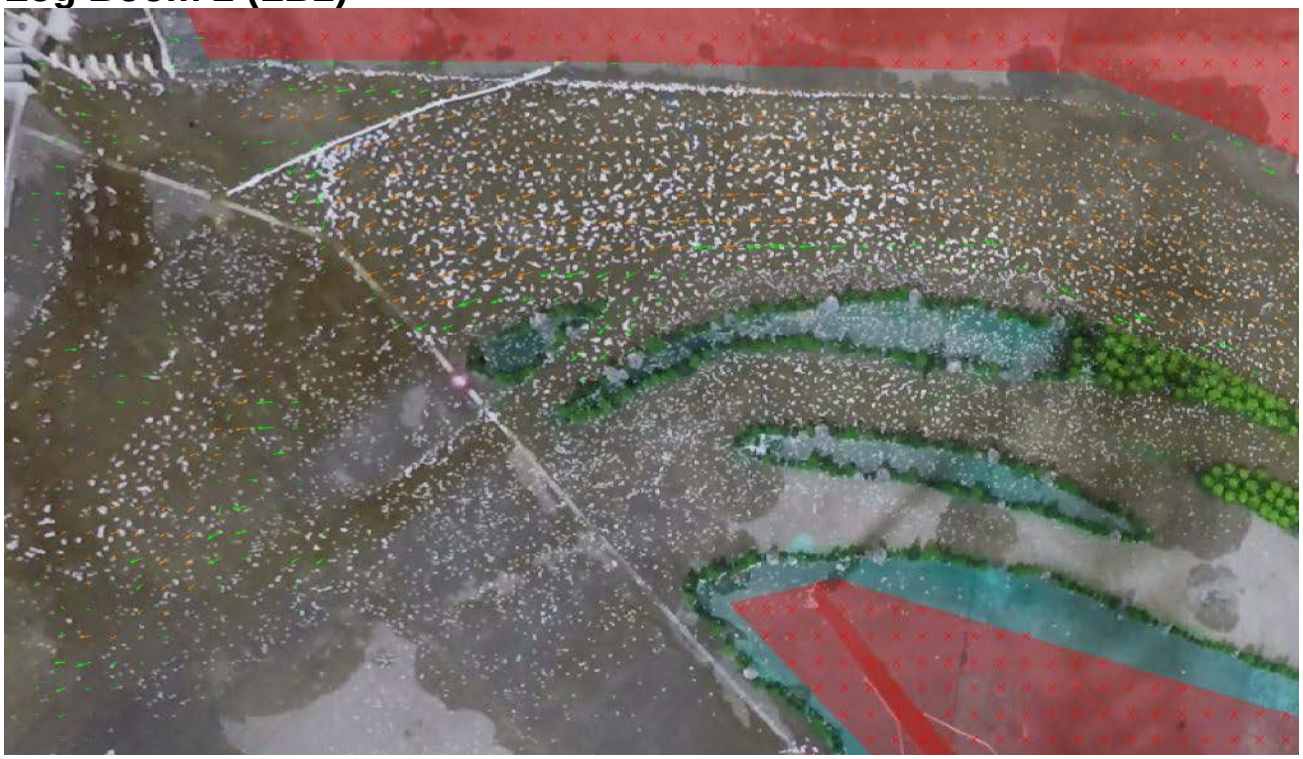

Image of LB2 with LSPIV mean velocity vector at River Q 800 cfs, Dam Q 550 cfs, Canal Q 250 cfs, with sluice gates closed.

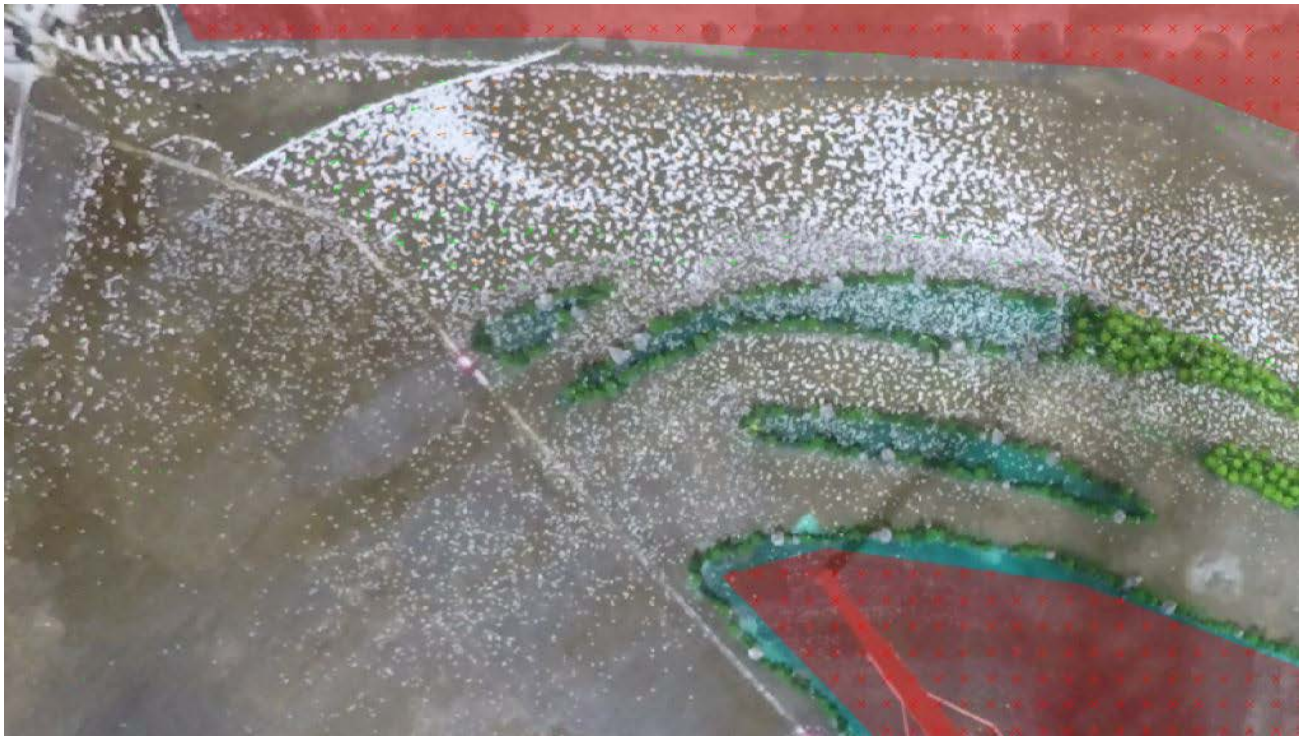

Image of LB2 with LSPIV mean velocity vector at River Q 800 cfs, Dam Q 800 cfs, Canal Q 0 cfs, with sluice gates open.

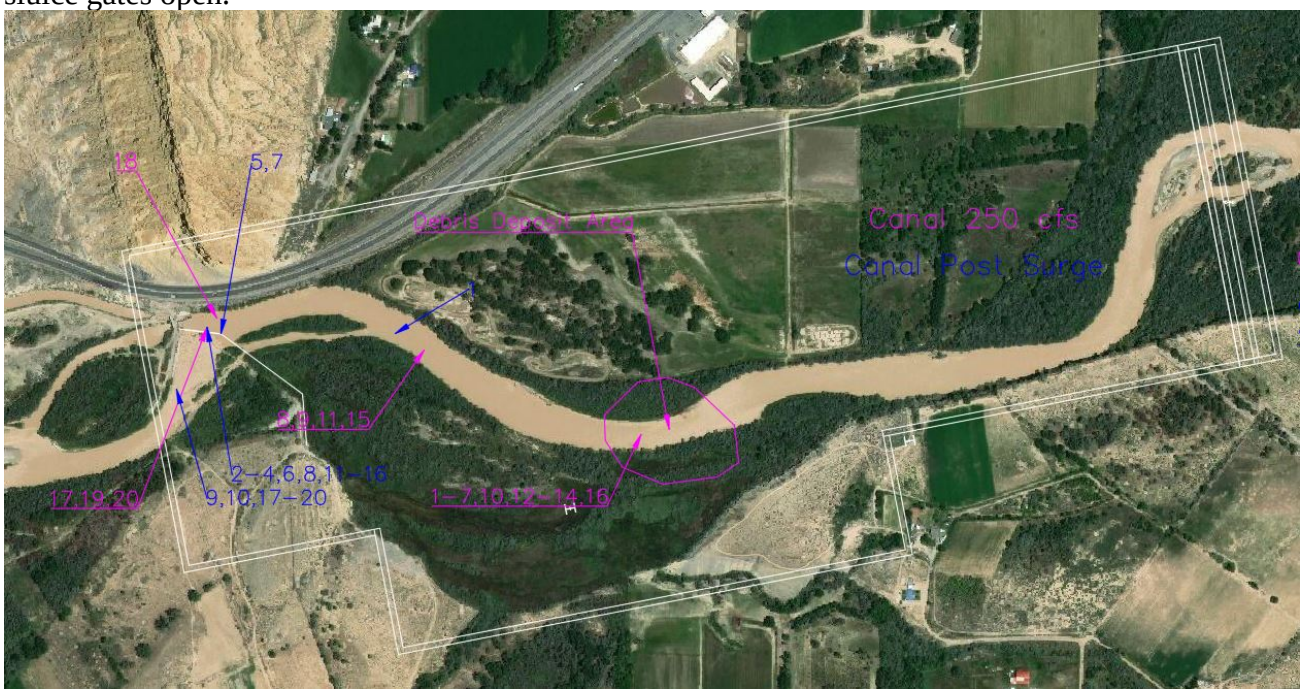

Image of debris capture location of the river modeled at the LB2 condition with River Q 800 cfs and Canal Q 250 cfs, with sluice gates closed.

Image of debris capture location of the river modeled at the LB2 condition with River Q 800 cfs and Canal Q 0 cfs, with sluice gates open.

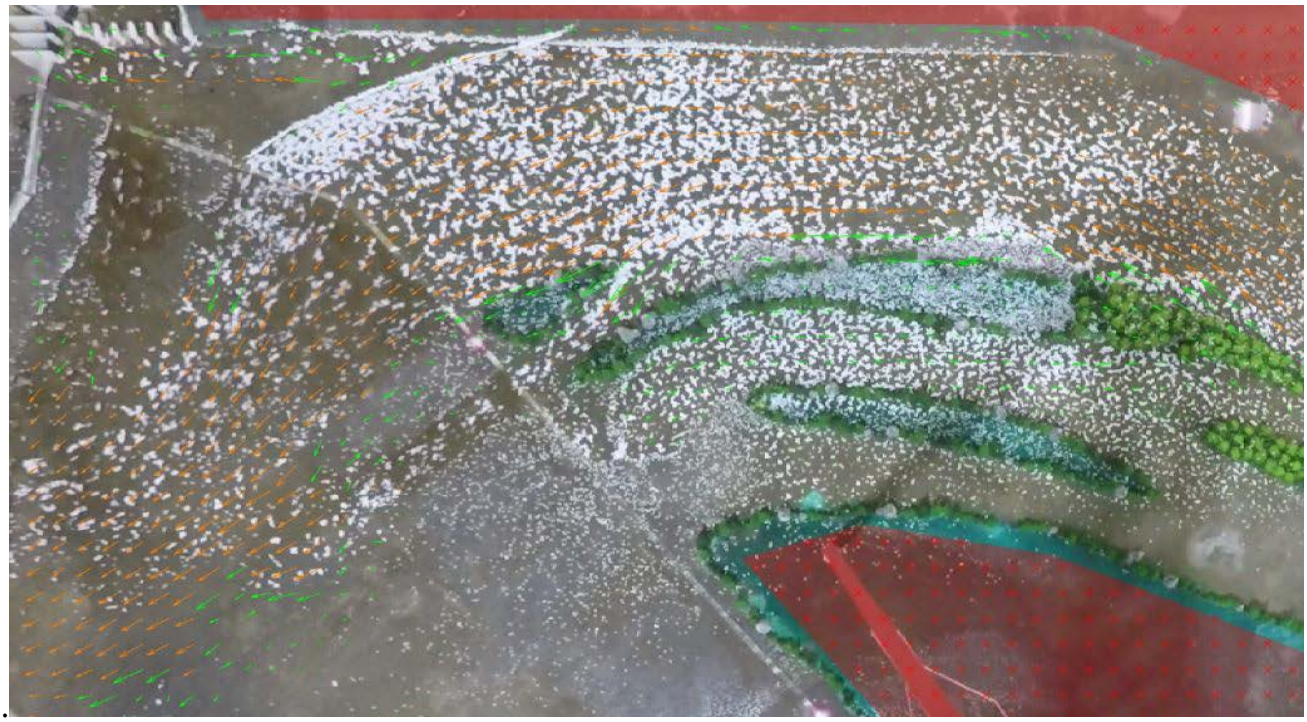

Image of LB2 with LSPIV mean velocity vector at River Q 2,500 cfs, Dam Q 2100 cfs, Canal Q 400 cfs, with sluice gates closed.

