FRESHWATER MAP

Sacramento River Delta 3D Mapping Project Technical Report

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Executive Summary

This technical report is in response to item five in the Delta Stewardship Council project #6276. The data collection and analysis were completed by Freshwater Map of Bigfork, Montana. The objective of this phase-1 project was to demonstrate, to a broad audience, how our high-resolution, hydro-acoustic, river-mapping services could help people working toward water resource solutions for the delta. The overarching goal for the State of California is to balance human needs for freshwater with an ecological healthy river-delta system under the "co-equal goals" legislation. The fundamental question being addressed by all stakeholders is: how much water can be drawn from the delta and still maintain a healthy delta wide ecosystem? However, there is no agreement yet on how much the ecosystem needs or how a multitude of uses and flow regulation impacts both humans and the ecosystem. A suite of computer models has been developed and refined over the past two decades to address this fundamental question (Fig. 1). These models were developed to help guide resource decision agreement on how to manage freshwater that flows to and through the delta. The data that we collect can help initialize, validate and greatly enhance many of these models (Fig. 1). The data analysis presented in this technical report is a first pass summary of how the depth and flow data coupled to the sonar imagery can be used to help reach delta-wide agreement over water resource management.

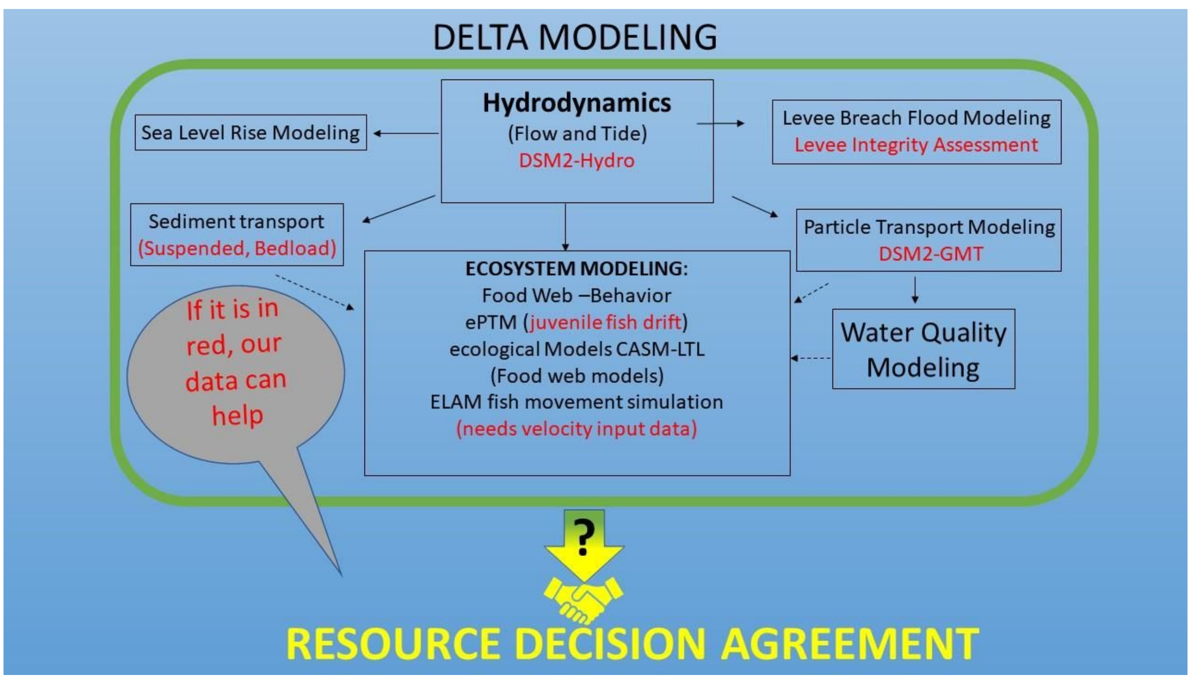


Figure 1. A schematic diagram showing some of the various models used to manage water resources in the delta and where the data that Freshwater Map collects can be useful.

The main hydrodynamic flow model is DSM2-Hydro which requires channel bathymetry data on a delta-wide basis. The main test for Freshwater Map was to demonstrate that we could collect bathymetry data and fuse it to existing LiDAR data representing levee topography. Hence, with the phase-1 pilot project we were tasked with mapping 33 km

(20 miles) of the Sacramento River between Clarksburg, CA and Isleton, CA as well as much of Elk Slough as possible for a total of approximately 58 km (Fig. 2). We collected these data using Acoustic Doppler Profilers (ADP), which simultaneously provide a measure of water depth, flow, and temperature deployed from small cat-rafts. We mapped the Sacramento River reach 3 times to assess flow dynamics including tidal influences and high spatial resolution discharge measurements suitable for water budget assessment. It took four days to map approximately 80 miles of the Sacramento River and Elk Slough. Elk Slough was assigned to us as a channel given its complexities associated with depth, dense aquatic vegetation and navigation hazards from large wood debris. We then fused the channel bathymetry data with existing topography of the levees (LiDAR data) thereby creating a Digital Elevation Model (DEM) in an ArcGIS database adjusted to the NGVD88 datum. Users can now extract elevation cross-sections wherever desired along the channels shown in Figure 2 and use that information to initialize DSM2-Hydro which feeds information required for all other models (Fig. 1). In addition, the DEM is necessary for levee integrity assessment and engineering design for levee maintenance. The flow data can be used to validate velocity prediction using DSM2-Hydro and the particle drift analysis portion of that data can be used to validate DSM2-GMT particle transport modeling using empirical data (see **Marotz and Lorang 2017** for an example of this approach applied to 225 miles of the Missouri River).

We also used a multi-beam sonar system to collect images of the entire channel bottom shown in Figure 2. This imagery of the bottom allows users to assess the composition of the channel bottoms (sand, mud) and what types of bedforms exist and where (e.g. sandbars, erosion scours) the extent and condition of subsurface levee rip-rap as well as other attributes of the channel such as location and size of large wood debris, patches and extent of aquatic vegetation. This data set, also collected in a four-day period, gives a complete measurable image of the channel bottom.

A main objective of our initial project was to demonstrate how we can assemble our flow data to assess flow variation and particle drift within the channel We also analysed how that flow changes from the surface to the bottom boundary of the channel and how those flow patterns reverse through the ebb to flood tidal cycle. To accomplish this objective, we used the flow data collected in the 20-mile-long Sacramento River reach (Fig. 2) over three consecutive days covering a complete ebb tide through flood cycle each day and then analyzed these data to map out the spatial flow patterns and velocities including the subsequent particle drift path differences imposed by tidal fluctuation. We did the same for Elk Slough by measuring flow up the channel during an ebb tide and down the during flood tide. We then used these data to create maps of the flow conditions for the surface (top 1 m) and channel bottom (bottom 50 cm) and mean conditions throughout the entire water column. Because the data is 3D throughout the water column we were then able to map the flow vectors for each condition (surface, bottom, mean water column) showing magnitude and direction of flow and connected those vectors to demonstrate the rate and distance of particle drift for each layer.

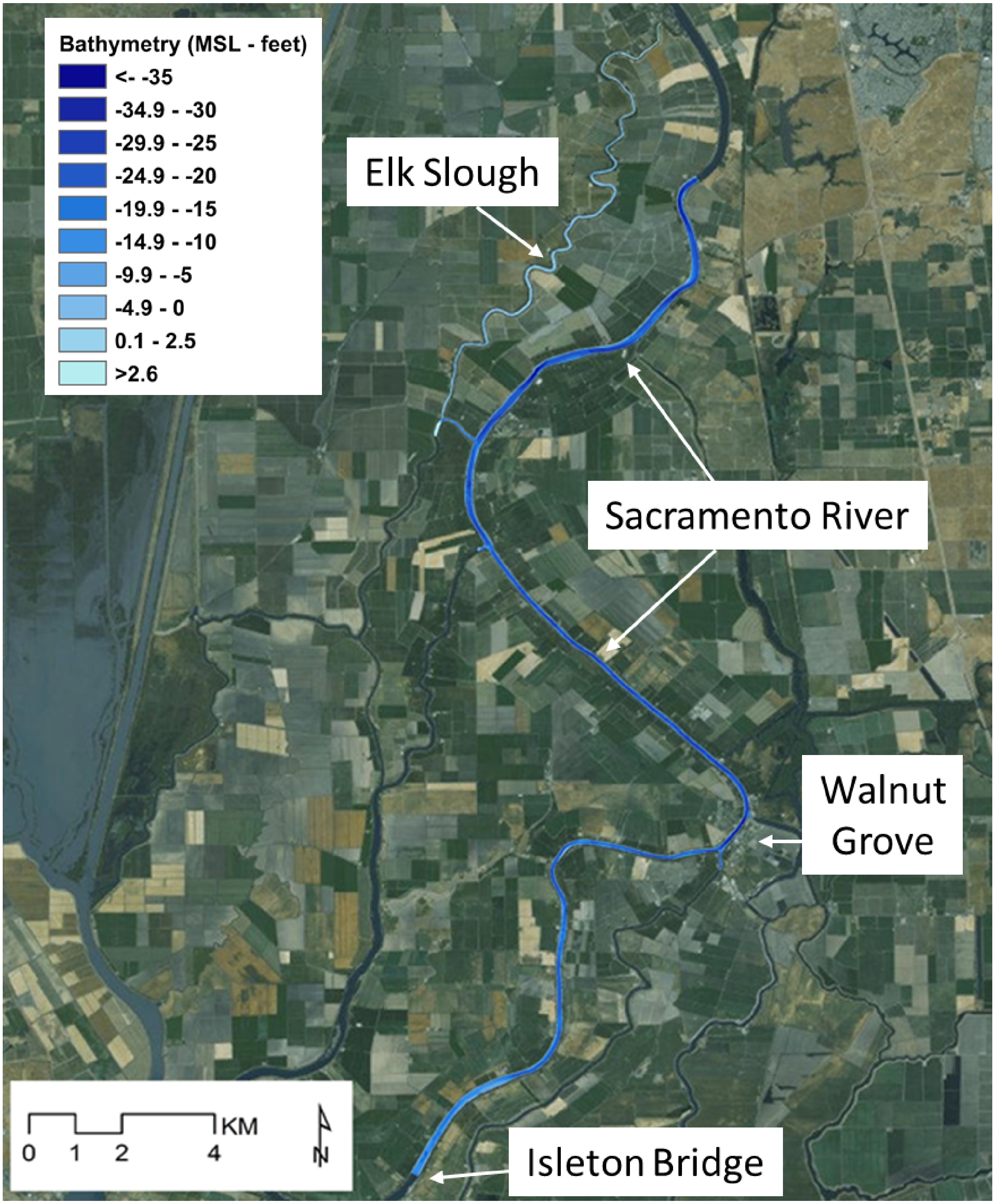


Figure 2. A bathymetry map of the study area linked to aerial imagery (2016 NAIP imagery) showing the extent of the study reach. This map displays as an ArcGIS bathymetric Digital Elevation Model (DEM) allowing maps of specific areas at a higher scale to be created where ever desired.

This type of data analysis is essential for assessing both suspended and bedload sediment transport flux but also the movement of fish, including delta smelt, drift, out-migration patterns of juvenile salmonids, drifting patterns of various species of sturgeon embryos and juveniles as well as drifting patterns for parcels of water that carry nutrients and pollutants. We also measured and mapped water temperature that is linked to flow turbulence and drives many ecological processes from metabolism and decay to bio-geo-chemical processes. The return intensity signals for each acoustic beam (5 per ADP) have also been recorded and archived. The return signals are directly related to the concentration of suspended particles in the water column and hence could be used as a surrogate for 3D spatial mapping of water clarity coupled to the flow. These data could then be related to similar data being collected a gauging stations throughout the delta to help improve water quality modeling and assess migration ques for delta smelt.

Our approach to measuring patterns of flow and drift paths could be very helpful for particle transport and water quality modeling DSM2-GMT which is then used to feed results to higher order food web modeling. Therefore, it is imperative that both DSM2-Hydro and DSM2-GMT be accurate within their inherent limitations. Indeed, DSM2-Hydro is a 1D model that assumes all the water in a channel flows the same direction and at the same velocity throughout the water column. It is then used to drive the particle drift and water quality modeling efforts that are then dependent on those 1D assumptions. As we know and demonstrate in this report using the data collected, flow in the delta is anything but 1D. It is complex and changes with tide, channel dimensions, bedforms, wood debris and density of aquatic vegetation and composition of the levee banks below the water surface. These complexities impact both the net delta outflow of freshwater and aquatic habitat essential to the ecology of the delta.

Our motivation is to enable readers to use this report to understand how our datasets can help move modeling into a 3D representation of flow and particle drift on a delta-wide scale. Indeed, we could map the entire delta in a matter of months and create a delta-wide DEM of the channel bathymetry and levee topography accessible to all stakeholders and useful for all modeling efforts and engineering analysis. Moreover, we offer the ability to measure flow complexity delta-wide that can be used to assess how much water can be drawn from the delta while still maintaining a healthy delta ecosystem. These 3D datasets enable delta flow modeling to move far past the capabilities and accuracy of the current of 1D models.

The remainder of this technical report describes the data collection process and the approach used to create the contract deliverables.

Deliverables

- Create a high-resolution image of the channel bed throughout the reach using our 2D sonar imaging device showing all bedforms (submerged bars, and ripples etc.) wood, sunken trees, banks and shallow shelf areas, substrate composition (sand vs gravel) , overlaid on existing aerial imagery of the river reach and superimposed on measured channel bathymetry. (Deliverable # 2)
- Create three separate flow velocity maps of the river reach identified above. One each for the bottom boundary layer (1 m along the bottom), surface flow of the top layer and the third showing mean water column conditions. (Deliverable # 3,6)
- Create a surface-water temperature map for each run. Temperature reading shall be taken at approximately -10cm from the water surface to reflect heating during time-span of collection and mixing due to turbulence. (Deliverable # 3,6)
- Create transect plots of the flow field for every 10 m along the slough showing 3D flow field and calculating discharge. This creates a water budget for the length of the river reach together with the potential to identify spatial locations of water loss, which is an indicator of possible levee failure locations. (Deliverable # 4,6)
- Create particle drift maps for the bottom boundary (1 m from bottom), surface (from approximately -50 cm to approximately -30 cm from the surface), and mean water column for river reach. Each map will depict one to 5 kilometers of river reach. Velocity along each path shall be plotted with an appropriate grid of flow vectors to help interpret the patterns of drift. (Deliverable # 4,6)
- Write a technical memo describing data collection and analysis process and methods. (Deliverable # 5)
- Present results and findings at a 1-day meeting with lead researchers and other interested parties in Sacramento to be scheduled by Council. (Deliverable # 7)

Remaining Report Organization

1. Equipment and ADP Data Collection Methods
2. Sonar Bottom Mapping
3. Bathymetric Maps
4. Fusing Channel Bathymetry to Levee Topography (DEM)
5. Temperature Mapping
6. Flow Mapping
7. Flow Vector Mapping and Particle Tracking
8. The Elk Slough Challenge
9. High-Density Spatial Discharge Assessment
10. Summary

Each section is written so that it can be read independently of the other.

1.1 Equipment

ADP and GPS

We deploy Teledyne RiverPro Acoustic Doppler Profilers (ADP) with fully integrated Hemisphere, Vector V102 GPS compass units deployed from catamaran rafts to measure water depth, flow velocities and vectors of flow direction (Fig. 3). Data collection software for river mapping was written by Teledyne in collaboration with Freshwater Map specifically for our unique lagrangian data collection needs.

The GPS units have a horizontal accuracy of 0.5 m with position points collected at the same frequency (2 per second) concurrent with the collection of the ADP data ensembles (Fig. 3). GPS accuracy during the data collection depends on the number of useful satellites (up to 5) in view for maximum horizontal accuracy. The maximum of 5 satellites in use and 8 in view occurred throughout the data collection period. The RiverPro ADPs use 5 beams designed specifically for shallow river application and has a depth range capacity of 20 cm to 30 m. The maximum accuracy of the depth measurement is 1% of the actual depth for each data point. Depth accuracy ranges from 2 mm in the shallowest areas to 2 cm in the deepest pools.

These instruments collect 2 complete data ensembles of flow direction and magnitude from 20 cm below the water surface to 30 m max depth. Water depth is taken from the center beam and surface water temperature from the sensor in the ADP head (Fig 3). Flow velocity is based on the Doppler principle. Sound is emitted along a directed acoustic beam path and is reflected back to the receiver in the ADP head by particles being carried with the flow. That sound returns with a Doppler shift in frequency that is linearly related to the flow velocity in that part of the water column. Because multiple beams are being used simultaneously with measures of raft orientation flow direction can also be determined for each cell in the data ensemble (Fig. 3). The intensity of the return signal is also recorded and is related to the concentration of suspended particles in the water column.

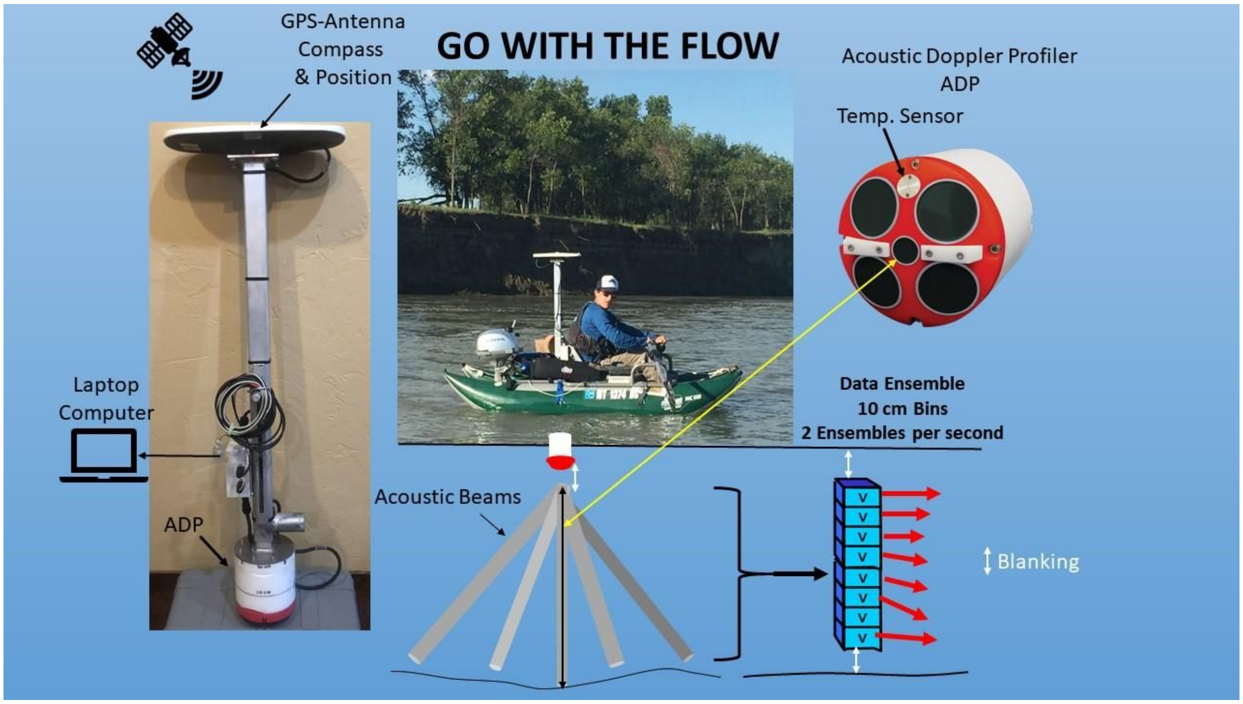


Figure 3. A schematic showing a river technician collecting data from a complete instrumented raft with additional schematics showing ADP and GPS instruments used to collect the depth, flow, temperature and position data and how that data is collated into data ensembles representing 10 cm depth intervals.

