College of Agricultural & Environmental Sciences
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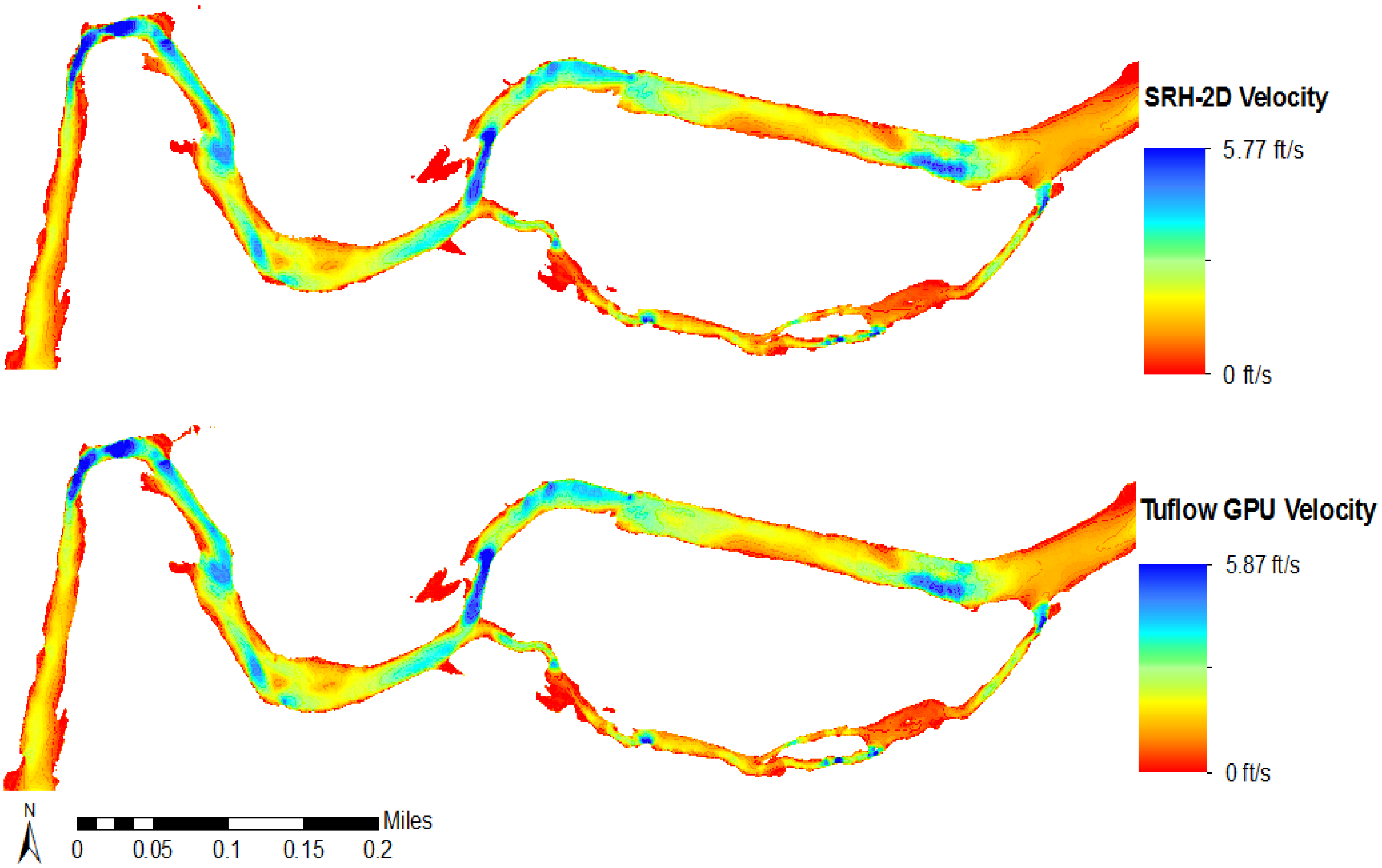
Near-Census 2D Model Comparison Between SRH-2D And TUFLOW GPU For Use In Gravel/Cobble Rivers



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Prepared for: Yuba County Water Agency

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1. Introduction

Two-dimensional depth-averaged (2D) hydrodynamic models are numerical algorithms that simulate the spatial pattern of depth and velocity in a river. These models can then be used for a wide variety of practical applications involving flood inundation, sediment transport processes, geomorphic change, riparian vegetation succession, and aquatic physical habitat. There are many 2D modeling computer programs and each can have a different functionality depending on what applications it emphasizes. Therefore, for any particular application it is wise to run tests to make sure that a given model is suitable for that use.

Recent advances in computer modeling provide a potential for a different product to offer advantages that could outweigh the benefits of consistency with regards to continuing with the same software. No two modeling software packages will produce identical results, but with the amount of LYR research that has been done using results from SRH-2D, it would be indispensable for the new model to produce results that can be justifiably compared to the previous SRH-2D results and subsequent analyses.

1.1. SRH-2D

Sedimentation and River Hydraulics – Two-Dimensional (SRH-2D) is a public-domain 2D model developed by Yong Lai of the U.S. Bureau of Reclamation (Lai, 2008). SRH-2D is a very stable and computationally efficient model. The current version of the flow hydraulics model is v.2.2, though there is a version 3.2 that adds mobile bed sediment transport as well. SRH-2D is certified by the U.S. Federal Emergency Management Agency as meeting National Flood Insurance Program requirements for flood hazard mapping activities, including both steady state and unsteady hydrograph simulations. A website about SRH-2D is available at the URL below:

https://www.usbr.gov/tsc/techreferences/computer%20software/models/srh2d/index.html.

SRH-2D requires independent software for computational mesh generation, with the commercial software known as the Surface-water Modeling System® (SMS) by Aquaveo, LLC (Provo, UT) serving as a common graphical user interface for this purpose. SRH-2D uses a hybrid structured-unstructured, arbitrarily-shaped computational mesh using both quadrilateral and triangular elements. This provides the benefit of yielding a mesh that is carefully designed by an expert to match the river setting for the model application.

Pasternack (2011) is a textbook that provides training in the use of SRH-2D as well as workflows for using 2D model output for a variety of spatially explicit geomorphic and ecological analyses.

1.2. TUFLOW GPU

TUFLOW GPU is one of three commercial 2D models developed by and available from BMT WBM Pty Ltd (Huxley and Syme, 2016; WBM Pty Ltd, 2016). Like SRH-2D, TUFLOW GPU is a very stable and computationally efficient model. TUFLOW GPU has been tested against several international flood challenge scenarios and found to perform well. The current version of TUFLOW GPU is 2016-03-AE and this is compatible with 64-bit operating systems. A website about TUFLOW GPU is available at the URL below:

http://www.tuflow.com/TUFLOW.aspx

TUFLOW GPU has several options for computational mesh generation, including the freeware QGIS, the widely used commercial software ArcGIS, and several commercial graphical user interfaces including SMS. TUFLOW GPU uses a fixed square grid, so it takes very little expert decision-making and troubleshooting to create the mesh, and the mesh resolution can be changed with a simple edit to one line of text in the geometric control file. Further time saving measures are incorporated in the preparatory stages of model development through standardization of procedures so that additional river scenarios may be developed quickly. There is also high efficiency through automated batching of many simulations. TUFLOW GPU also outputs its results in a raster grid format, which eliminates the need for post-processing steps that take hybrid mesh point outputs and interpolates them to a mesh (Pasternack, 2011).

