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Simulation of Flows at the USGS Gage Station in Hereford, Texas

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Introduction

The Tierra Blanca Creek begins in Curry County, New Mexico and enters Texas in southwestern Deaf Smith County. The creek then flows east-northeast for seventy-five miles, across southern Deaf Smith and Randall counties, to join Palo Duro Creek east of Canyon near the old T Anchor Ranch headquarters site in northeastern Randall County. The junction of the two streams forms the Prairie Dog Town Fork of the Red River, although in the upper course it is often called Palo Duro Creek.

Hereford, originally called Bluewater, was founded near the ephemeral stream in Deaf Smith County in 1898. Buffalo Lake is formed by a dam on the stream near Umbarger, and a smaller reservoir, McSpadden Lake, is on the Tierra Blanca southeast of downtown Canyon (Texas State Historical Association, 2013).

The Texas Department of Public Transportation has funded the USGS to monitor a gage station near where the US 60 bridge crosses the Tierra Blanca Creek outside of Hereford, Texas. This location represents about 194 acres of drainage area including the John Pitman Municipal Golf Course. Figures # is a Google Earth satellite image of the study area.

Figure #. Satellite imagery of the Tierra Blanca Creek drainage area northeast of the US 60 bridge crossing.

In 2007, two USGS crest-stage gages were established along the thalweg of the Tierra Blanca Creek on the golf course 1.5 miles downstream of the US 60 bridge crossing. The gages allow the USGS to determine whether storm flows in the Tierra Blanca exceed the bridge design flows.

To determine water surface elevations, the USGS uses the slope-area method of measuring open channel flow (Equation 1):

$$Q = \frac{A^{5/3}S^{1/2}}{P^{2/3}n} \qquad [1]$$

Where A = cross sectional area,
S = the hydraulic gradient,
P = the wetted perimeter, and
n = roughness coefficient.

The hydraulic gradient is taken as the slope of the channel and n corresponds with roughness values for a grass-lined channel (n = 0.022 – 0.033).

The slope-area method depends on a uniform flow pattern, accurate determination of the roughness coefficient, and accurate measurement of the cross-sectional area. The gaging location was ideal for measuring the cross sectional flow area until 2010 when the golf course constructed three golf-cart path culverts (Figure #): one just upstream of the upstream gage, one just downstream of the downstream gage, and another about 350 feet downstream of the downstream gage. These culverts are suspected to influence the flow pattern to such an extent that the slope-area method is now suspect.

Figure #. Satellite imagery of the culvert paths and the USGS crest-stage gages at the John Pitman Municipal Golf Course.

If these new culverts cause the peak water surface measurements to substantially increase at the gages, the flow calculation will estimate higher than the actual discharges. More specifically, the second culvert may slow the water under high flow conditions; the resulting raised water surface elevation would cause an unrealistic flat hydraulic gradient between the two gages.

Overestimation of downstream flows would cause unnecessary concern over the safety of the US 60 bridge crossing. This report documents the construction and application of one-dimensional and two-dimensional hydraulic models to estimate the possible effect of the culverts.

Purpose of the Two-Dimensional Model

A one-dimensional hydraulics-only Storm Water Management Model (SWMM) of the site has already been developed (Kaatz, 2012) and shows the placement of the culverts impacts the water surface elevation readings by as much as 10%. One-dimensional modeling cannot account for the effects of scouring or water recirculation, so some additional investigation is necessary.

A two-dimensional model was developed to include these recirculation effects and answer some questions that cannot be addressed by one-dimensional modeling. This two-dimensional model may be used to determine how flow along the river cross-sections is distributed for varying flow rates before and after the development of culverts. Additionally, there is some evidence of swirling water near the culvert crossings. The two-dimensional model is able to capture the vorticity of the flow and present these recirculation zones.

The two-dimensional model was created using the same hydraulic data as the one-dimensional model so the results may be directly comparable. Deviations in the results between the two models are of interest to reinforce the validity of the two-dimensional modeling effort. If the two-dimensional model is in agreement with the conclusions derived from the one-dimensional model, further investigation will need to be conducted to determine how far the stage-crest gages should be moved from the influence of the culverts.

High-Resolution Elevation Survey

To develop a model of the river system, the bathymetry of the riverbed needed to be surveyed. The Texas Tech University Water Resources Center provided a Total Station, data logger, surveying rod, and prism to the surveying team (Dr. William Asquith, Dr. Ted Cleveland, Travis Kaatz, and Janice Rainwater) on October 3, 2012. USGS reference markers at the site were used to reference elevation measurements.

A total of nineteen cross-sections perpendicular to the channel flow were catalogued along a 550-foot channel length. The distance between cross-sections never exceeded 130 feet, and the floodplains were surveyed until 5 feet above the thalweg elevation was obtained on either side of the creek. The floodplains are relatively flat (Figure #), so the cross-sections averaged 281.8 feet in length.

Figure #. Travis Kaatz holds the survey rod along the moderately sloped floodplain.

The culvert crossings were of particular interest. Notice in Figure # that the tops of the culverts were not completely flat. The tops of the culverts were surveyed on both the upstream and downstream edges to capture the geometry of the surface. Additional cross-sections were taken less than one foot upstream and downstream of each culvert to capture the inlet and exit invert elevations.

Figure #. View of the downstream side and top of the second culvert.

Figure #. View of the upstream culvert entrance and the corrugated metal culvert.

The 285 data points collected by the survey were used to create a three-dimensional rendering of the river in Surfer. All survey data were reported as points in UTM coordinates, and the Surfer renderings show the x-axis along the bottom, the y-axis up the left, and the z-axis as elevation contours at 6-inch intervals. The elevation datum was chosen to be the USGS reference in the trees downstream of Culvert 1, annotated in the surface plot, Figure #, as “RM 10 forced high point.” Figure # shows the survey cross-sections beginning with Cross-Section 18 and ending with Cross-Section 0 (downstream).

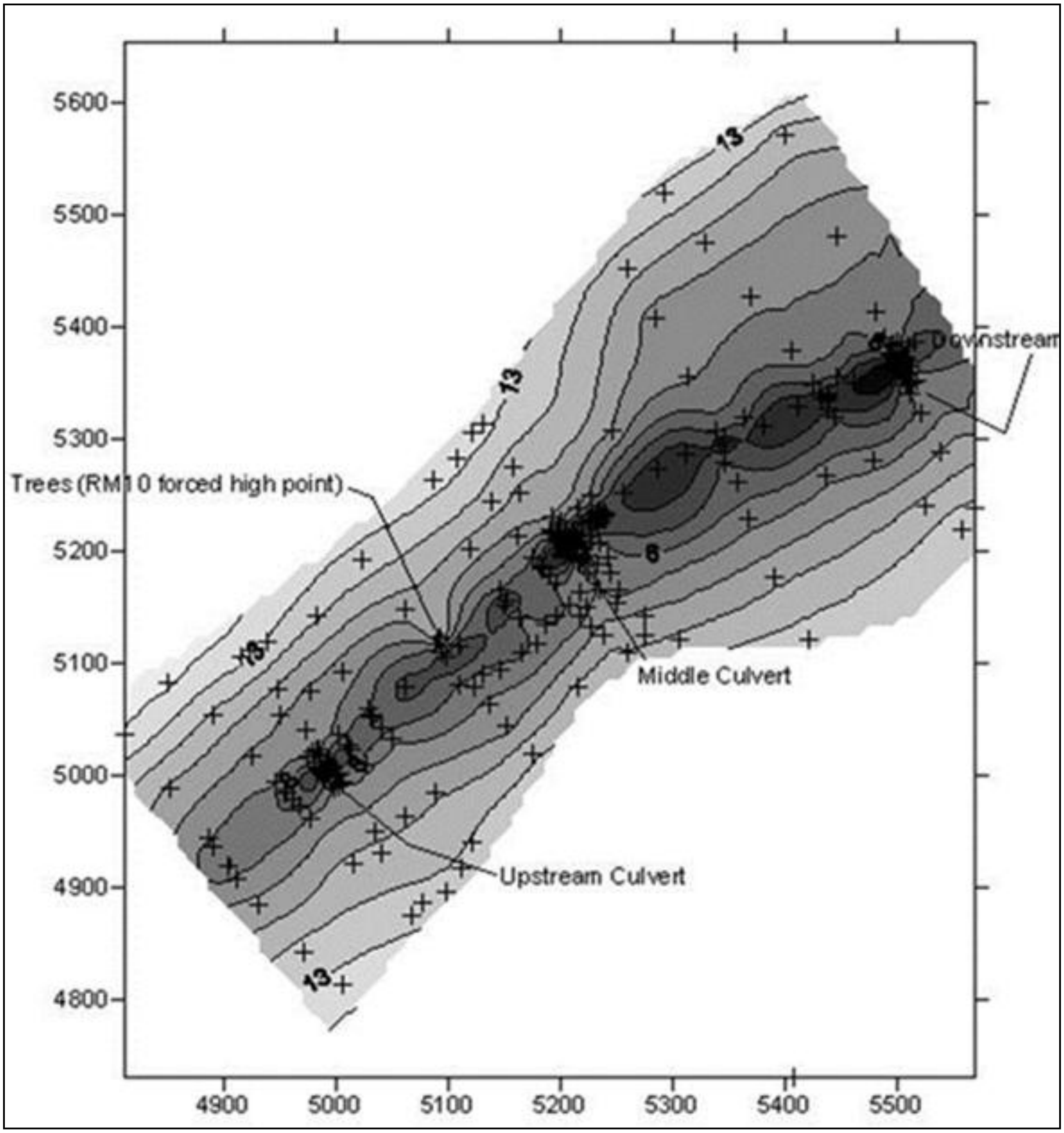


Figure #. Surface plot with 6-inch elevation contours.