Multi-Beam Sonar: High Resolution Bottom Imaging

We deploy, from a 17-foot jet boat, a Blueview M900-2250 multi-beam, dual frequency imaging sonar made by Teledyne Marine (Fig. 4). The instrument is attached to a computer-controlled pan-tilt (Fig. 4). The sonar data is collected and viewed in real-time by the vendor-supplied Pro-Viewer software and stored on the hard-drive of a laptop. Post processing geo-rectified the tiff images using the manufacturer's Pro-mapper software. The sonar has a maximum field of view of 130^{o} with a maximum range of 100 m, with optimum resolution between 2 and 40 m in front of the sensor head with a 60 m wide field of view composed of 768 beams operating at 900 kHz with a resolution of 1.3 cm (Fig. 4). The 2250 kHz frequency operation offers ability for ultra-high resolution of 0.6 cm over a range of 0.5 to 7 m. The study area imaged for this project consisted of bank-to-bank imaging and took four days to complete. Fish are seen in the raw imagery but because they are swimming they do not appear in the processed Geo-Tiff images. However, notes were taken where fish were visible and those raw files can be played back recording the locations and target sizes. Bottom and bank composition (rip-rap, sand, mud) are clearly visible as are bedforms (sand bars, scour holes) including large wood debris and aquatic vegetation.

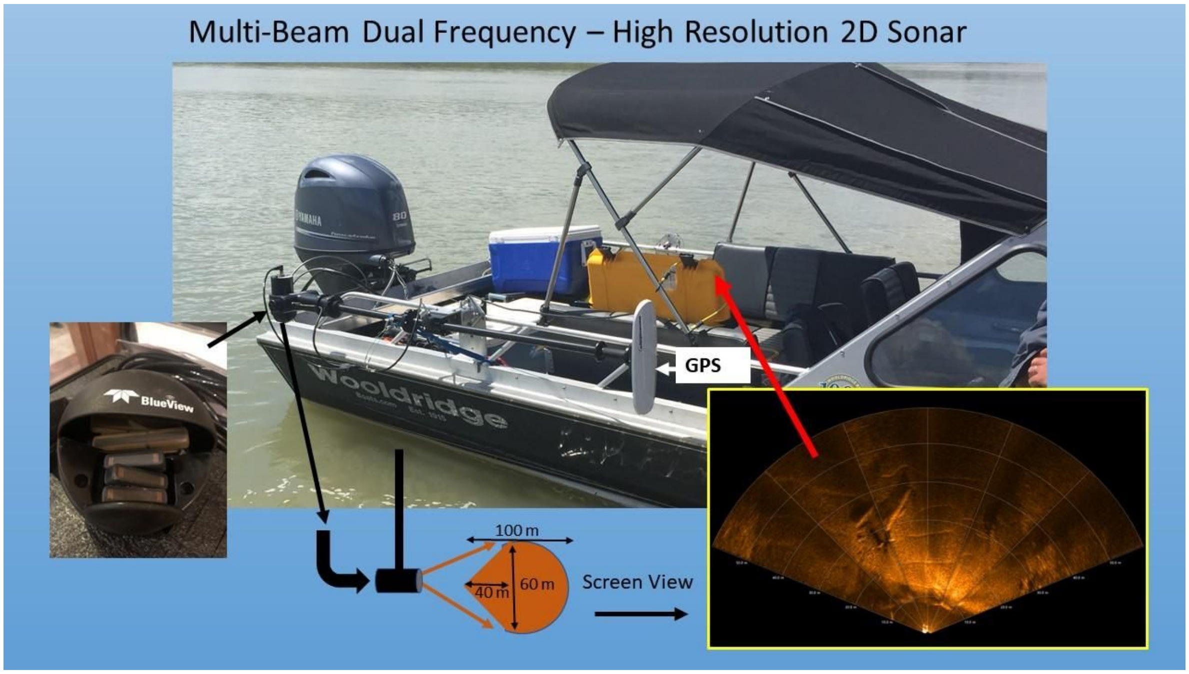


Figure 4. A schematic composite of photos and drawings depicting the boat, BlueView sonar, pan tilt with GPS and raw data examples (yellow box).

1.2 ADP Data Collection Methods

Depth, velocity, temperature and discharge data were collected on the Sacramento River between October 17, 2017 and October 20, 2017. The team of eight River Technicians made three daily runs down a reach on the Sacramento River starting at the Clarksburg launch ramp (38^0 22'58.76" N; $121^0$31'15" W). The team maintained a pre-set distance apart and semi-staggered positioning (Figs. 5 and 6).

Figure 5. A photograph of one of the eight river-rafts, showing equipment configuration, at the Walnut Grove Bridge.

Figure 6. A photograph of several of the river technicians collecting data on Elk Slough.

On Day Four, October 20th, the team put in at Steamboat Slough and ran upstream to Sutter Slough and Elk Slough. Four members of the team (Fig. 7) collected data upstream to Clarksburg on Elk Slough (38^{0}34’57” N; 121^{0} 31’42” W), turning around and returning to Sutter Slough (38^{0}19’56.24”N; 121^{0}35’02.37”W).

Figure 7. River Technicians and equipment during a lunch break at the end of Elk Slough in Clarksburg, CA

The remaining four team members took 13 full pass measurements on Sutter Slough from 38^{0} 19’52.39” N; 121^{0}35’05.62” W to 38^{0}19’ 38.97” N; 121^{0} 34’32.55” W capturing flow and bathymetry through much of the tidal range.

Data collection paths are plotted in ArcGIS using a solid circle symbol representing recorded depth measurement with the diameter of the symbol representing the maximum horizontal accuracy of the GPS signal (+/- 0.50 m) and color corresponding to the water depth at that point (Fig. 8). Depth measurements and corresponding GPS locations were recorded twice per second. Plots of that data show two examples of data-collection paths (Fig. 8). The dot paths in both examples show continuous alignment along the flow path with no displaced positions which would indicate a GPS error. Depth contours are interpolated between transect paths within ArcMap.

The ADP data was exported using Teledyne’s WinRiver II software for each individual boat.

The team collected data for approximately seven hours for each of the four days in the field. The total number of depth and temperature data points collected exceeds 1,600,000. The total number of velocity measurements of 10 cm bins throughout the water column exceeds 80 million, conservatively assuming average depth of 5 meters.

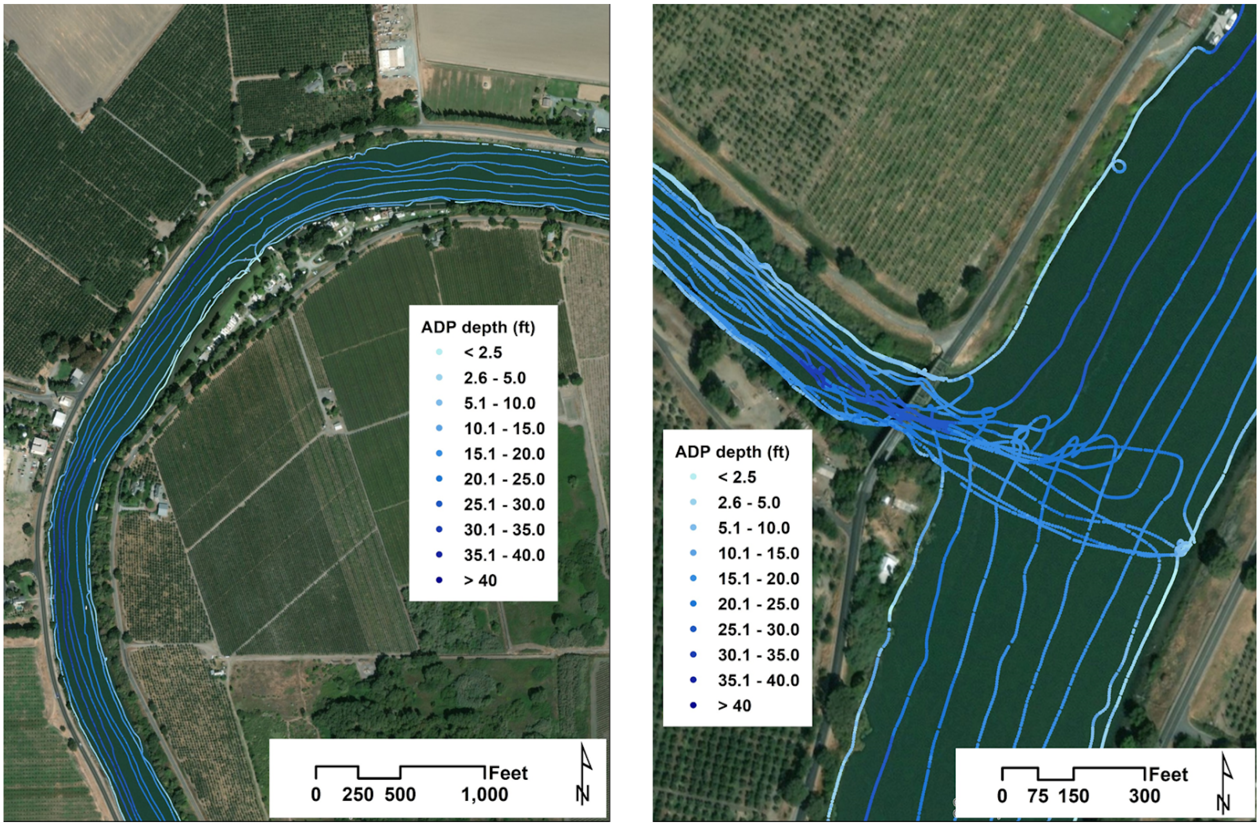


Figure 8. A plot of raw ADP data for an example reach on the Sacramento near the town of Ryde (left) and the entrance to Steamboat slough (right). Each dot represents the depth (color) for a specific data ensemble where each track represents the collection path for an individual raft. Track divergence is due to avoidance of boaters, docks and other obstacles.

2. Sonar Bottom Imaging

Knowledge of substrate composition is critical to understanding the ecological condition and potential impacts from water supply management. It is a key component in determining the type and value of aquatic habitat and when attempting to quantify habitat abundance which is important when trying to determine how much water can be extracted from the delta while maintaining the legislative imperative of co-equal goals. Understanding and quantifying the subsurface composition of the rivers and sloughs throughout the delta is also essential to cost effectively assess levee integrity and plan levee maintenance.

Modeling of sediment bedload transport requires knowledge of the bottom bedforms and substrate type. Imaging the bottom provides the basic bottom boundary conditions required of all modeling. When the bottom is mapped models can be advanced, change in the bedform can be measured, and fundamental management questions can be addressed.

Sonar imaging data was collected by motoring up and then down the Sacramento River (Figs. 9, 10, 11). Elk Slough was imaged bank-to-bank in a single pass (Fig. 12). Multiple imaging passes were made at the bridges and in Georgiana (Fig. 13) and Sutter Sloughs (Fig. 12). The subsurface bank and channel bottom can be seen over a 60 m wide swath

40 m in front of the boat (Fig. 9). The dotted white line shows where the data is being extracted for the post processing step (right panel) and the extent of the processed data being posted against the 2016 NAIP imagery is shown in the left panel (Fig. 9). Data from this reach was run previously to create an image of the whole reach (left panel). Large wood debris can be seen, as well as the sand waves composing the bottom (Figs. 9, 10, 11, 12). Note the slice of missing data in the processed image (Fig. 9 left panel). This occurs due to turning the boat too rapidly. The same gaps can also occur by going too fast. Hence a balance needs to be struck between boat speeding and steady navigation.

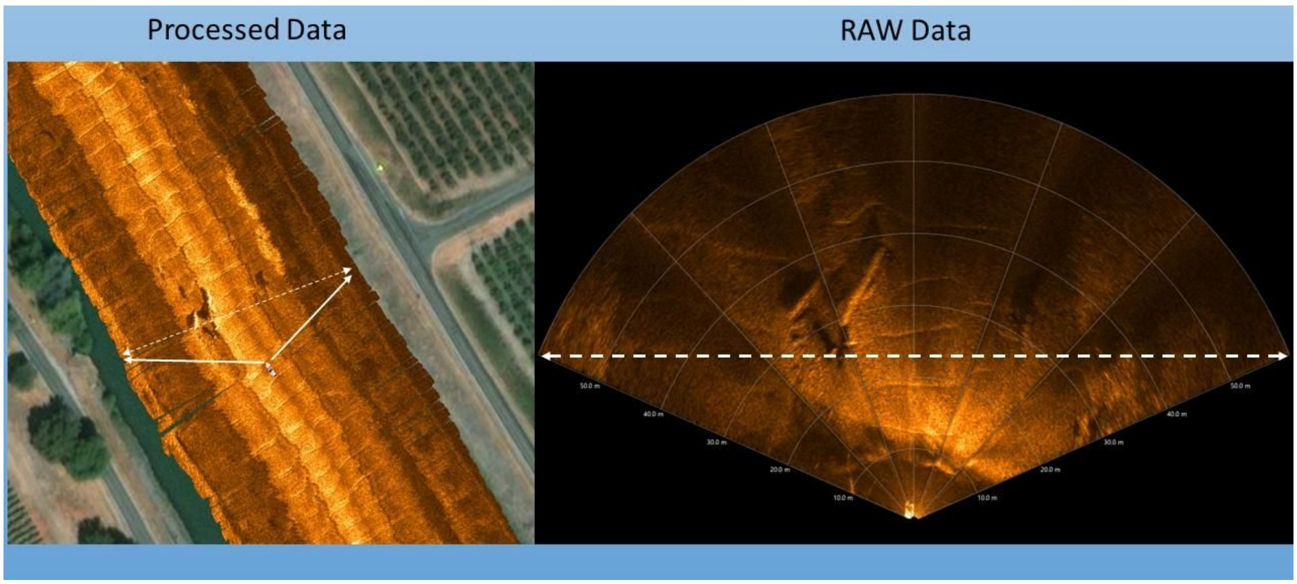


Figure 9. Two panel plots showing a screenshot of raw data as displayed in ProViewer (right) and a screen shot of the same data being processed in ProMapper (left) to produce a geo-rectified tiff image.

Once the imagery is collected and post-processed to create geo-rectified Tiff images they were then mosaiced into large river segments within ArcGIS. The next step was to clip areas of bank-overlap to fit the actual river boundary (Fig. 10). Mosaiced river segments were organized into river right and river left data collections with significant overlap (Fig. 11). The user can decide which images provide the best view of the bottom area in which they may be interested. There is a difference in what the bottom looks like depending on the direction from which the images are collected (Fig. 12). This difference arises from how the sound is reflected off the bottom features. When looking up stream at the steep slip face of a bar sound is reflected with greater intensity than when looking downstream at the same location (Fig. 11). In areas of high intensity sampling (i.e., Georgiana Slough, Isleton Bridge, Painters bridge) multiple river left and river right files were collected creating several views from which the end user can pick and choose which BlueView run to display (Figs. 10, 11, 12, 13).

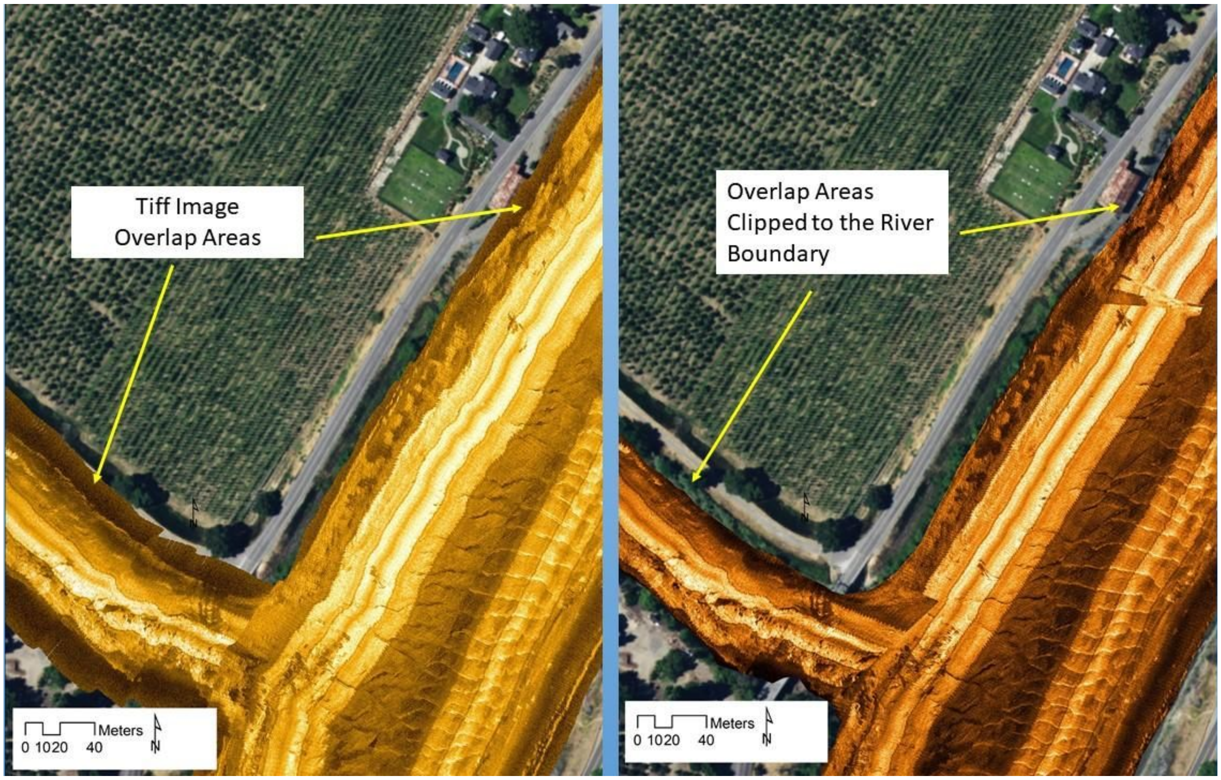


Figure 10. Two panel plots showing Tiff image overlaps (left panel) and the same image with those areas clipped to the water surface (right panel).