Image of LB2 with LSPIV mean velocity vector at River Q 2,500 cfs, Dam Q 2,500 cfs, Canal Q 0 cfs, with sluice gates open.

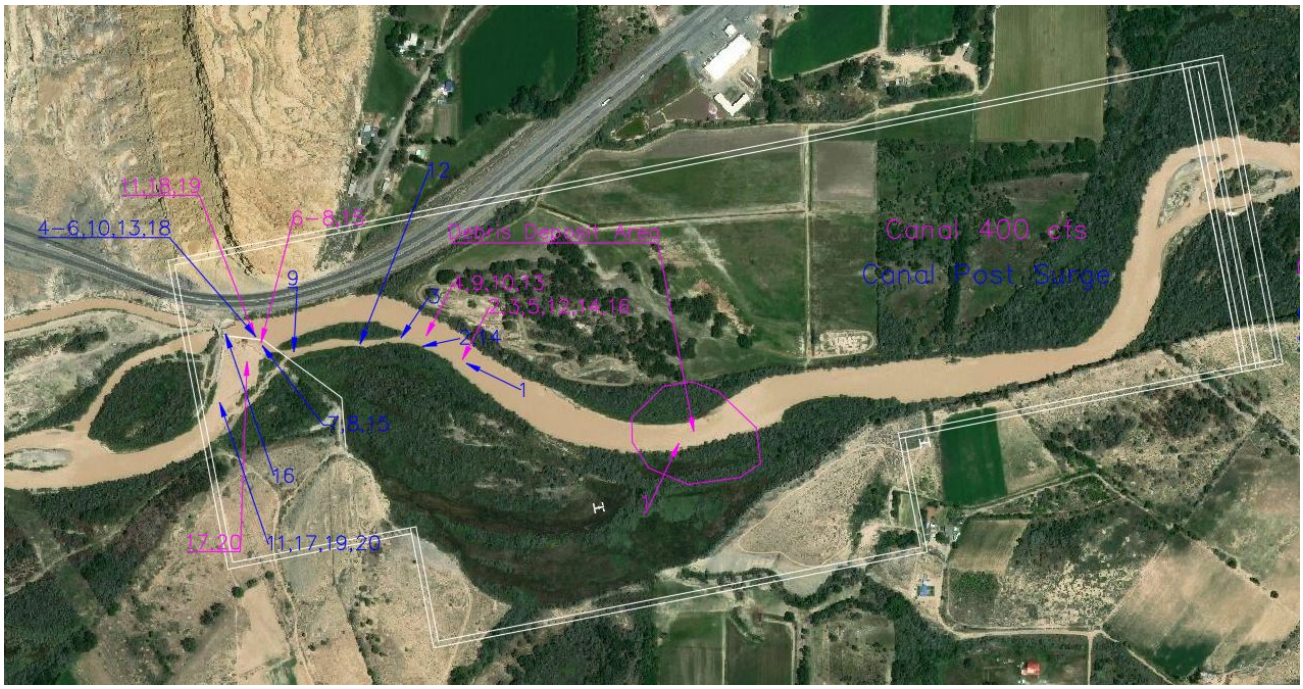

Image of debris capture location of the river modeled at the LB2 condition with River Q 2500 cfs and Canal Q 400 cfs, with sluice gates closed.

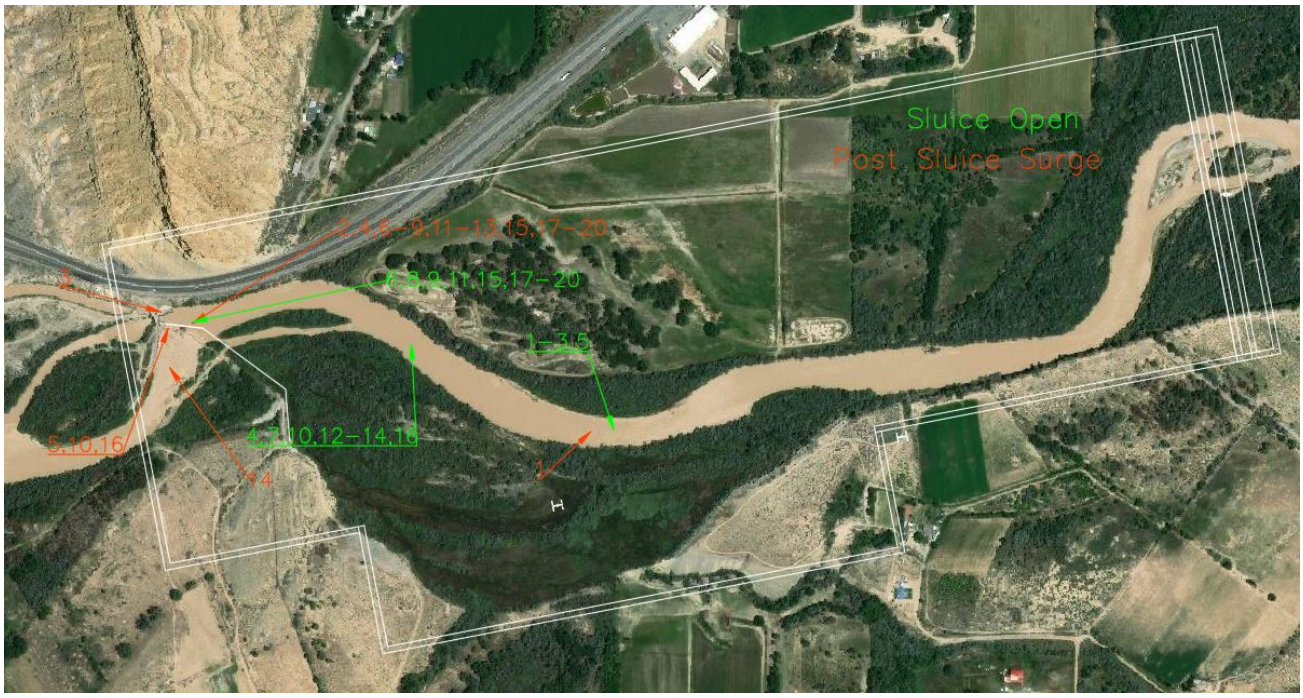

Image of debris capture location of the river modeled at the LB2 condition with River Q 2500 cfs and Canal Q 0 cfs, with sluice gates open.

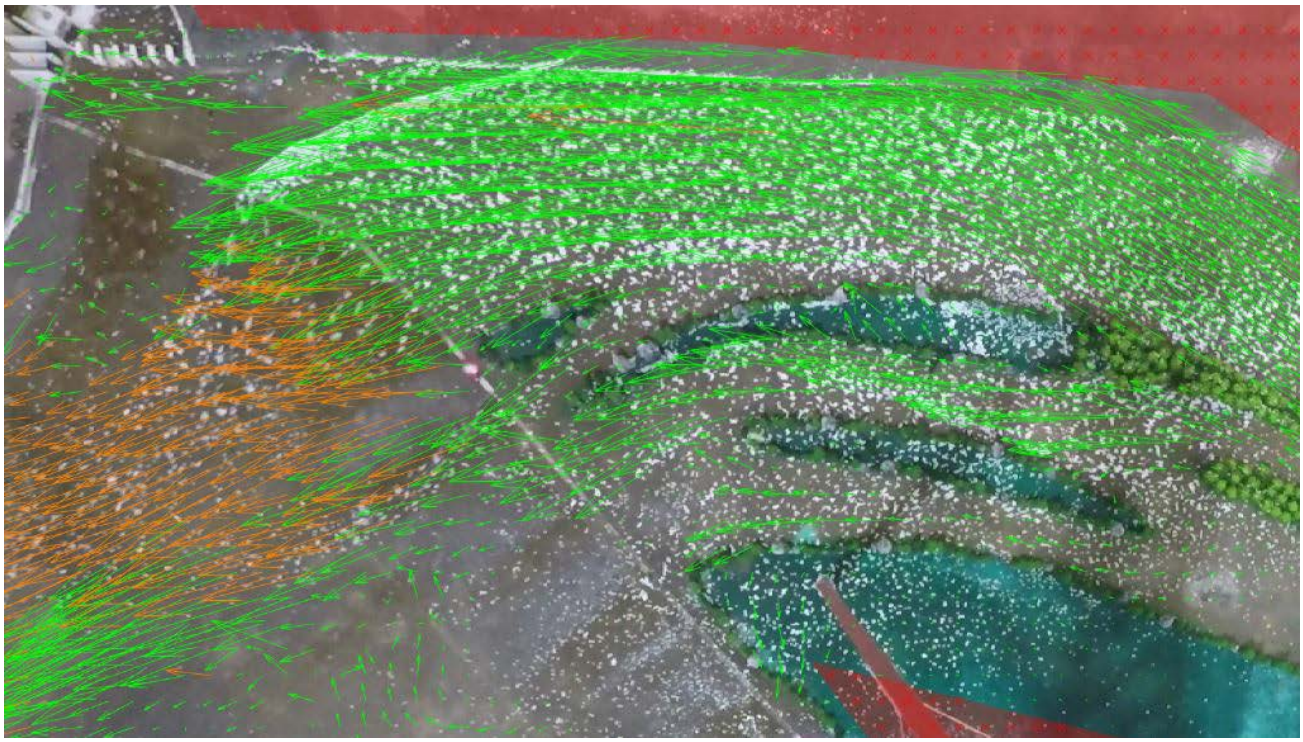

Image of LB2 with LSPIV mean velocity vector at River Q 5,000 cfs, Dam Q 4500 cfs, Canal Q 500 cfs, with sluice gates closed.