Given a fixed mesh, TUFLOW GPU is ideally suited for parallel processing that fundamentally changes the utility of 2D modeling for science, engineering, and management. Parallel processing means that a computer program can split one large model into many small parts and then solve the parts simultaneously taking advantage of all available computer processors. A personal computer's motherboard now typically has 2-20 processing cores on 1-2 central processing units (CPUs). Most 2D models cannot perform parallel processing, and if they could, they would likely be limited to the number of cores on a single CPU. To take advantage of multiple CPUs requires additional programming and features. Meanwhile, computers also have a Graphics Processing Unit (GPU) to handle the display of graphics on a monitor. Because of the demand by video game players for ever better graphics and the associated robust market for gaming hardware and software, the power and future growth of GPUs is much more dynamic than those for CPUs. The company NVidia has produced individual GPU cards for desktop PCs using their proprietary Cuda parallel processing architecture that now have thousands of cores, not 1-20 like on a CPU. For example, the current flagship consumer-grade GPU card, the Geforce GTX 1080Ti, has 3,584 cores and costs $700 from retailers. Considering that the previous year's GTX 1080 model only had 2,560 cores, the rate of improvement of GPUs is impressive. TUFLOW GPU can also run across multiple GPU cards in parallel. Note that TUFLOW GPU does require the CPU for model pre-processing steps. BMT WBM Pty Ltd provides a website that shows hardware benchmarking results for different CPU and GPU combinations at this URL:

http://wiki.tuflow.com/index.php?title=Hardware_Benchmarking

1.3. Lower Yuba River 2D Modeling Of the 2006-2008 Map

The 37.1-km lower Yuba River (LYR) drains 3480 km^2 of Dry Summer Subtropical mountains and flows east to west from the Sierra Nevada foothills downstream of Englebright Dam to its confluence with the Feather River (Figure 1). The river segment is a single-thread channel (~ 20 emergent bars/islands at bankfull) with low sinuosity, high width-to-depth ratio, and slight to no entrenchment (Wyrick and Pasternack, 2012). The river corridor is confined in a steep-walled bedrock canyon for the upper 3.1 river kilometers (RKM), then transitions first into a wider confined valley with some meandering through Timbuctoo Bend (RKM 28.3-34.0), then into a wide, alluvial, lowland valley downstream to the mouth.

From 2006-2008 the topography of the LYR corridor was mapped, except for the short canyon section of the Narrows. Complete details of the methodology, including spatially explicit uncertainty analysis, as well as a discussion of the implications the DEM differencing maps have on the interpretation of the LYR's landscape evolution are available in Pasternack (2009), Carley et al. (2012), and Pasternack et al. (2014). Outside the 880 cfs (24.92 m^3/s) inundation area, points were mostly collected with LiDAR, yielding an average grid point spacing of one point every 0.43 m. (554 pts/100 m^2). Within the 880 cfs inundation area, points were collected with a mix of LiDAR, boat-based single-beam echosounding and ground surveys, yielding a lower average grid point spacing of one point every 1.3 m. (59.8 pts/100 m^2).

Barker (2011), Abu-Aly et al. (2013), and Pasternack et al. (2014) reported the details of SRH-2D modeling of the 37-km lower Yuba River (LYR). Five model domains were used to divide the river into smaller computational meshes to manage run times, except that there was no model domain for the Narrows Reach that is an inaccessible canyon lacking a topographic map (Figure 2). Breaking the river into discrete domains afforded the important benefit of allowing observational data collected at model breaks to be used to condition model runs and improve model results- a standard procedure known as data assimilation. For a variety of Yuba Accord River Management Team studies (YARMT, 2013), Yuba River Development Project (YRDP) relicensing studies, and academic journal articles, the SRH-2D model of the LYR was used to simulate steady state hydraulics at 28 discharges from 300 to 110,400 cfs. The SRH-2D model of the LYR met or exceeded all model validation tests for water surface elevation, depth, velocity magnitude, velocity direction, and mass conservation (Barker, 2011).

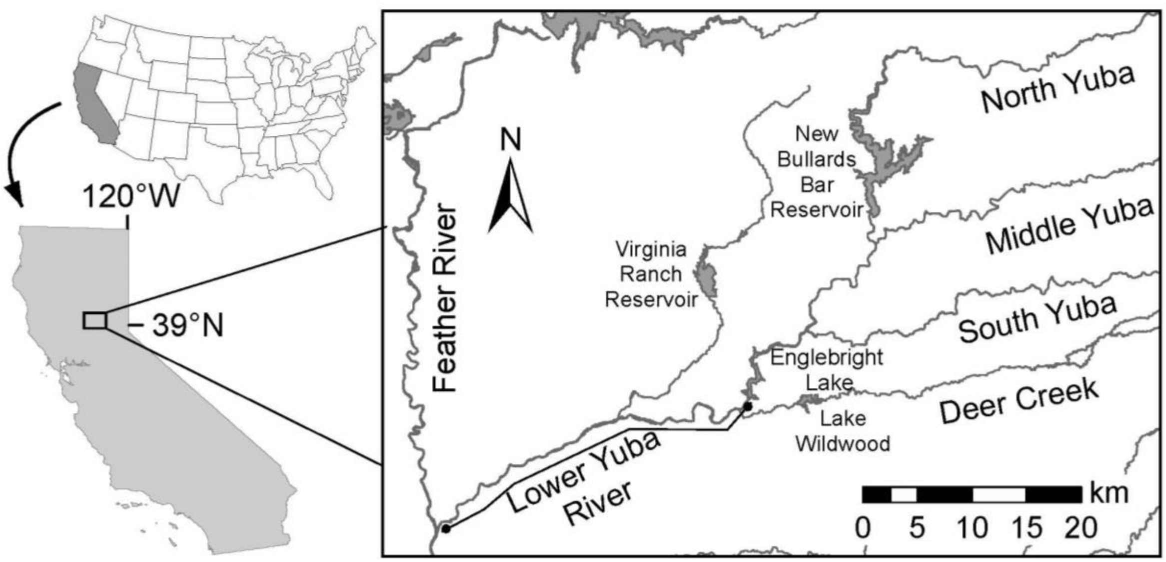

Figure 1. Location of the Yuba watershed within California in the western U.S. The LYR is the segment from Englebright Dam to the confluence with the Feather River.

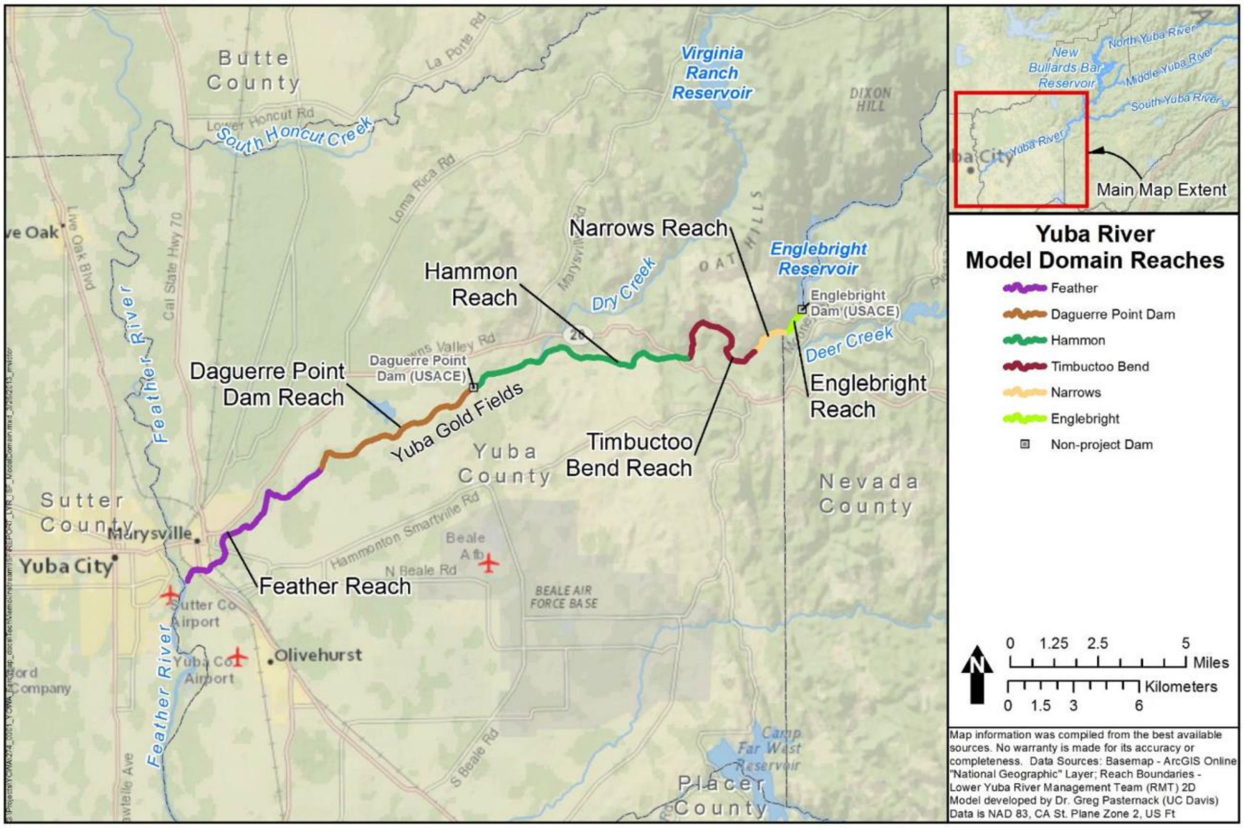

Figure 2. Map of the LYR showing the five hydraulic modeling domain reaches and the Narrows Reach that was not modeled. From YCWA (2013).