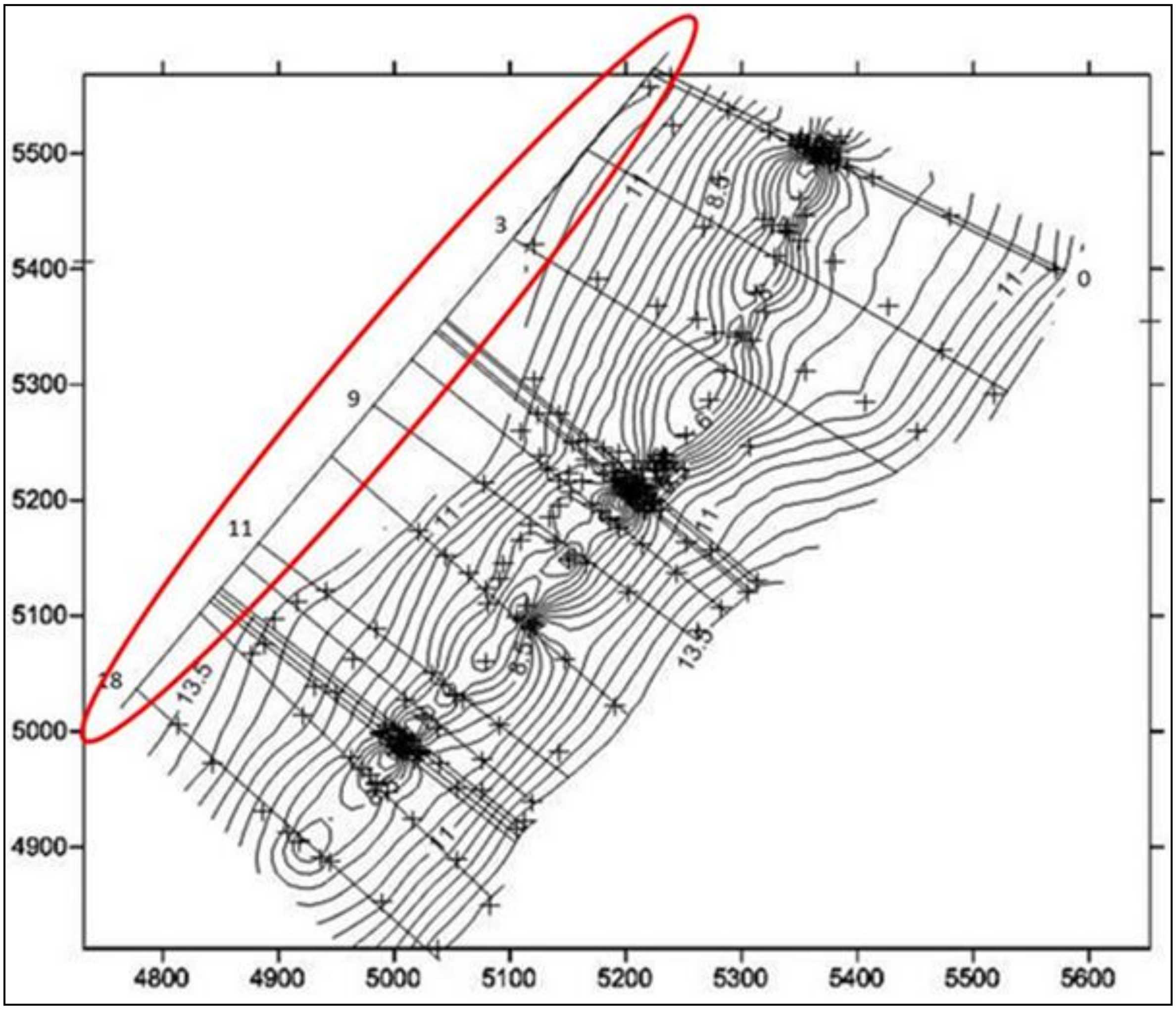


Figure #. Survey cross-sections

To use the survey data in a one-dimensional hydraulic model, cross-sections must be input as stations and elevations. To convert the x-y-z data into station-elevation data, a line essentially parallel to the river was used as a datum (note the red ellipse in Figure #.). Station measurements were taken as the distance to each survey point perpendicular to the datum. The elevations corresponding to each point were unchanged. Any error associated with this assumption would be quite small because the floodplains were so flat. The distances between each cross-section were calculated along the thalweg of the riverbed parallel to the datum.

Two-Dimensional Flow Model

Pre-Development Model

The pre-development model represents the Tierra Blanca Creek before the construction of the golf cart paths. Survey cross-sections that describe the culverts were excluded and the remaining cross-sections were interpolated to define a continuous stream without culverts or scour holes. Figure # presents the calculation grid for the Tierra Blanca Creek without culverts. The compound channel was defined by 168 nodes, a low channel region (shown by the purple rectangle), and an approximation of the thalweg. The two red circles indicate the nodes at the gage locations.

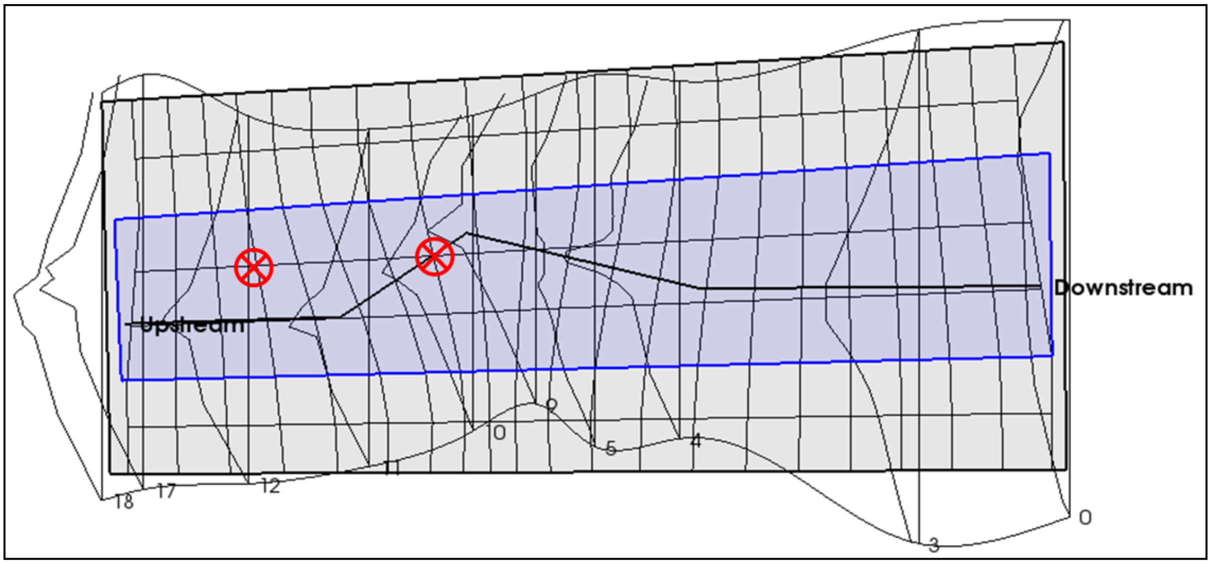


Figure #. iRIC calculation grid, transverse cross-sections, and gage locations for the river without culverts.

This pre-development model was run assuming uniform flow rates 5.66 m^3/s (200-cfs), 8.50 m^3/s (300-cfs), 11.33 m^3/s (400 cfs), and 14.16 m^3/s (500-cfs). Table # presents the iRIC-generated depth plots with velocity vectors and Excel-generated graphs of the water-level change between the two gages. Though the depth plots are difficult to interpret, the red areas along the river support the supposition that water flows fastest where the water is deepest. The dark blue areas indicate the extent of the flow area. The entire depth plot is reflective of the grid geometry.

The difference in water surface elevation between the gages represents the hydraulic gradient of the stream, a parameter of the slope-area method (Equation 1). The importance of the hydraulic grade line provides another useful way to compare pre- and post-development results.

Table #. Depth plots and change in water surface elevation for the pre-development model.

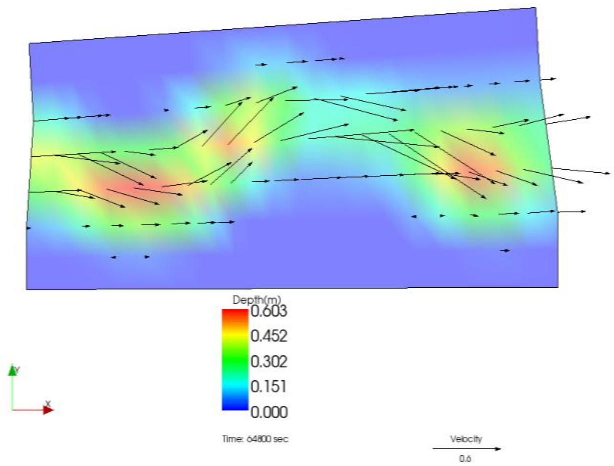
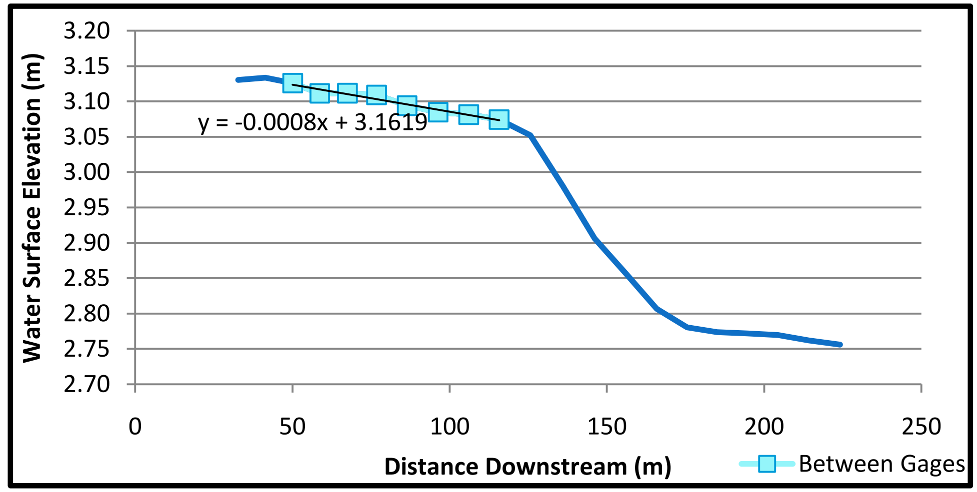
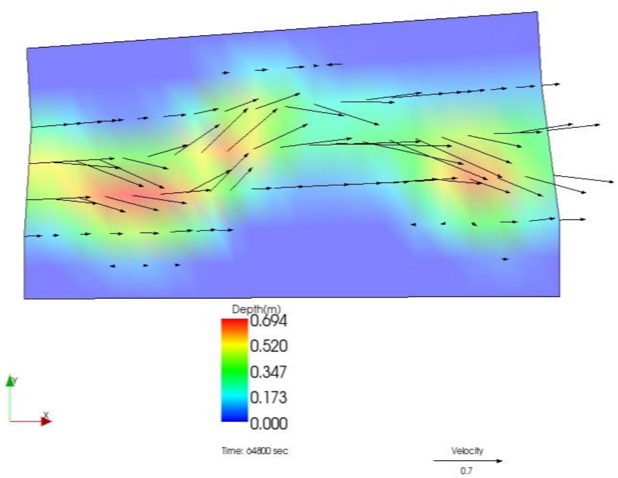
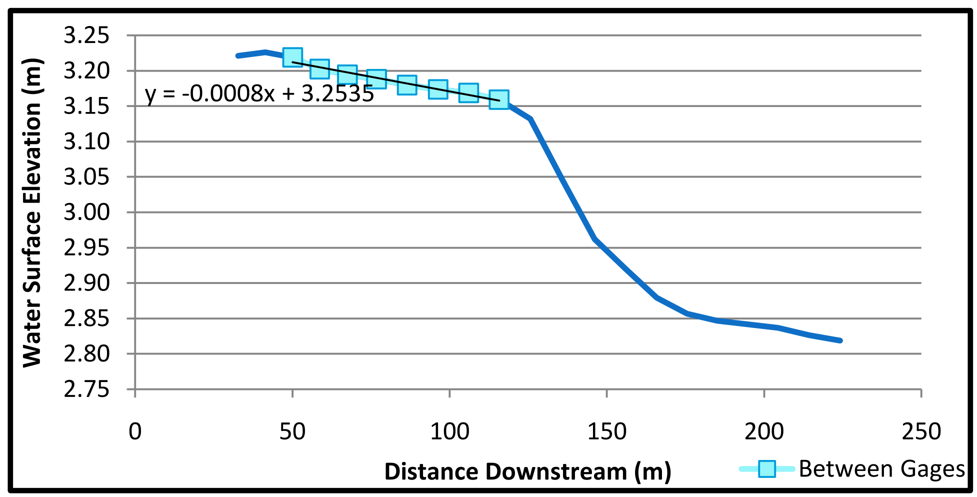
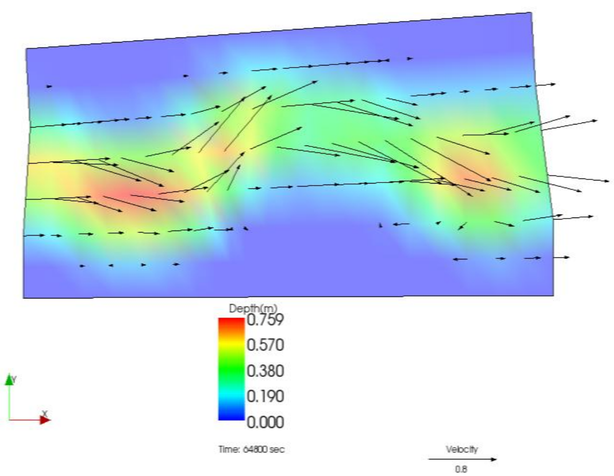
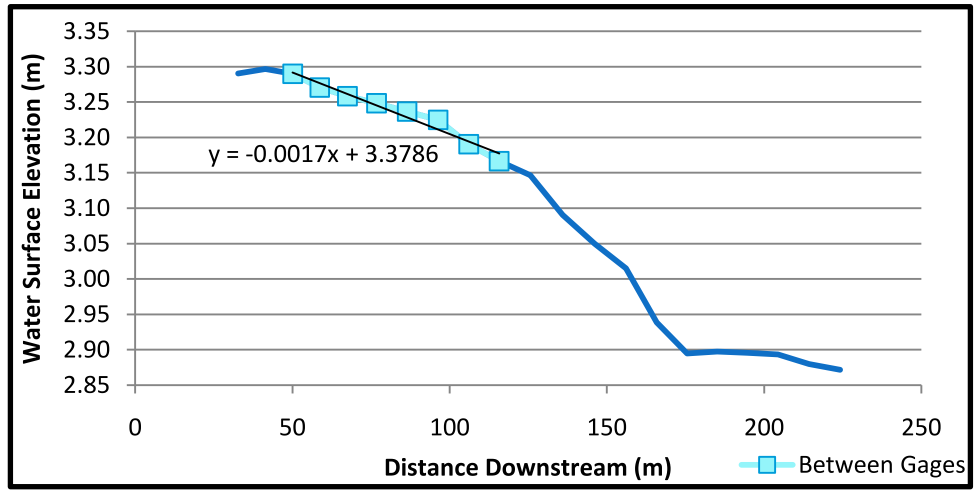
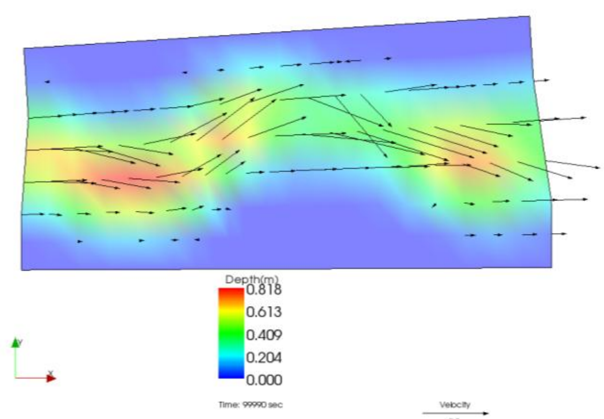
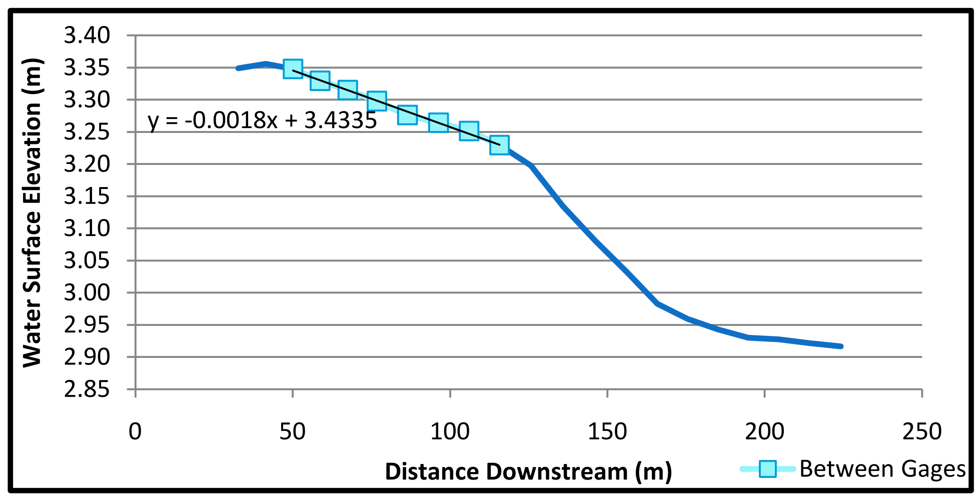
iRIC-generated Depth Plots with Velocity Vectors	Water Surface Elevation Graphs
	