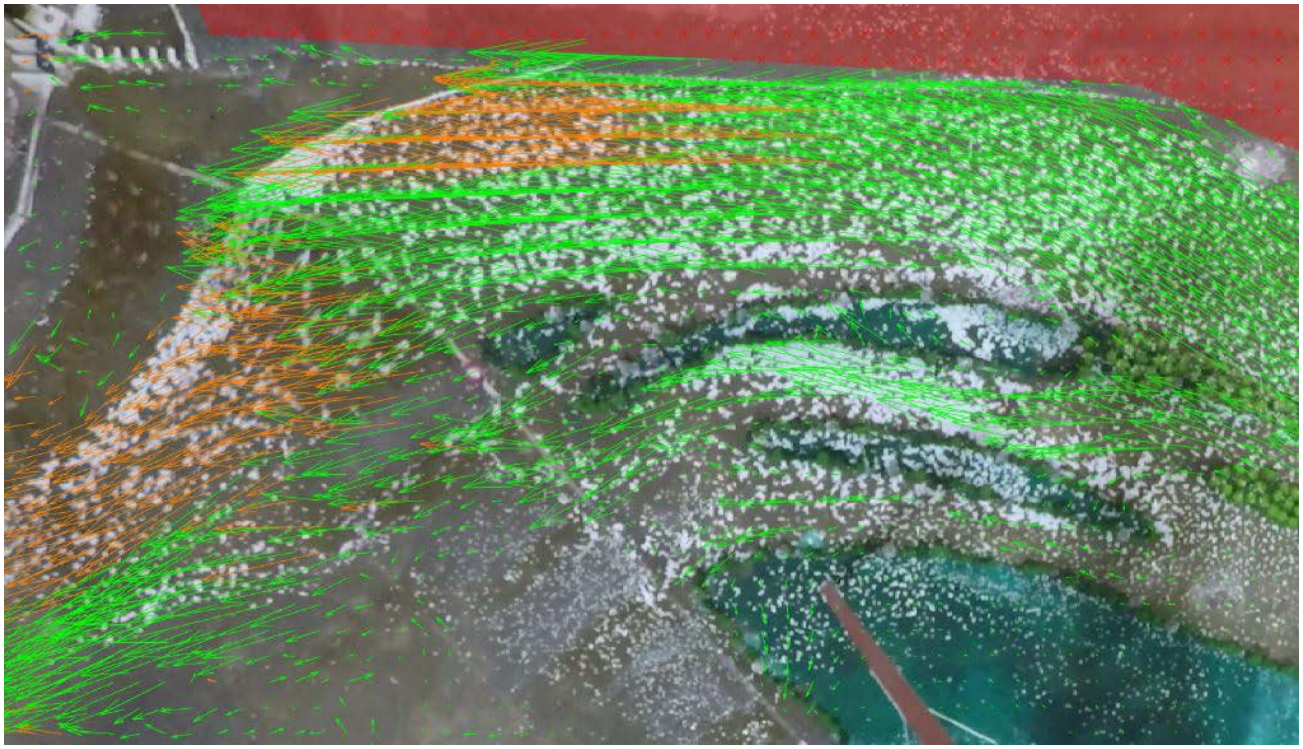

Image of LB2 with LSPIV mean velocity vector at River Q 5,000 cfs, Dam Q 5,000 cfs, Canal Q 0 cfs, with sluice gates open.

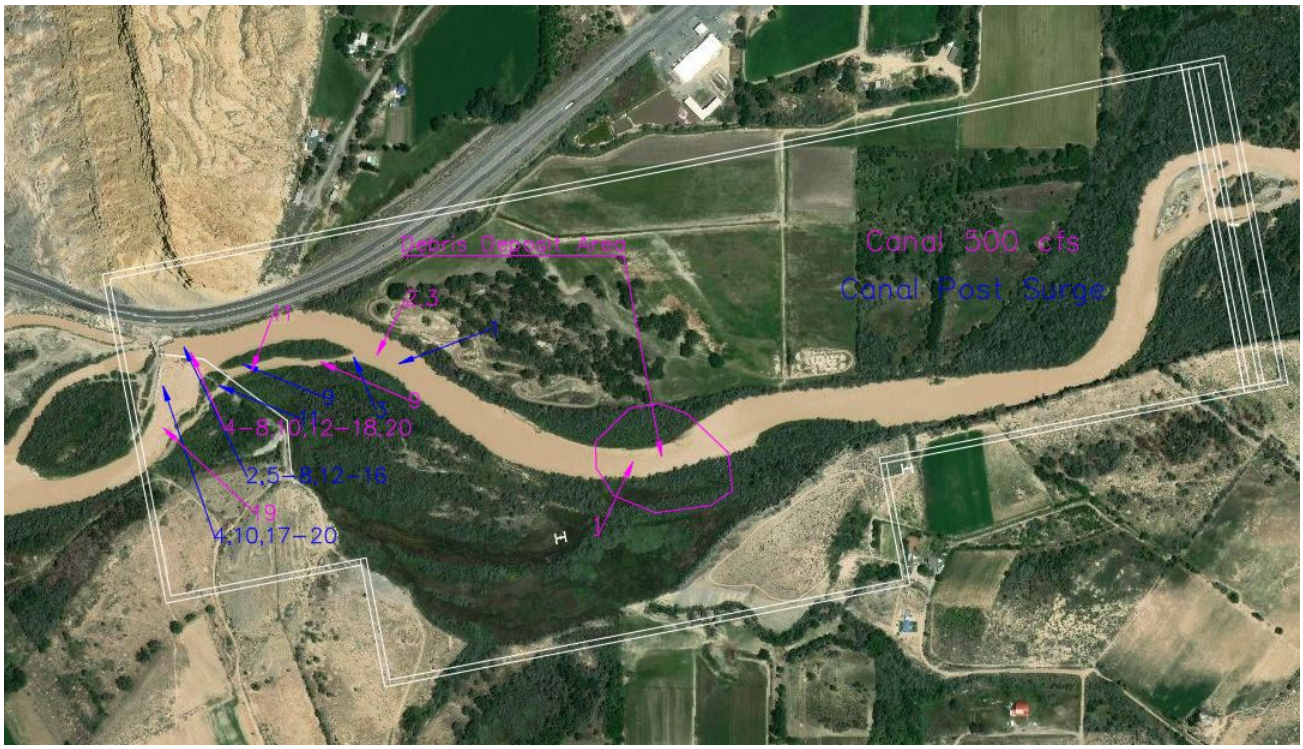

Image of debris capture location of the river modeled at the LB2 condition with River Q 5000 cfs and Canal Q 500 cfs, with sluice gates closed.

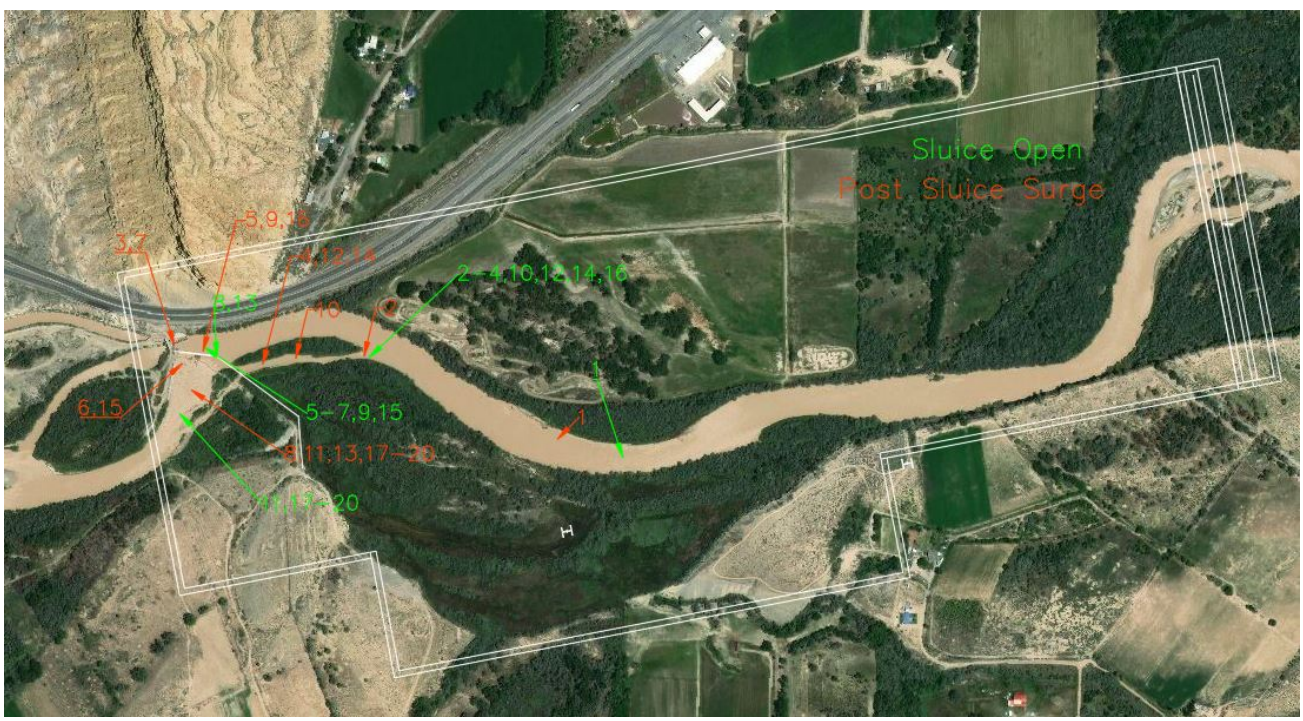

Image of debris capture location of the river modeled at the LB2 condition with River Q 5000 cfs and Canal Q 0 cfs, with sluice gates open.

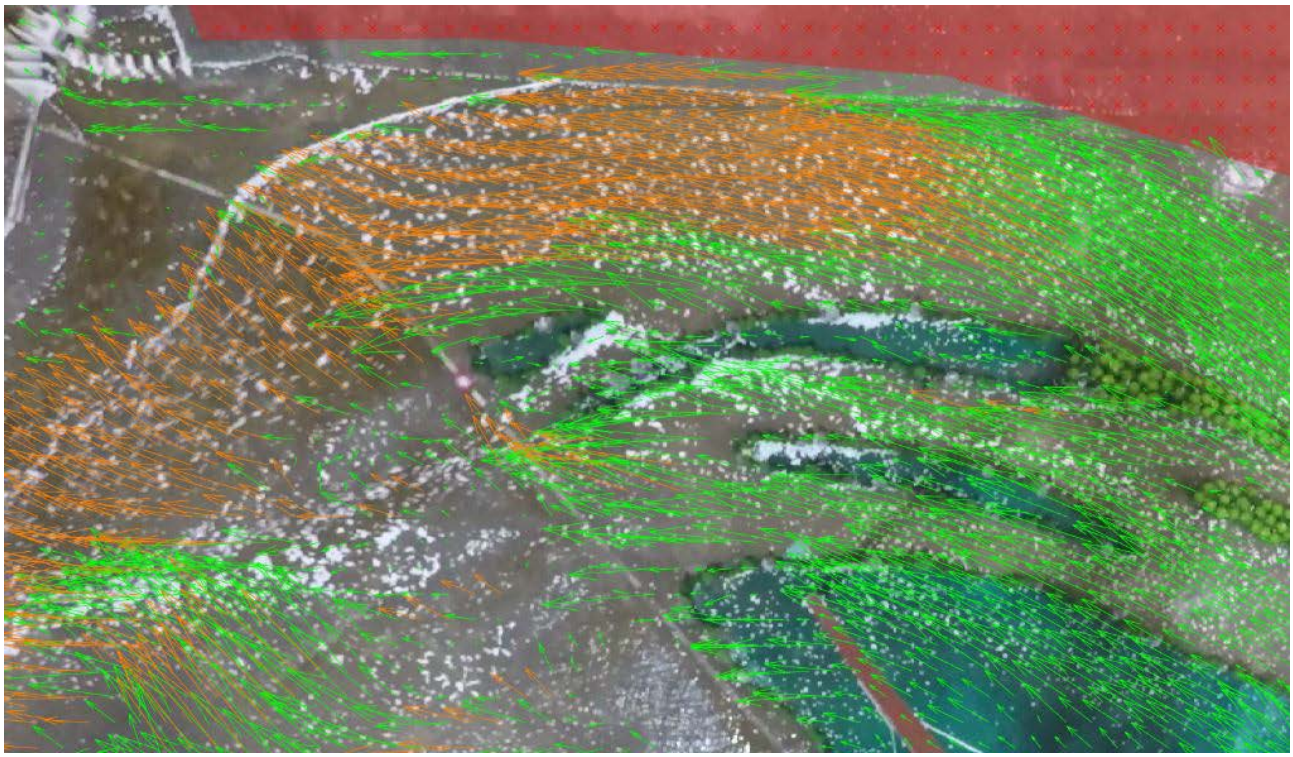

Image of LB2 with LSPIV mean velocity vector at River Q 12,000 cfs, Dam Q 11400 cfs, Canal Q 600 cfs, with sluice gates closed.