1.4. Why Switch From SRH-2D To TUFLOW?

The SRH-2D modeling of the 2006-2008 map of the LYR is complete. There is no need to re-develop models in any other program given the availability of these model results. In 2014 a new topographic map of the LYR was produced, as will be explained in detail shortly. As a result there is a need for new 2D models for the newer map. Notably, the new map includes the Narrows reach, creating the ability to make one 2D model from Englebright Dam to the Highway 20 bridge, because it is problematic for a variety of reasons to have a model boundary in the vicinity of the confluence with Deer Creek and another at the head of Timbuctoo Bend. Given the speed of TUFLOW GPU, it is worthwhile to consider what benefits or penalties would arise from switching to using it instead of SRH-2D.

The number of computational elements in each SRH-2D model domain for the LYR in the 2008 map varied, as three different meshes were used for each model domain to span different discharge ranges. Even divided into five domains, the meshes are large. Typically there were hundreds of thousands to over one million computational elements in each mesh, so the run time for an individual simulation was generally days to weeks. For example, the DGR mesh for flows of 1000-10,000 cfs has 1,333,183 computational cells. Some of the meshes included backwater areas separated from the main stem river by a sill, which necessitated that very small inflows be added at the upstream end of each backwater to fill them. This replicates the natural process of hyporheic flow that causes water to seep through gravel/cobble bars into the heads of backwaters, so that is a reasonable modeling approach. However, the problem is that it takes a very long time for the backwaters to fill up at such a low discharge. A procedure was developed to run a model with a higher backwater inflow to fill the backwaters and then drop those down to the normal small value just as they became full. Even this approach adds days to weeks to model simulations, primarily impacting the first simulation of the lowest discharge for a given mesh. Higher discharges are run using the output of a lower-discharge simulation as an input, so those do not require a backwater filling computation every time. Finally, the drought of 2012-2016 necessitated running very low discharges, and these require the longest run times of all. Overall, the entire process of running computational meshes with hundreds of thousands of computational elements takes a long time. The work got done and the results were used for many applications, but it took a lot of time and limited analyses to 28 discharges, with relatively few flood discharges simulated.

As a test, a simulation of the 2008 DGR model domain that took 20 days to solve (only counting simulation time) was re-developed and run using TUFLOW GPU to see how the run time compared. The TUFLOW GPU version was identical in terms of its model parameterization and mesh resolution, but different in its mesh structure. *TUFLOW GPU completed the simulation in ~ 5 hours*. Reducing run time from 20 days to 5 hours is transformative in terms of what can be accomplished over a given time span- or alternately it could allow for even higher resolution models and larger model extents.

For the newer 2014 map, a single SRH-2D model from Englebright Dam to the Highway 20 bridge necessitates including a small inflow for Deer Creek, and this creates another spin-up problem similar to that for the backwaters described in the previous paragraph. Also, it is a very large computational domain. In SRH-2D, the low-flow mesh has 1,315,635 computational cells. *Running this model domain in SRH-2D takes literally one month at the first low flow whereas TUFLOW GPU solves the same domain in the same resolution in 3 hours*. Once again, going from 30 days to 3 hours is fundamentally transformative in terms of what is possible.

2. Purpose

Given the dramatic difference in computational time between SRH-2D and TUFLOW GPU, further progress in near-census river science involving larger model domains and meter to submeter mesh resolution would benefit greatly from using TUFLOW GPU. However, there is no point in using a model if the results it produces are inaccurate. Both SRH-2D and TUFLOW GPU have been vetted through a variety of model inter-comparison studies for flood hazard scenarios, but TUFLOW GPU has not been thoroughly vetted for a wide range of discharges in a complex gravel/cobble river like the LYR.

There are two ways to go about vetting TUFLOW GPU for use on the LYR. First, one could collect observational data and do a model validation analysis (Pasternack, 2011). That would be beneficial, but it would not address the fact that one of the uses of new models for 2014 is to compare against the 2008 results to help understand how the river has changed. Second, one could do head-to-head analysis of model results for SRH-2D and TUFLOW GPU when each is used on an expert basis to produce the best possible model results given the same mesh resolution and similar model parameterization. In this scenario, one cannot say which model is "right", because there is no observational data to make that determination. However, one can identify the similarities and differences, and this becomes informative to know what to look out for when comparing results between the two models. Ideally, both model validation and model inter-comparison should be done.

The purpose of this study was to perform a model inter-comparison to evaluate the difference in model output between SRH-2D and TUFLOW GPU for the LYR using the new 2014 topographic map with steady state, baseflow discharges. These low flows are the most challenging to simulate accurately due to the greatest variety of hydraulic conditions associated with the inverse relationship between depth and velocity common to this scenario (Brown and Pasternack, 2008). The primary performance testing involved quantifying the statistics for deviations in the magnitude of depth (D), velocity (V), and water surface elevation (WSE). Secondarily, GIS maps were used to inspect model differences to understand their spatial patterning. Also, 2D velocity vectors were inspected to see if the two models yielded similar 2D flow patterns, including eddy recirculations.

Direct model validation of TUFLOW GPU and SRH-2D against observational data has been done, but will not be reported in this report to keep this report focused. Instead, those validations will be reported in a separate model validation report.

3. 2014 LYR Topographic Map and 2D Models

In 2014 the topography of the LYR corridor was re-mapped using more advanced technology and better data processing methods (Weber and Pasternack, 2016). This time, the entire LYR corridor was mapped and it was done at a much lower discharge, which meant more of the terrain was accessible for near-infrared (NIR) LiDAR mapping. This time, green LiDAR capable of mapping channel bathymetry down to ~9-15' depth was used in conjunction with improved NIR LiDAR that yielded a higher point density, even through vegetation. Combining green and NIR LiDAR instruments also insured seamless mapping across the land-water boundary. This time, multibeam echosounding was done to map deep areas in detail. Other additional technologies and methods were used to produce a significantly better map. Compared to the point density numbers previously stated for the 2006-2008 map, this time there were 512 pts/100 m^2 in the water and 1317 points per 100 m^2 on bare land- that's about ten times more data in the water than before and more than double the bare land data. Figure 3 shows the detrended map with geomorphic reach breaks to see topographic variability within the LYR.

New 2D models have been built for the 2014 LYR map using both SRH-2D and TUFLOW GPU. Both types of models were set up with the same resolution and the same parameterization to the extent possible. In both cases, the model is actually composed of four independent computational base flow meshes whose results are merged to produce one overall result for the entire river. The meshes do not necessarily align with geomorphic reaches, as there are eight geomorphic reaches compared to the four model domains. The four model domains from upstream to downstream are given the following names based on their starting and ending locations: Englebright-to-Highway20 (EDH20), Highway20-to-Daguerre Point Dam (H20DPD), DPD-to-Marysville gage (DPDMRY) and Marysville-to-Feather River (MRYFR).