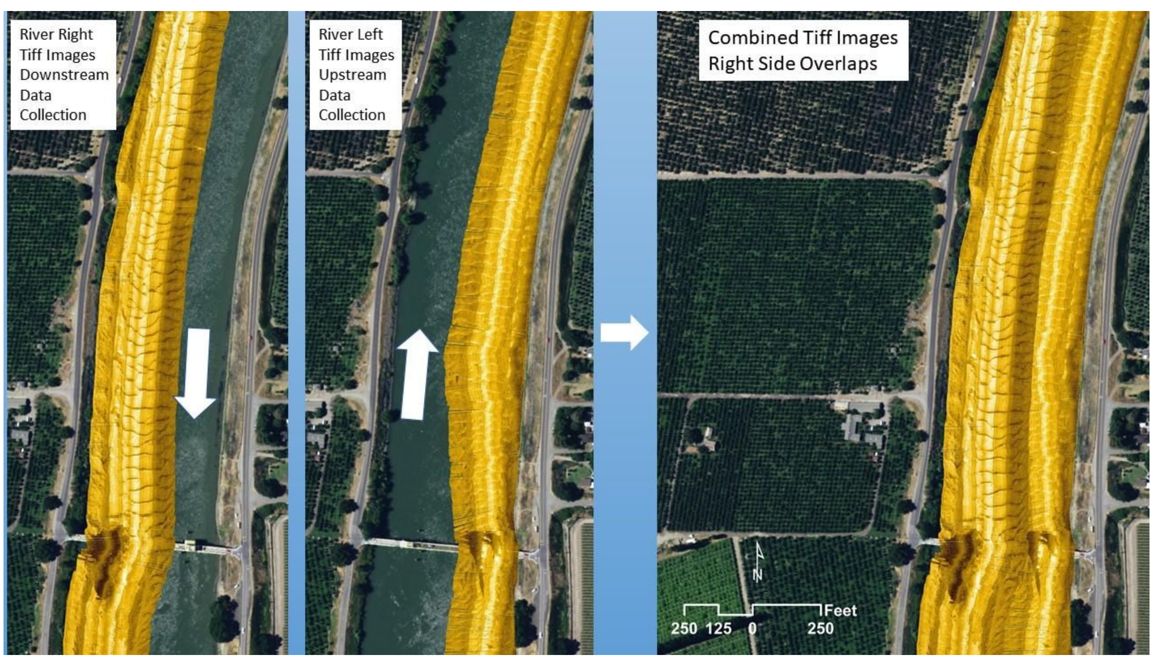


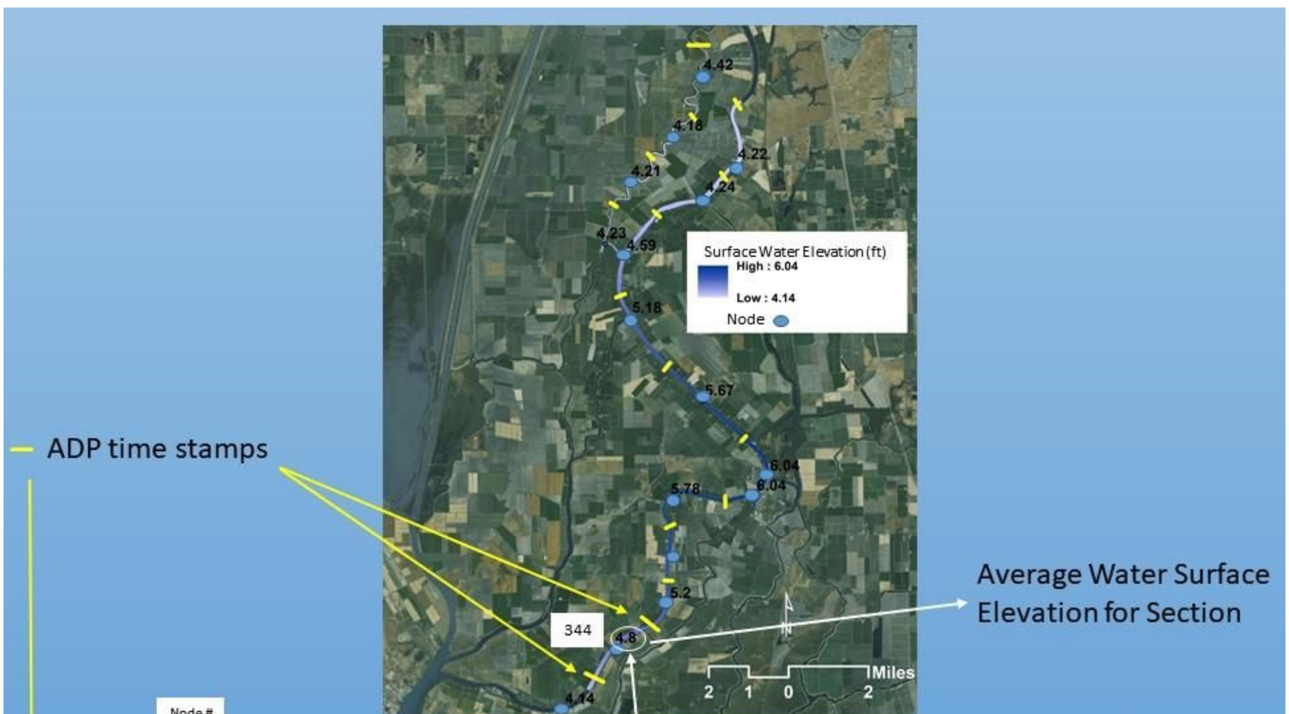
Figure 11. Two panel plots showing Tiff images from downstream collection (left panel) and upstream (right panel). Overlaying the images gives complete coverage with the downstream lying on top (right panel). Note the bottom complexity near the bridge piers.

Figure 12. An example of sonar Tiff images of Elk Slough, Sutter Slough and the Sacramento River displayed against the 2016 NAIP imagery. Note the complexity of the channel bottom in these areas due to how river flow transports and deposits sediment creating different bed forms and the impacts to those processes due to bridge piers and confluence zones of sloughs and the river.

Figure 13. An example of sonar imagery the Sacramento River near Walnut Grove.

3. Bathymetric Maps

To create the bathymetry map, we used ADP data collected on October 17th for the main channel and ADP data collected on October 20th for Elk and Sutter Sloughs. A shoreline polygon was digitized from the 2016 NAIP aerial imagery to help define the extent of the bathymetry interpolation. The ADP and shoreline data were then used to generate a river bathymetry data file for the study reach. The bathymetry was interpolated using the Topo to Raster Tool in ArcGIS at a 2m resolution to match the LiDAR based DEM provide to us by the Delta Stewardship Council. Elk and Sutter Sloughs were interpolated separately from the main channel and then merged together to produce one bathymetry dataset for the entire study reach (Fig. 15). The bathymetry represents water depth from a relative water surface that is set to a zero-elevation plane. To convert the channel bathymetry to actual Mean Sea Level Elevations we used the water surface elevation data provided to us by the Delta Stewardship Council. The following describes our protocol for this bathymetric conversion from relative depth to depth contours relative to mean sea level (NGVD88).



Node #	336	337	338	339	340	341	342	343	344	346	347	348	349	350	339	296	297
10/16/2017 3:15	6.17	5.99	5.95	5.87	5.81	5.73	5.66	5.62	5.47	5.27	5.14	4.93	4.76	4.61	5.87	6.2	6.17
10/16/2017 3:30	6.14	5.94	5.9	5.8	5.74	5.64	5.56	5.52	5.37	5.16	5.02	4.77	4.58	4.41	5.8	6.13	6.11
10/16/2017 3:45	6.1	5.88	5.84	5.73	5.66	5.54	5.44	5.4	5.24	5.03	4.88	4.61	4.4	4.2	5.73	6.02	6.01
10/16/2017 4:00	6.06	5.82	5.77	5.65	5.58	5.44	5.32	5.28	5.12	4.88	4.73	4.44	4.22	4.01	5.65	5.9	5.9
10/16/2017 4:15	6.01	5.75	5.69	5.57	5.48	5.33	5.2	5.16	4.98	4.74	4.57	4.27	4.04	3.83	5.57	5.78	5.78
10/16/2017 4:30	5.96	5.67	5.61	5.48	5.39	5.22	5.08	5.04	4.85	4.6	4.43	4.11	3.88	3.66	5.48	5.67	5.67
10/16/2017 4:45	5.9	5.59	5.53	5.39	5.29	5.11	4.96	4.92	4.73	4.46	4.29	3.96	3.73	3.5	5.39	5.57	5.57
10/16/2017 5:00	5.84	5.51	5.45	5.3	5.2	5	4.85	4.81	4.61	4.33	4.15	3.82	3.58	3.35	5.3	5.47	5.47
10/16/2017 5:15	5.77	5.43	5.36	5.21	5.1	4.9	4.74	4.69	4.49	4.21	4.03	3.68	3.43	3.19	5.21	5.38	5.37
10/16/2017 5:30	5.71	5.35	5.28	5.12	5.01	4.79	4.63	4.58	4.37	4.09	3.9	3.55	3.29	3.04	5.12	5.28	5.28
10/16/2017 5:45	5.64	5.27	5.2	5.04	4.92	4.69	4.52	4.47	4.26	3.97	3.78	3.41	3.15	2.89	5.04	5.19	5.19

Figure 14. A schematic showing river segments bounded by yellow lines with nodal positions within each segment (blue dots) and average water surface elevations (datum NGVD88) that occurred during the time interval ADP data was collected within each river segment used to create the bathymetry maps. The link between spreadsheet data and spatial location (nodes) is depicted.

The water surface elevation data for every 15 minutes over the time duration we were collecting ADP data was created by the Department of Water Resources (DWR) for a series of nodal locations within the study reach. The Sacramento River and Elk Slough were segmented into discrete reaches based on these nodal locations (Fig. 14).

A spreadsheet was provided that listed numbered nodal positions within the reach corresponding to the water surface elevation (datum NGDV88). Water surface elevation at each nodal point was listed on 15-minute intervals. We averaged the appropriate data based on the time-stamps from the ADP data to determine an average water surface elevation within each river segment (Fig. 14). This information was then clipped to our shoreline polygon to match the extent of our bathymetry dataset. To create the final bathymetry dataset relative to Mean Sea Level we subtracted the relative bathymetry data from the water stage dataset creating depth values tied to the NGVD88 datum (Figures 15, 16, 17 and 18). This portion of the process could be eliminated and the final DEM made much more accurate by collecting survey grade water surface elevation data at the same time the ADP data is being collected, thereby increasing operational efficiency of future projects.

The bathymetric contours can be overlain on sonar imagery allowing the user to toggle back and forth to help investigate aquatic habitat in terms of depth and bottom characteristics (Fig. 19 and 20). This can be used to assess ecological impacts to aquatic habitat due to water management decisions. Water depth, substrate composition and flow at a specific habitat location are needed to quantify ecological impacts of changing flows within the delta. Examples of these analyses follow.

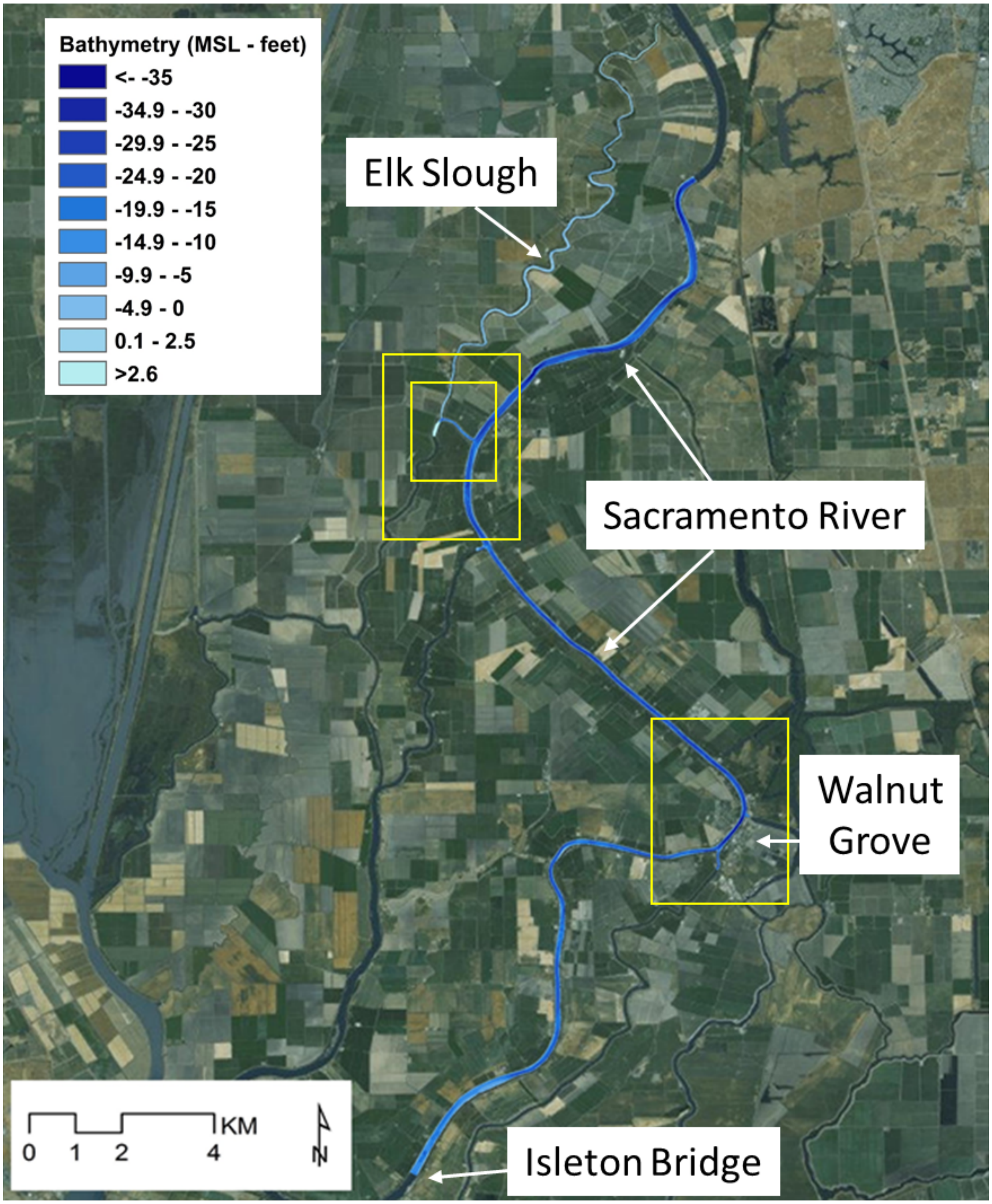


Figure 15. A color-coded bathymetry map of the complete study area. The yellow boxes show areas enlarged in figures 16, 17, 18, 19, & 20.

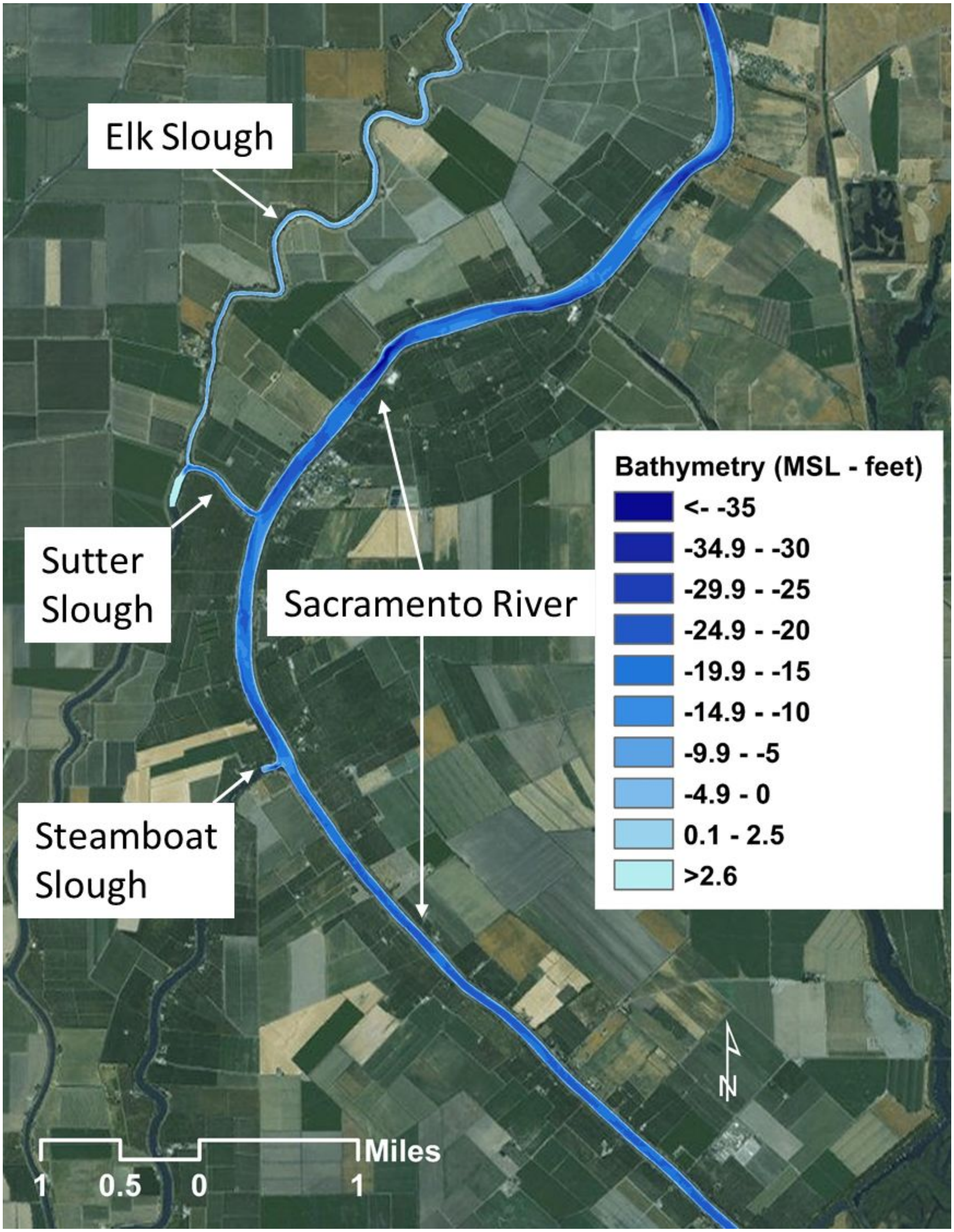


Figure 16. A color-coded bathymetry map of the Sacramento River showing the confluences with Steamboat and Sutter Sloughs and Elk Slough.

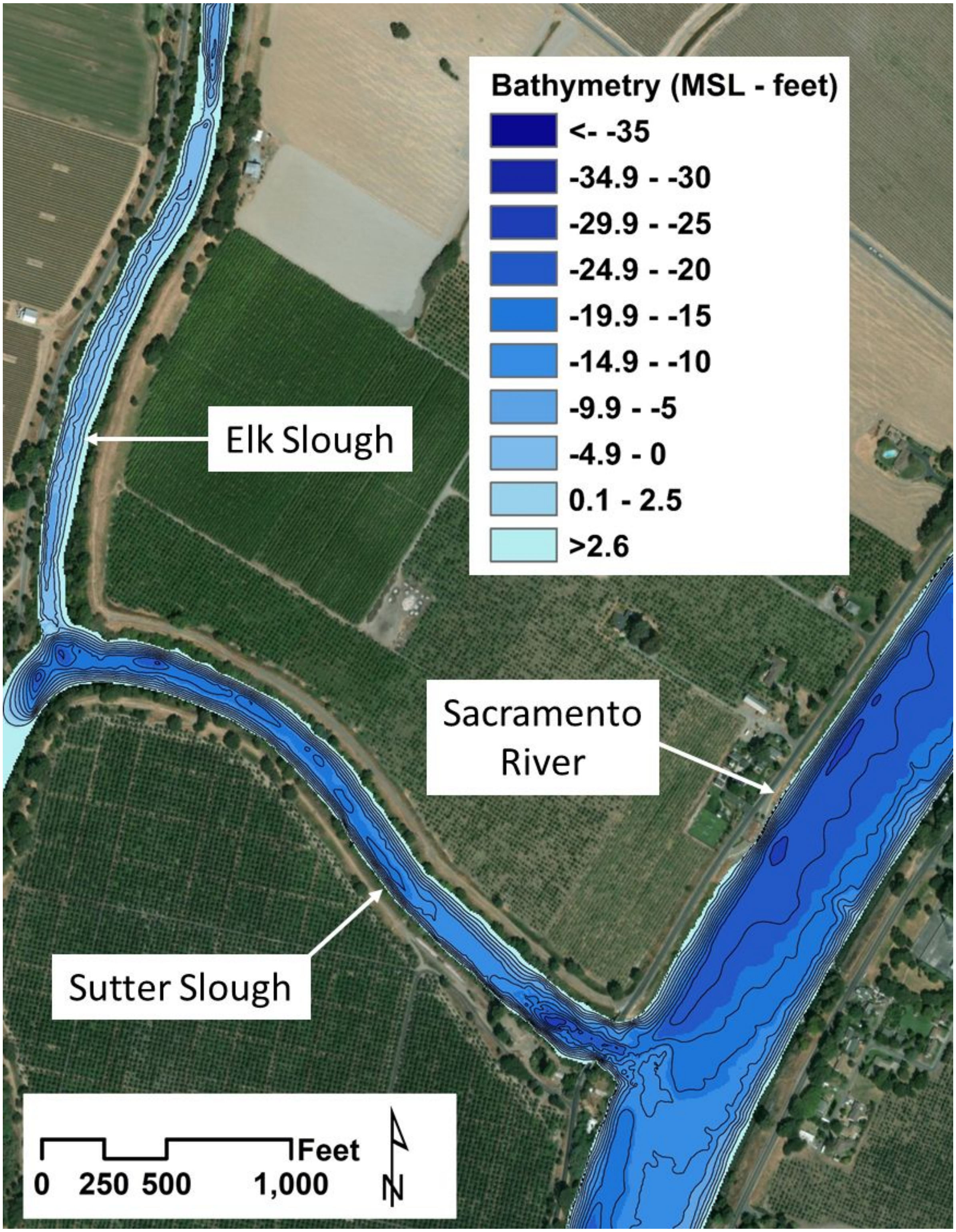


Figure 17. A bathymetry map with overlain depth contours of the Sacramento River near the confluences with Sutter and Elk Sloughs.