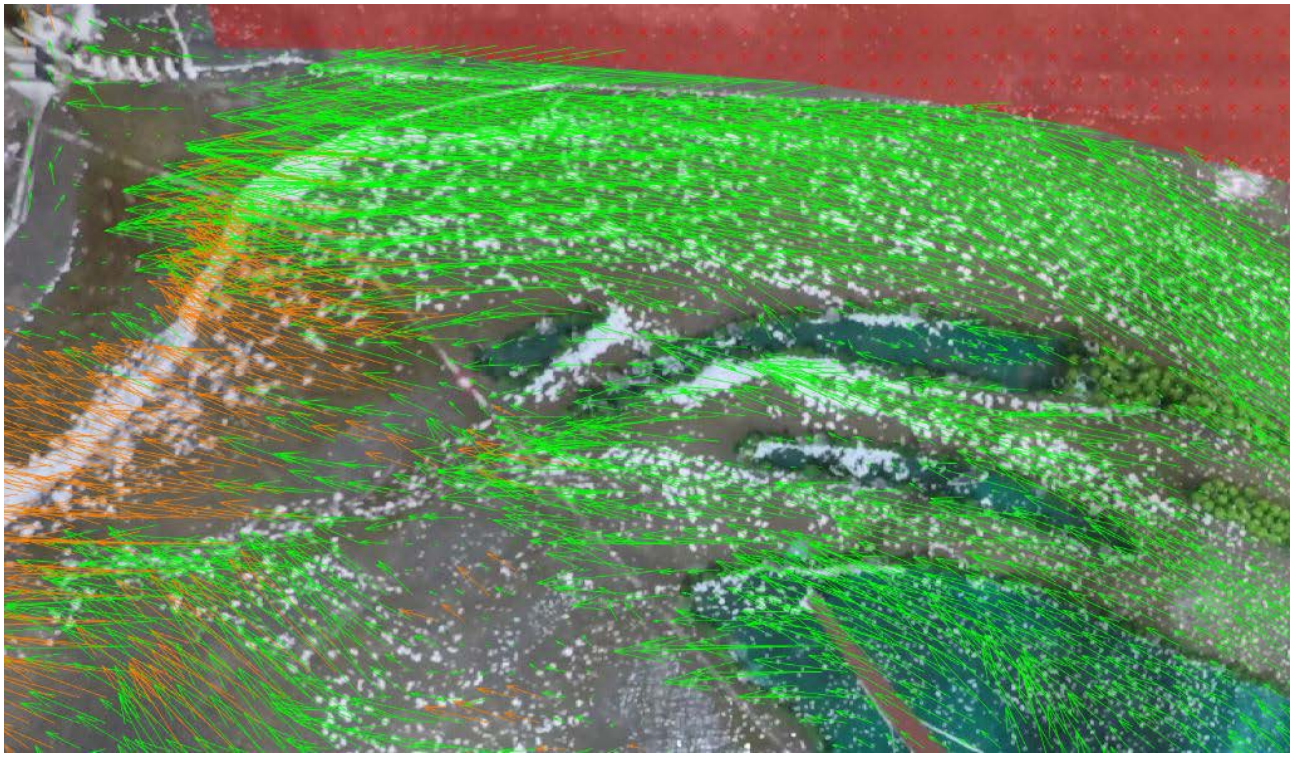

Image of LB2 with LSPIV mean velocity vector at River Q 12,000 cfs, Dam Q 12,000 cfs, Canal Q 0 cfs, with sluice gates open.

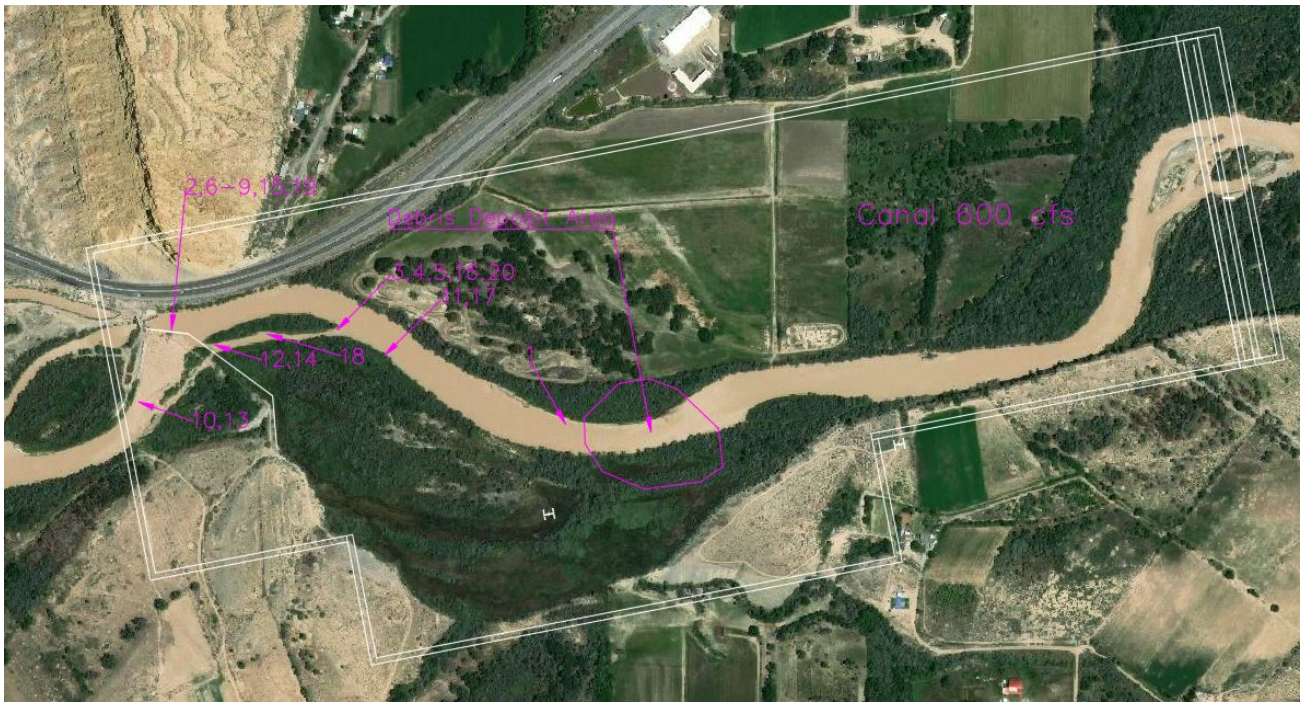

Image of debris capture location of the river modeled at the LB2 condition with River Q 12000 cfs and Canal Q 600 cfs, with sluice gates closed.

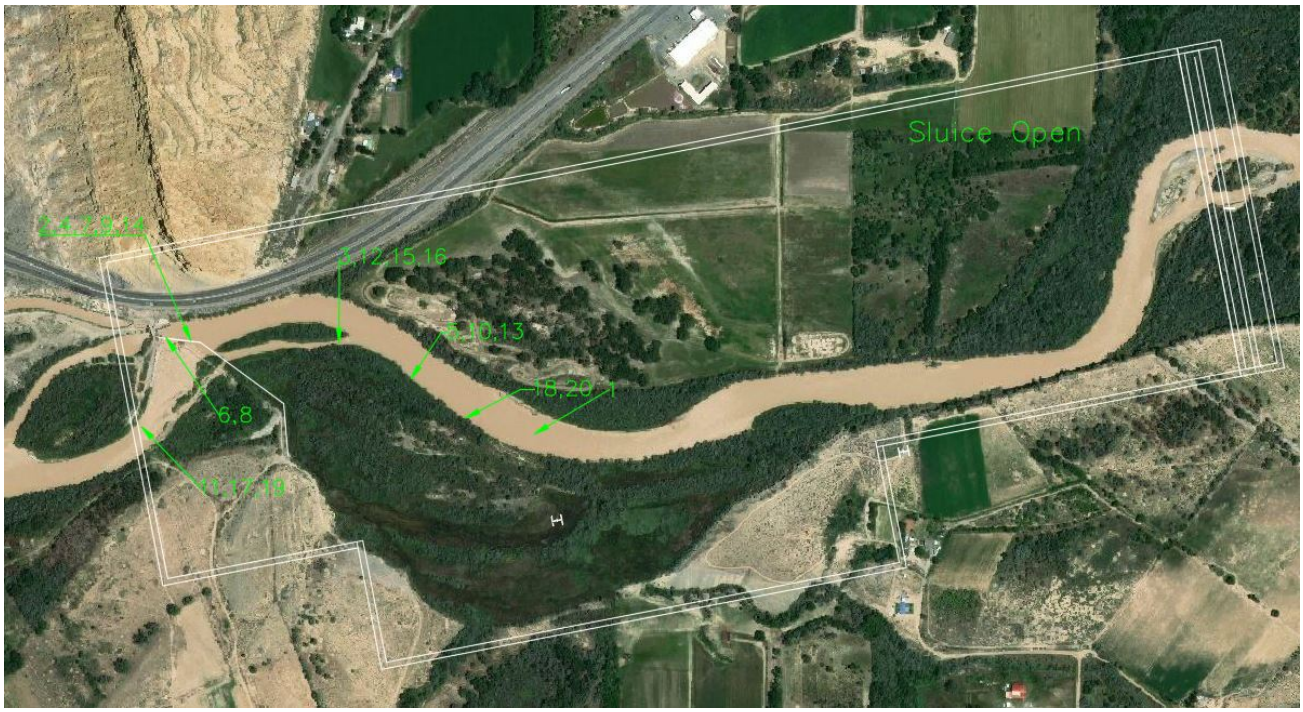

Image of debris capture location of the river modeled at the LB2 condition with River Q 12000 cfs and Canal Q 0 cfs, with sluice gates open.

Rock Structure 2 (RS2)

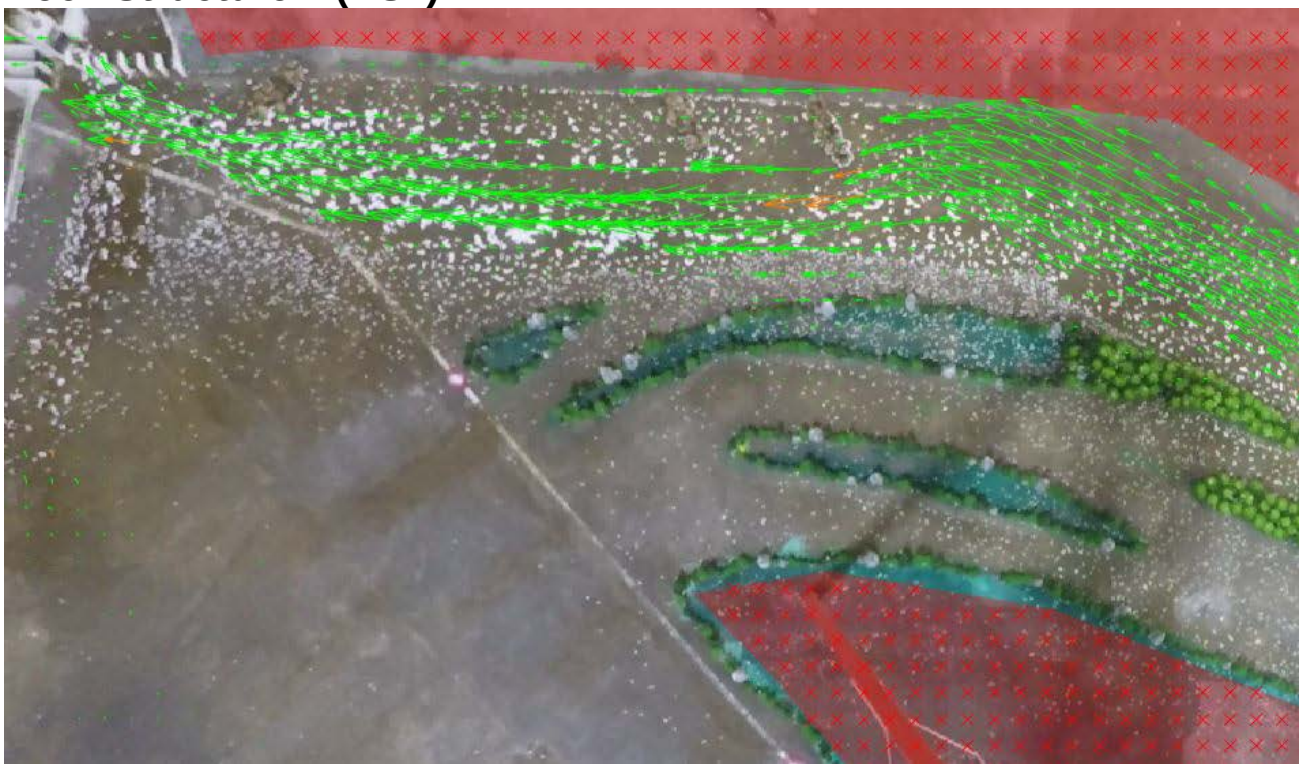

Image of RS2 with LSPIV mean velocity vector at River Q 800 cfs, Dam Q 600 cfs, Canal Q 200 cfs, with sluice gates closed.