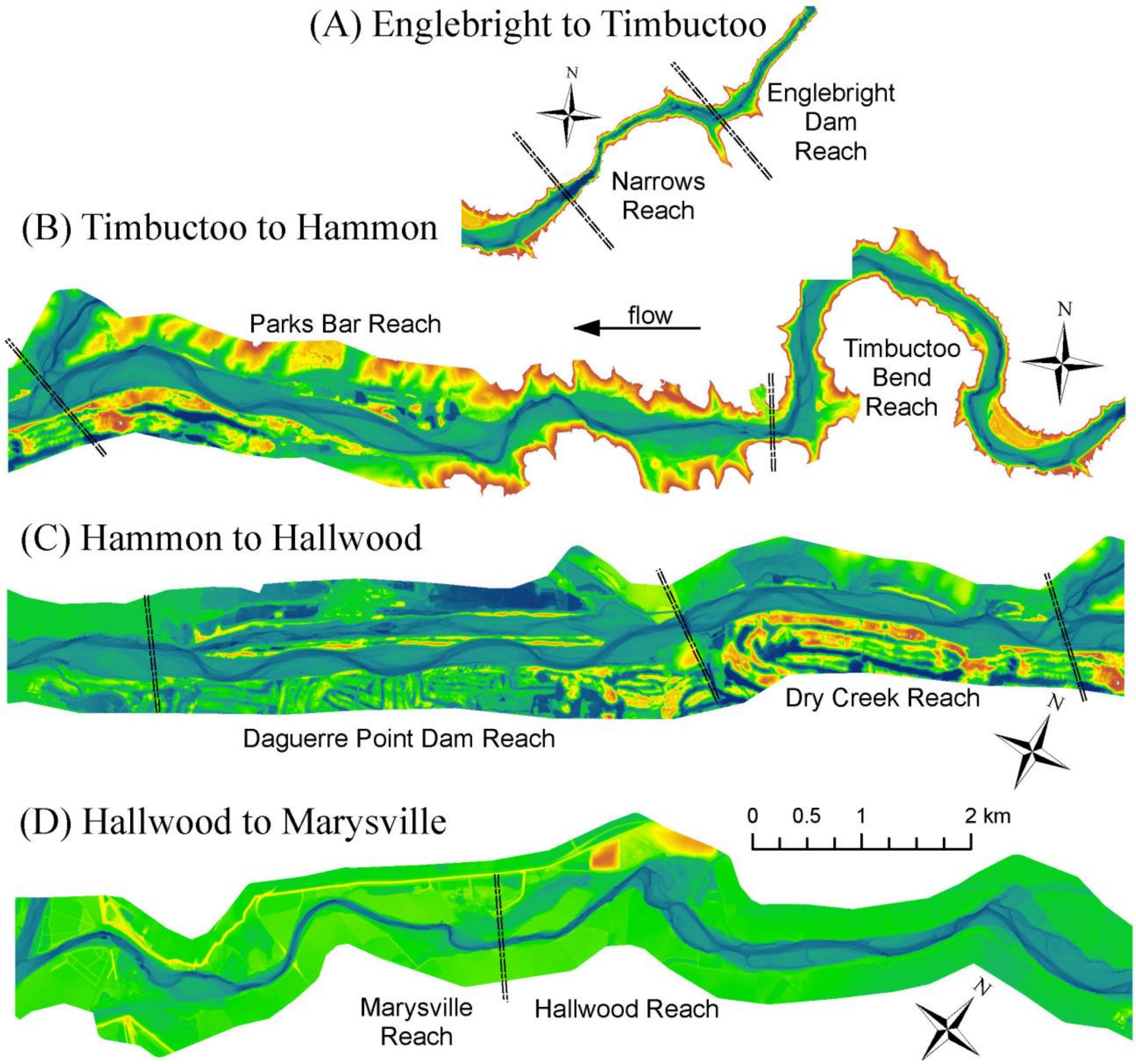

Figure 3. Detrended LYR DEM that shows local topographic variability. Black double lines show geomorphic reach breaks. Elevation is shown from -46' (dark blue) to +100' (dark red).

4. Methods

4.1. Test Flows

Two discharges occurring on the same day were analyzed for this model comparison based on available observational data to subsequently validate the models in a separate report. The EDH20 and H20DPD model domains upstream of DPD were run at a flow of 543.5 cfs. The DPDMRY and MRYFR models below DPD were run at a flow of 398 cfs. These values correspond to the flows and diversions reported by CDEC that occurred on September 27, 2014, the date of the LiDAR survey flight used to produce the 2014 LYR map.

4.2. Model Run Times

Starting SRH-2D model runs from dry is time consuming as the model domain has to first "fill" with water before the results can begin to converge on a final result. In addition, the three downstream domains have deeper backwater areas that take even longer to fill. The final model runs in SRH2D were started using the water level from a previous model run of a similar flow and not from dry, therefore shaving days (if not weeks) off of the total run time. Even so, the final SRH-2D models were run for 6, 14, 7, and 6 days (EDH20, H20DPD, DPDMRY, and MRYFR, respectively) on a 2-yr old workstation computer.

In stark comparison to SRH-2D, the EDH20 model took only 4 hours 22 minutes to run starting from scratch using TUFLOW GPU. From upstream to downstream, the three other models ran for 5 hours 15 minutes, 23 hours 8 minutes, and 2 hours 15 minutes, respectively. Those times include the time it took for a backwater 'filling' run. This shows the incredible efficiency of the TUFLOW GPU software compared to SRH-2D. Specifically, TUFLOW run times were 7 to 64 times faster than SRH-2D.

4.3. Data Analyses

Model outputs from all model domains were merged to create one overall result for the entire river. Model outputs of water depths similar to the mean grain size of a river's bed material are extraneous as it is not conclusive that there would be surficial water at that location. Some 2D models have the ability to set a lower bound constraint to depth for use during modeling, but not SRH-2D. Otherwise, standard practice is to remove model outputs with locations whose depth is below a cutoff value depending on the riverbed. The mean grain size in the LYR is ~ 0.33 ft, therefore locations with depths < 0.3 ft were removed prior to any analysis. In addition, some areas of the LYR were excluded from analysis, including (i) the Narrows Reach, (ii) the section from Englebright Dam to two channel widths past the Narrows 1 powerhouse, (iii) the area adjacent to Daguerre Point Dam, and (iv) backwater and heavily vegetated areas. Each area was excluded for a different reason, but the primary aim was to have locations where the comparison would be as fair as possible, and these four areas each raised concerns for the inter-comparison.

For SRH-2D, rasters of WSE, D, and V were created using the same procedure from Pasternack (2011) that was used for the 2008 LYR model. For TUFLOW GPU, the model natively outputs the desired rasters. The main inter-comparison involved subtracting one raster form the other to obtain the deviation raster using the Spatial Analyst Raster Calculator. Deviations were calculated as SRH-2D minus TUFLOW GPU to have a standard procedure. The final deviation raster files were analyzed using the Zonal Statistics as Table tools in ArcGIS. Inevitably, any two models will have some spots where there are differences, but the main question is whether the statistical parameters of the deviation rasters indicate a significant difference in the models.

5. Results

5.1. Water Surface Elevation Statistics

The mean signed deviation for WSE was -0.03 ft (9 mm), which is one-tenth of the mean bed grain size for the LYR. The unsigned standard deviation is 0.02, which is small and shows that

95% of deviations are within 0.04 ft. These results support the null hypothesis that the models yield the same WSE results. The maximum deviations of up to 0.94 ft occur along bedrock and boulder banks where the difference in topographic interpolation to the computational meshes yields significantly different ground elevations, which in turn causes the WSE to be different.

WSE deviation, ft (all)		
	signed	unsigned
mean	-0.03	0.04
median	-0.03	0.03
std dev	0.02	0.02
min	-0.94	0.00
max	0.52	0.94

5.2. *Long Profiles of Water Surface Elevation Deviations*

In order to provide a visualization of the WSE results, scatter plots were produced as long profiles above and below DPD with values from the WSE deviation raster (Figure 4, Figure 5). Using ArcGIS, a thalweg line was delineated using the Least Cost Path tool and an inverse momentum ($1/(D*V^2)$) raster was made from the TUFLOW GPU hydraulic simulation results. Station points were created at 10-ft intervals along the thalweg line and WSE deviations (SRH-2D minus TUFLOW) were extracted at each point. The plots show that the majority of WSE deviations along the thalweg are very close to zero with a maximum unsigned deviation of 0.41. The mean and median of the WSE deviations along the thalweg is -0.04 ft.