Results for uniform flow at 5.66 m^3/sec	
	
Results for uniform flow at 8.50 m^3/sec	

Table #, Continued. Depth plots and change in water surface elevation for the pre-development model.

iRIC-generated Depth Plots with Velocity Vectors	Water Surface Elevation Graphs
	
Results for uniform flow at 11.33 m^3/sec	
	
Results for uniform flow at 14.16 m^3/sec	

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Post-Development Model

The culverts have a diameter of 1.22 meters and concrete headwalls. At the time of the survey, which happened to be about a week after a high flow event, the culverts were clear of debris but surrounded by brush. Figure # is a photograph of the upstream culvert taken during the survey. Notice the shallow riverbed and the geometry of the culvert crossings. The iRIC platform can only model open channels, that is, there can be no upper boundary between the channel and the sky. The effect of the culverts must be approximated by adjusting the flow area, so culverts were represented as 1 meter wide notches in the elevation (Figure #); this width is slightly narrower than the culvert diameter to better represent flow volume.

Figure #. View of the most upstream culvert and the upstream gage.

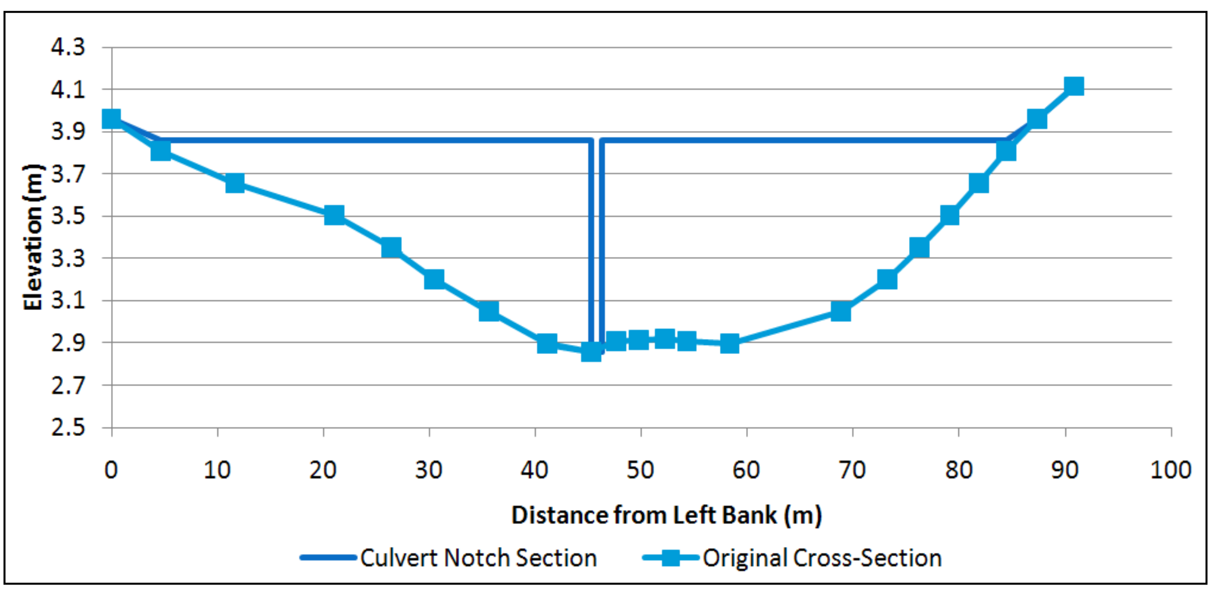


Figure #. Cross-section of the most upstream culvert represented in iRIC as a notch.

The survey data were adequately close (within 0.1 meter) to the culvert cross-sections to prevent iRIC from interpolating these cross-sections. This model accounts for the effects of scour holes, so the real survey data was not interpolated.

The most upstream and the most downstream survey data were culvert cross-sections, so two additional cross-sections, labeled 29 and -1, were added to extend the upstream and downstream ends of the river by ten meters. These extensions allowed for the centerline of the channel area (shown in purple) to include the culvert geometry.

Despite the extra cross-sections, the calculation grid for the stream with culverts was similar to the previous grid. The new grid also used 168 calculation nodes and has the same number of columns and rows as the pre-conditions grid. The shape of the grid cells is the only changed between the two grids, as shown in Figure #. The culvert cross-sections are circled in red and the locations of the USGS crest-stage gages are indicated.

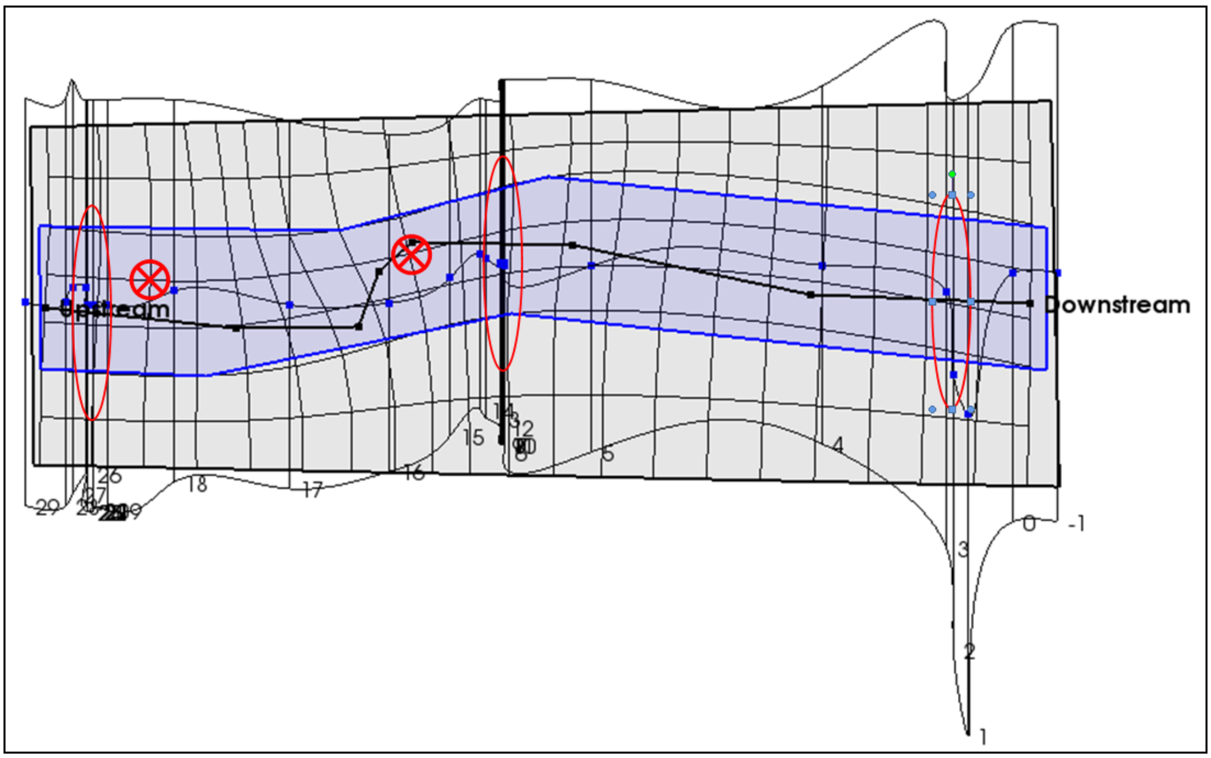
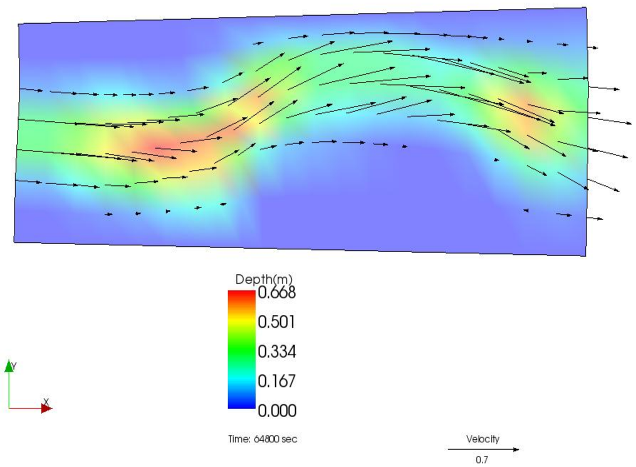
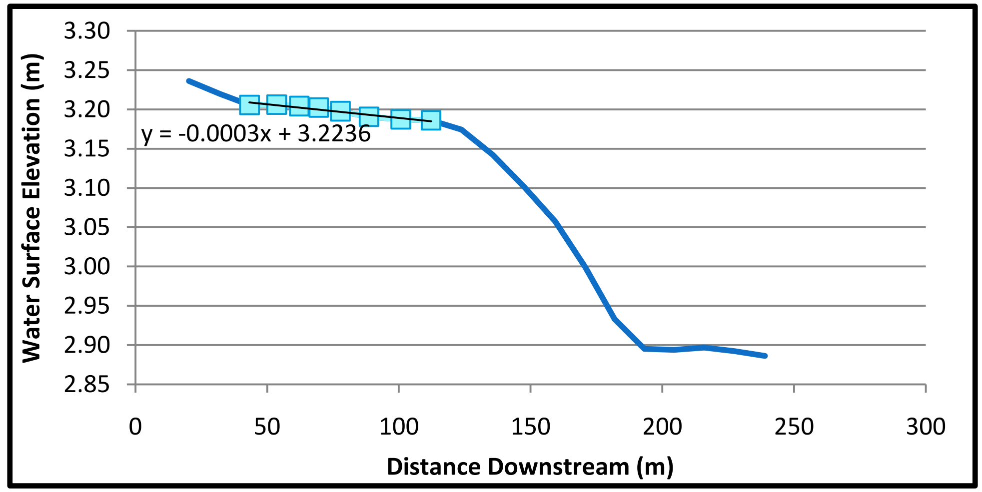


Figure #. iRIC calculation grid and transverse cross-sections for the river with culverts.