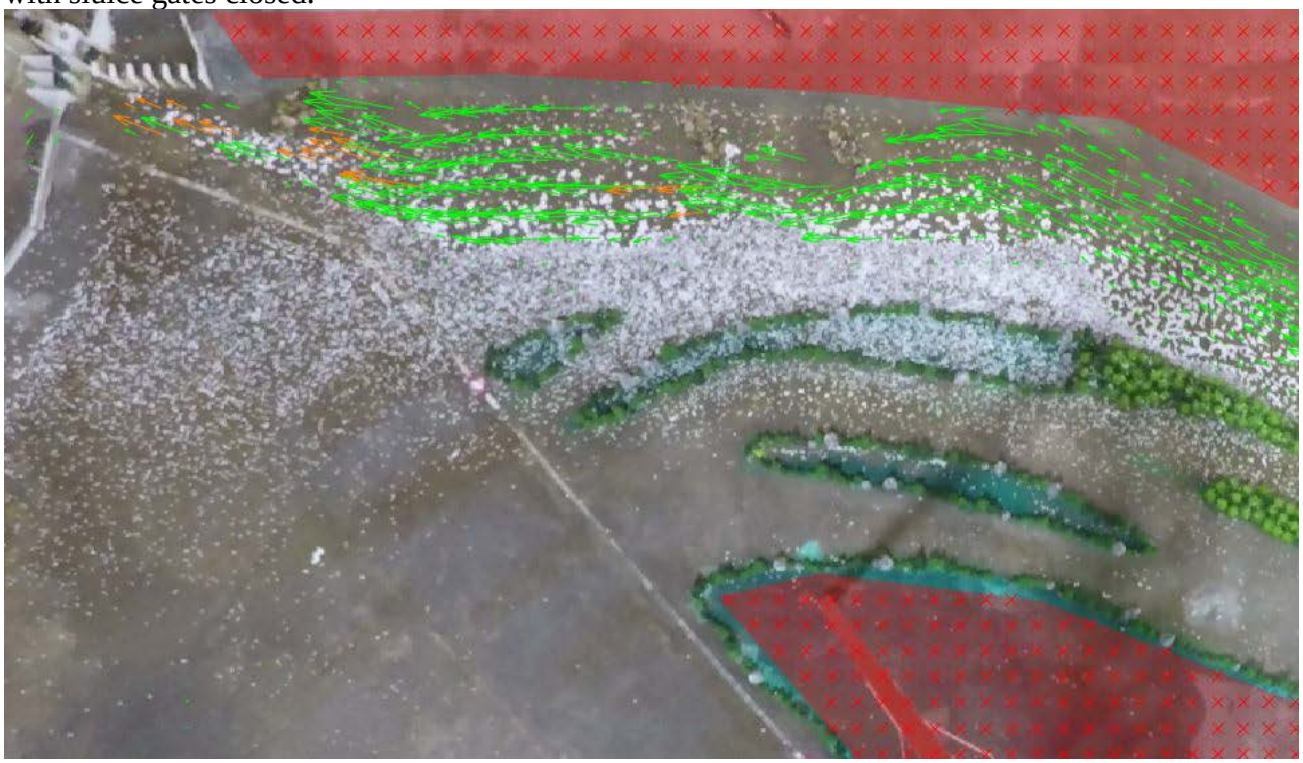

Image of RS2 with LSPIV mean velocity vector at River Q 800 cfs, Dam Q 800 cfs, Canal Q 0 cfs, with sluice gates open.

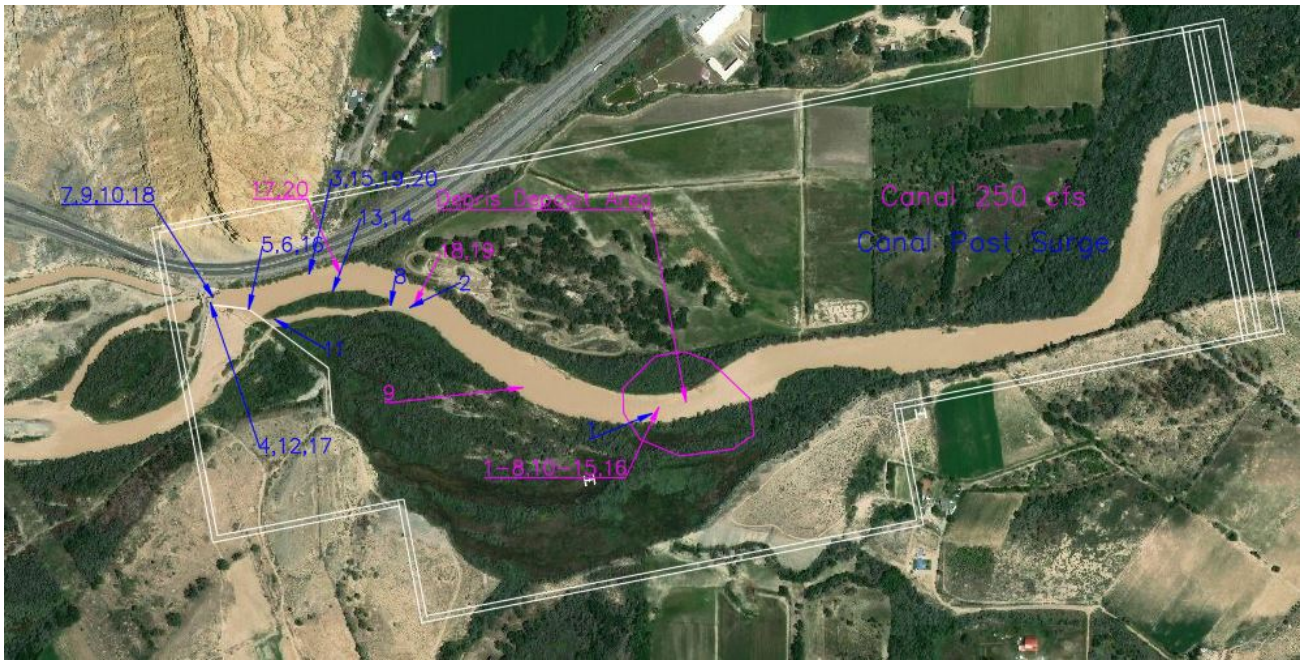

Image of debris capture location of the river modeled at the RS2 condition with River Q 800 cfs and Canal Q 250 cfs, with sluice gates closed.

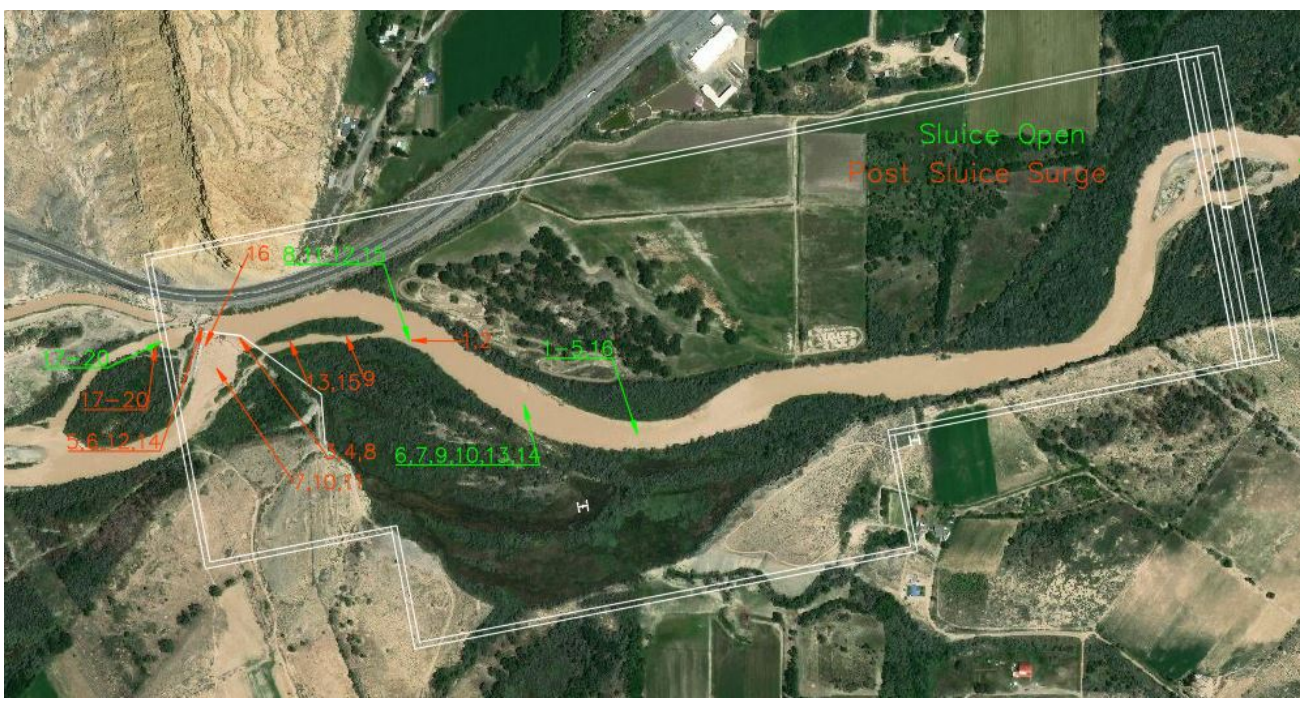

Image of debris capture location of the river modeled at the RS2 condition with River Q 800 cfs and Canal Q 0 cfs, with sluice gates open.

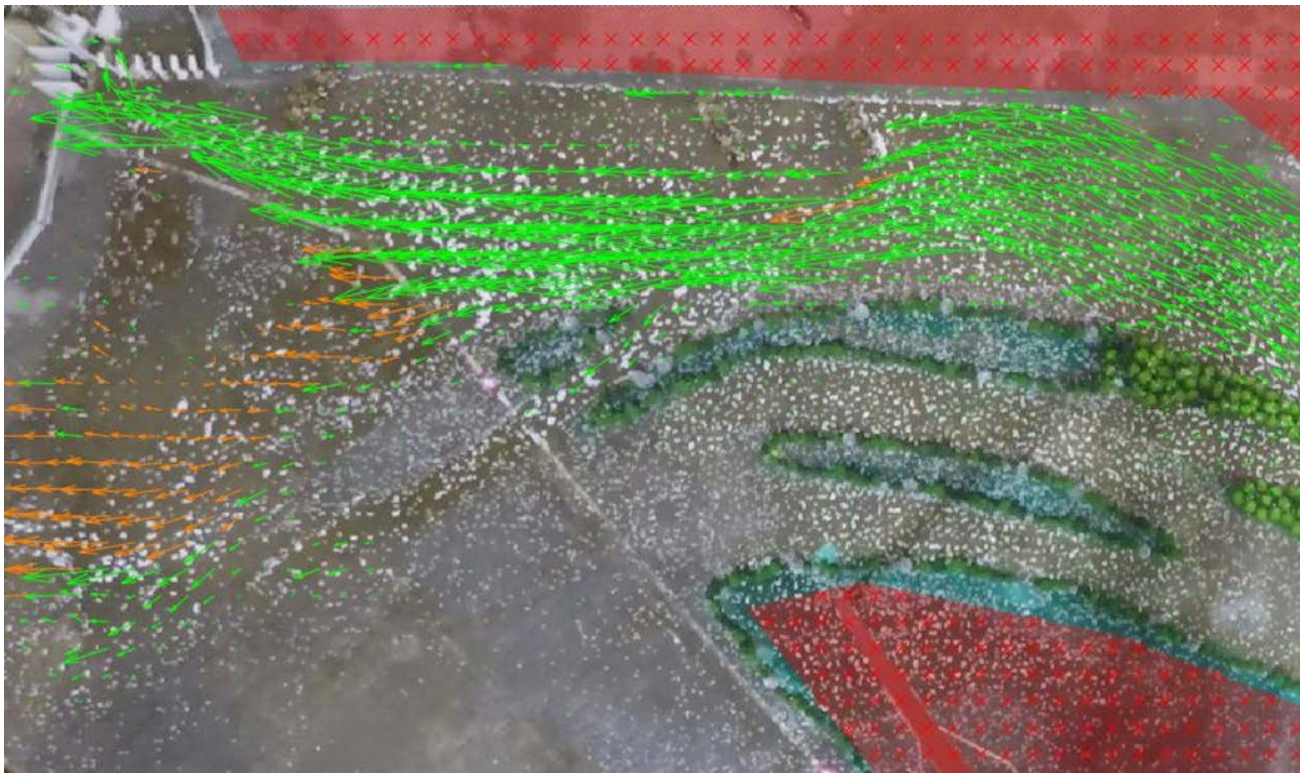

Image of RS2 with LSPIV mean velocity vector at River Q 2,500 cfs, Dam Q 2100 cfs, Canal Q 400 cfs, with sluice gates closed.