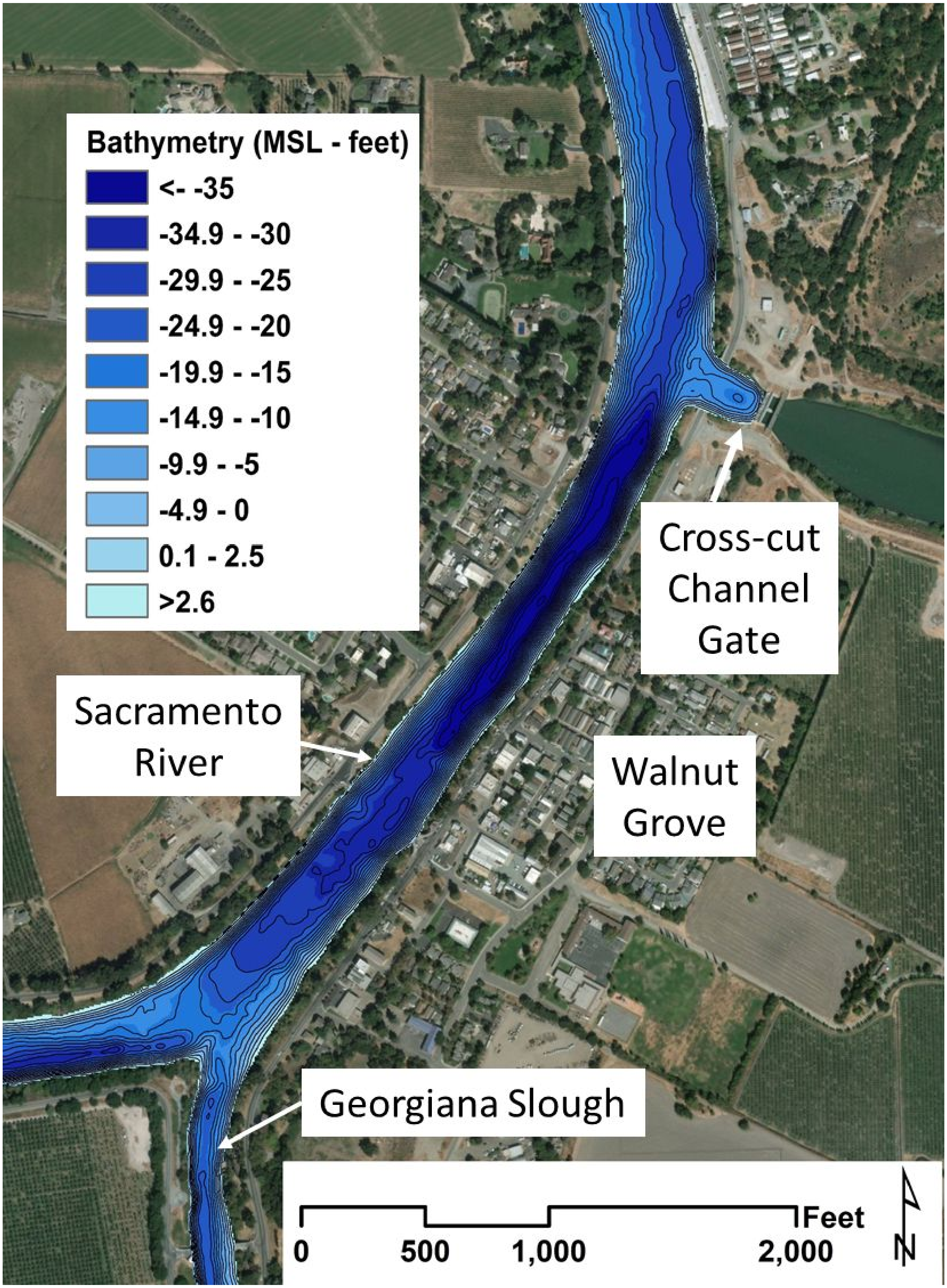


Figure 18. A bathymetry map with overlain depth contours of the Sacramento River near Walnut Grove.

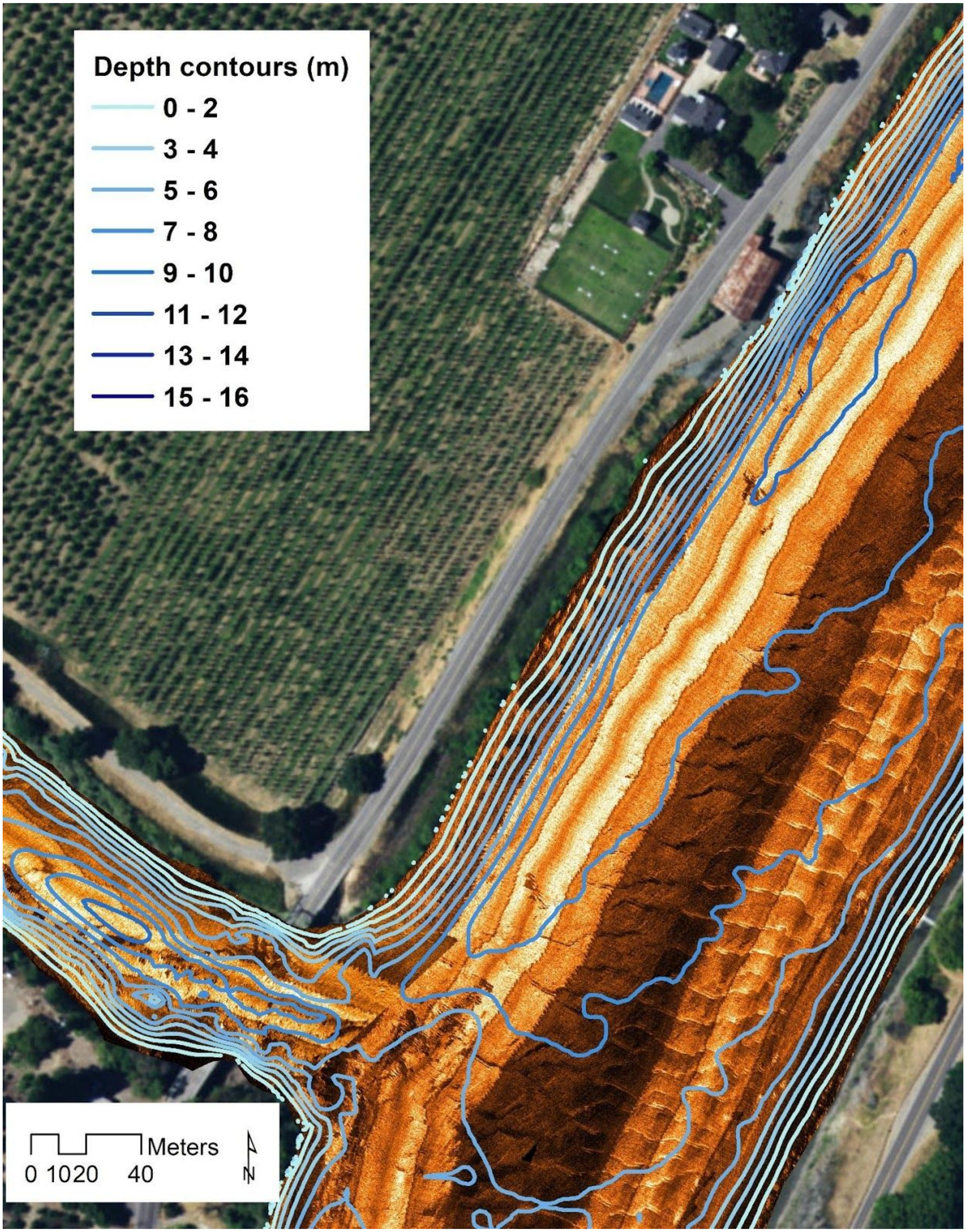


Figure 19. An example of sonar imagery with overlain depth contours of the Sacramento River near Sutter Slough mouth.

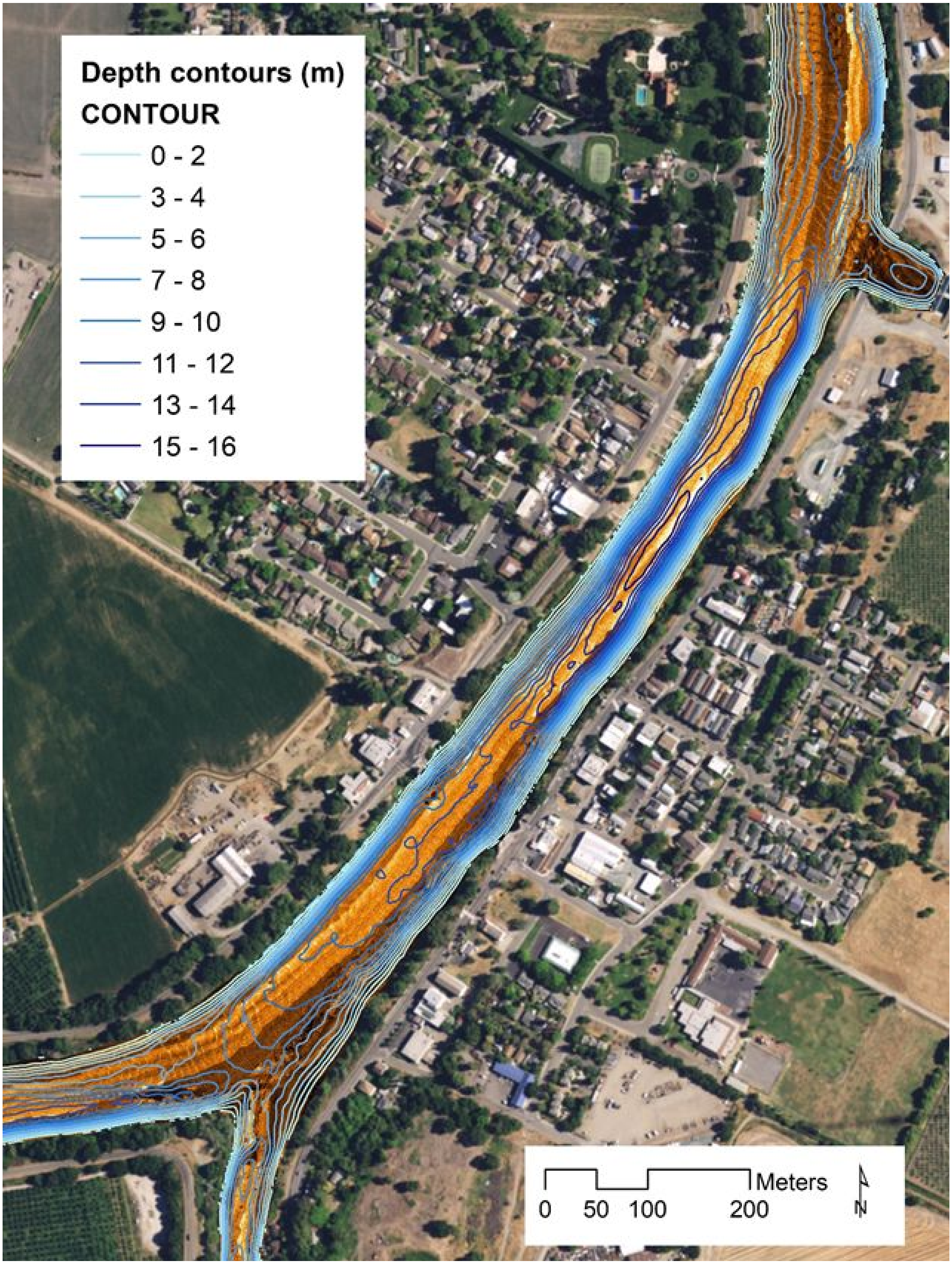


Figure 20. An example of sonar imagery with overlain depth contours of the Sacramento River near Walnut Grove.

4. Fusing Channel Bathymetry to Levee Topography to Create a Digital Elevation Model (DEM)

Linking river and slough bathymetry to levee topography as a single DEM is another main objective for this pilot project. Levee stability and maintenance questions are primary delta-wide concerns that require this kind of DEM. For example, determining how much rip-rap, and at what size configuration is required to protect a levee bank requires such information and enables development of cost estimates. Size and amount of material depends on expected flow velocities and volumes. The ability to extract cross-sections of the combined levees and channels is required to run basic flow models that can be used in this analysis as well as comparing with measured flow data explained in the sections 5 and 6.

Flow models are used to estimate depth and flow between successive transect locations which can range from 100s of meters apart to kilometers. We have provided interpolated depth and flow between data transects that are a maximum of 20 m apart coupled to coverage over distances of 100s of km. Ideally combining our data with computational flow modeling (CFM) provides the very best use of both methodologies. Data provided by Freshwater Map can be used to both initialize the boundary conditions upon which CFM are dependent and to validate the estimates produced from CFMs. In this way CFMs can be calibrated to the highest level and thereby be used to assess changes in water discharge due to various what-if scenarios regarding water resource management decision alternatives, assessment of various design ideas for in-channel structures, what size and how much rip-rap is required. Moreover, CFMs can then feed the very best information to “down line” models from water quality models to fish behavior models. And because our flow data is high-density 3D in format it can inform 1D, 2D and 3D CFM endeavors.

The following explains the process we undertook, and our results, followed by some suggestions on how to rapidly fill existing LiDAR data gaps at the same rate that we collect ADP and sonar data.

LiDAR Data

The original LiDAR data source, provided by NOAA, was edited to remove spurious water surface returns (Fig. 21, black areas in river, the white areas on levee bank represent missing data as well). An edited LiDAR based DEM representing the levees for the Sacramento River and Elk Slough was provided to FWM by the Delta Stewardship Council where these spurious water surface returns were removed, and the missing levee data were interpolated and filled in. The DEM provided represents the best representation possible, with existing data, of the levees and neighboring land. What we provide are the elevation contours of the channel and interpolation of missing data points between the water surface at the time we collected data and that lost in the process of removing spurious data. The method used to remove spurious water surface returns from the original DEM resulted in up to 10 meters of variance between the actual water surface and the levee bank.

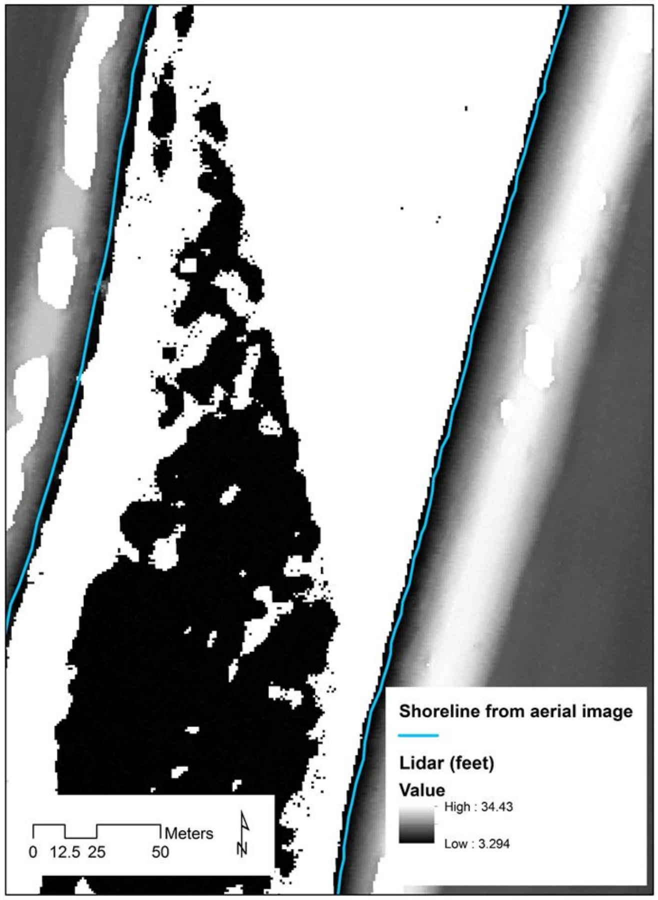


Figure 21. A panel plot showing LiDAR data in grey, water in white between blue lines. The light blue lines represent the water's edge digitized from 2016 NAIP aerial imagery (0.7 m horizontal accuracy). The black pixels in the river are water surface returns in this data set. The jagged edge along the grey shoreline is the water's edge as defined by the LiDAR based DEM. This LiDAR data was downloaded at https://coast.noaa.gov/dataviewer/#/lidar/search/where:ID=2523 **and represents original source data.**

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We integrate the normalized MSL bathymetry dataset into the LiDAR that was provided via a mosaicking tool in ArcGIS. However, due to differences in stage and interpretation of shoreline extent between the 2 datasets, there were gaps of missing data (Figs 22 & 23). A focal statistics algorithm (i.e., Focal Mean) was used to replace the missing data represented by red arrows in figure 22. This algorithm takes a point along the water surface polygon and looks at surrounding data cells from the DEM to estimate values for the missing data providing a linear interpolation between the two points.

The complete process of collecting ADP data, digitizing the water surface polygon from 2016 NAIP imagery through creating a bathymetric grid file in ArcGIS and linking that to water surface elevation occurring at the time of ADP data collection and the LiDAR based DEM is shown in Figure 24. The final product is a merged DEM representing the levee banks and channel bathymetry all relative to the NGVD88 datum (Fig. 25).