This model represents the current conditions and was run assuming uniform flow rates of 200-cfs (5.66 m^3/s), 300-cfs (8.50 m^3/s), 400-cfs (11.33 m^3/s), and 500-cfs (14.16 m^3/s). Table # presents the iRIC-generated depth plots with velocity vectors and Excel-generated graphs of the water-level change between the two gages. Notice the location of the culverts may be recognized by the presence of recirculation in the velocity vector field.

Table #. Depth plots and change in water surface elevation for the current-conditions model.

<table>
<tr><th>iRIC-generated Depth Plots with Velocity Vectors</th><th>Water Surface Elevation Graphs</th></tr>
<tr><td>
</td><td>
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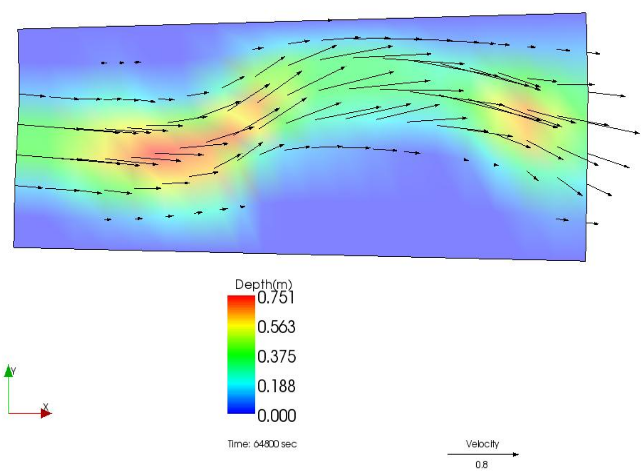
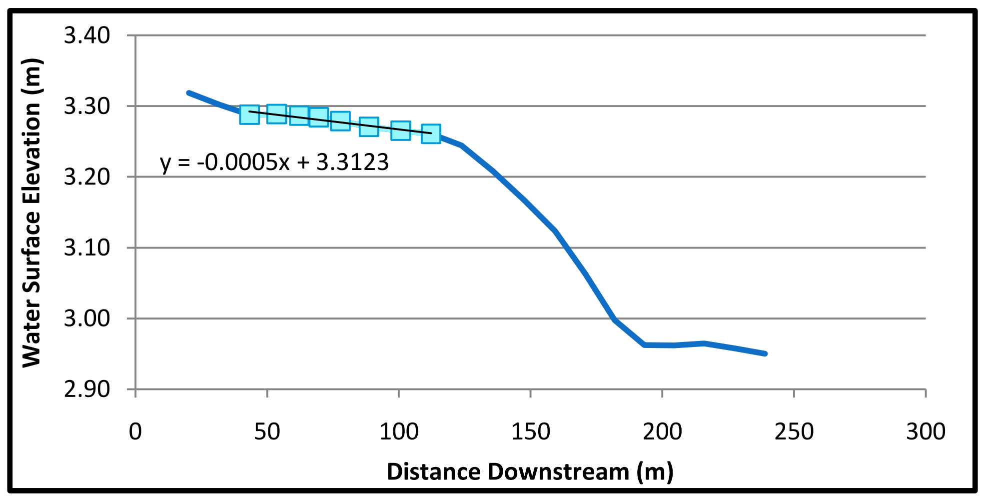
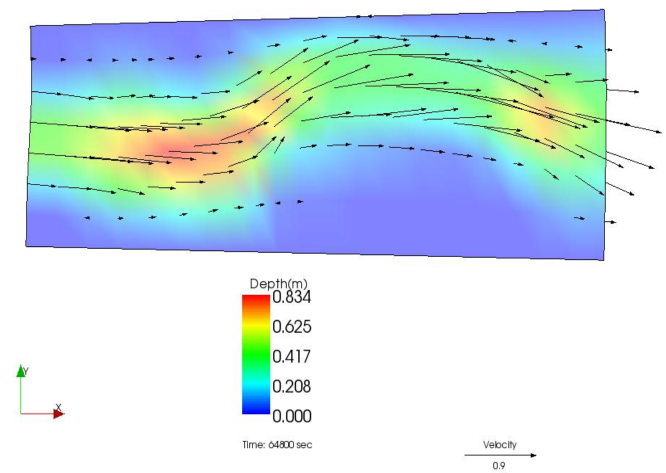
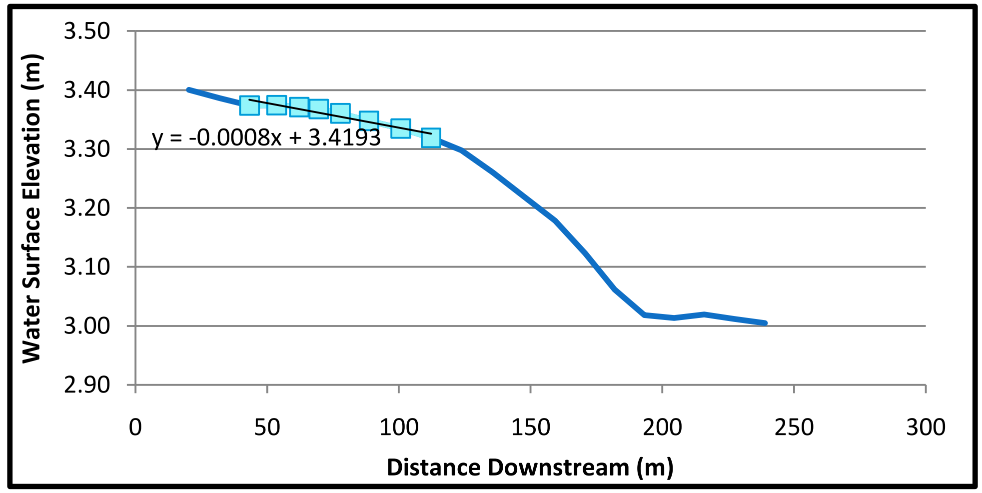
<tr><td colspan="2">Results for uniform flow at 5.66 m³/sec</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Results for uniform flow at 8.50 m³/sec</td></tr>
</table>

Table #, Continued. Depth plots and change in water surface elevation for the current-conditions model.

<table>
<tr><th>iRIC-generated Depth Plots with Velocity Vectors</th><th>Water Surface Elevation Graphs</th></tr>
<tr><td>
</td><td>
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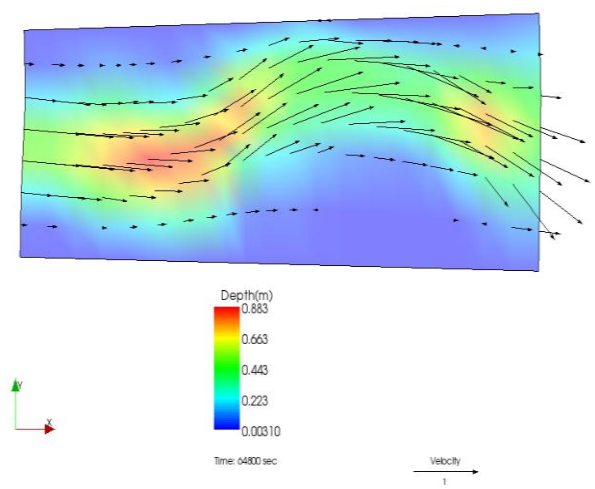
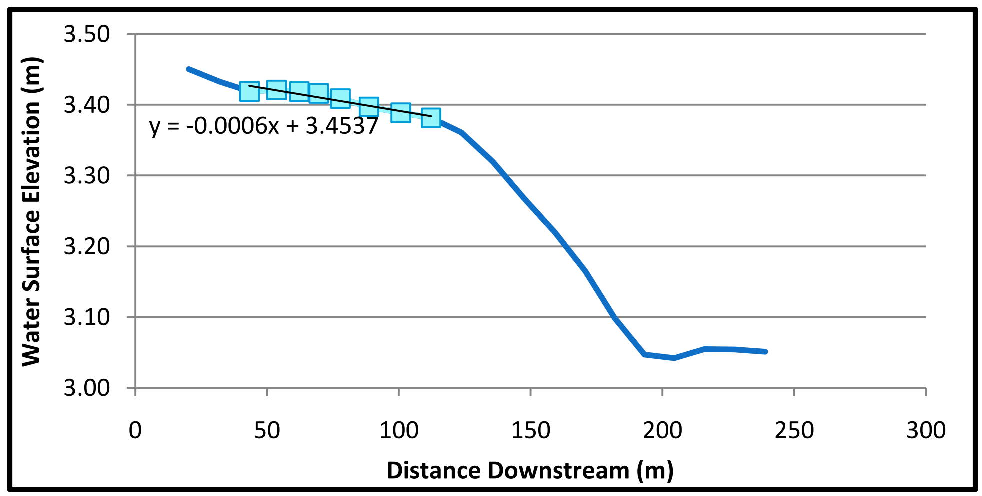
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">**Results for uniform flow at 14.16 m^3/sec**</td></tr>
</table>

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Interpretation of Results

The model converged to a solution for each of the eight flow scenarios. Table # presents the water surface elevations at the gage locations for each case.

Table #. Deviation between pre- and post-development water surface elevations.

Flow Rate (cms)	Gage	Water Surface Elevation (m)		% Difference
		No Culverts	Culverts	
5.66	Upstream	3.13	3.21	2.6
	Downstream	3.07	3.19	3.9
8.50	Upstream	3.22	3.29	2.2
	Downstream	3.16	3.26	3.2
11.33	Upstream	3.29	3.37	2.4
	Downstream	3.17	3.32	4.7
14.16	Upstream	3.35	3.42	2.1
	Downstream	3.23	3.38	4.6

The model reported an increase in the water surface elevation for every flow scenario after the addition of the culverts. It is important to note that both the SWMM and iRIC models show that water flows over the tops of the culverts for the 11.33 cms and 14.16 cms flow rates. The downstream gage was more affected than the upstream gage because of its position just upstream of the second culvert.

The deviation between the pre-development model and the model with culverts is of a similar magnitude (between 2.2% and 4.7%) regardless of whether the culverts are overtopped. For this modeling effort, the greatest deviations occur when the flow rate is 11.33 cms. The tight range in the percent difference supports the accuracy of the model.