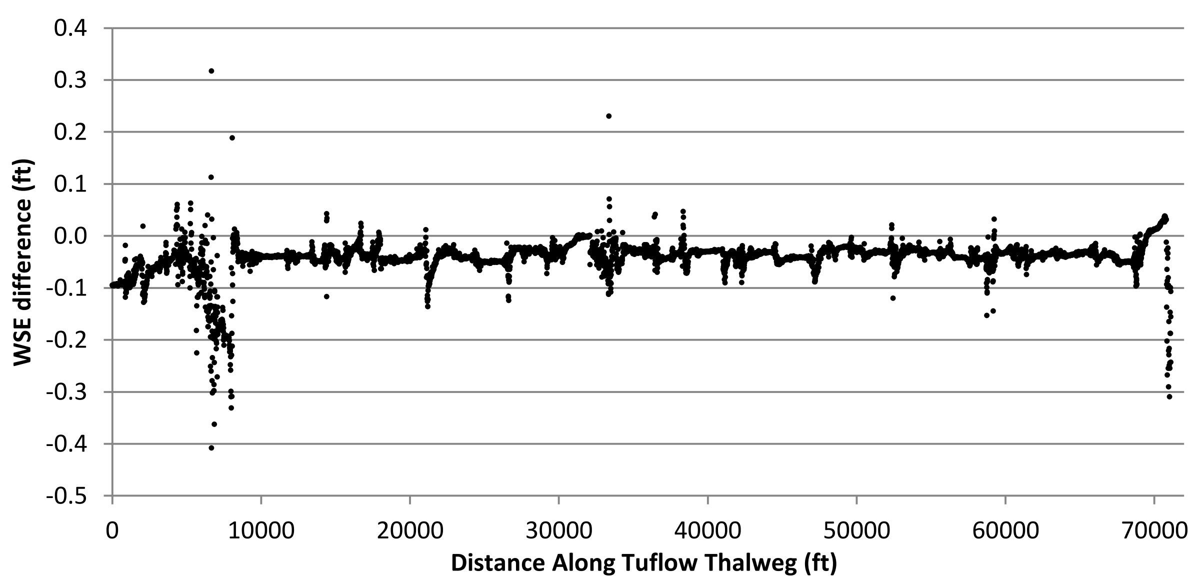

Figure 4. Water surface elevation deviations (SRH-2D minus TUFLOW GPU) in feet. Shown for above DPD.

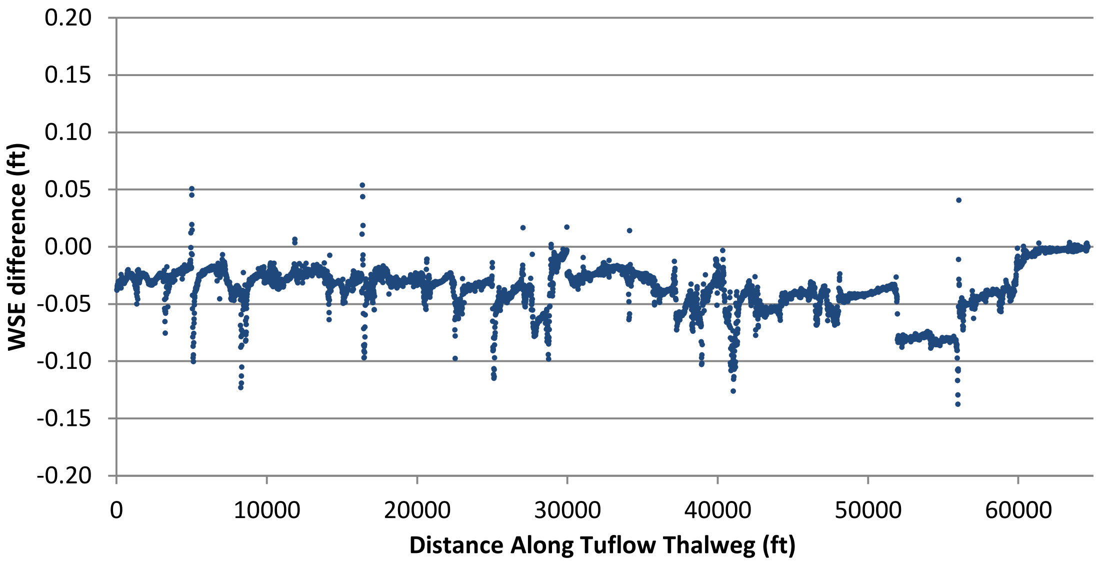

Figure 5. Water surface elevation deviations (SRH-2D minus TUFLOW GPU) in feet. Shown for below DPD. Note that Y-axis scale is different from that of Figure 4.

5.3. Depth And Velocity Statistics

The signed mean deviations for D and V (aka V_{mag}) were -0.03 ft and -0.02 ft/s, respectively. The unsigned D and V standard deviations were 0.42 ft and 0.15 ft/s, respectively. When the data were converted to a percent difference metric, the relative magnitude of the deviations were revealed. Interpreting percent difference for velocity is tricky, because it is well known that for low velocities a small deviation will yield a large percent difference. For example, if the models yield V of 0.1 and 0.2 cm/s in a pool, then that is a 100% difference, but it is not scientifically meaningful. On the other hand, if the velocity percent differences were 100% for velocities of ~ 2-3 ft/s, then that would be very significant, because that is in the range for Chinook adult spawning habitat preference. On a percent basis, depth was different by a median of -1.35% and a mean of -3.29%. For velocity the median and mean differences were -1.27% and -333.61%, respectively. The V mean results were significantly skewed by a few values of large percent deviation at low velocity and thus are not representative of the central tendency, because the distribution is not normal. The median percent difference is at a normal small value. In assessing where depth and velocity deviations are the highest, the outcome is once again that these deviations are associated with the banks of the river where differences in topographic interpolation between the two types of meshes yield different mesh elevations and thus differences in all hydraulic metrics. Also, the water tends to be slow at the edge, creating ripe conditions for high percent deviations in velocity.

Depth deviation, ft (all)

	signed	unsigned
mean	-0.03	0.19
median	-0.03	0.08
std dev	0.42	0.38
min	-32.67	0.00
max	26.29	32.67

V_{mag} deviation, ft/s (all)

	signed	unsigned
mean	-0.02	0.08
median	-0.01	0.03
std dev	0.15	0.13
min	-4.28	0.00
max	5.51	5.51

Depth % difference (all)

	signed	unsigned
mean	-3.29	8.82
median	-1.35	3.92
std dev	21.72	20.11
min	-6027.36	0.00
max	96.86	6027.37

V_{mag} % difference (all)

	signed	unsigned
mean	-333.61	340.38
median	-1.27	3.47
std dev	32213.02	32212.95
min	-23064890	0.00
max	99.76	23064890

When the data were analyzed by percent rank, the result is that 57.9% of depths and 60.1% of velocities are within 5% difference. For depth, 77.9% are within 10% difference. As an example, if the depth is 3', then the difference for 77.9% of points was within 0.3' (90 mm). Considering that this is close to the mean grain size of the LYR (90 mm vs 97 mm), it is a small uncertainty. Velocity uncertainty is a bit bigger, with 75.4 % of the data within 10% difference. For a spawning velocity of 3 ft/s, the uncertainty is that it could be between 2.7 to 3.3 ft/s, which does not change the habitat condition.