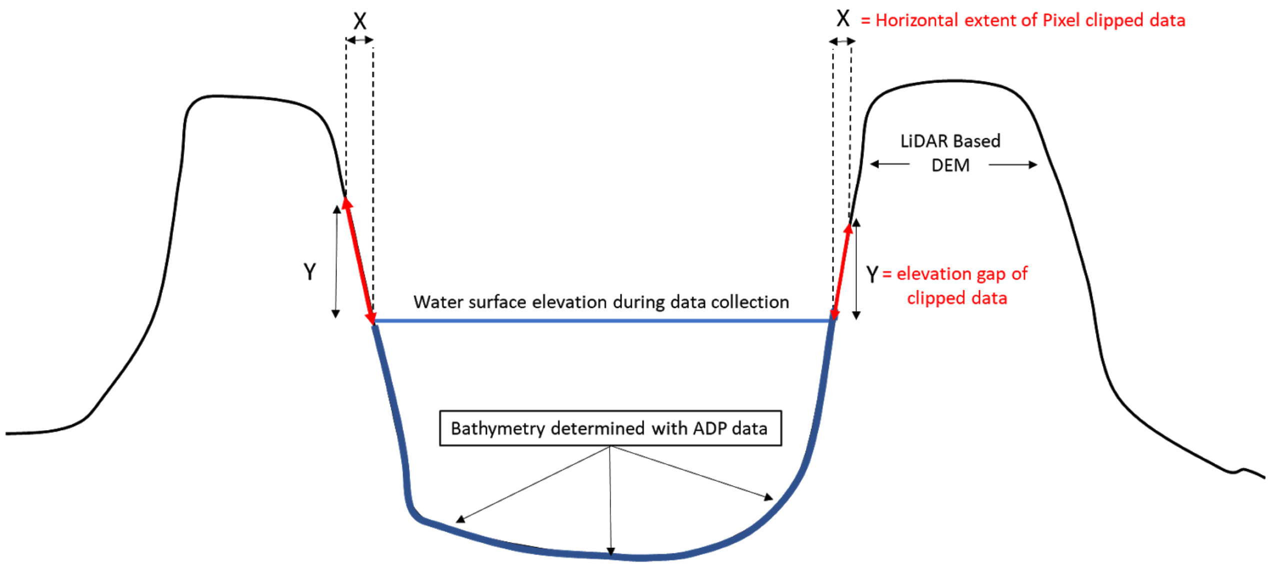

Figure 22. A schematic cross-section showing the range of missing data due to the pixel data clip (red arrows). The Y-values (red arrows) are plotted in Figure 23 for our study reach. The spatial variation and range depend on how the water surface edge was clipped from the original data files.

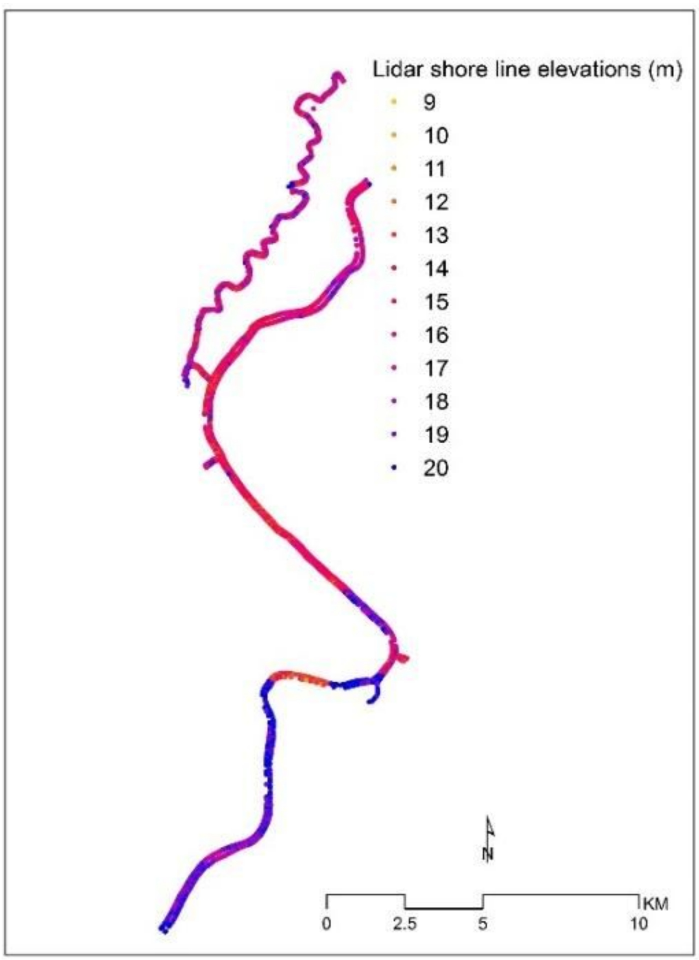

Figure 23. Spatial location and range of missing data (y-values in figure 22 due to pixel data clip).

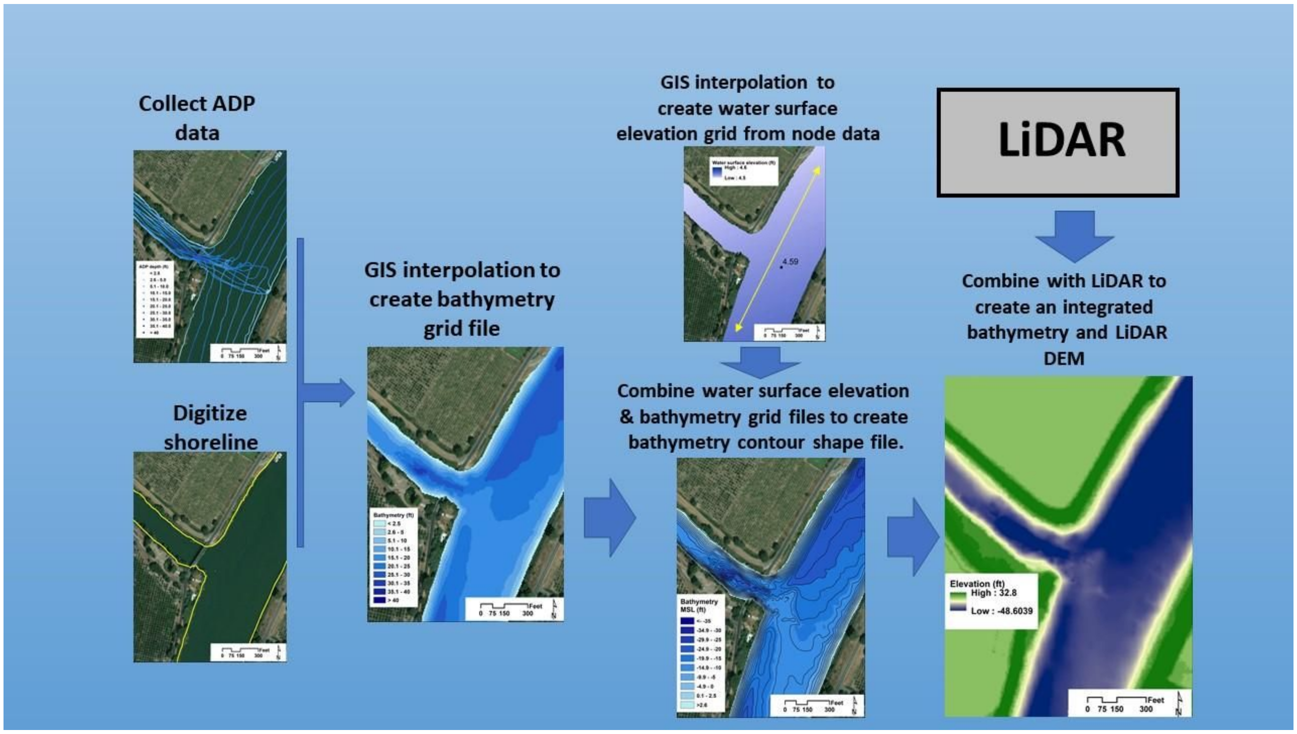

Figure 24. A schematic diagram showing the workflow steps implemented to create combined DEM representing the delta floodplain, levees and channel bathymetry.

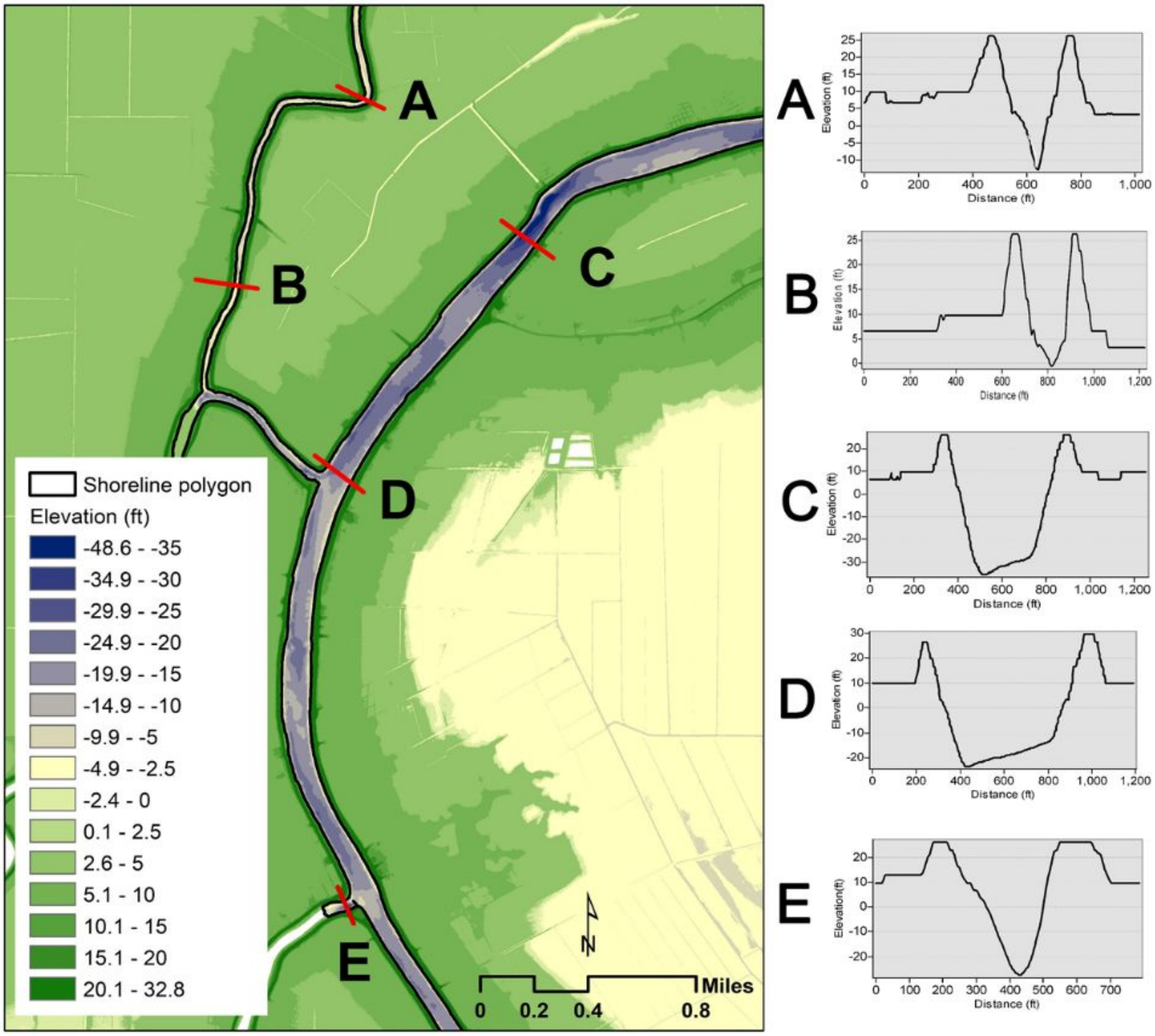

Figure 25. The colored map shows the bathymetric map linked to LiDAR data. This data exists as a single Digital Elevation Model (DEM) where the bathymetric counters are linked as elevation data to best match the topography of the bare-earth floodplain DEM created from the LiDAR point cloud data. Five example cross-sections are shown (A-E). Transects like these can be extracted from the DEM wherever desired and used to assess levee engineering questions as well as to initiate flow modeling.

Boat-Mounted Mobile LiDAR Data

FWM collaborated with Alta Scientists and Engineers, a consulting firm located in Idaho, on an R&D project aimed at collecting bank topography from a moving boat. A LiDAR scanner was mounted horizontally in our jet boat (Fig. 26). This orientation allows a LiDAR scan from the water surface to the top of the bank while motoring along the bank approximately 50 m away from the bank.

The initial results of this data collection are quite promising given that details of the river bank are clearly defined (Figs. 26, 27 & 28). Post processing of the data would produce a 4 to 5 cm accurate point cloud for the DEM that could be used to fill in the missing data points (red lines in figure 22) and simultaneously as sonar imagery of the bottom was being collected. Coupling a survey grade GPS rover antenna and base station would then allow 2 cm level measures of water surface elevation data to also be collected. This approach would provide the most accurate approach to creating a fused channel bathymetry and levee DEM (Figure 25) which is a very important and needed data set for addressing delta-wide water resource questions.

Figure 26. A photograph of the LiDAR scanner and GPS unit mounted in our jet boat.

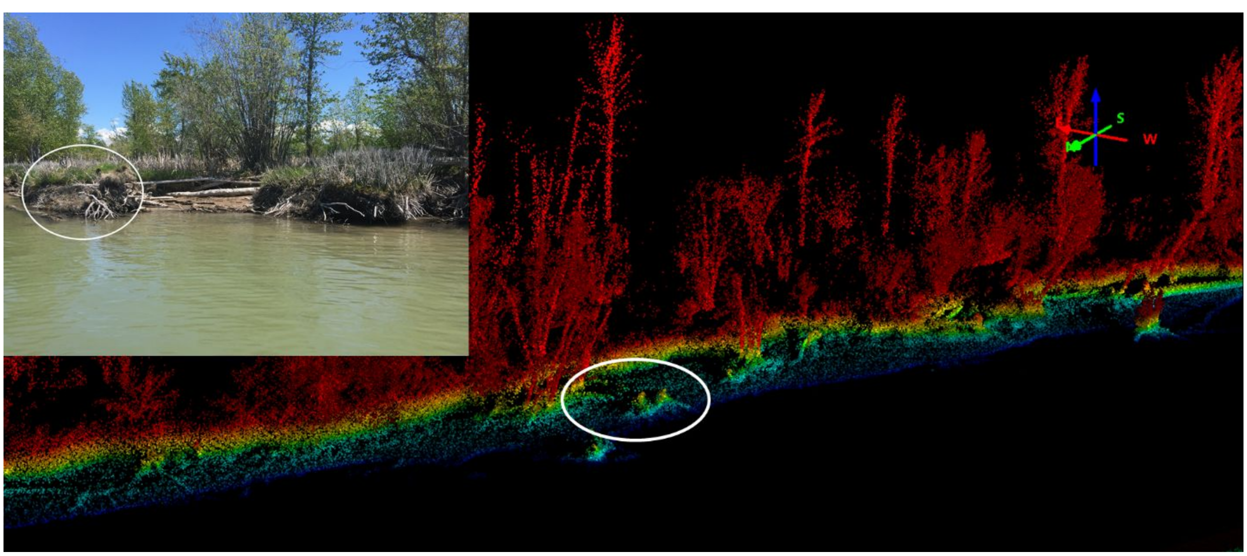

Figure 27. A photo of the river bank (insert) compared to a color enhanced 3D plot of raw unprocessed LiDAR data. The white circle marks similar locations.

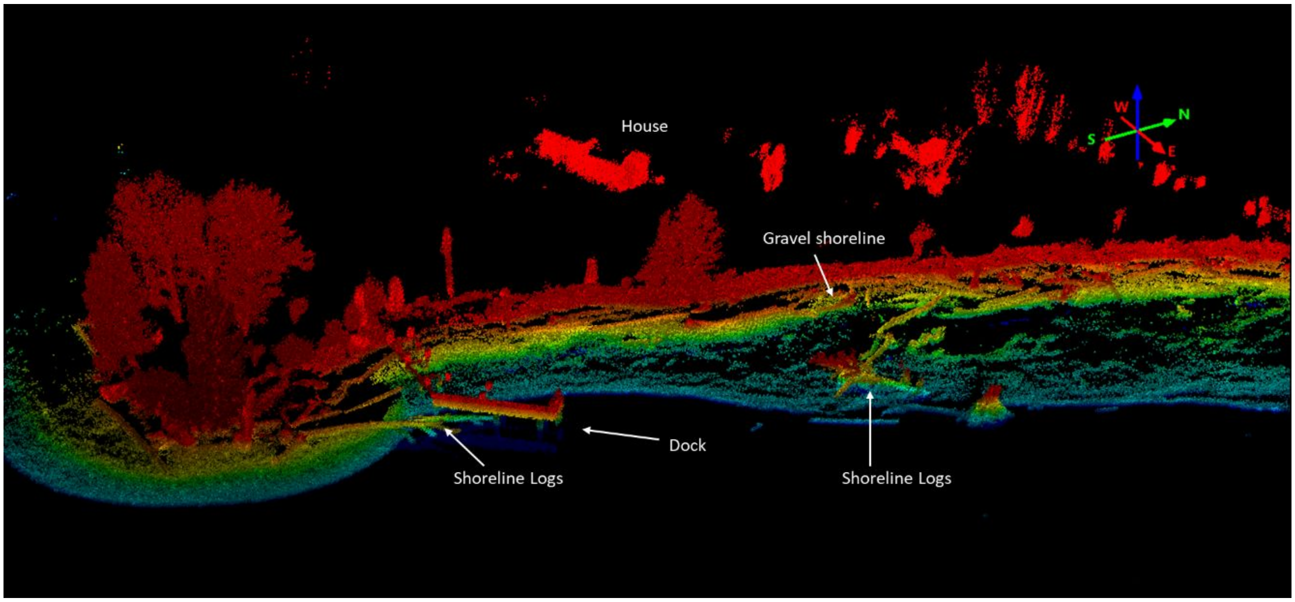

Figure 28. A color enhanced 3D plot of raw unprocessed LiDAR data.

5. Temperature Mapping

Water temperature is a primary driver of metabolism, decay of organic matter and many bio-geo-chemical processes. Therefore, water temperature data is vital to most ecological and water quality models used to assess such processes impacting the ecological health of the delta. Solar radiation and air temperature heat the surface waters while turbulent mixing of deep cooler waters control water column water temperature. Our ADPs have a temperature sensor mounted in the ADP head (Fig. 3) and that data is recorded along with the acoustic data and at the same frequency. We use the Topo-to-Raster method with ArcGIS to interpolate these spatially specific data points in the same fashion that the bathymetry maps are created and plot those maps against the 2016 NAIP imagery (Fig. 29 - 33). This method creates a hydrologically correct raster surface from point data.

Heating of the surface water as the day progresses is apparent in all the maps where data from the morning through late afternoon are plotted (Figs 29, 30 and 31). Each day the surface water temperature in the Sacramento River and Elk Slough began around 14^{o} C and hit a high around 16^{o}C by mid-day. Heating was slightly different on each of the three days with day twp surface water temps reaching the highest and starting off slightly warmer on day three (Fig. 31). Elk Slough showed the most interesting heating pattern. The river team started at the bottom in the morning around 0900 and made it up to the top of the slough by 1300 against an Ebb tide, hence the water was flowing out of the slough. Notice that the peak water temperatures were measured approximately midway up the slough before they began to cool on the upper 1/3 of the channel (Fig. 30). This could be due to cloud cover and or influx of cooler water at the top of the slough or mixing of cooler bottom water as the slough drained with the tide. The surface temperature is complicated and the patterns we measure reflect turbulent mixing of water due to flow in the channels. This mixing pattern is reflected nicely in the surface water map near Ryde on the Sacramento

River (Fig. 32).