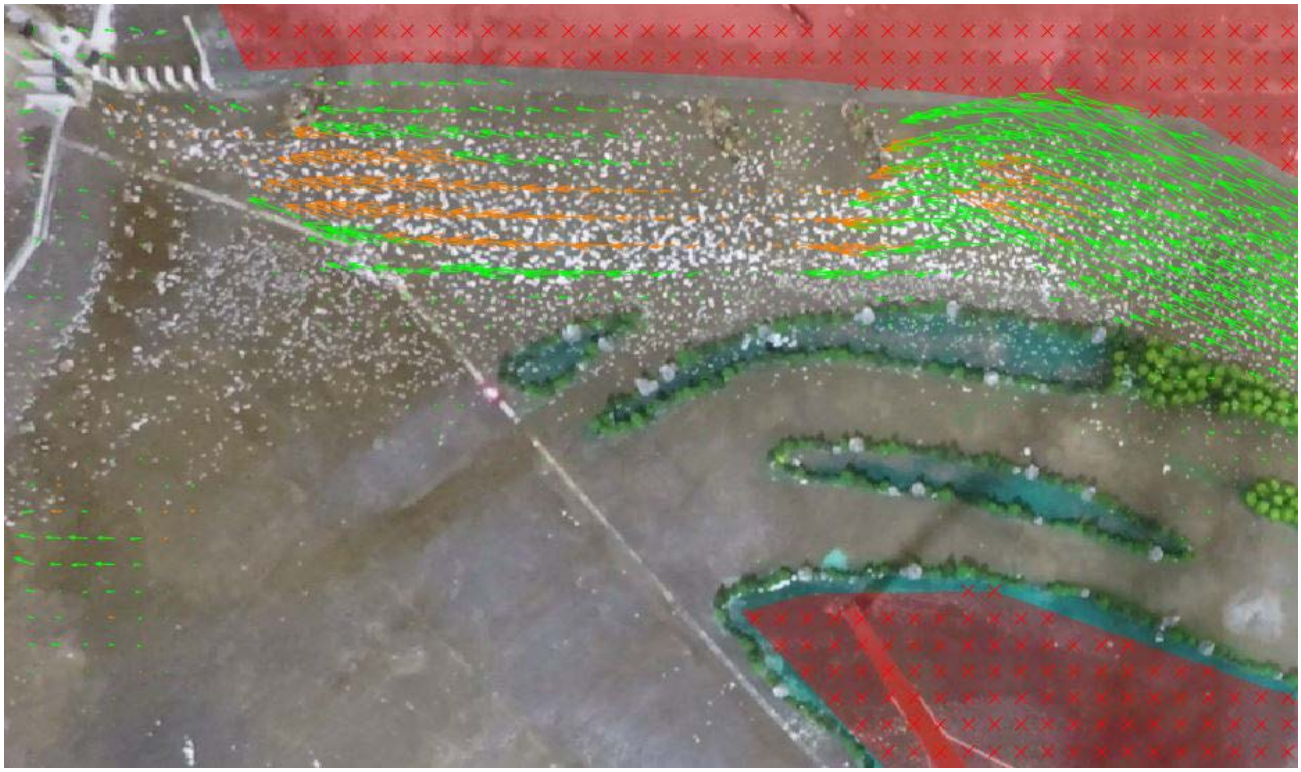

Image of RS2 with LSPIV mean velocity vector at River Q 2,500 cfs, Dam Q 2,500 cfs, Canal Q 0 cfs, with sluice gates open.

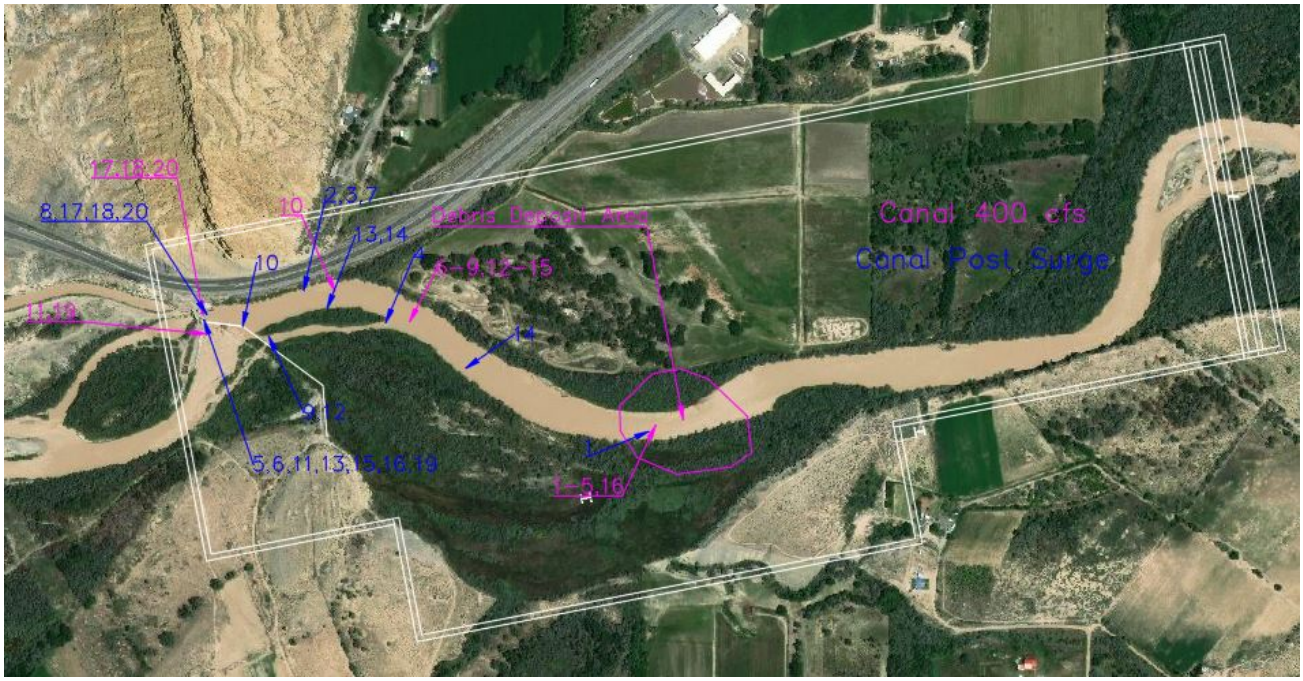

Image of debris capture location of the river modeled at the RS2 condition with River Q 2500 cfs and Canal Q 400 cfs, with sluice gates closed.

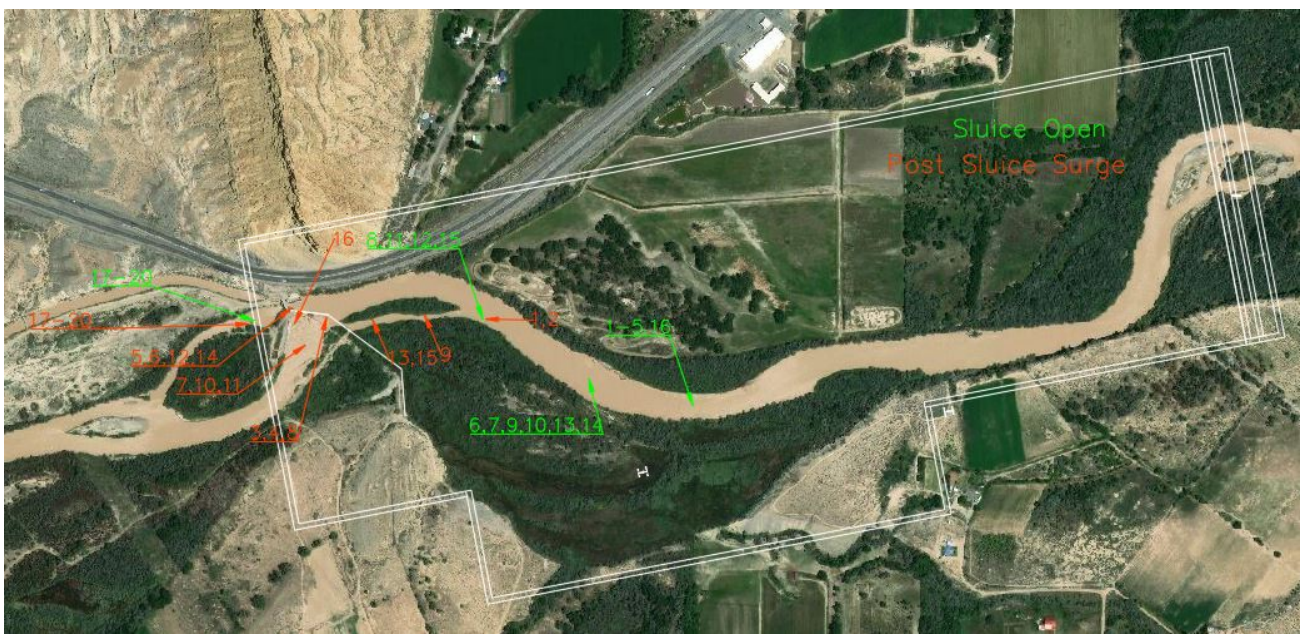

Image of debris capture location of the river modeled at the RS2 condition with River Q 2500 cfs and Canal Q 0 cfs, with sluice gates open.