Though the magnitude of the hydraulic gradient is small between the gages, it is impactful to the slope-area flow calculations to the one-half power. Table # shows the construction of culverts consistently decreased the hydraulic gradient from the pre-development values. The second culvert causes the water level to be higher at the downstream gage, effectively flattening the slope of the water surface between the gages.

Table #. Slope of the hydraulic gradient between gages

Flow Rate (cms)	Hydraulic Gradient (m/m)		% Difference
	No Culverts	Culverts	
5.66	0.00078	0.00029	62.7
8.50	0.00091	0.00041	55.0
11.33	0.00187	0.00084	55.3
14.16	0.00181	0.00056	68.9

Comparison to One-Dimensional Model

Table # shows the SWMM results alongside the iRIC model results. The SWMM values represent steady-state flow conditions at eighteen hours of simulation time (Kaatz, 2012), so the water surface elevations reported for the iRIC values were chosen at eighteen hours for comparison. Both models show that the culverts increased the water levels at the gages, but the two-dimensional model reported consistently lower water levels than the one-dimensional model. Figure # plots the information in Table #.

Table #. Water surface elevations and deviations between 1-dimensional and 2-dimensional models for Tierra Blanca Creek with and without culverts.

Flow rate (cms)	Gage	Water Surface Elevation (m)					
		No Culverts			Culverts		
		1-D Model	2-D Model	% Difference	1-D Model	2-D Model	% Difference
5.66	Upstream	3.00	3.13	4.2	3.28	3.21	2.2
	Downstream	3.06	3.07	0.3	3.31	3.19	3.8
8.50	Upstream	3.28	3.22	1.9	3.39	3.29	3.0
	Downstream	3.36	3.16	6.3	3.41	3.26	4.6
11.33	Upstream	3.38	3.29	2.7	3.47	3.37	3.0
	Downstream	3.46	3.17	9.1	3.50	3.32	5.4
14.16	Upstream	3.44	3.35	2.7	3.52	3.42	2.9
	Downstream	3.54	3.23	9.6	3.54	3.38	4.7

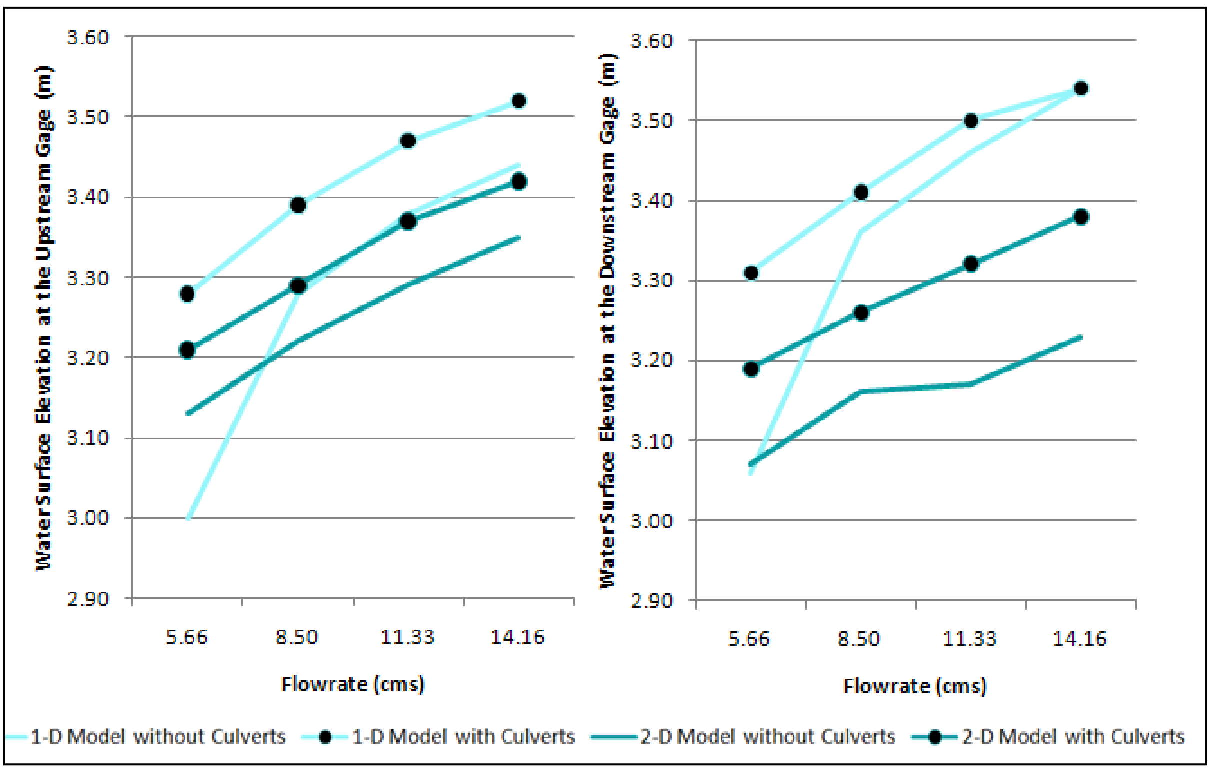

Figure #. Graphical comparison of 1-dimensional and 2-dimensional modeling results for water surface elevation with and without culverts at the gage locations.

Conclusions

The results show that the culverts affect the water level readings at the USGS gages. These results are supported by both one-dimensional and two-dimensional modeling.

Benefits of the Two-Dimensional Model

Two-dimensional solutions are not forced to follow pre-defined flow paths, so for the modeling of Tierra Blanca Creek, this two-dimensional model is well able to model where flows spread out and follow the topography. In this flooding situation, two-dimensional results have considerably less uncertainty than one-dimensional solutions. Comparison of the two-dimensional modeling effort to the one-dimensional model reassures that the culverts increase the water level at the gages.

The two-dimensional model indicates some recirculation in the presence of culverts; this recirculation explains the presence of scour holes and pitting upstream of the culvert headwalls. As expected, the highest flow velocity occurs along the thalweg of the river and the majority of the flow volume takes place in the riverbed, rather than the floodplains, for all flow simulations. The SWMM model could not capture these effects because a one-dimensional model must assume unidirectional flow.

It may sometimes be appropriate to use one-dimensional modeling to obtain starting flow values or estimate an initial water surface elevation. This modeling effort did not require such input and proves that two-dimensional models may be run independent of one-dimensional models. This assertion is supported by the similar results between the SWMM and iRIC models.

Recommendations for Future Study

The new culverts are impacting the water levels at the gage locations, so the crest-stage gages do not provide an accurate representation of peak flow. It is recommended that the gages be moved away from the influence of the culverts to aid in accurate flow calculations at the US-60 bridge crossing.

It has been proposed that the gages be moved further downstream in order for water surface measurements to be accurate within one-tenth of a foot. To calculate the necessary downstream distance the site should be represented by a two-dimensional International River Interface Cooperative (iRIC) model both with and without the culverts.

Ideally, new survey data should be taken to represent the river for several hundred feet upstream and downstream of the culverts. A new model could then be developed to determine the extent of the culverts' influence on the water level.

Another way to approximate the necessary distance would be to artificially extend the existing two-dimensional model and find where the water level stabilizes upstream and downstream of the existing culverts. Comparison to the pre-development model may also be necessary.

Works Cited

Kaatz, T. (2012). *USGS Flow Gage Station Near Hereford, TX.* Lubbock, Texas: Texas Tech University.

Texas State Historical Association. (2013). *Tierra Blanca Creek*. Retrieved February 5, 2013, from Handbook of Texas Online: http://www.tshaonline.org/handbook/online/articles/rbt49

Appendix A

2-Dimensional Modeling Raw Results Tables for the Tierra Blanca Creek without Culverts

Table A1. Centerline Flow Data for the Creek without Culverts and 200 CFS (5.66 m^3/s) Flowrate after Eighteen Hours of Simulation Time

	Depth (m)	Elevation (m)	Water Surface Elevation (m)	Vorticity (1/s)	X-Velocity (m/s)	Y Velocity (m/s)	Velocity Magnitude (m/s)
	0.440	2.690	3.130	0.000	0.728	0.040	0.729
	0.421	2.713	3.134	0.000	0.558	-0.063	0.562
Upstream Gage	0.367	2.758	3.126	-0.002	0.560	-0.241	0.610
	0.314	2.797	3.111	0.035	0.465	-0.197	0.505
	0.291	2.821	3.112	0.041	0.252	-0.028	0.254
	0.287	2.823	3.109	0.036	0.234	0.017	0.235
	0.317	2.777	3.094	0.049	0.265	0.137	0.298
	0.433	2.652	3.085	0.037	0.341	0.342	0.483
	0.535	2.546	3.081	0.003	0.387	0.364	0.531
Downstream Gage	0.456	2.618	3.074	-0.016	0.416	0.228	0.474
	0.279	2.773	3.052	-0.023	0.580	0.128	0.594
	0.182	2.799	2.981	-0.037	0.916	0.070	0.919
	0.205	2.701	2.906	-0.046	0.889	-0.077	0.893
	0.231	2.625	2.856	-0.028	0.802	-0.340	0.871
	0.232	2.574	2.807	-0.003	0.838	-0.506	0.979
	0.286	2.495	2.780	0.013	0.696	-0.404	0.805
	0.356	2.418	2.774	0.028	0.465	-0.192	0.503
	0.383	2.389	2.772	0.033	0.316	-0.034	0.317
	0.349	2.421	2.769	0.024	0.302	0.057	0.307
	0.267	2.494	2.762	0.018	0.375	0.088	0.385
	0.219	2.537	2.756	0.018	0.378	0.055	0.382

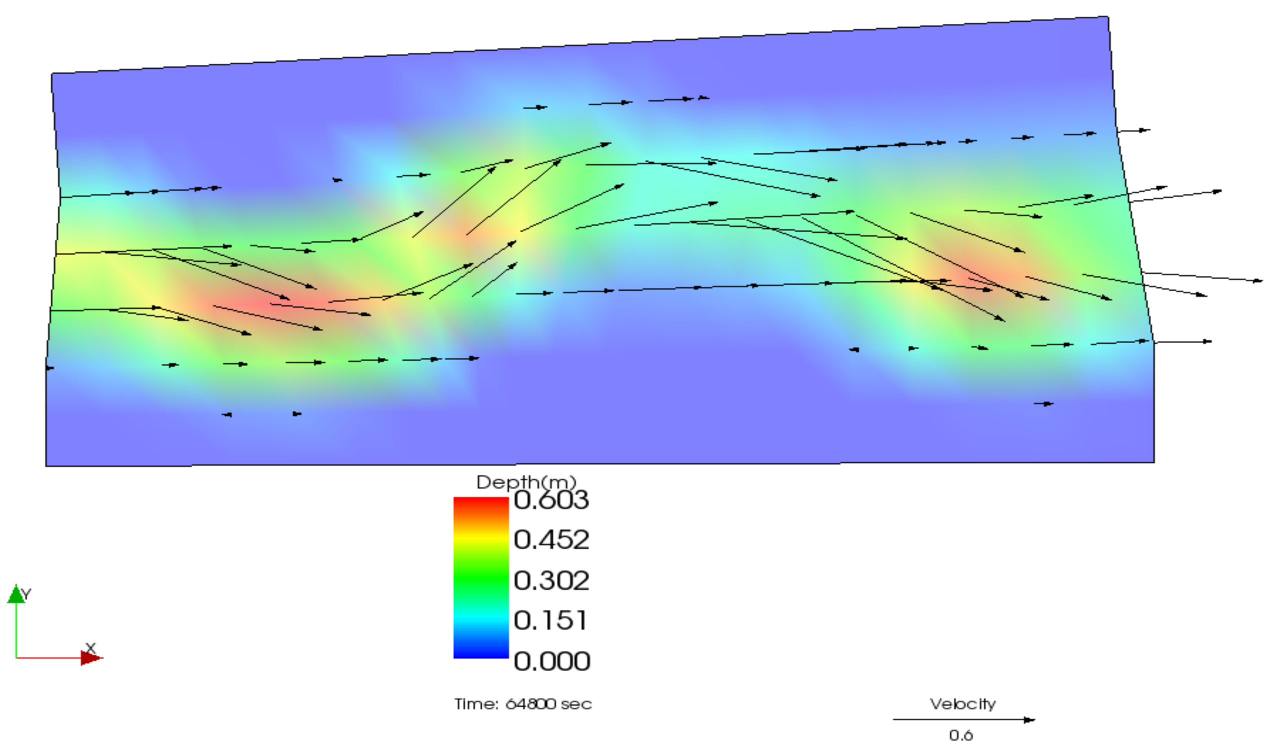

Figure A1. iRIC-generated Depth Plot with Velocity Vectors for 200 CFS (5.66 m^3/s) Flowrate