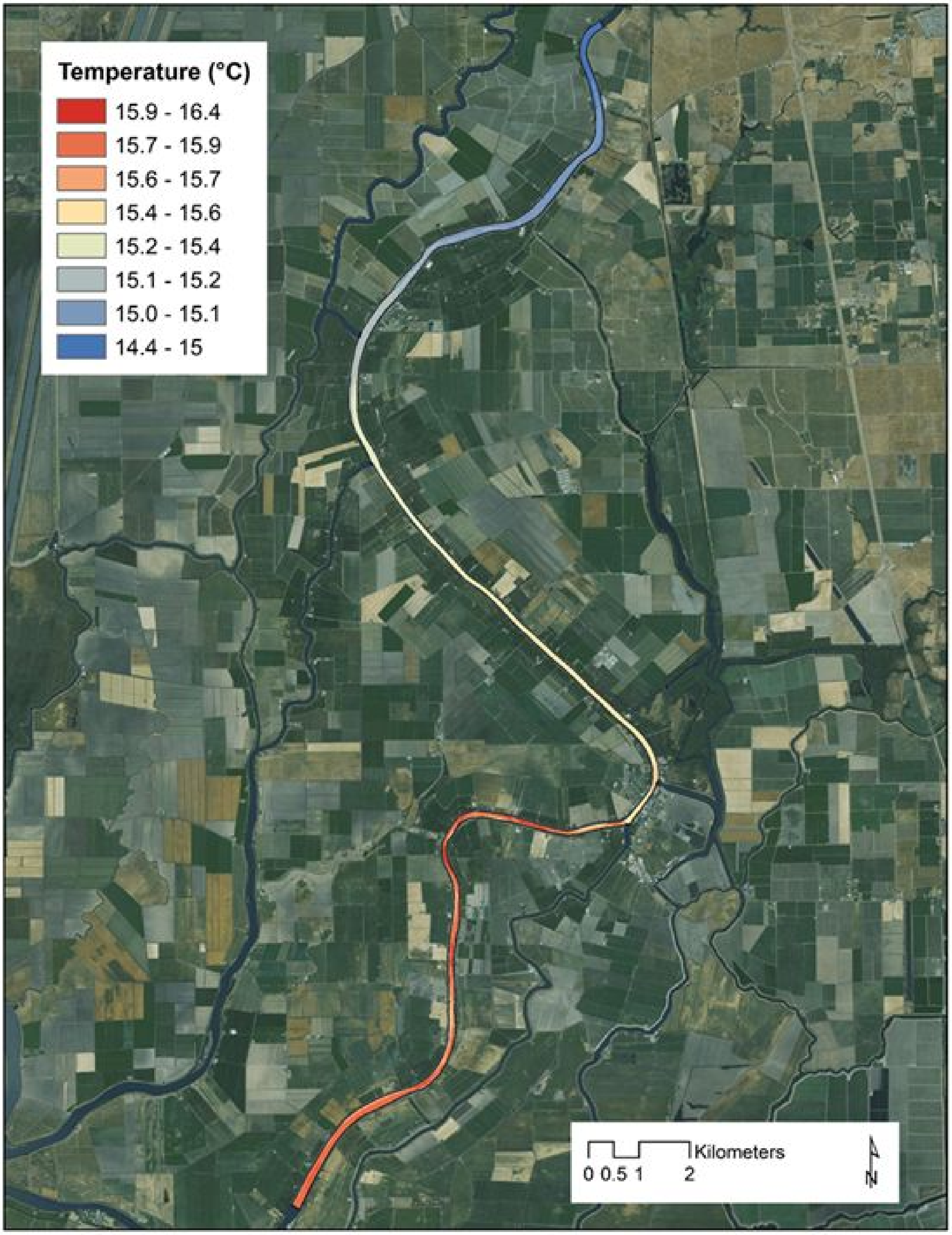

Figure 29. A map showing surface-water temperature for day one (10-17-17) on the Sacramento River. Data was collected starting at the top at 0900 and ending at 1630.

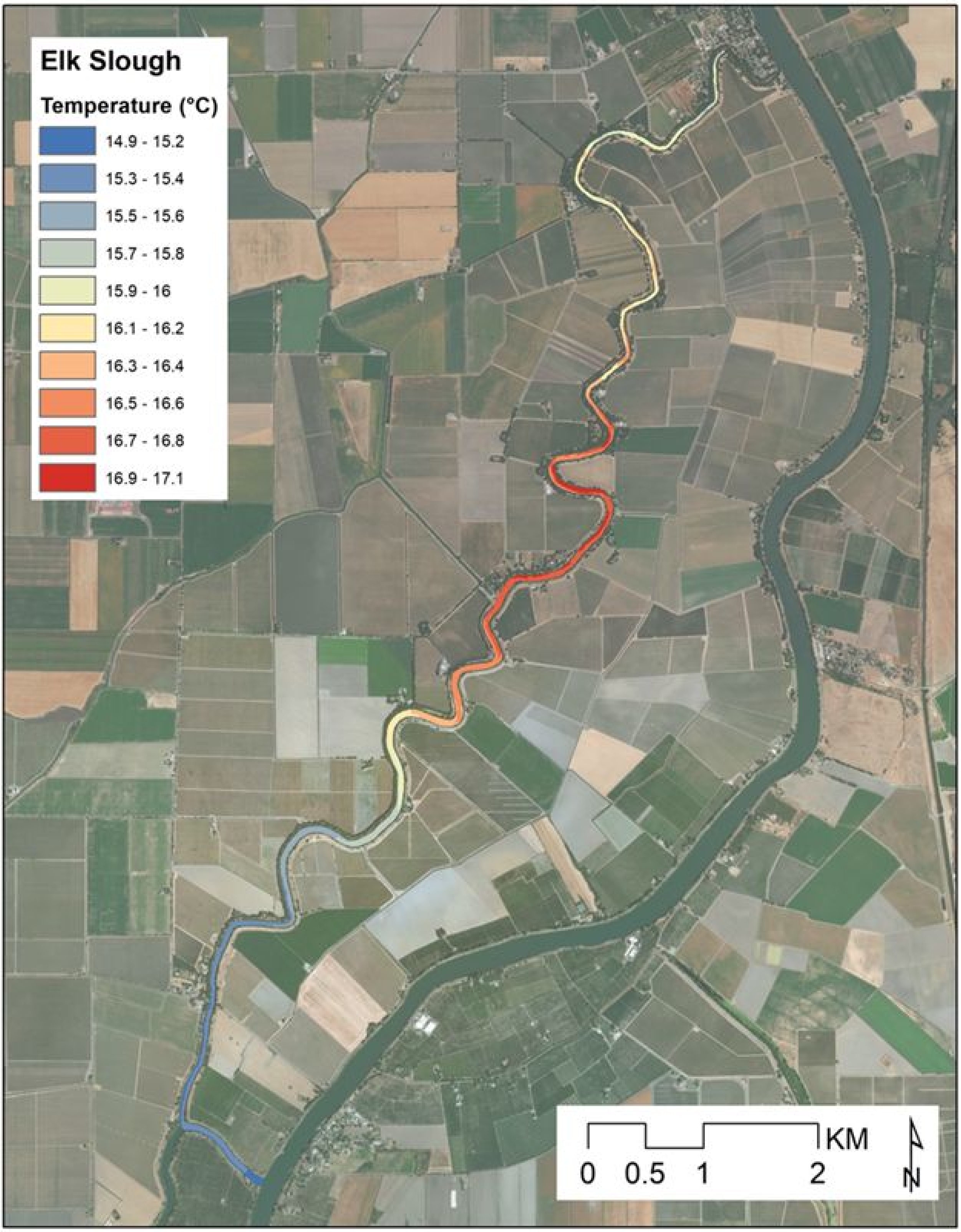

Figure 30. A map showing surface-water temperature for Elk Slough collected going up slough from the bottom starting at 0900 and ending at 1300 on 10-20-17.

Comparison of surface-water temperature maps in the Walnut Grove area for days 1-3 show similar mixing as well as heating in the closed area of the cross-cut channel (Fig. 33). Tidal influence of flow played a factor in this area as shown by the following section of flow maps.

The take home value here is that these types of temperature maps contain valuable information for interpreting processes important to evaluating water resource management decisions for the delta.

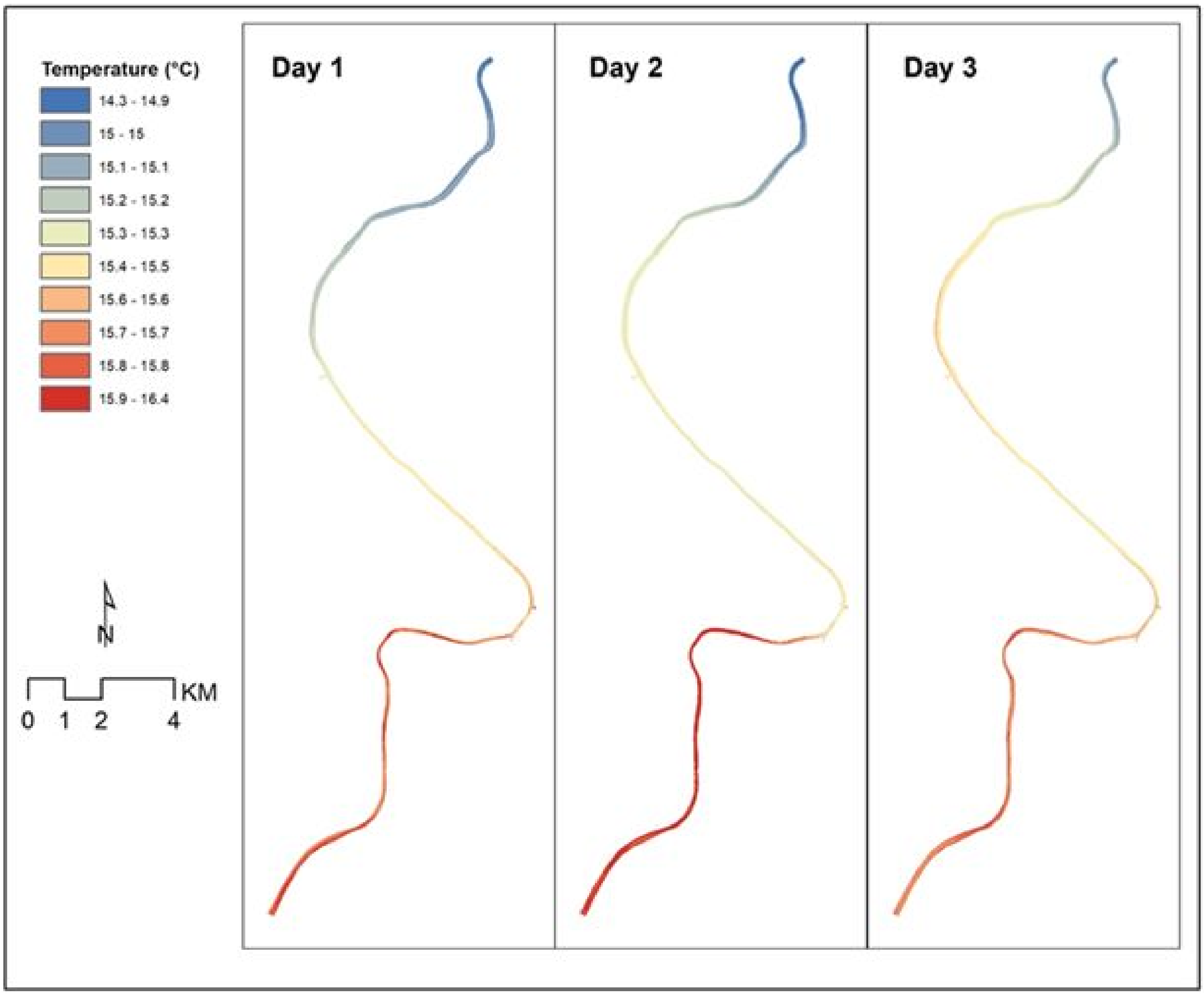

Figure 31. A three-panel map showing water-surface temperature for Sacramento River on each of the three data collection days (10-17,18 & 1, 2017). Each day began in the morning 0900 at the top of the map and ended at the bottom around 1630 at the Isleton Bridge.

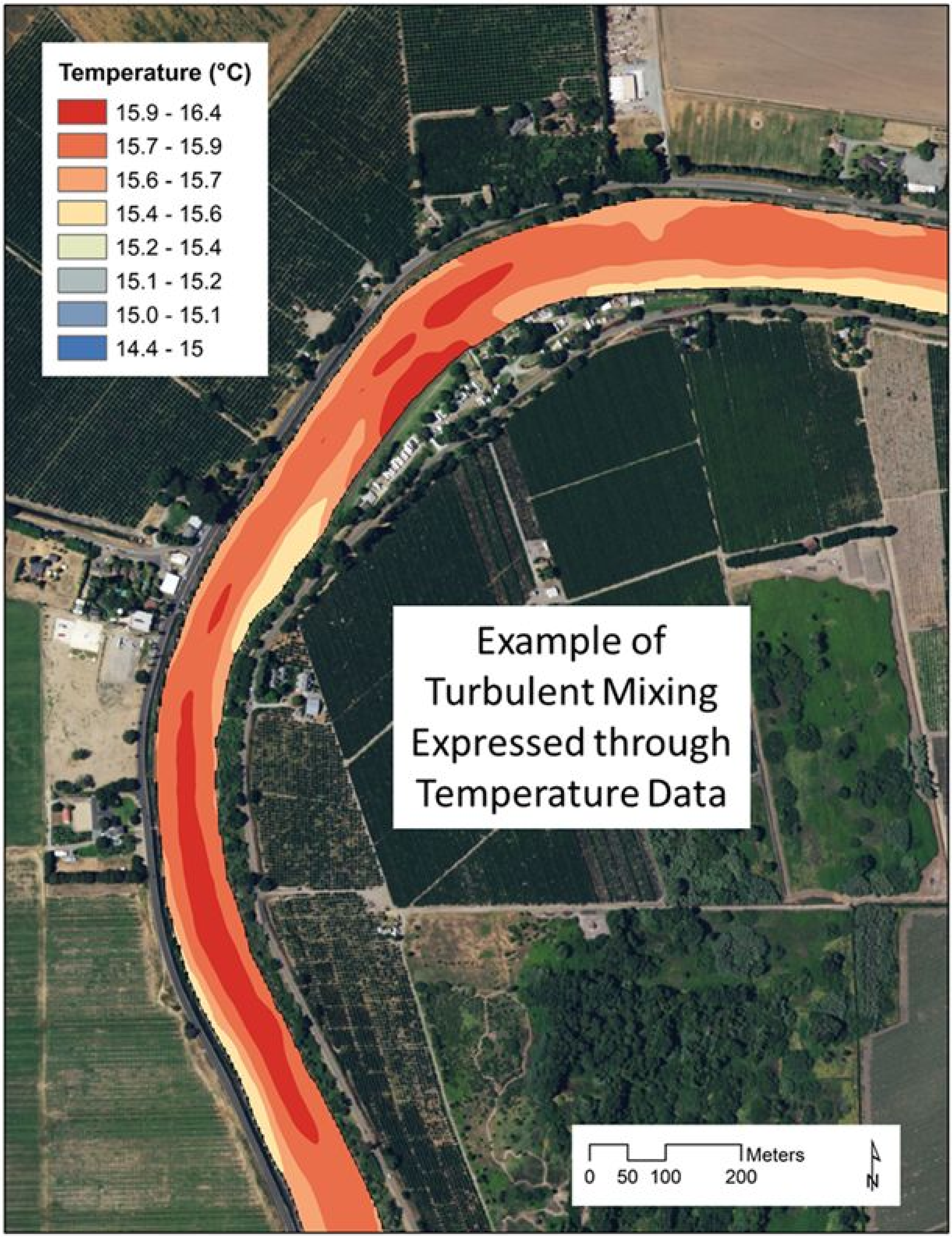

Figure 32. A surface-water temperature map collected on day one (10-17-17) near Ryde on the Sacramento River. This plot shows a nice example of turbulent mixing as expressed through temperature data.

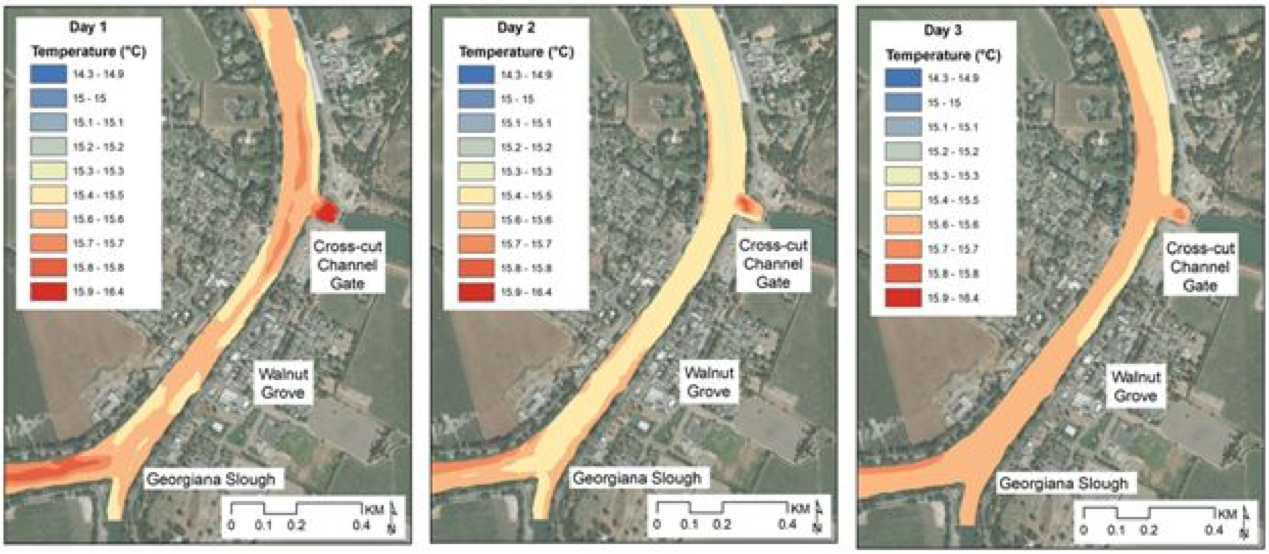

Figure 33. A three-panel map showing surface-water temperature for days 1-3 on the Sacramento River near Walnut Grove. These data were collected each day around 1200 and at about the low tide slack water condition.

6. Mean Flow Mapping

Flow data is critical to quantifying the net delta outflow of freshwater. It is also critical for assessing aquatic habitat and changes to that habitat related to water resource decisions that impact flow (e.g. pumping, closing and opening channels). Hence, another important objective of our initial project was to demonstrate how we can assemble our flow data to assess flow variation within the channel due to river discharge, channel complexity and tidal influences as well as flow regulation decisions. The cross-cut channel was closed during our data collection hence flow was forced to stay in the Sacramento River.

To accomplish the flow variation objective, we used data collected in the 20-mile-long Sacramento River reach (Fig. 2) over three consecutive days covering a complete ebb tide through flood cycle each day (Fig. 34) and then analyzed these data to map the spatial mean flow patterns and velocities impacted by tidal fluctuation (Figs 35, 36, 37, and 38) . We did the same for Elk Slough by measuring flow up the channel during an ebb tide and down the during flood tide (Fig. 34). Elk Slough data analysis is presented separately in section 8.

In addition we were tasked with analyzing flow variance between the top 1 meter of the water column to the bottom boundary layer (bottom 0.50 cm) of the channel. The objective was to be able to compare how those flow patterns change across large spatial scales (20 miles of river) and over a ebb to flood tidal cycle.

Our ADPs use five acoustic beams to create and record 10-cm binned data ensembles twice per second as well as ensemble position with a GPS measuring at the same frequency (Fig. 3). We export the mean flow data for each ensemble as determined internally by the Teledyne software from the raw acoustic data coupled to the GPS position data. Then we import that data into ArcGIS and use the Topo-to-Raster method to interpolate these spatially specific data points in the same fashion that the bathymetry maps are created and plot those maps with the 2016 NAIP imagery. This method creates a hydrologically correct raster surface from point data.