Depth

within %diff	% rank (all)
1	15.8
2	29.7
3	41.3
4	50.6
5	57.9
10	77.9
20	90.2
25	92.7
50	97.6
100	99.4

V_{mag}

within %diff	% rank (all)
1	18.6
2	34.3
3	45.8
4	54.0
5	60.1
10	75.4
20	84.9
25	87.1
50	92.3
100	95.7

5.4. *Example Depth and Velocity Scatterplots*

Depth and velocity values from SRH-2D and TUFLOW GPU raw model results were sampled at 2000 points and plotted to provide a head-to-head comparison that visualizes how similar the two models are (Figure 6, Figure 7). The points were created on a uniform grid within the SRH-2D wetted area polygon using ETGeoWizards© tools in ArcGIS. For both the depth and velocity plots, the trendlines have a slope of 1.00 when significant figures are considered and a very small y-intercept close to zero. There is more scatter at lower velocities, but both depth and velocity results from SRH-2D and TUFLOW models follow a linear, one-to-one, relationship.

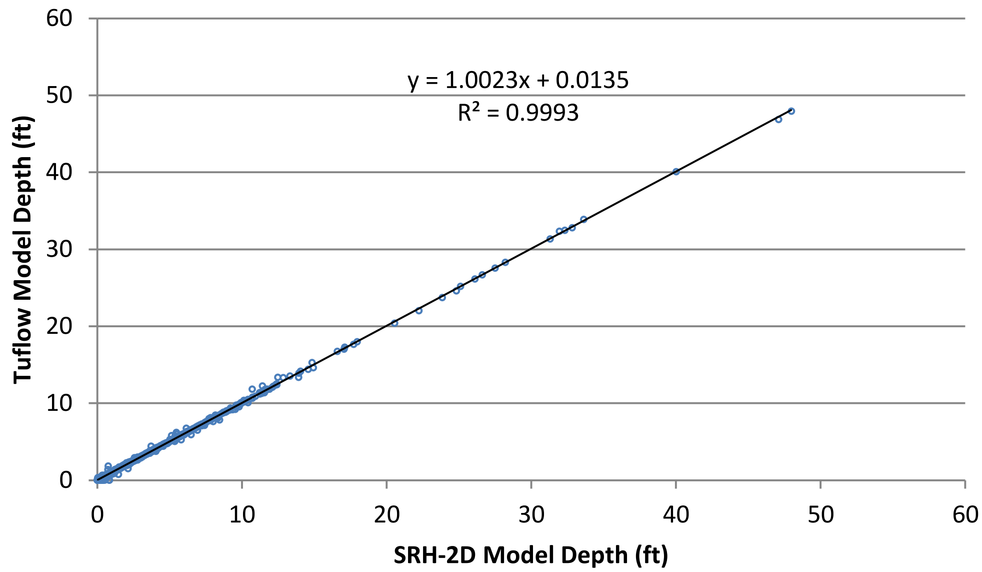

Figure 6. Modelled depth values at 2000 points along a uniform grid.

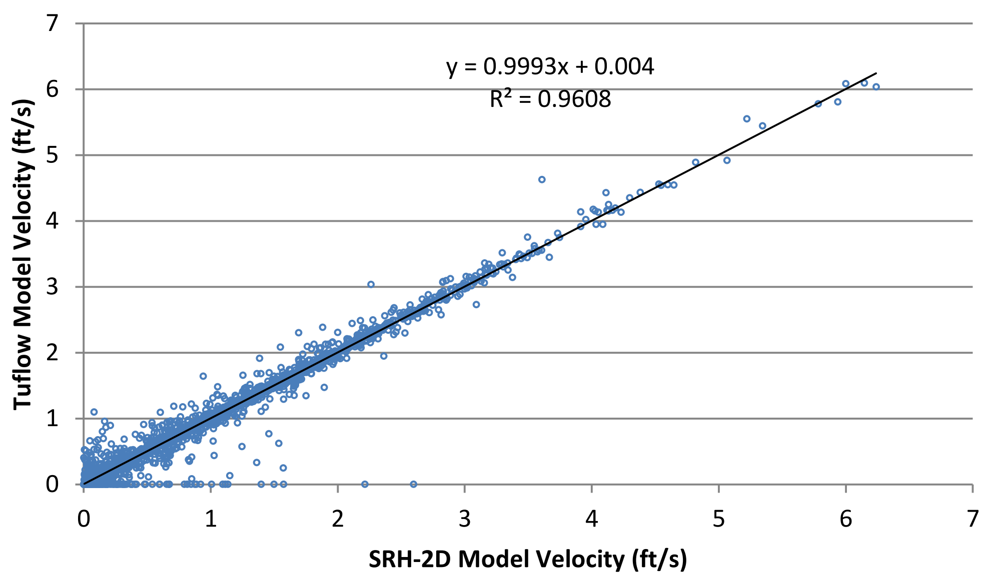

Figure 7. Modelled velocity values at 2000 points along a uniform grid.

5.5. *Example Deviation Maps*

To provide a visualization of the deviations to help understand the statistical results, some example maps were produced (Figure 8, Figure 9). The maps show that the majority of the river has small deviations in depth and velocity, but there are typical locations where the models differ. The biggest differences are along steep, jagged edges. For example, in the two figures, the far left scene shows the downstream end of Rose Bar that has very steep alluvial banks from lateral migration and that is where some moderate deviations occur. Continuing downstream from there (up in the figure), the right bank is bedrock and boulder, and the deviations are even larger there. Note that the majority of these “large” deviations are within 1 ft, but some areas have deviations up to 3 ft. Along some cliffs, the deviations are 3-33 ft, which just means that the exact position of deep pools along a very steep bank is slightly different in the two models. Although this creates a big deviation mathematically, the significance in practical geospatial terms is negligible, because again it is just a slight spatial shift.

The pattern of velocity deviations is not as sensitive to the bank effect as depth, and instead the maps show more of a difference in lateral distribution of high and low velocities. TUFLOW GPU seems to give higher velocities in chutes than SRH-2D. In a previous intercomparison between FESWMS and SRH-2D done by our lab group for internal purposes, SRH-2D was found to under predict peak velocities, compared to both FESWMS and field observations, so this outcome is not a surprise. However, in other locations SRH-2D produces higher velocities than TUFLOW GPU and there is no obvious reason as to why one is higher or lower.