Table A2. Centerline Flow Data for the Creek without Culverts and 300 CFS (8.50 m^3/s) Flowrate after Eighteen Hours of Simulation Time

	Depth (m)	Elevation (m)	Water Surface Elevation (m)	Vorticity (1/s)	X-Velocity (m/s)	Y Velocity (m/s)	Velocity Magnitude (m/s)
	0.531	2.690	3.221	-0.001	0.849	0.047	0.850
	0.514	2.713	3.226	-0.001	0.672	-0.051	0.674
Upstream Gage	0.461	2.758	3.219	-0.005	0.667	-0.228	0.705
	0.405	2.797	3.202	0.020	0.643	-0.256	0.692
	0.374	2.821	3.194	0.047	0.435	-0.094	0.445
	0.366	2.823	3.188	0.039	0.379	0.099	0.392
	0.403	2.777	3.180	0.026	0.440	0.266	0.514
	0.522	2.652	3.174	0.023	0.457	0.393	0.603
	0.623	2.546	3.169	0.001	0.490	0.373	0.615
Downstream Gage	0.541	2.618	3.159	-0.016	0.525	0.219	0.569
	0.359	2.773	3.132	-0.018	0.702	0.079	0.707
	0.247	2.799	3.045	-0.027	1.119	0.033	1.119
	0.261	2.701	2.962	-0.033	1.160	-0.023	1.160
	0.295	2.625	2.920	-0.024	0.997	-0.198	1.017
	0.305	2.574	2.879	-0.016	0.978	-0.352	1.040
	0.362	2.495	2.857	-0.007	0.863	-0.346	0.930
	0.429	2.418	2.847	0.010	0.686	-0.232	0.724
	0.453	2.389	2.842	0.026	0.533	-0.101	0.542
	0.416	2.421	2.837	0.026	0.461	0.015	0.461
	0.332	2.494	2.826	0.022	0.510	0.071	0.515
	0.282	2.537	2.819	0.022	0.513	0.050	0.515

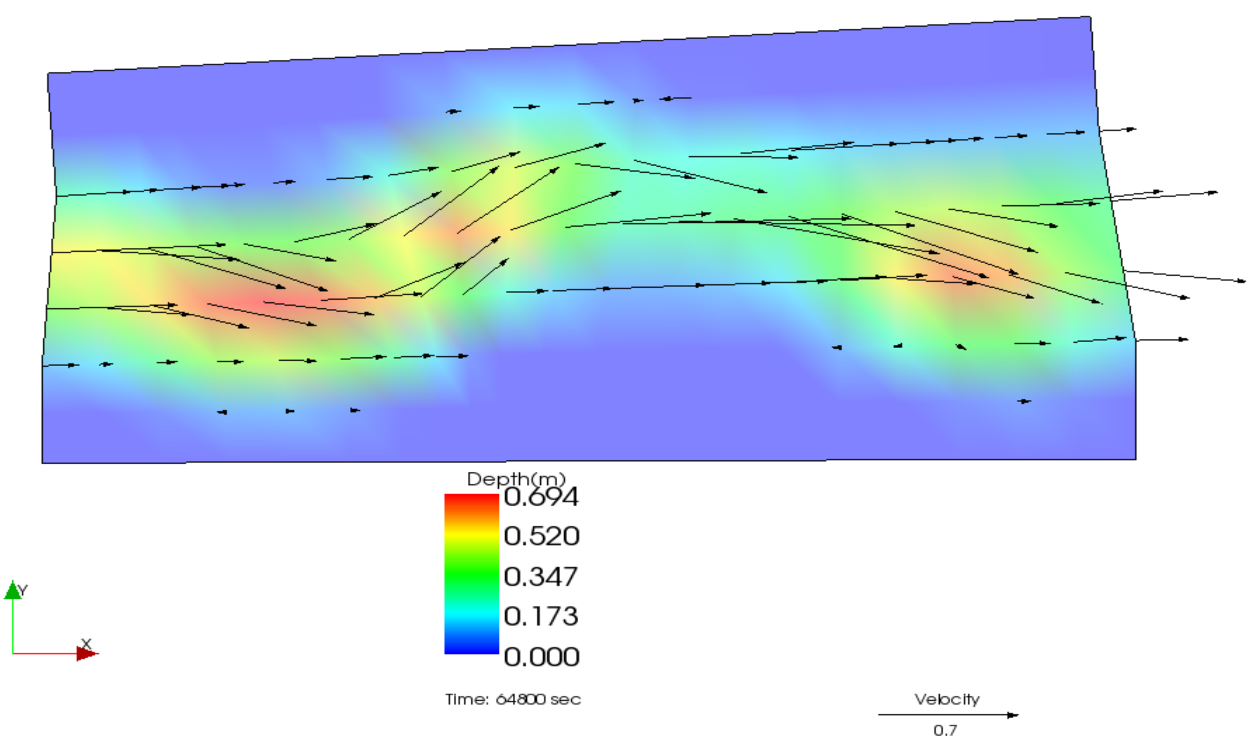

Figure A2. iRIC-generated Depth Plot with Velocity Vectors for 300 CFS (8.50 m^3/s) Flowrate

Table A3. Centerline Flow Data for the Creek without Culverts and 400 CFS (11.33 m^3/s) Flowrate after Eighteen Hours of Simulation Time

	Depth (m)	Elevation (m)	Water Surface Elevation (m)	Vorticity (1/s)	X-Velocity (m/s)	Y Velocity (m/s)	Velocity Magnitude (m/s)
	0.600	2.690	3.290	-0.002	0.942	0.052	0.943
	0.584	2.713	3.297	-0.002	0.765	-0.030	0.765
Upstream Gage	0.531	2.758	3.290	-0.014	0.756	-0.205	0.783
	0.474	2.797	3.271	0.005	0.757	-0.278	0.807
	0.438	2.821	3.258	0.033	0.595	-0.139	0.611
	0.426	2.823	3.248	0.037	0.505	0.093	0.513
	0.459	2.777	3.237	0.029	0.529	0.331	0.625
	0.573	2.652	3.225	0.021	0.532	0.570	0.779
	0.644	2.546	3.190	-0.035	0.537	0.564	0.779
Downstream Gage	0.548	2.618	3.167	-0.055	0.578	0.219	0.618
	0.373	2.773	3.147	-0.039	0.711	-0.086	0.716
	0.292	2.799	3.090	-0.021	1.041	-0.175	1.055
	0.349	2.701	3.050	-0.019	0.994	-0.247	1.024
	0.390	2.625	3.015	-0.004	0.959	-0.435	1.053
	0.364	2.574	2.939	0.043	1.002	-0.572	1.154
	0.400	2.495	2.895	0.061	0.925	-0.436	1.023
	0.479	2.418	2.897	0.064	0.606	-0.176	0.631
	0.507	2.389	2.896	0.054	0.522	0.017	0.523
	0.472	2.421	2.893	0.041	0.520	0.120	0.533
	0.385	2.494	2.880	0.026	0.628	0.167	0.650
	0.335	2.537	2.872	0.026	0.635	0.102	0.643

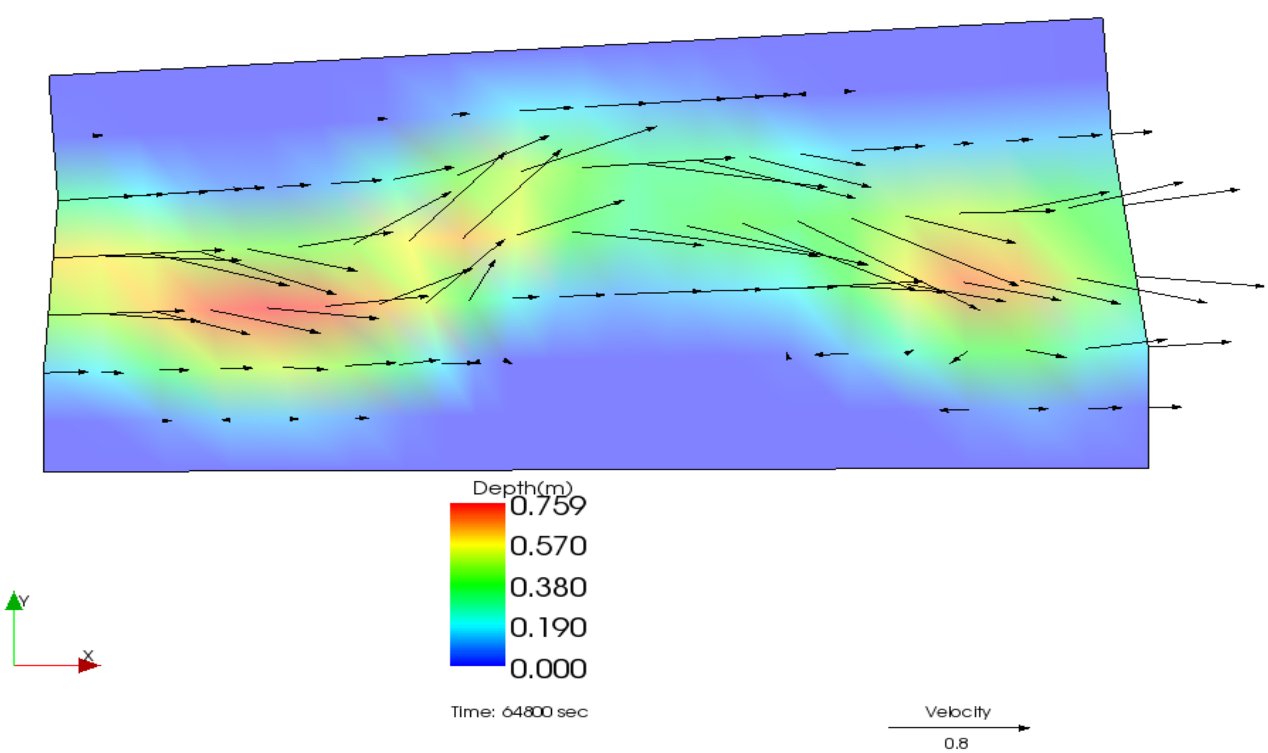

Figure A3. iRIC-generated Depth Plot with Velocity Vectors for 400 CFS (11.33 m^3/s) Flowrate

Table A4. Centerline Flow Data for the Creek without Culverts and 500 CFS (14.16 m^3/s) Flowrate after Eighteen Hours of Simulation Time

	Depth (m)	Elevation (m)	Water Surface Elevation (m)	Vorticity (1/s)	X-Velocity (m/s)	Y Velocity (m/s)	Velocity Magnitude (m/s)
	0.659	2.690	3.349	-0.003	1.019	0.056	1.021
	0.643	2.713	3.356	-0.003	0.842	-0.034	0.842
Upstream Gage	0.590	2.758	3.348	-0.007	0.829	-0.202	0.853
	0.532	2.797	3.329	0.007	0.852	-0.258	0.891
	0.494	2.821	3.315	0.034	0.711	-0.117	0.720
	0.475	2.823	3.298	0.033	0.672	0.138	0.686
	0.499	2.777	3.276	0.021	0.754	0.395	0.851
	0.613	2.652	3.264	0.017	0.770	0.574	0.960
	0.705	2.546	3.251	-0.023	0.704	0.527	0.880
Downstream Gage	0.611	2.618	3.229	-0.044	0.761	0.272	0.808
	0.424	2.773	3.197	-0.038	0.941	0.035	0.941
	0.336	2.799	3.135	-0.031	1.246	-0.117	1.252
	0.380	2.701	3.081	-0.031	1.266	-0.294	1.300
	0.408	2.625	3.033	-0.009	1.224	-0.394	1.286
	0.408	2.574	2.983	-0.007	1.210	-0.375	1.266
	0.465	2.495	2.959	-0.005	1.044	-0.338	1.097
	0.525	2.418	2.943	0.017	0.841	-0.265	0.882
	0.541	2.389	2.930	0.036	0.688	-0.145	0.703
	0.507	2.421	2.927	0.036	0.584	-0.011	0.584
	0.427	2.494	2.922	0.030	0.602	0.053	0.604
	0.380	2.537	2.917	0.030	0.604	0.044	0.606