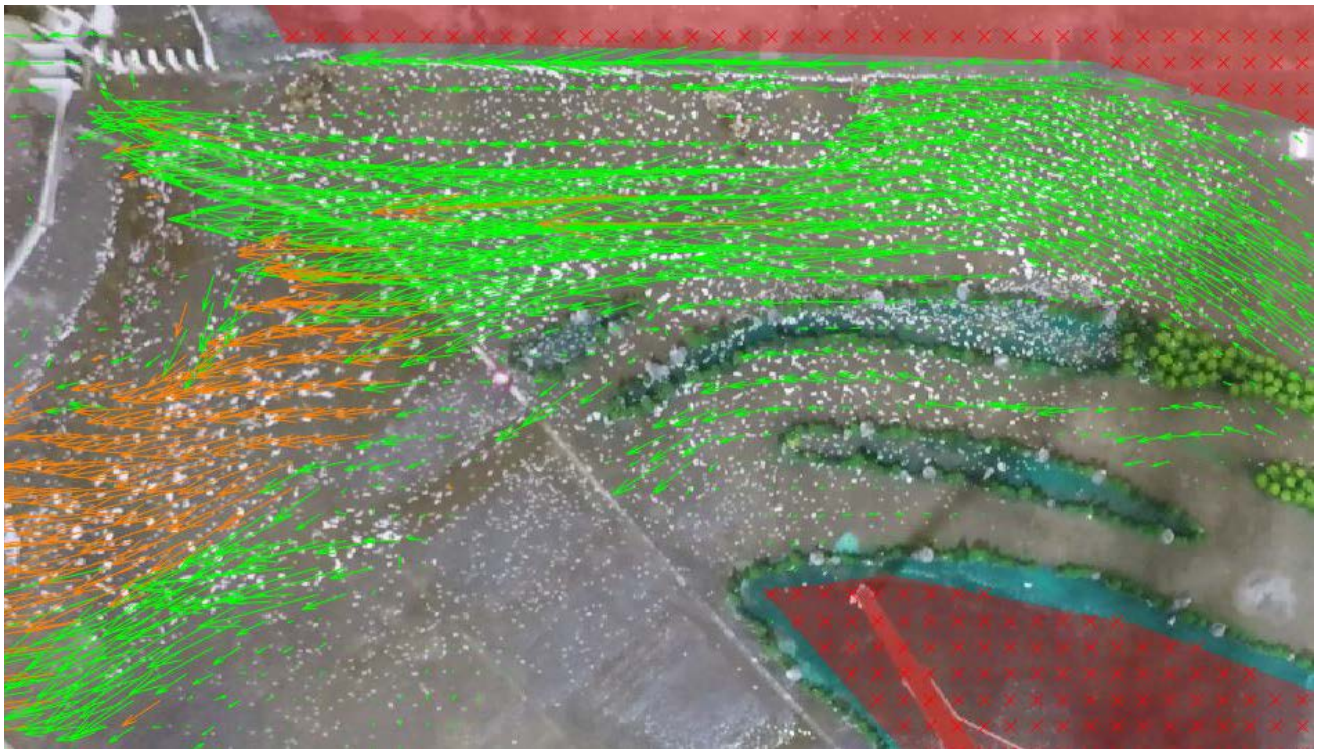

Image of RS2 with LSPIV mean velocity vector at River Q 5,000 cfs, Dam Q 4500 cfs, Canal Q 500 cfs, with sluice gates closed.

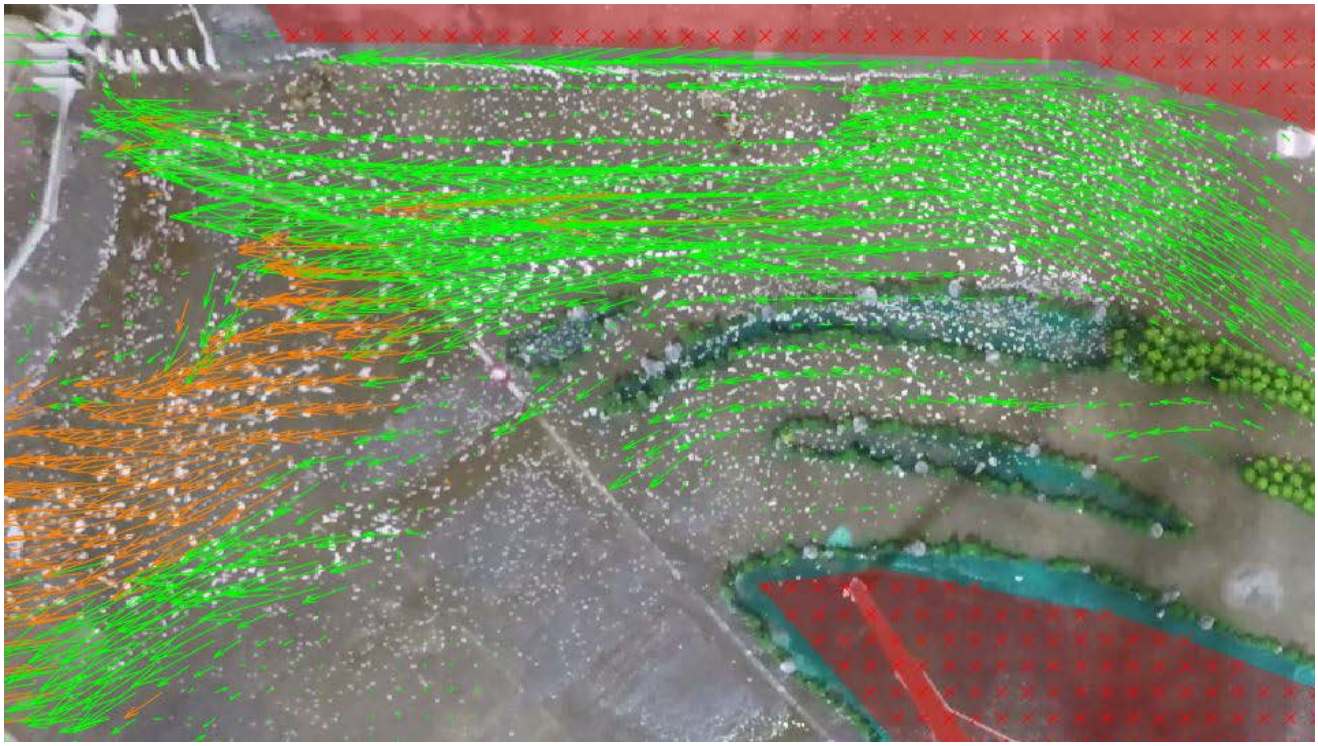

Image of RS2 with LSPIV mean velocity vector at River Q 5,000 cfs, Dam Q 5,000 cfs, Canal Q 0 cfs, with sluice gates open.

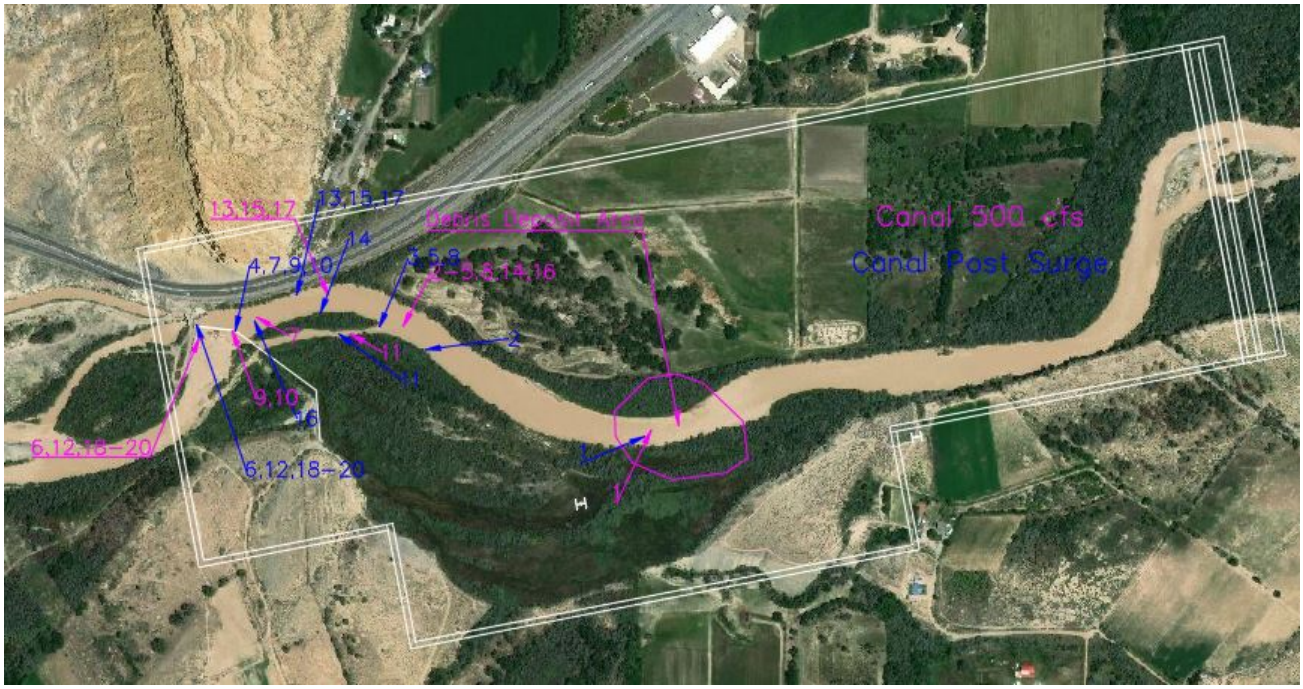

Image of debris capture location of the river modeled at the RS2 condition with River Q 5000 cfs and Canal Q 500 cfs, with sluice gates closed.

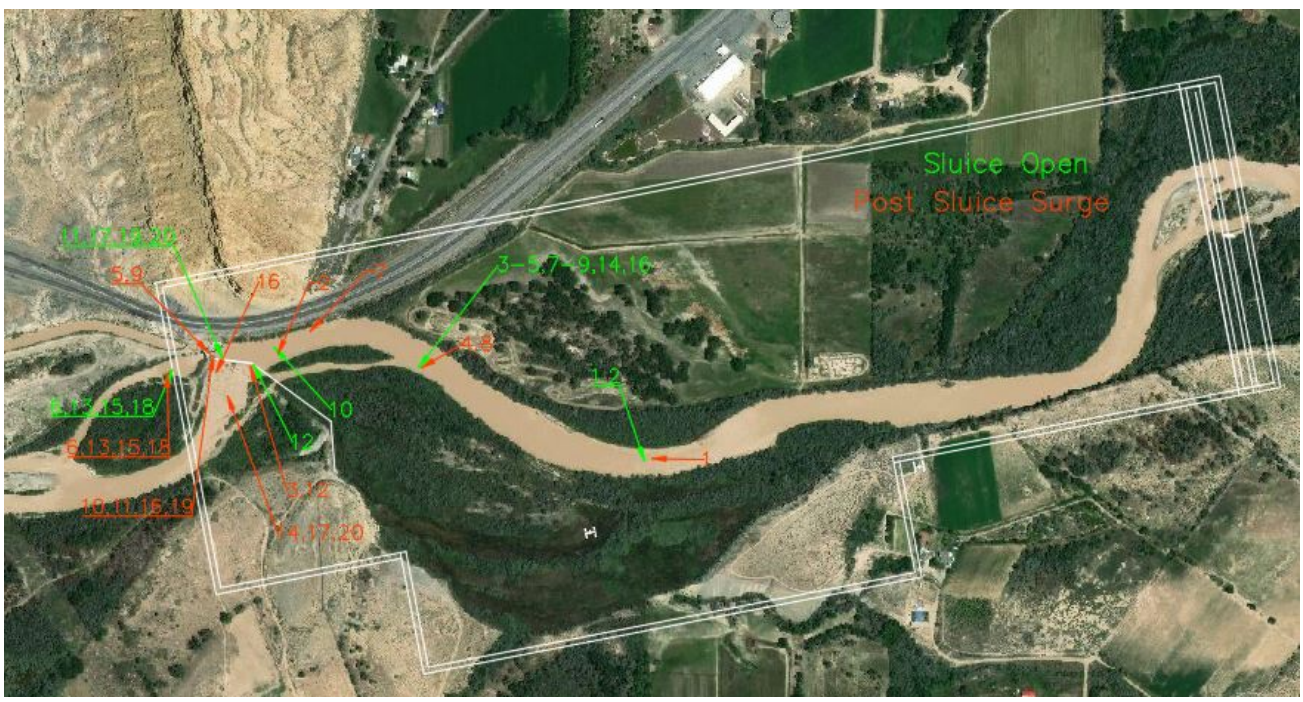

Image of debris capture location of the river modeled at the RS2 condition with River Q 5000 cfs and Canal Q 0 cfs, with sluice gates open.