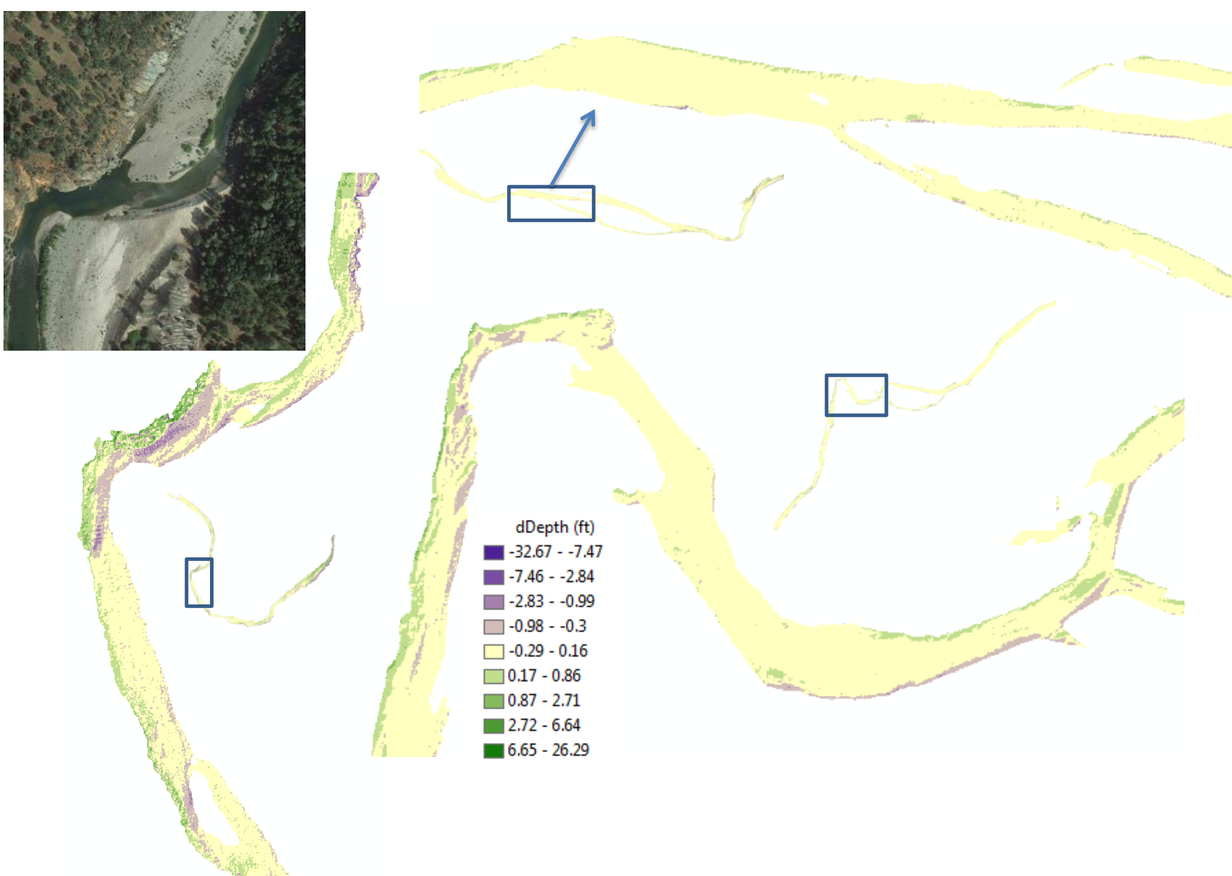

Figure 8. Depth deviation maps (SRH-2D minus TUFLOW).

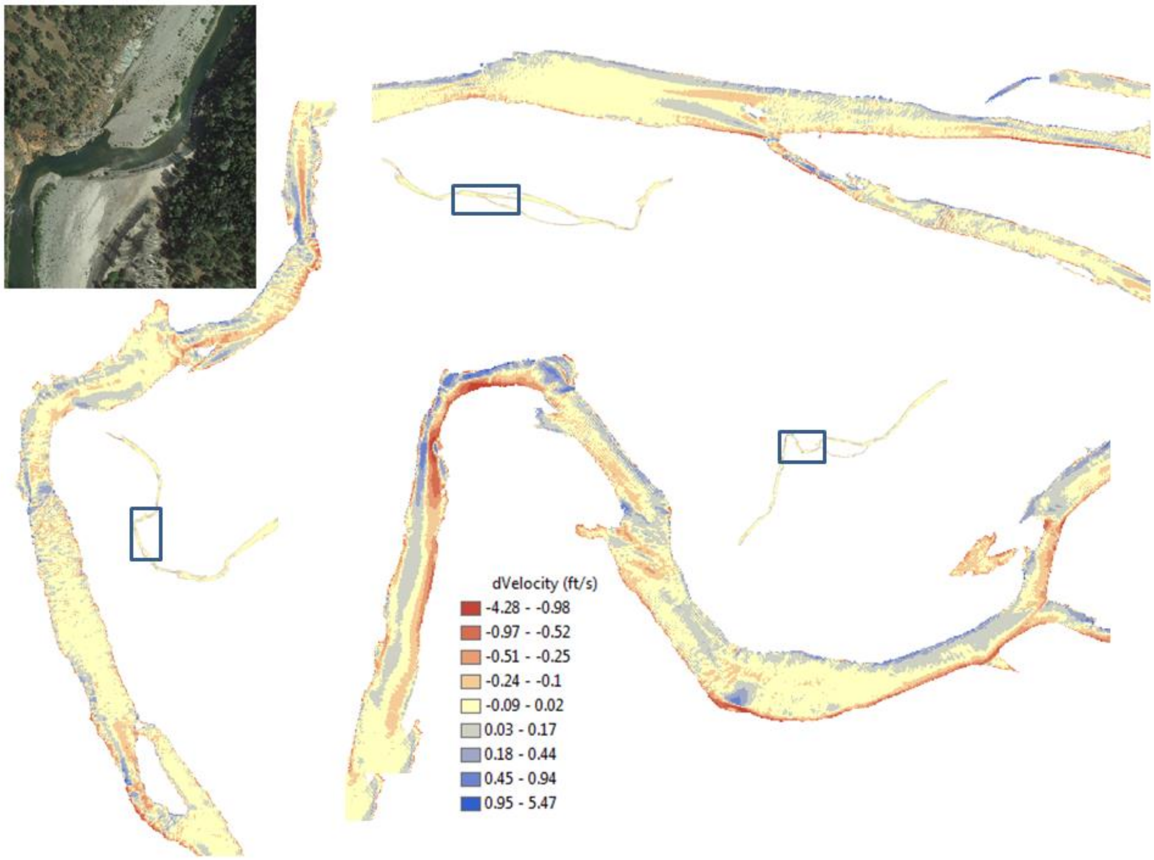

Figure 9. Velocity deviations in the same three example sites as shown in Figure 8.

5.6. Eddy Comparisons

The presence, size, and shape of velocity vector recirculations (aka eddies) in 2D models is primarily controlled by the turbulence closure scheme. SRH-2D uses a parabolic closure scheme whereas TUFLOW GPU uses a Smagorinsky formulation. We have done our best to parameterize the two schemes to yield as similar outcomes as possible. There is no standard for comparing 2D models for the velocity vectors and there is rarely any field observations to test eddies. In general, the most important thing to assess is that a 2D model produces eddies and does not have flow smoothly wrap around flow obstructions. Both of these models do produce eddies given the parameters used, so that is the first test. Next, one can look at the velocity vectors in the main channel and make sure they are both very similar, usually within 5° of each other. Finally, one can look at large eddies and see if they have the same vortex pattern, size, and shape.

Figure 10 shows a comparison of the velocity vector field at a site, including both velocity magnitude (contour lines) and direction (arrows). In this example, the two yield extremely similar vector patterns for both the main channel and the large eddy.

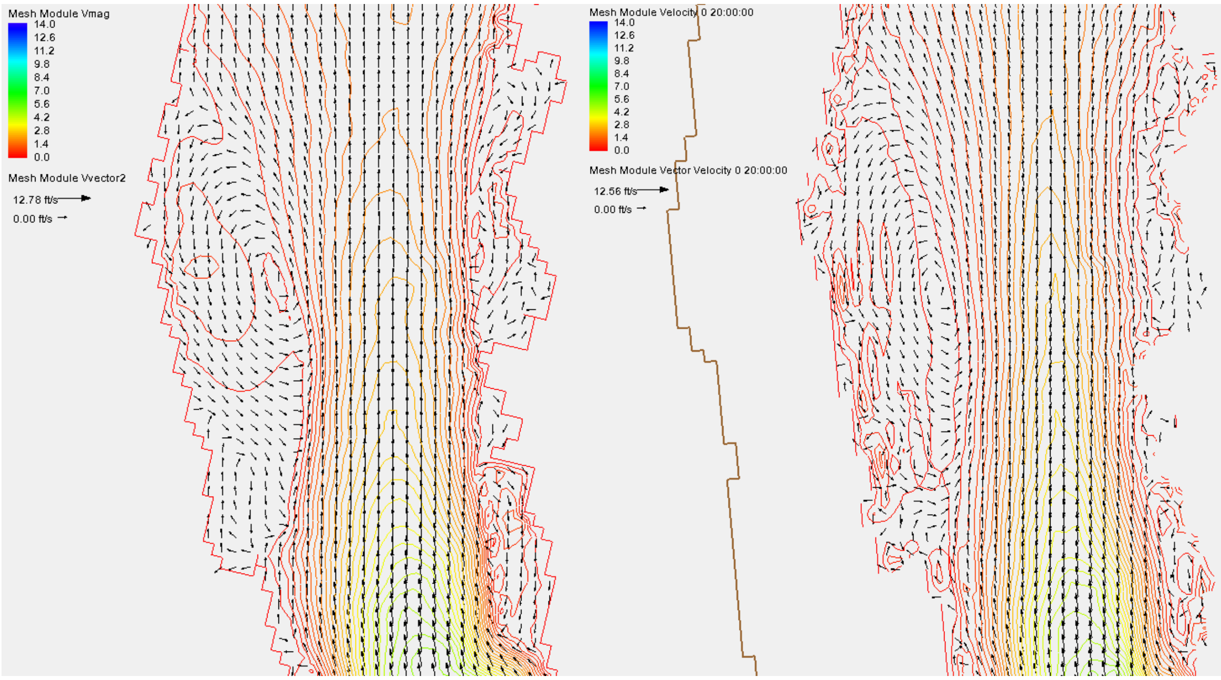

Figure 10. Comparison of velocity vectors in SRH-2D (left) and TUFLOW GPU (right).