To assess flow in the top surface layer and the bottom boundary layer of the water column we used Freshwater Map's patent-pending software, River Analyzer (RA), and associated software components developed in MATLAB.

Depth-specific velocity data from ensemble bins representing the top 1 m of the surface layer and the bottom boundary layer (0.5 m) were selected from the data and then converted to a 2m grid using 2D ordinary kriging (Chiles and Delfiner 1999). That data grid was then passed back to ArcGIS where the Topo-to-Raster method to interpolate these spatially specific data points was used to plot those maps with the 2016 NAIP imagery (Fig. 39.).

The integrated DEM linking river and slough bathymetry to levee topography (section 5) allows users to extract cross-sections of the combined levees and channels to run DSM2-Hydro. Flow data provided by Freshwater Map, and presented below in the form of maps, can be used to both initialize the boundary conditions and to validate the estimated flow values produced from DSM2-Hydro on very broad scales. And because our flow data is high-density and 3D in format it can inform other 1D, 2D and 3D CFM endeavors.

Our data collection period was influenced by an ebb tide in the morning (Fig, 34). The river team put in at Clarksburg each morning around 9 am and begin the data collection down river riding an ebb tide coupled with river discharge (Fig.34). By the time the team reached Walnut Grove the river was approaching slack tide and encountered the switch to flood tide conditions in different locations each day. By the time the team reached Isleton Bridge they were encountered the peak flood tide and change over to ebb (Fig. 34). These spatial changes in tidal influence have a dramatic impact on the mean flow in the Sacramento River and Elk Slough (Fig. 35). Complex patterns of mean flow were mapped at the confluence of Sutter Slough with the Sacramento and with Elk Slough (Fig. 36). Flow in the Walnut Grove area was especially dramatic as mean flow was nearly stagnant in the Sacramento while water was flowing with high velocity down Georgiana Slough (Fig. 37). The gate at the cross-cut channel was closed during these measurements. By the time the river team was recording flow just above Isleton Bridge, mean flow was downstream on river right and upstream along river right (Fig.38). When comparing the flow velocities for the top surface layer with the bottom boundary for the Walnut Grove area on day three one can see that most of the surface water coming into Walnut Grove is flowing downriver, some near Georgiana Slough beginning to reverse flow, while the entire bottom boundary is flowing up river (Fig. 39).

These tidal influences on the 3D nature of flow in the Sacramento River and Elk Slough are presented in more detail in the following section where actual flow vectors are plotted rather than just mean flow conditions.

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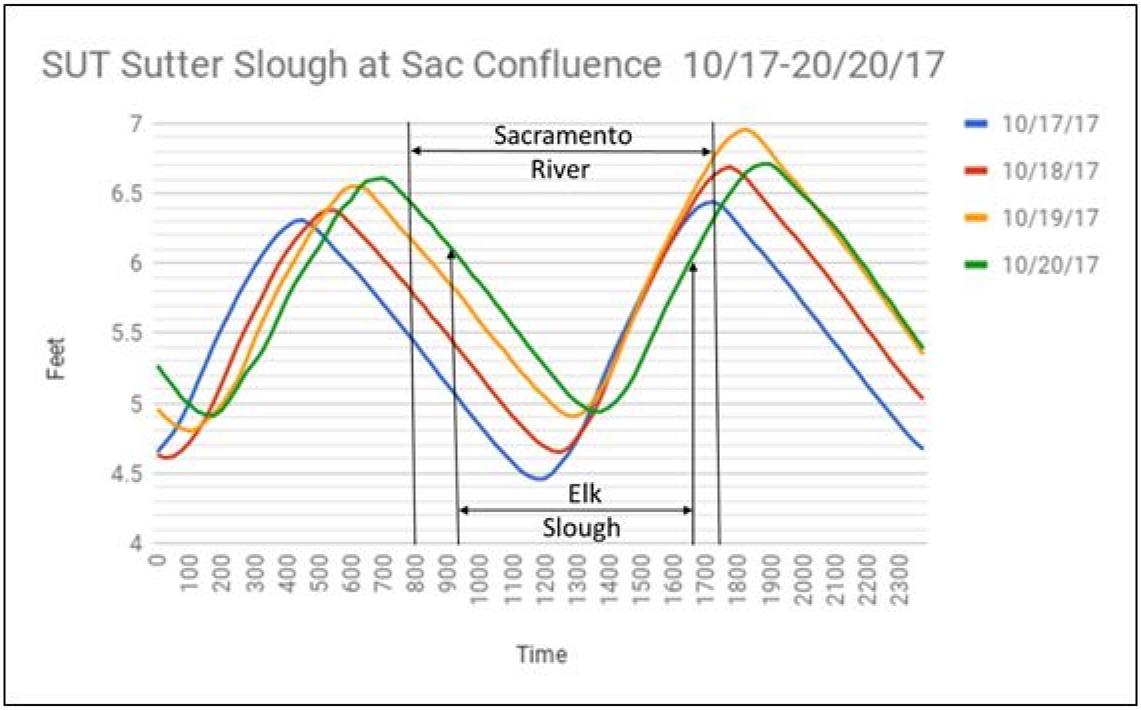

Figure 34. A plot of tidal change during the four days that ADP data was collected for the Sacramento River and Elk Slough. The black lines depict time frames when data was collected. For the Sacramento River low slack tide occurred when the river team reached Walnut Grove each day. On 10-20-17 the team went up Elk Slough against an outflowing ebb tide and then back down the slough during an incoming flood tide.

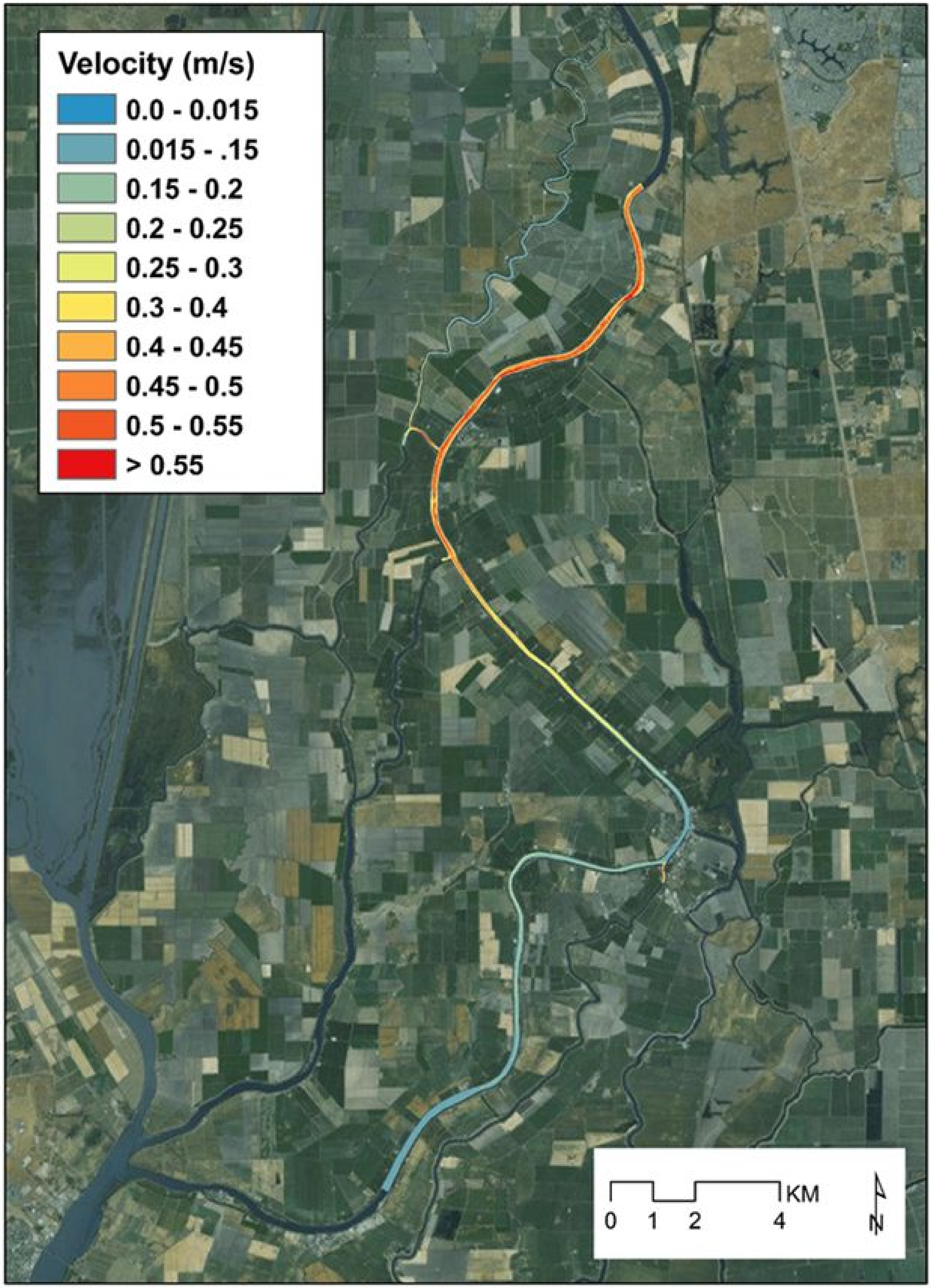

Figure 35. A plot showing mean flow velocity for the Sacramento River on 10-17-17 and Elk Slough on 10-20-17. Note that the higher velocities occurred in the top half of the Sacramento River and change over to slack and very slow mean flow half way down the river.

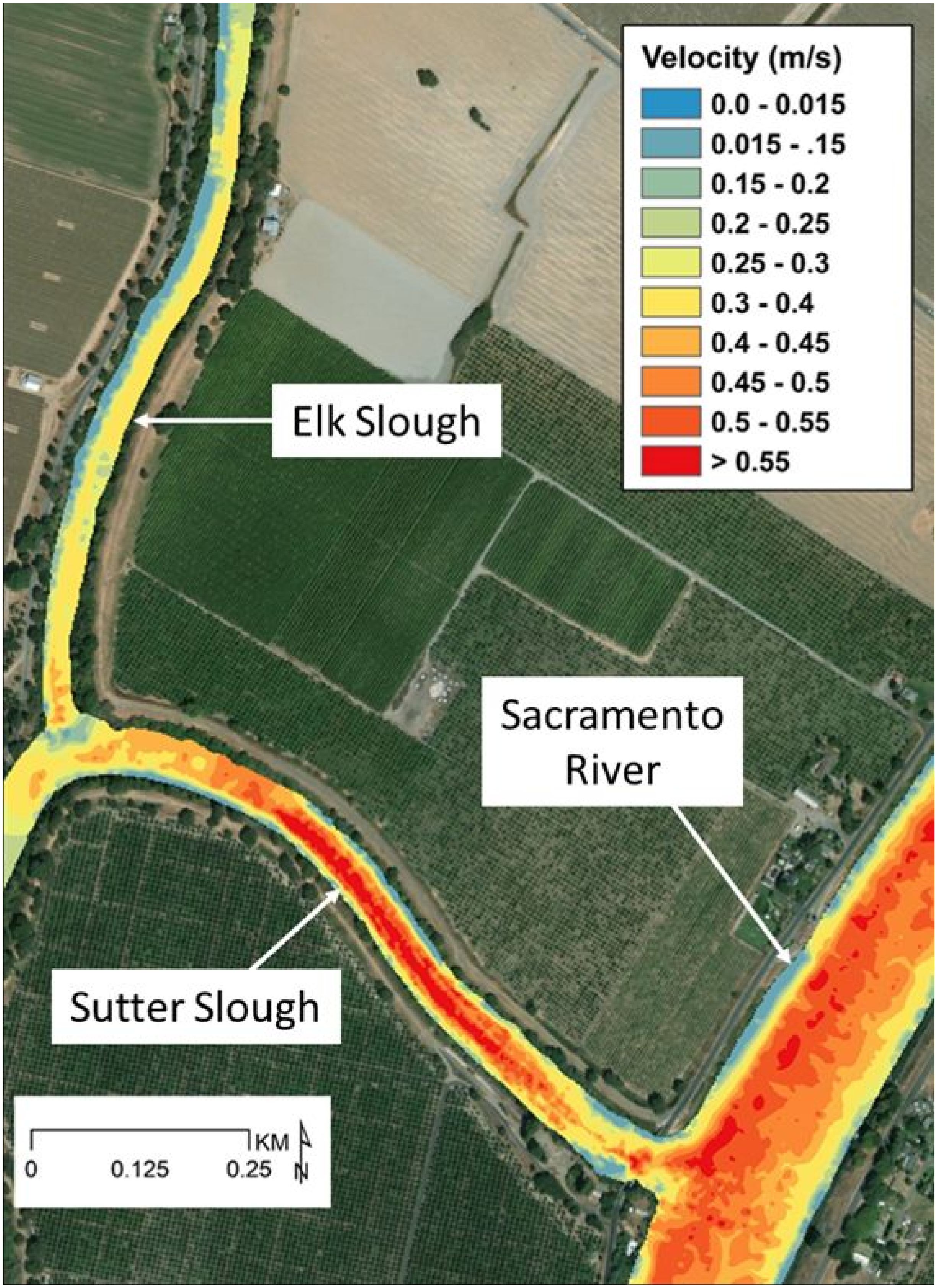

Figure 36. A plot of mean flow conditions for the Sacramento River and Elk and Sutter Sloughs. Note the complex patterns of different flow velocities with slower flow along the channel boundaries and faster flow in mid-channel positions.

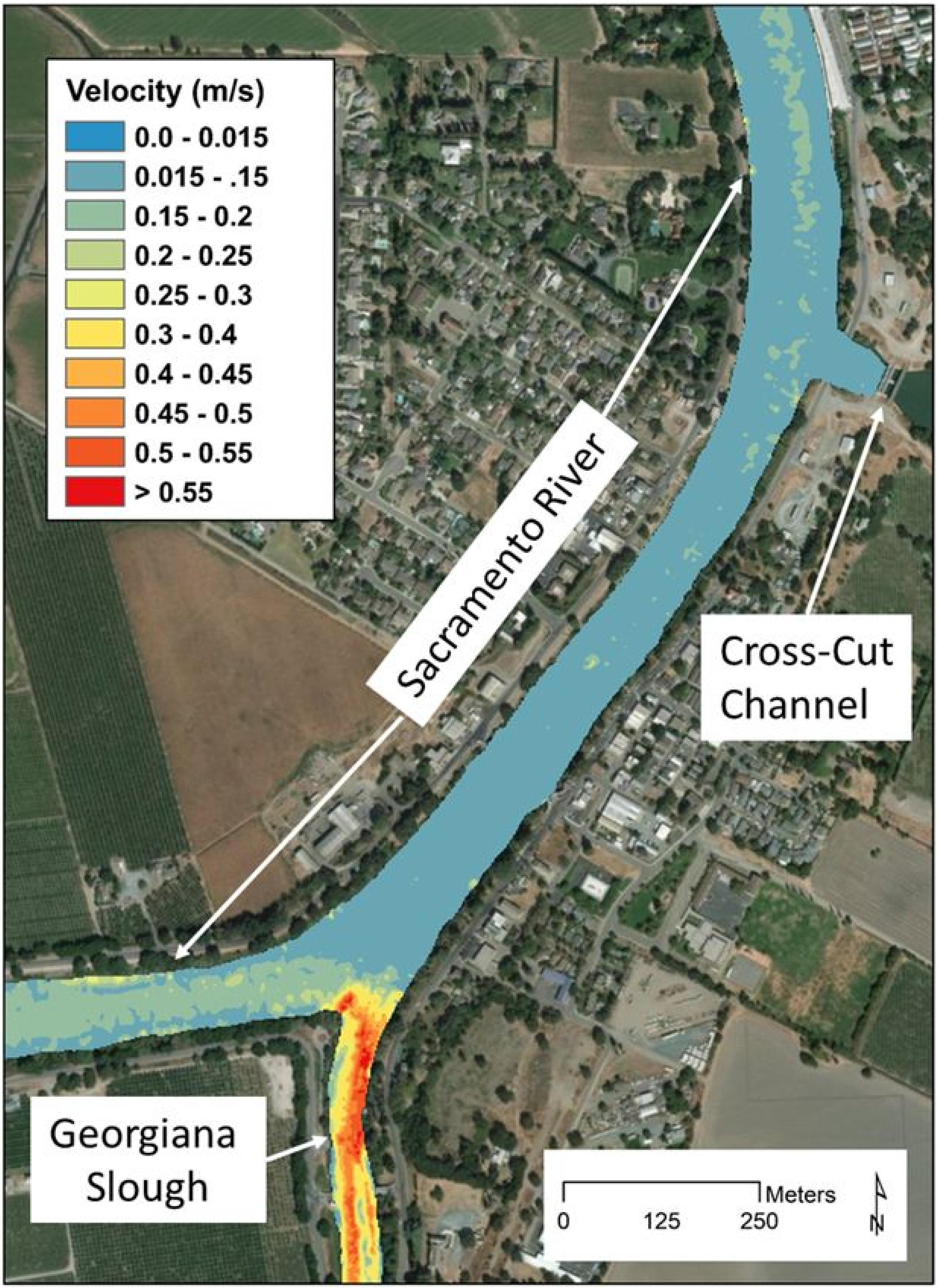

Figure 37. A plot of mean flow conditions for the Sacramento River and Georgian Slough. Note the complex patterns of different flow velocities in Georgiana Slough compared with the Sacramento River.

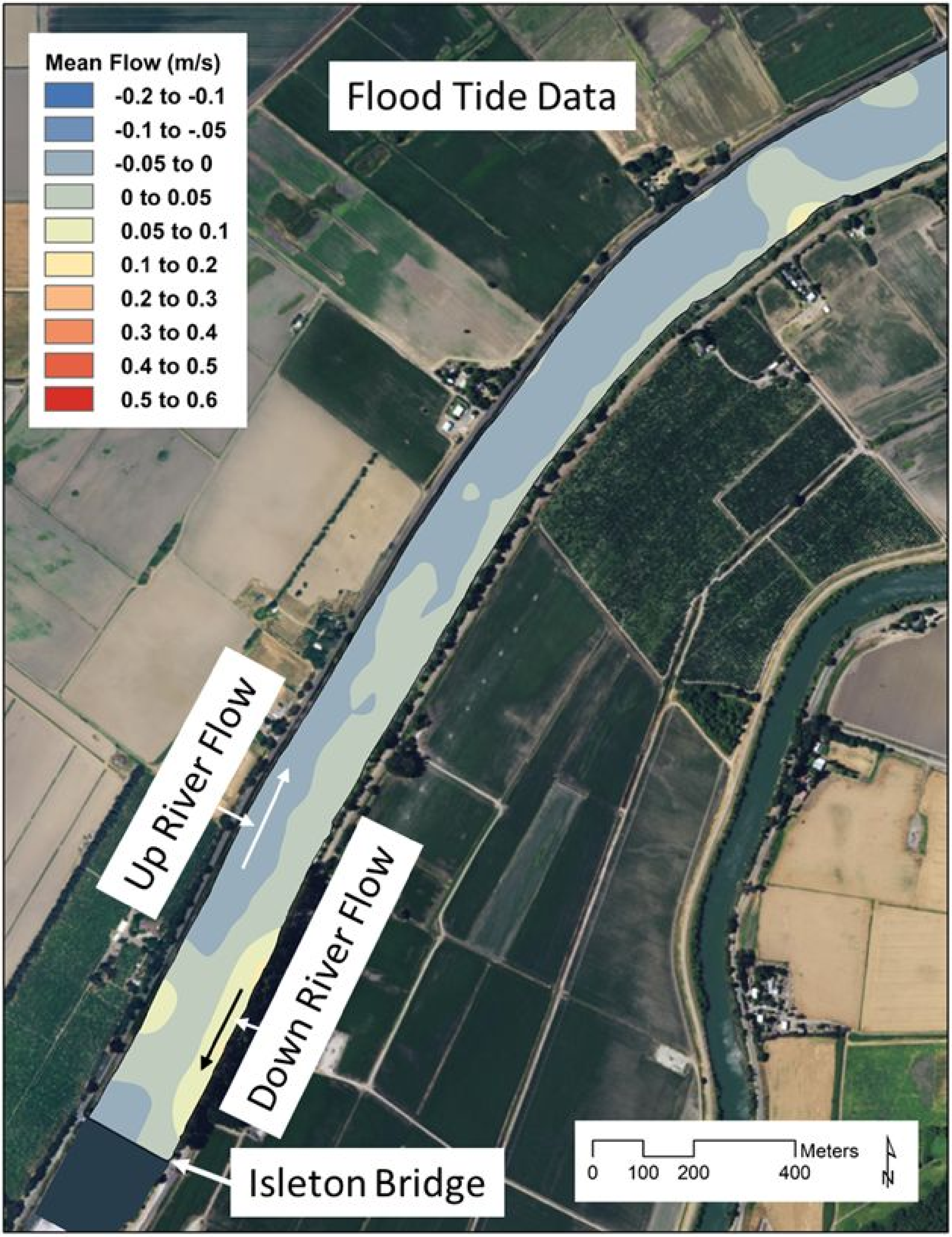

Figure 38. A plot of mean flow conditions for the Sacramento River at the Isleton Bridge on 10-17-17. Note the complex patterns of different flow velocities and direction in the Sacramento River immediately upstream of the bridge.