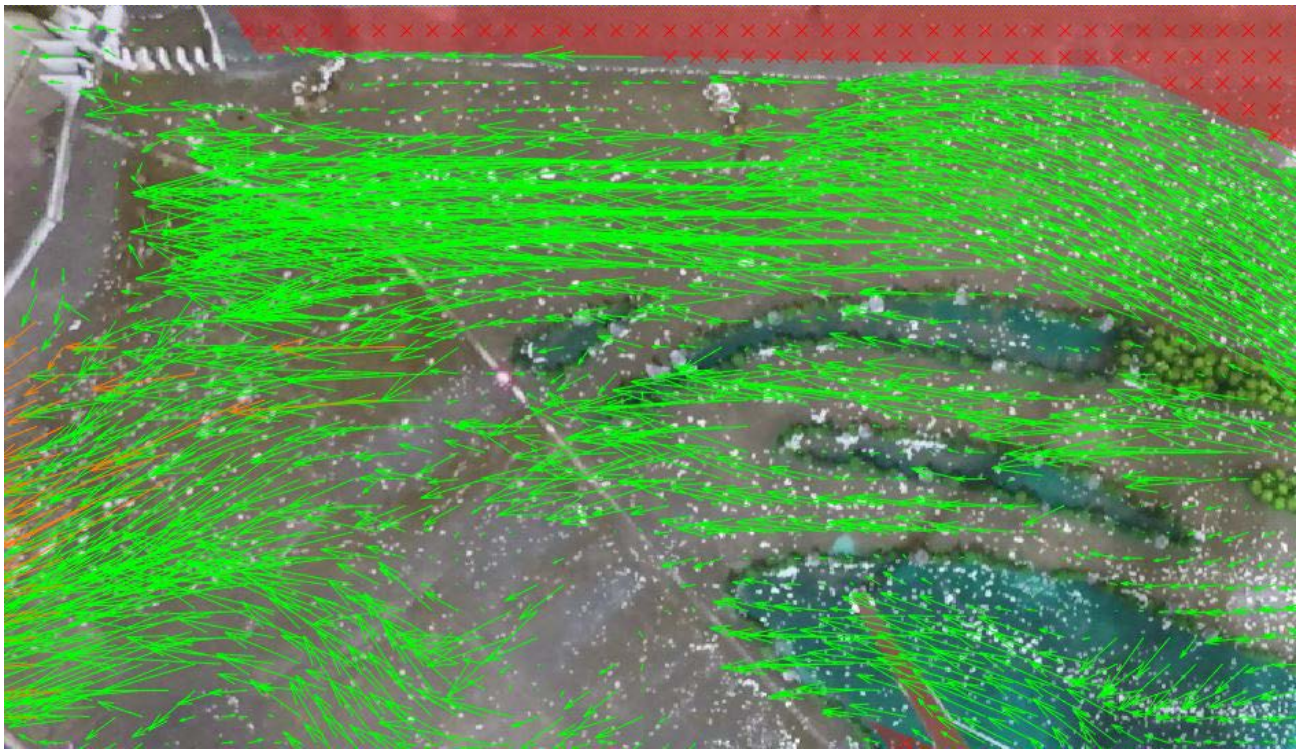

Image of RS2 with LSPIV mean velocity vector at River Q 12,000 cfs, Dam Q 11400 cfs, Canal Q 600 cfs, with sluice gates closed.

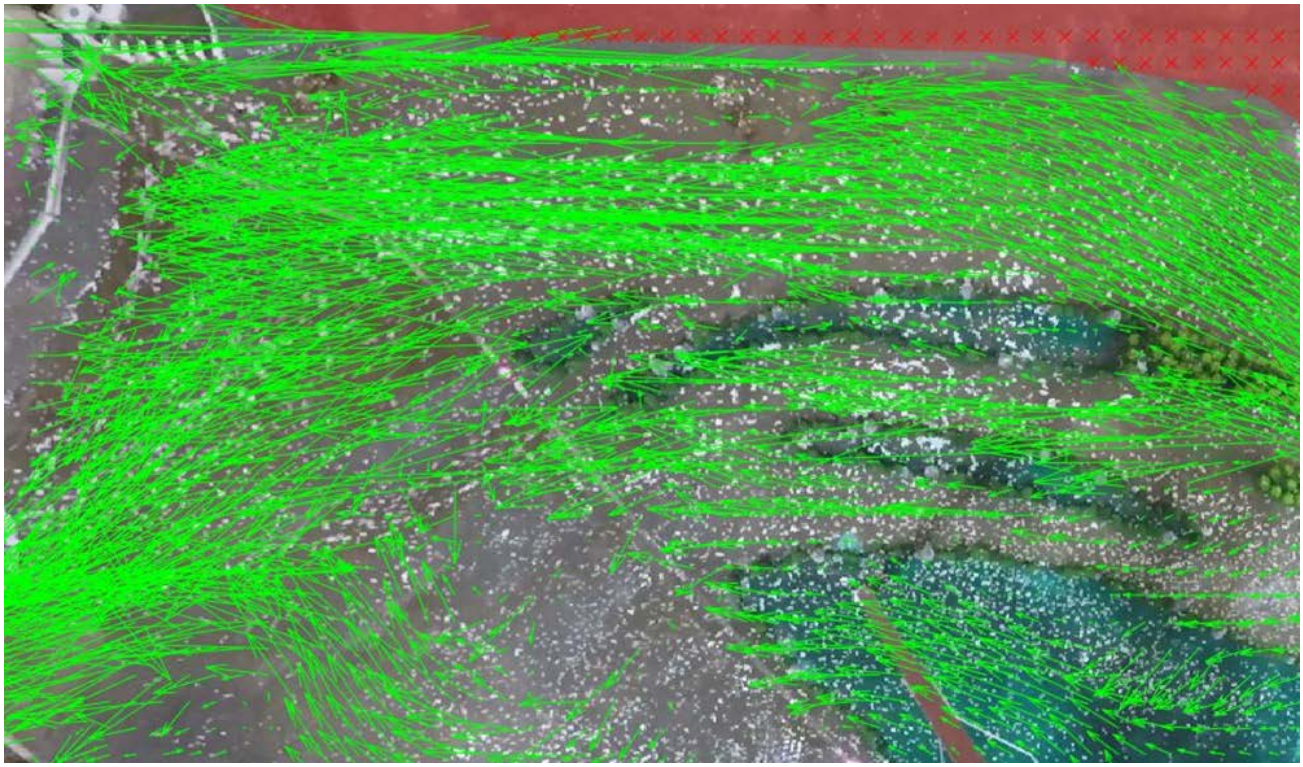

Image of RS2 with LSPIV mean velocity vector at River Q 12,000 cfs, Dam Q 12,000 cfs, Canal Q 0 cfs, with sluice gates open.

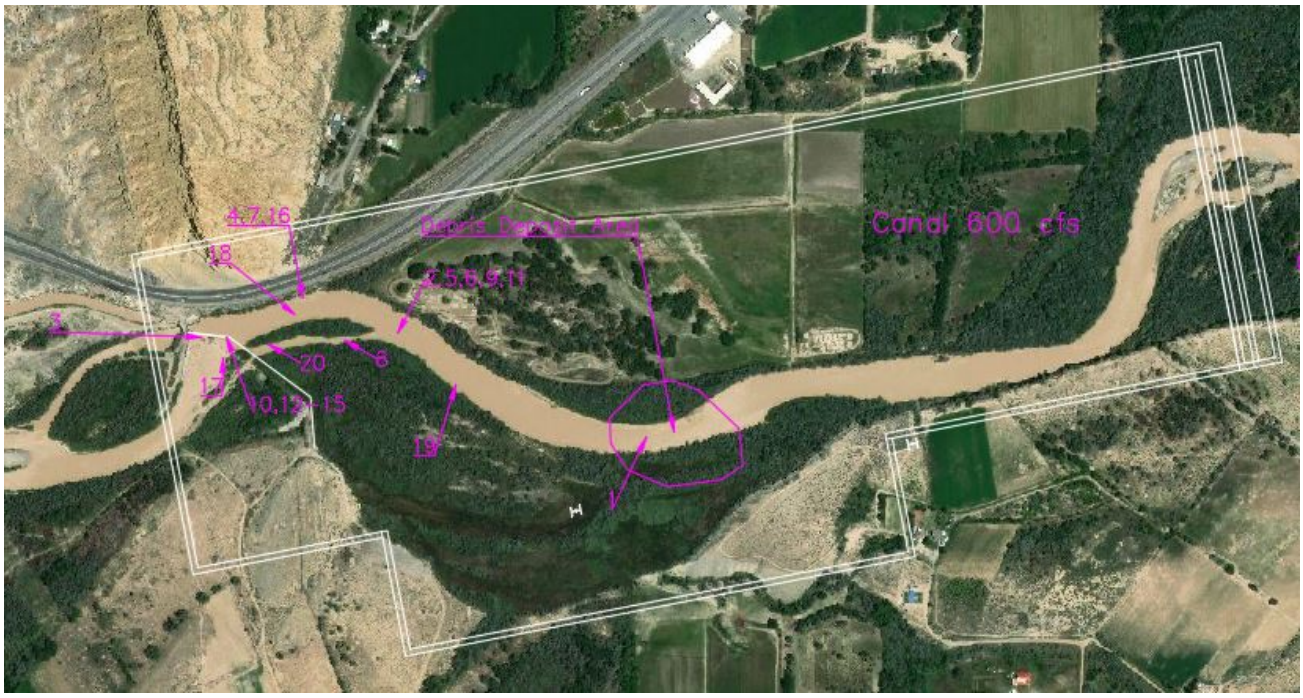

Image of debris capture location of the river modeled at the RS2 condition with River Q 12000 cfs and Canal Q 600 cfs, with sluice gates closed.

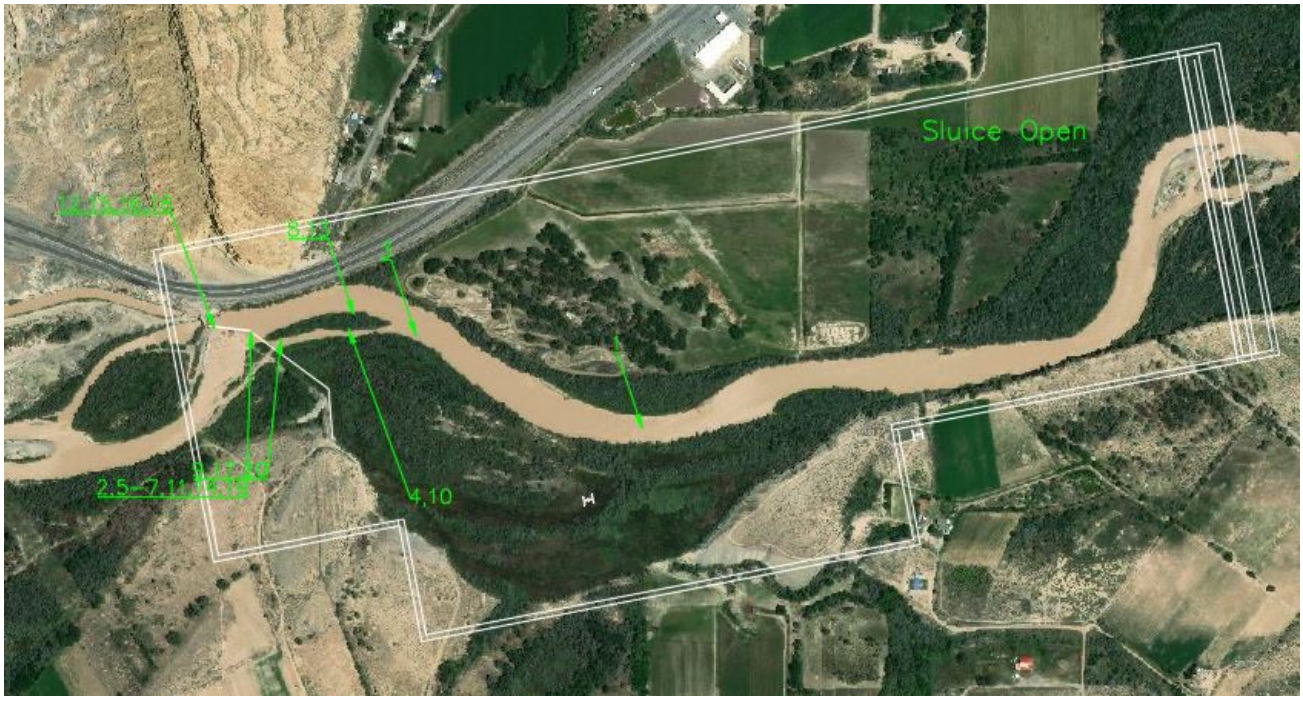

Image of debris capture location of the river modeled at the RS2 condition with River Q 12000 cfs and Canal Q 0 cfs, with sluice gates open.