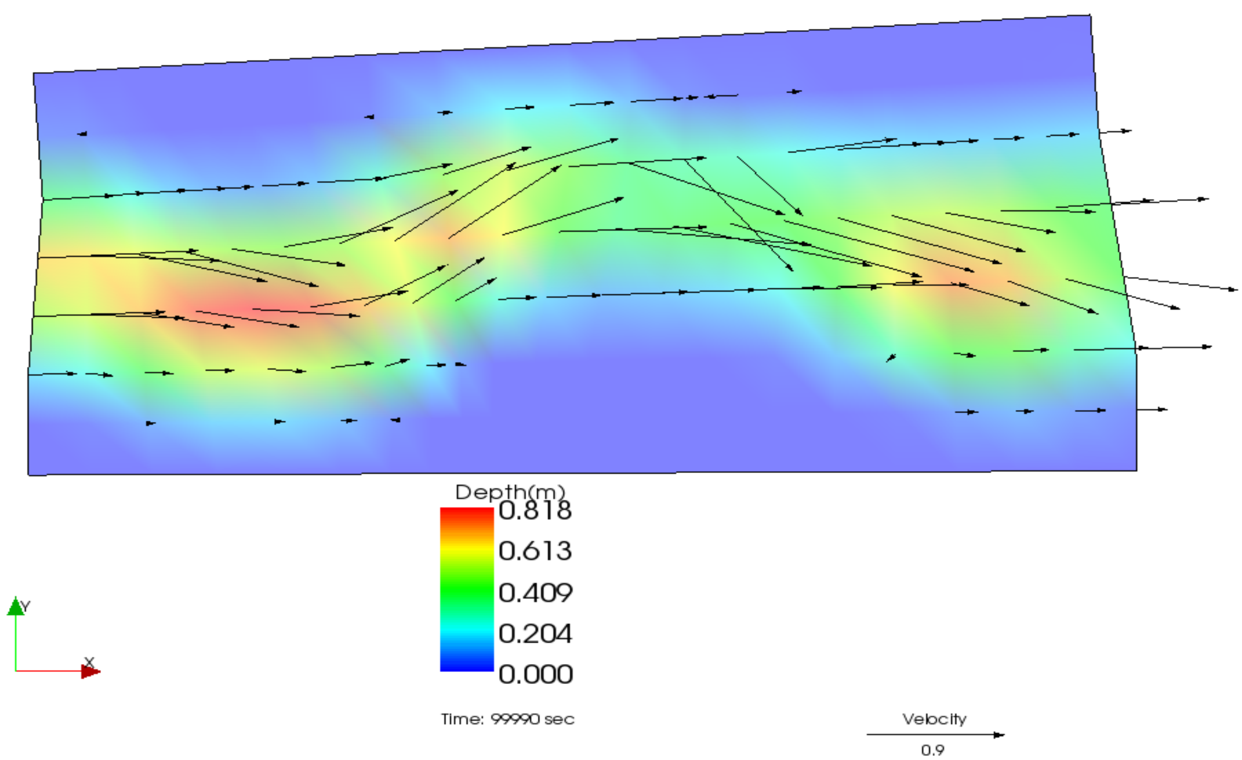

Figure A4. iRIC-generated Depth Plot with Velocity Vectors for 500 CFS (14.16 m^3/s) Flowrate

Appendix B

2-Dimensional Modeling Raw Results Tables for the Tierra Blanca Creek with Culverts

Table B1. Centerline Flow Data for the Creek with Culverts and 200 CFS (5.66 m^3/s) Flowrate after Eighteen Hours of Simulation Time

	Depth (m)	Elevation (m)	Water Surface Elevation (m)	Vorticity (1/s)	X-Velocity (m/s)	Y Velocity (m/s)	Velocity Magnitude (m/s)
	0.277	2.959	3.236	0.029	0.584	-0.041	0.585
	0.288	2.932	3.220	0.029	0.671	-0.048	0.672
Upstream Gage	0.359	2.846	3.206	0.034	0.529	-0.030	0.530
	0.441	2.765	3.206	0.028	0.393	-0.006	0.393
	0.474	2.730	3.204	0.015	0.334	0.005	0.334
	0.462	2.740	3.202	0.005	0.309	0.005	0.309
	0.387	2.811	3.198	0.008	0.339	0.026	0.340
	0.341	2.850	3.191	0.019	0.387	0.125	0.406
	0.473	2.714	3.187	0.022	0.396	0.236	0.461
Downstream Gage	0.578	2.608	3.186	0.010	0.409	0.260	0.485
	0.425	2.749	3.175	0.000	0.527	0.223	0.572
	0.282	2.860	3.142	-0.006	0.727	0.153	0.743
	0.270	2.831	3.102	-0.013	0.774	0.065	0.777
	0.267	2.791	3.058	-0.016	0.816	-0.030	0.816
	0.253	2.746	3.000	-0.015	0.904	-0.157	0.917
	0.247	2.686	2.933	-0.012	0.986	-0.265	1.021
	0.315	2.580	2.895	-0.006	0.833	-0.274	0.877
	0.486	2.407	2.894	0.008	0.539	-0.202	0.576
	0.584	2.313	2.897	0.011	0.334	-0.077	0.343
	0.450	2.442	2.892	0.004	0.406	-0.023	0.407
	0.322	2.564	2.886	0.004	0.408	-0.054	0.412

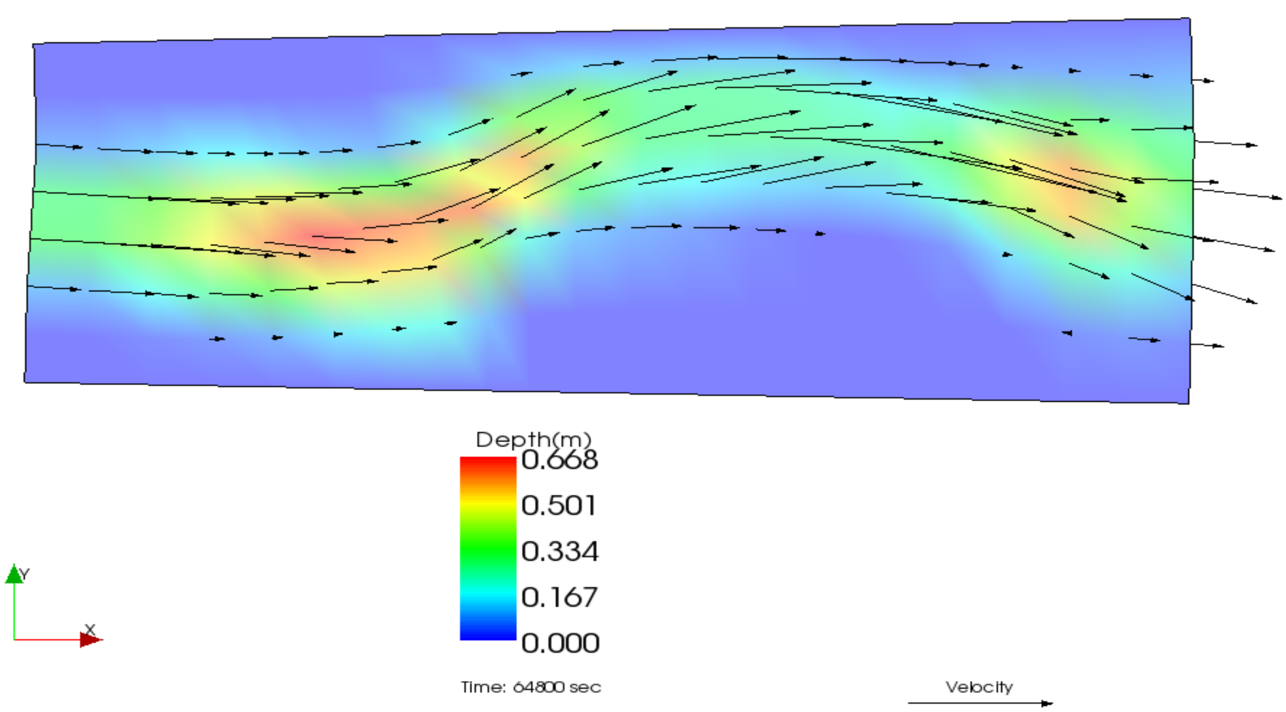

Figure B1. iRIC-generated Depth Plot with Velocity Vectors for 200 CFS (5.66 m^3/s) Flowrate

Table B2. Centerline Flow Data for the Creek with Culverts and 300 CFS (8.50 m^3/s) Flowrate after Eighteen Hours of Simulation Time

	Depth (m)	Elevation (m)	Water Surface Elevation (m)	Vorticity (1/s)	X-Velocity (m/s)	Y Velocity (m/s)	Velocity Magnitude (m/s)
	0.360	2.959	3.319	0.027	0.692	-0.049	0.693
	0.370	2.932	3.302	0.027	0.783	-0.057	0.785
Upstream Gage	0.442	2.846	3.288	0.030	0.653	-0.048	0.655
	0.524	2.765	3.289	0.029	0.499	-0.037	0.501
	0.557	2.730	3.286	0.026	0.429	-0.030	0.430
	0.544	2.740	3.284	0.026	0.389	-0.001	0.389
	0.468	2.811	3.279	0.028	0.422	0.059	0.426
	0.421	2.850	3.271	0.027	0.477	0.163	0.504
	0.551	2.714	3.265	0.016	0.452	0.262	0.522
Downstream Gage	0.652	2.608	3.261	0.012	0.476	0.304	0.565
	0.495	2.749	3.245	0.003	0.630	0.278	0.689
	0.348	2.860	3.208	-0.007	0.831	0.186	0.852
	0.336	2.831	3.167	-0.015	0.874	0.081	0.878
	0.332	2.791	3.123	-0.018	0.920	-0.012	0.920
	0.317	2.746	3.063	-0.016	1.036	-0.133	1.044
	0.311	2.686	2.998	-0.012	1.126	-0.254	1.154
	0.382	2.580	2.962	-0.008	0.984	-0.282	1.024
	0.555	2.407	2.962	0.002	0.698	-0.221	0.732
	0.652	2.313	2.965	0.008	0.519	-0.127	0.534
	0.515	2.442	2.958	0.007	0.559	-0.094	0.567
	0.386	2.564	2.950	0.007	0.562	-0.105	0.572