Brown and Pasternack (2013) performed a detailed analysis of a large eddy in the Englebright Dam reach using SRH-2D and compared it to both videos of the recirculation as well as surface particle tracking data. Because there is a subaqeuous bedrock sill, the recirculating water gets deflected back toward the head of the obstruction, and this causes a secondary vortex to occur in the most isolated part of the separation zone. This double vortex was verified through both visual observation and data in that study. The new SRH-2D model made in this study shows that same outcome again with a double vortex (Figure 11, left). In contrast, the TUFLOW GPU model only shows a single vortex. Because the double vortex is controlled by the subaqeuous sill, this means that the fixed sized cells in TUFLOW GPU are not capturing the topographic effect well enough compared to the hybrid mesh structure of SRH-2D. It is possible that a finer mesh is needed for such a narrow bedrock sill that is only ~ 1 fixed grid cell in width, especially given that it is not orthogonal to the mesh.

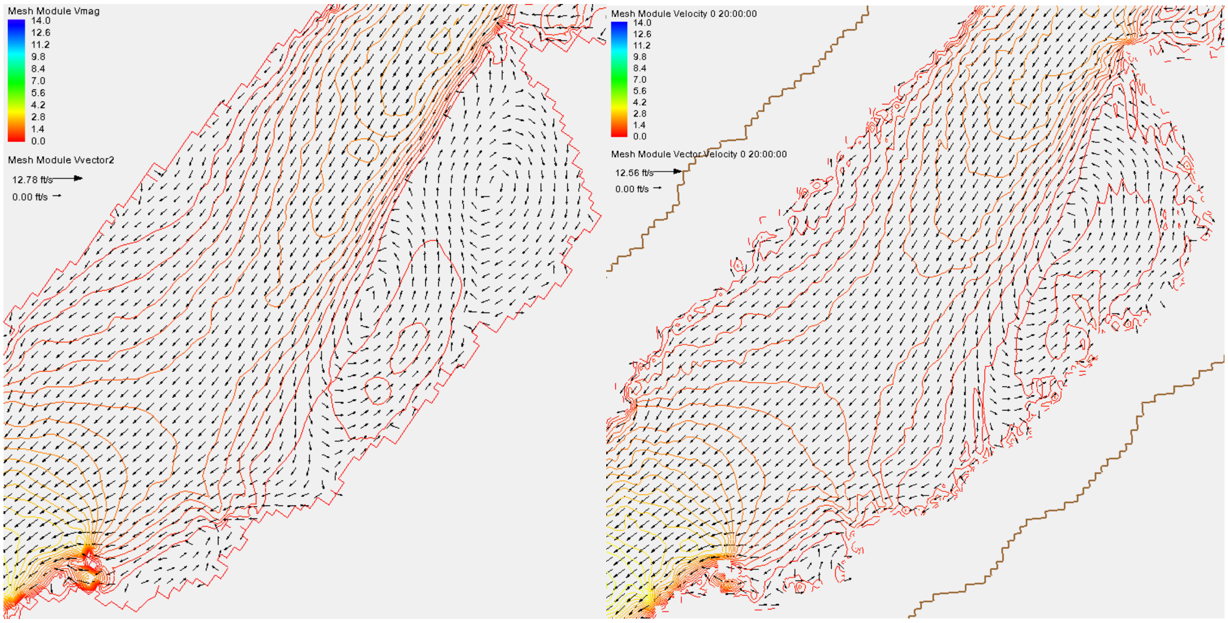

Figure 11. Comparison of a large eddy in the Englebright Dam reach. SRH-2D on left.

As a final example, Figure 12 shows a complex site with multiple chutes, eddies, and an island. The velocity fields are very similar in the two models, which provides a lot of confidence in the use of either model. SRH-2D provided a divided island with a flow path between them, while TUFLOW GPU has a single large island, but this had almost no effect on the flow field other than in this difference in wetting/drying.

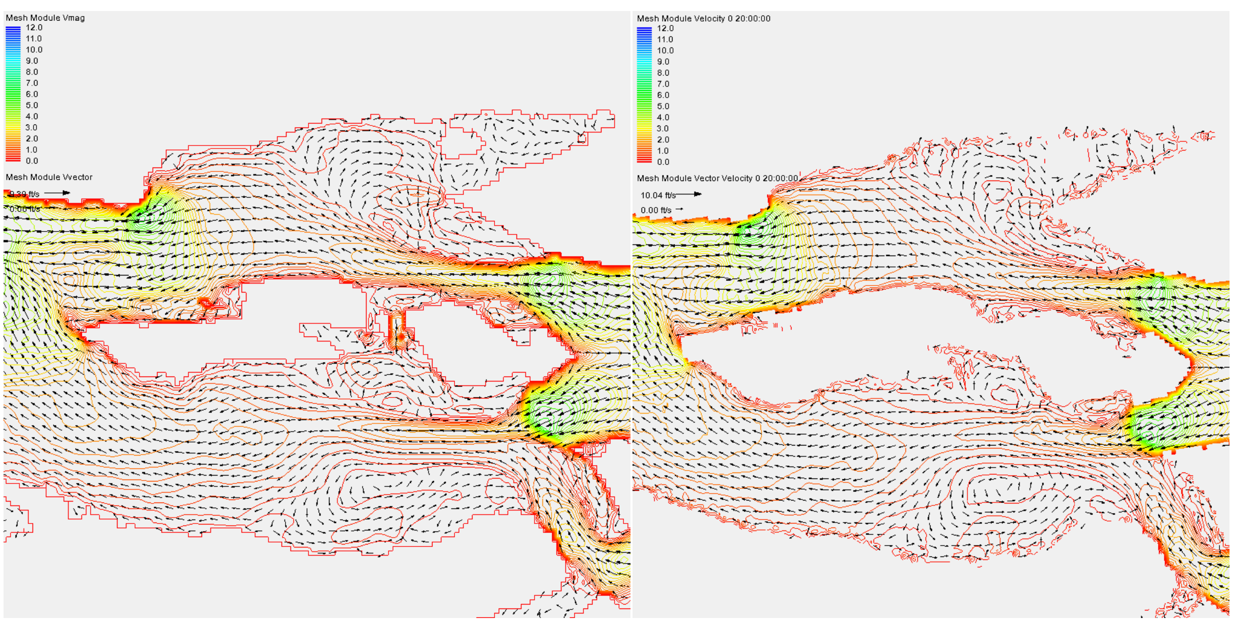

Figure 12. Comparison of a complex velocity vector field in the LYR. SRH-2D on left.

6. Conclusions

SRH-2D and TUFLOW GPU models of the entire lower Yuba River were run for 543.5 cfs or 398 cfs flows for the two upstream and two downstream model domains, respectively. Statistical analyses show that the vast majority of the model outputs from TUFLOW GPU are indistinguishable from those from SRH-2D. The primary differences occur where there are steep topographic slope breaks, given that one uses a hybrid mesh and one uses a fixed grid mesh. However, even though a hybrid mesh can theoretically perform better along steep slopes by mindful mesh design unique to each run, in most situations users are not going to re-mesh for every discharge and spend days to months carefully specifying mesh structure at 3-ft resolution over 37 km of river. Given that both meshes have cells that cut across steep terrain, the differences do not suggest one model is better than another. Also the biggest differences simply reflect a small lateral shift in positioning. Therefore, we conclude that (i) there is no reason to refrain from switching to TUFLOW GPU to take advantage of the dramatic reduction in run time (7-64 times faster) and (ii) model results from TUFLOW GPU are directly comparable to previous SRH-2D results, except along steep banks. Because of this and its valuable time saving features, TUFLOW GPU should be used for future scientific analyses on the lower Yuba River.

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