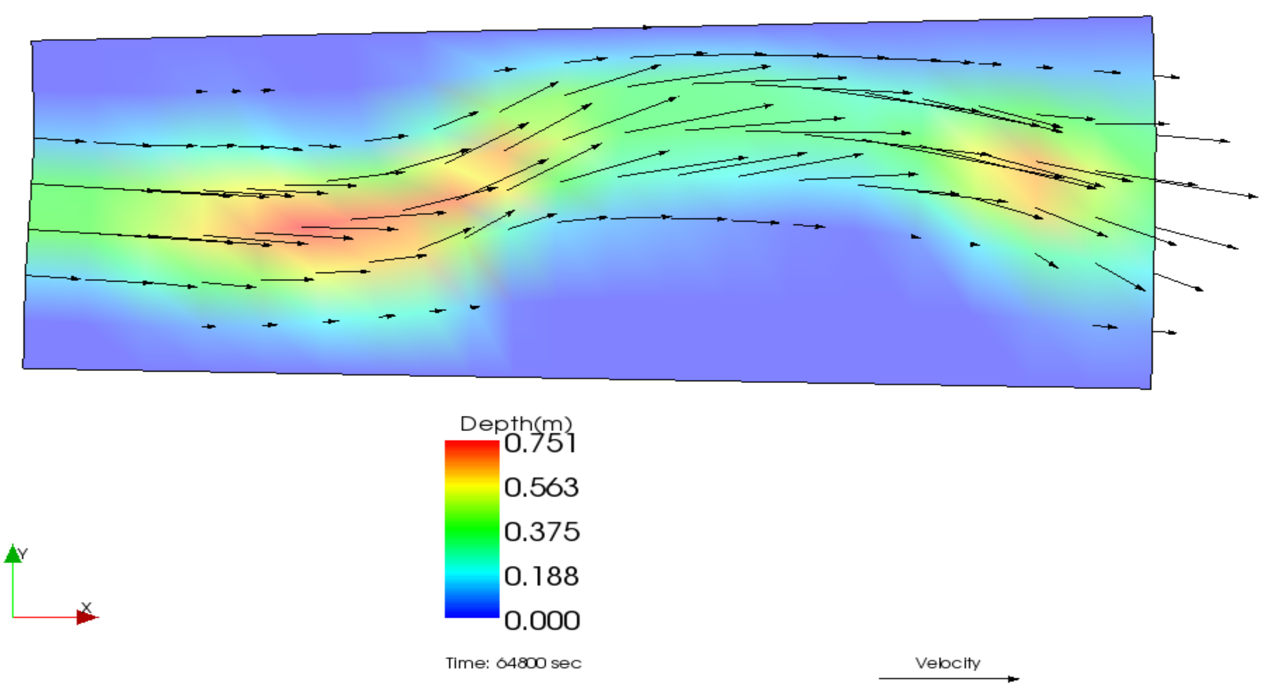

Figure B2. iRIC-generated Depth Plot with Velocity Vectors for 300 CFS (8.50 m^3/s) Flowrate

Table B3. Centerline Flow Data for the Creek with Culverts and 400 CFS (11.33 m^3/s) Flowrate after Eighteen Hours of Simulation Time

	Depth (m)	Elevation (m)	Water Surface Elevation (m)	Vorticity (1/s)	X-Velocity (m/s)	Y Velocity (m/s)	Velocity Magnitude (m/s)
	0.441	2.959	3.400	0.026	0.777	-0.054	0.778
	0.454	2.932	3.386	0.026	0.846	-0.064	0.849
Upstream Gage	0.528	2.846	3.374	0.028	0.736	-0.051	0.737
	0.609	2.765	3.374	0.024	0.588	-0.032	0.588
	0.641	2.730	3.371	0.018	0.519	-0.025	0.520
	0.627	2.740	3.368	0.017	0.488	-0.005	0.489
	0.549	2.811	3.360	0.022	0.529	0.042	0.531
	0.498	2.850	3.348	0.031	0.584	0.167	0.608
	0.620	2.714	3.335	0.028	0.596	0.354	0.693
Downstream Gage	0.711	2.608	3.319	0.016	0.688	0.423	0.807
	0.548	2.749	3.298	0.005	0.817	0.300	0.871
	0.400	2.860	3.261	-0.004	0.969	0.149	0.980
	0.388	2.831	3.219	-0.010	1.010	0.040	1.011
	0.387	2.791	3.178	-0.013	1.037	-0.037	1.038
	0.377	2.746	3.123	-0.011	1.127	-0.138	1.135
	0.375	2.686	3.061	-0.010	1.203	-0.274	1.234
	0.438	2.580	3.018	-0.018	1.154	-0.349	1.205
	0.606	2.407	3.013	-0.011	0.880	-0.283	0.924
	0.706	2.313	3.019	0.005	0.647	-0.161	0.666
	0.570	2.442	3.012	0.006	0.660	-0.124	0.671
	0.441	2.564	3.005	0.006	0.663	-0.131	0.676

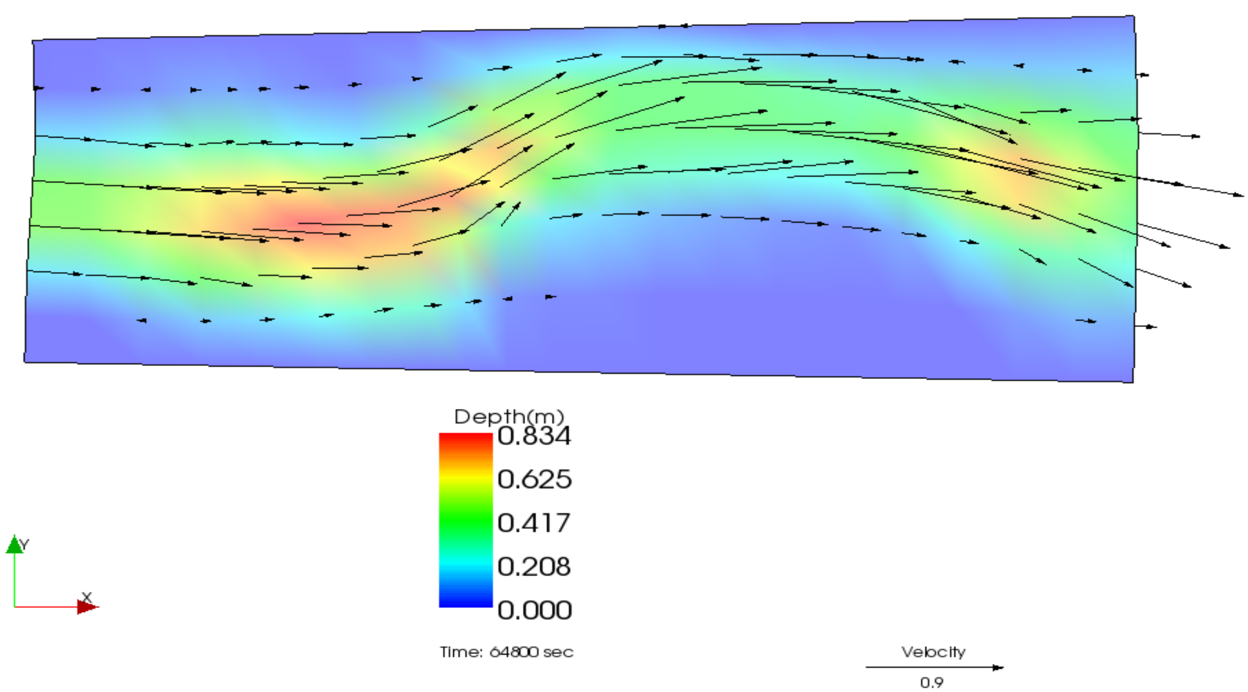

Figure B3. iRIC-generated Depth Plot with Velocity Vectors for 400 CFS (11.33 m^3/s) Flowrate

Table B4. Centerline Flow Data for the Creek with Culverts and 500 CFS (14.16 m^3/s) Flowrate after Eighteen Hours of Simulation Time

	Depth (m)	Elevation (m)	Water Surface Elevation (m)	Vorticity (1/s)	X-Velocity (m/s)	Y Velocity (m/s)	Velocity Magnitude (m/s)
	0.491	2.959	3.450	0.024	0.843	-0.059	0.845
	0.501	2.932	3.433	0.024	0.937	-0.065	0.940
Upstream Gage	0.573	2.846	3.419	0.025	0.833	-0.052	0.834
	0.656	2.765	3.421	0.021	0.681	-0.035	0.682
	0.689	2.730	3.419	0.015	0.606	-0.023	0.607
	0.676	2.740	3.416	0.013	0.567	0.001	0.567
	0.598	2.811	3.409	0.018	0.598	0.049	0.600
	0.547	2.850	3.397	0.029	0.641	0.156	0.659
	0.674	2.714	3.389	0.036	0.612	0.299	0.681
Downstream Gage	0.773	2.608	3.382	0.026	0.637	0.384	0.743
	0.612	2.749	3.361	0.011	0.798	0.363	0.877
	0.459	2.860	3.319	-0.001	1.002	0.260	1.035
	0.436	2.831	3.268	-0.005	1.136	0.113	1.142
	0.428	2.791	3.219	-0.011	1.173	-0.038	1.174
	0.419	2.746	3.165	-0.013	1.210	-0.166	1.221
	0.412	2.686	3.098	-0.013	1.306	-0.312	1.342
	0.467	2.580	3.047	-0.020	1.293	-0.428	1.363
	0.635	2.407	3.042	-0.010	0.992	-0.398	1.069
	0.742	2.313	3.055	0.015	0.699	-0.269	0.749
	0.612	2.442	3.054	0.022	0.655	-0.211	0.688
	0.487	2.564	3.051	0.022	0.658	-0.174	0.681

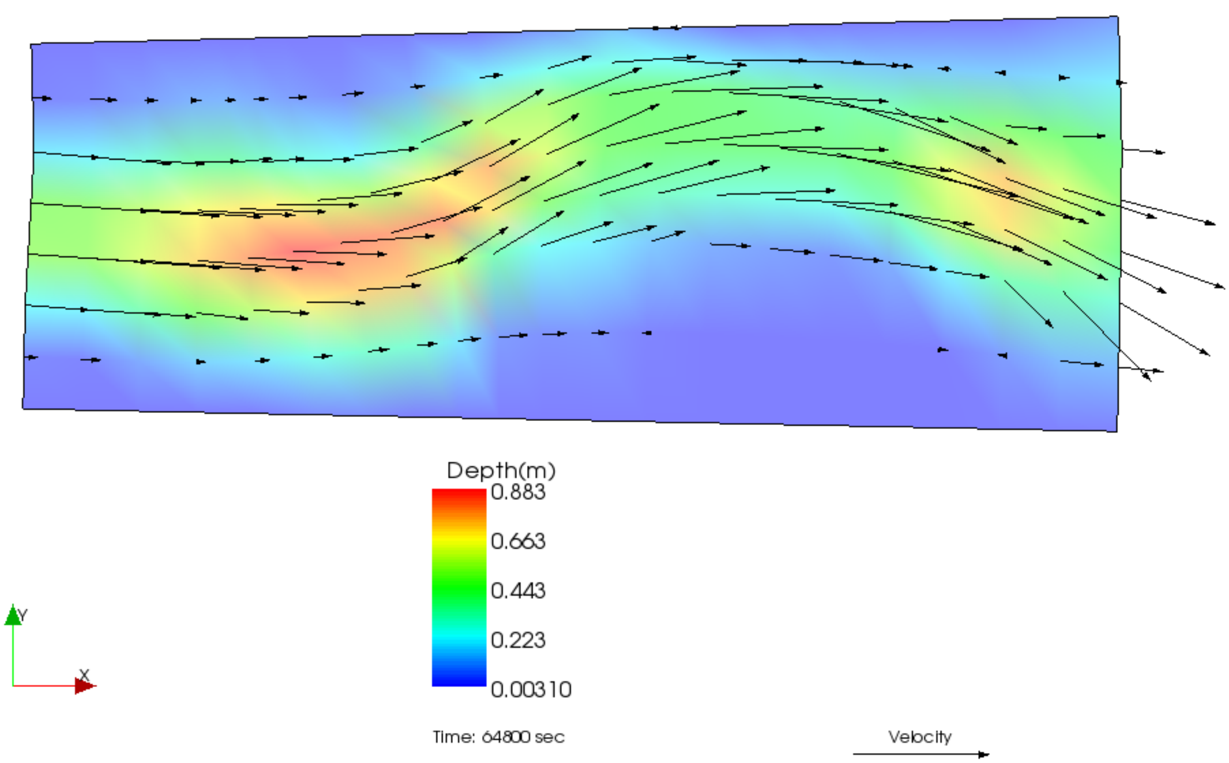

Figure B4. iRIC-generated Depth Plot with Velocity Vectors for 500 CFS (14.16 m^3/s) Flowrate