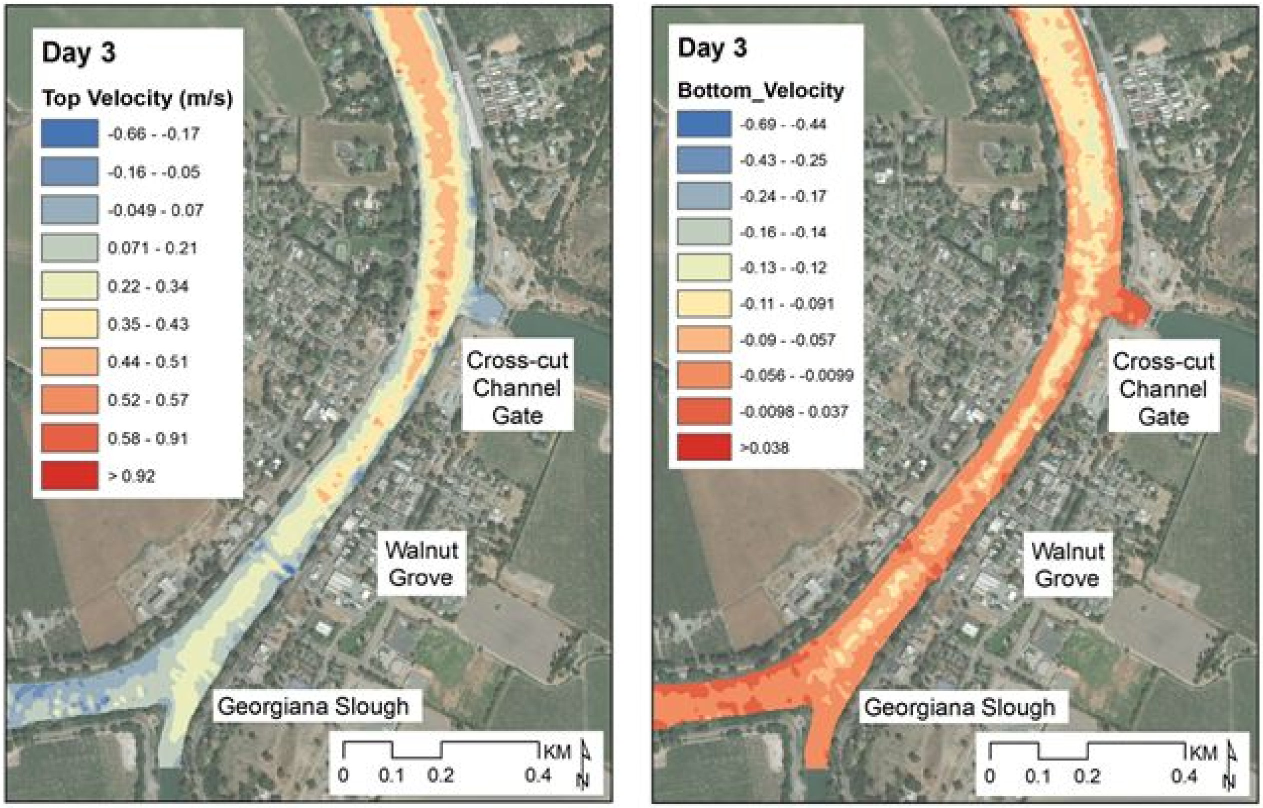

Figure 39. A two-panel plot of the Sacramento River near Walnut Grove comparing surface-water flow velocity in the top meter of the water column with bottom boundary flow velocity. Note that negative values represent flow upstream. Most of the surface water is flowing downstream above Georgiana Slough while the bottom boundary water is flowing upstream.

7. Flow Vector Mapping and Particle Drift Tracking

The 3D nature of the flow data (velocity and directional vectors for each bin) can be used to validate the DSM2-GMT particle transport model outputs. Our task here was to assess particle drift flow paths and flow vectors for the mean water column, top surface layer and the bottom boundary layer of the water column. These results presented below (Figs. 40-45) are “snap-shots” of how dispersive and complex the actual drifting conditions might be under the particular river discharge and tidal condition at that particular site. These types of maps and drift analysis are useful in assessing the 1D DSM2-GMT particle drift outputs and water quality modeling output. Moreover, they are very useful in assessing juvenile outmigration drift pathways as well as the delta smelt “tide-surfing” hypothesis. These results are useful in assessing dispersion patterns for drifting embryos of both white and green sturgeon in the same way they were used to assess pallid sturgeon drift dispersion on the Missouri River. These results are very useful in assessing dispersion and drift including guiding clean-up of contaminant plumes from irrigation return flows to accidental pipeline breaches, trucking and rail spills or shipping accidents.

An RA software module called “Drifter” uses the velocity vectors from each of three layers, surface, bottom boundary and mean water column, to create flow vectors and velocities for each 2m gridded cell. The approach was used to assess drift pathways, durations and overall dispersion of pallid sturgeon embryos for 225 miles of the Missouri River and published in the Journal of Applied Ichthyology (Martoz and Lorang 2017). The same methodology was applied to the delta data set. The methods are summarized below.

We segregated the Sacrament River into 20 drift segments and 10 drift segments for Elk Slough. Drift simulation is a 3-step process beginning with selecting the bins from data ensembles that correspond to the drift layers of interest which, in this case, compose the top 1 meter of the water surface, the bottom boundary layer and the mean water column. Although derived from a 3D hydraulic data, our drift simulations assume horizontal drift paths (no vertical exchange) for all layers run independent of each other. Simulations of drift in the bottom boundary layer use data from three bins or 30cm above the deepest valid cell above the river bottom (above the bottom blanking distance Fig. 3). This eliminates using interpolated data from below the deepest accurate velocity measurement and ensures that our drift speed simulations represent the fastest flow speed and direction in the bottom boundary layer. The same procedure of ensemble bin selection is done for the top layer starting with the first cell below the surface blanking distance (Fig. 3). The mean flow vector for each ensemble is calculated for the mean water column drift analysis.

The second step is kriging the RA flow information (speed and direction) that is interpolated from the raw data ensembles to put that data onto a Cartesian plane coordinate system, so the flow vectors can be linked cell by cell to create flow pathways with velocity information for each cell. Drifter then connects those flow vectors to calculate drift paths and drift speeds along those pathways. The third step is drift simulation from a given start point.

Drift simulations begin in two transect locations, 1) at the top of each river segment, and 2) the midpoint of each segment. Ten start points were spaced at regular intervals along each transect, starting and ending two meters in from each bank. Each of 160 drift simulations conducted for each layer ended when the particle reached the end of each segment, stalled in zero velocity, or made no downstream progress for three days of simulated duration. The fate of each drifter was categorized based on river geometry (riverbank, eddies or reaching the end of the segment).

Once RA has connected all of the flow vectors and start points have been input then “drift” is simulated using fourth-order Runge-Kutta kriging approach for the 2 m gridded velocity data and using one-minute time-step intervals with 3-day simulation limit on the time step duration (Chiles and Delfiner, 1999). Hence, a drift path ends if it reaches water that is so slow that it cannot reach the next cell or recirculates in small area of connected cells with slow moving water. These conditions are indicated as yellow dots in the following figures and red dots indicate a drift path end along a shoreline (or island if they exist) or at the end of a drift segment. This results in the ability to quickly locate all stall positions along the river banks, along islands, no velocity zones along the bottom and zones of flow recirculation (eddies).

For each drift simulation the flow vector at a select number of grid locations appropriate for readable maps (cannot plot them all and produce a readable map) are plotted as white arrows and the connected flow paths emanating from the start locations are plotted as red lines (Figs. 40-45). Comparing day 1 results to day 3 along the Sacramento River near the entrance to Steamboat Slough shows two different flow path patterns (Figs. 40 and 41). The day 1 drift patterns (Fig. 40) converge above Steamboat Slough and do not enter the slough mouth while on day 3 river right and left have divergent flow patterns where some drifters penetrate into Steamboat Slough. These results have significance in terms of out migrating juvenile salmonids. On day 3 a larger percentage may get diverted into Steamboat Slough while on day 1 they would have to actively swim to the slough mouth to enter it and not be carried downstream. Those two populations of juveniles would have two different potential outcomes. This is just an illustration of how these results are powerful tools to assess ecological questions for the delta.

Likewise a similar analysis can be made for day 1 bottom boundary layer drift near the cross-cut channel (Fig. 42). Here flow velocities are much slower than the mean water column velocities shown in figures 40 and 41. It can be seen how closing the gate at the cross-cut channel diverts flow and drift out into the main portion of the channel, where, since we have data on depth, velocity, temperature, and substrate composition, one can begin to predict predation on target species. Again demonstrating how these data and analyses can be used to assess ecological aspects of water resource management decisions through expanding the capabilities of current methods that employ model results from DSM2-Hydro that then drive DSM2-GMT particle transport model outputs.

The potential drift scenarios get much more complicate near the mouth of Georgiana Slough (Figs 43 and 44). Comparing the surface layer flow and drift to the bottom boundary flow and drift show widely different results. Surface flow above Georgiana is all moving downriver but flow below shows chaotic patterns pointing upstream. The drifters released at the Georgiana mouth drift slightly upstream before being caught in the flow downstream into Georgiana but they all stall in a low flow velocity zone on the surface (Fig. 43). By looking at the mean flow for this location on the same day (Fig. 37) there appears to be strong mean flow downstream in Georgiana. Surface water must be backed up due to the tide and deeper flow must be stronger. In contrast, the bottom boundary flow in this location is not as strong in the upstream direction below Georgiana or as strong downstream and the drift patterns deflect back into the Sacramento (Fig. 44). Most drifters appear to start in a no-flow zone, do not move and do not get labeled with a yellow dot . A look at bottom boundary flow downstream of Ryde on the Sacramento shows a much more coherent and stronger upstream flow and drift pattern (Fig. 45). This may be important insight for interpreting delta smelt tidal drift patterns.

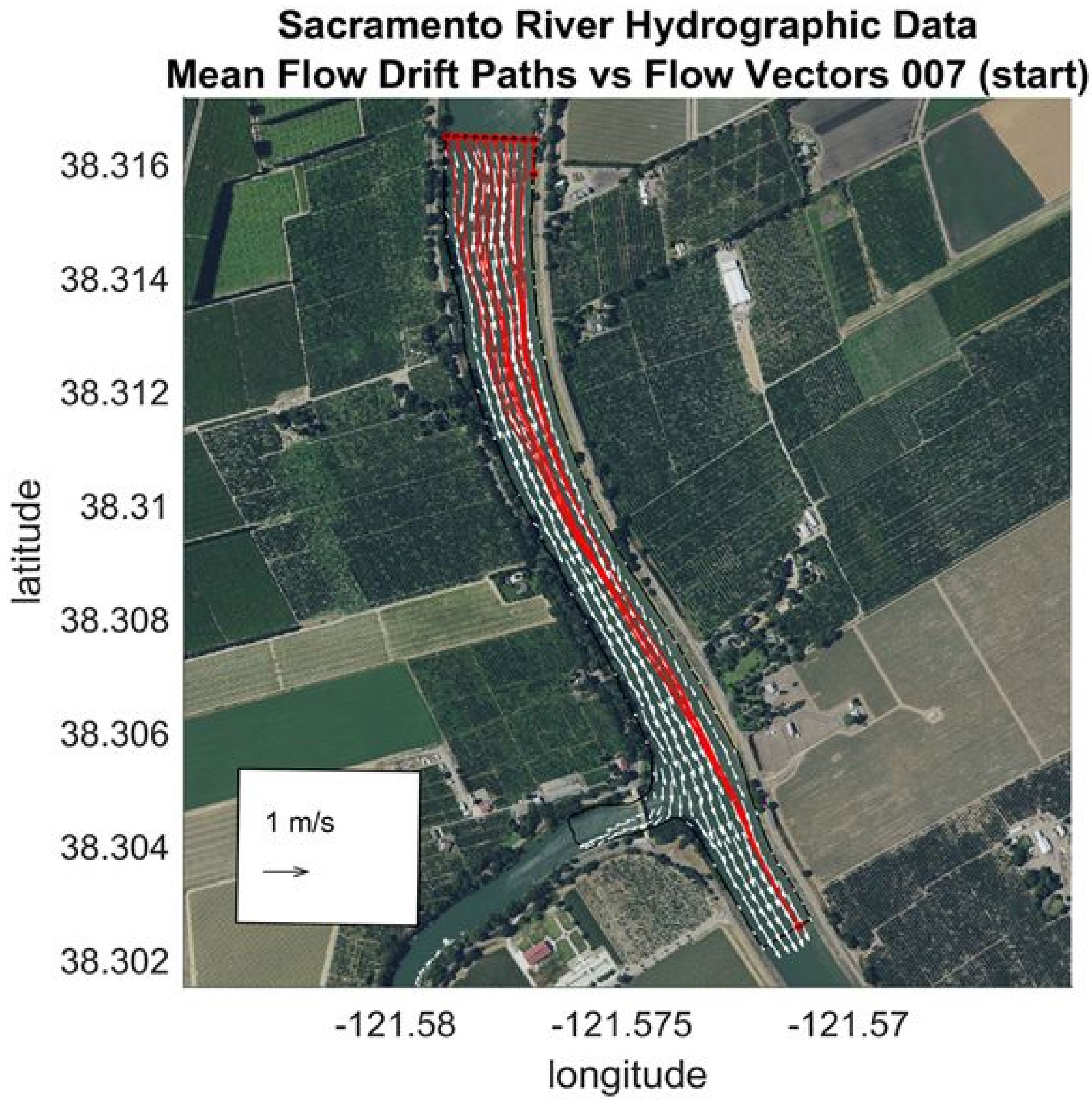

Figure 40. A plot of mean flow drift paths (red arrows) relative to the flow vectors (white arrows) for the Sacramento River near Steamboat Slough (Day 1, 10-17-17).

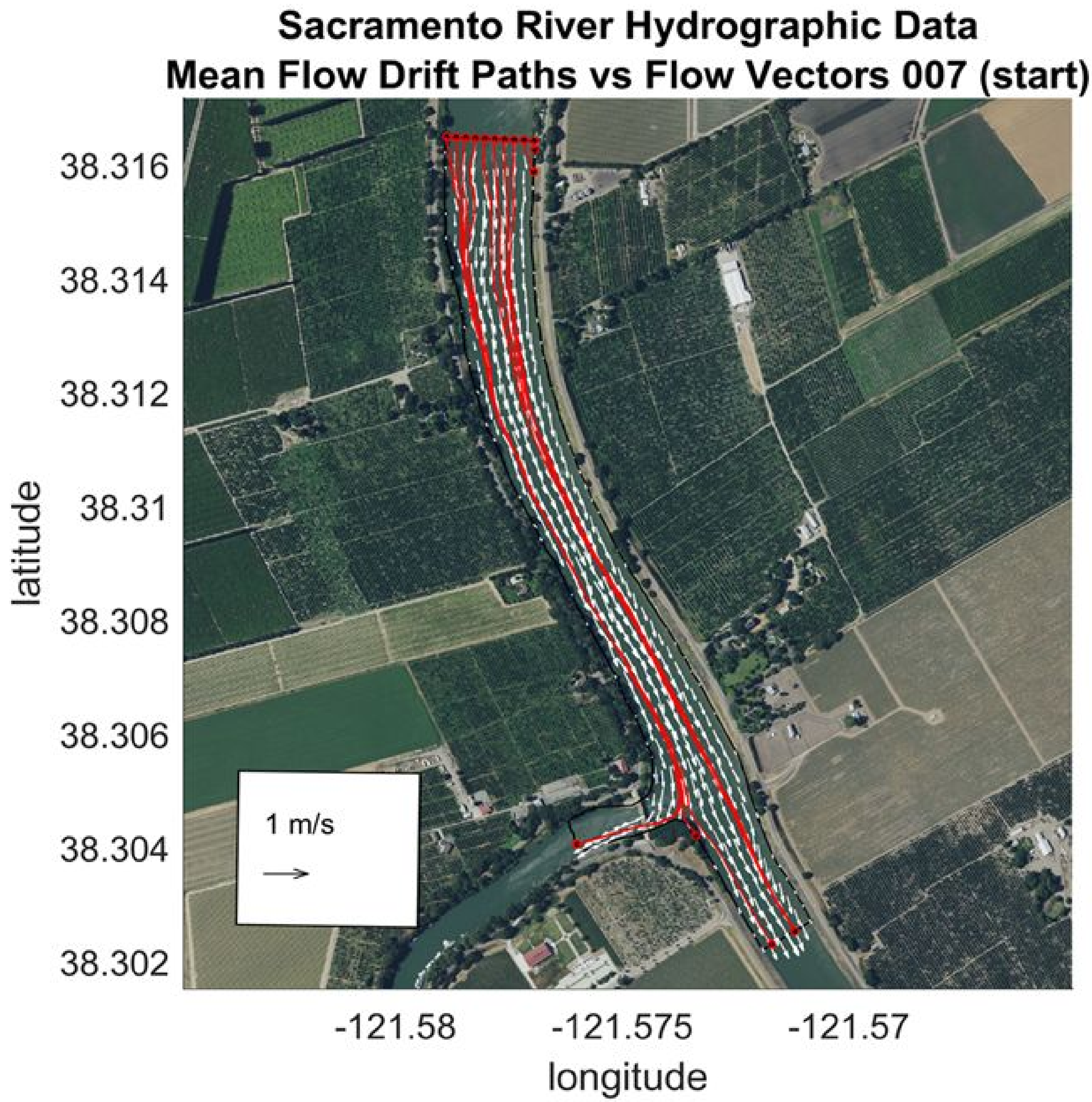

Figure 41. A plot of mean flow drift paths (red arrows) relative to the flow vectors (white arrows) for the Sacramento River near Steamboat Slough (Day 3, 10-19-17). Note slightly different drift paths for day three relative to day one that extend into Steamboat Slough. Note that fewer drift paths extend through the length of the segment. Three drift paths end at a shoreline near the top river left and another on the shoreline river right just past Steamboat Slough.

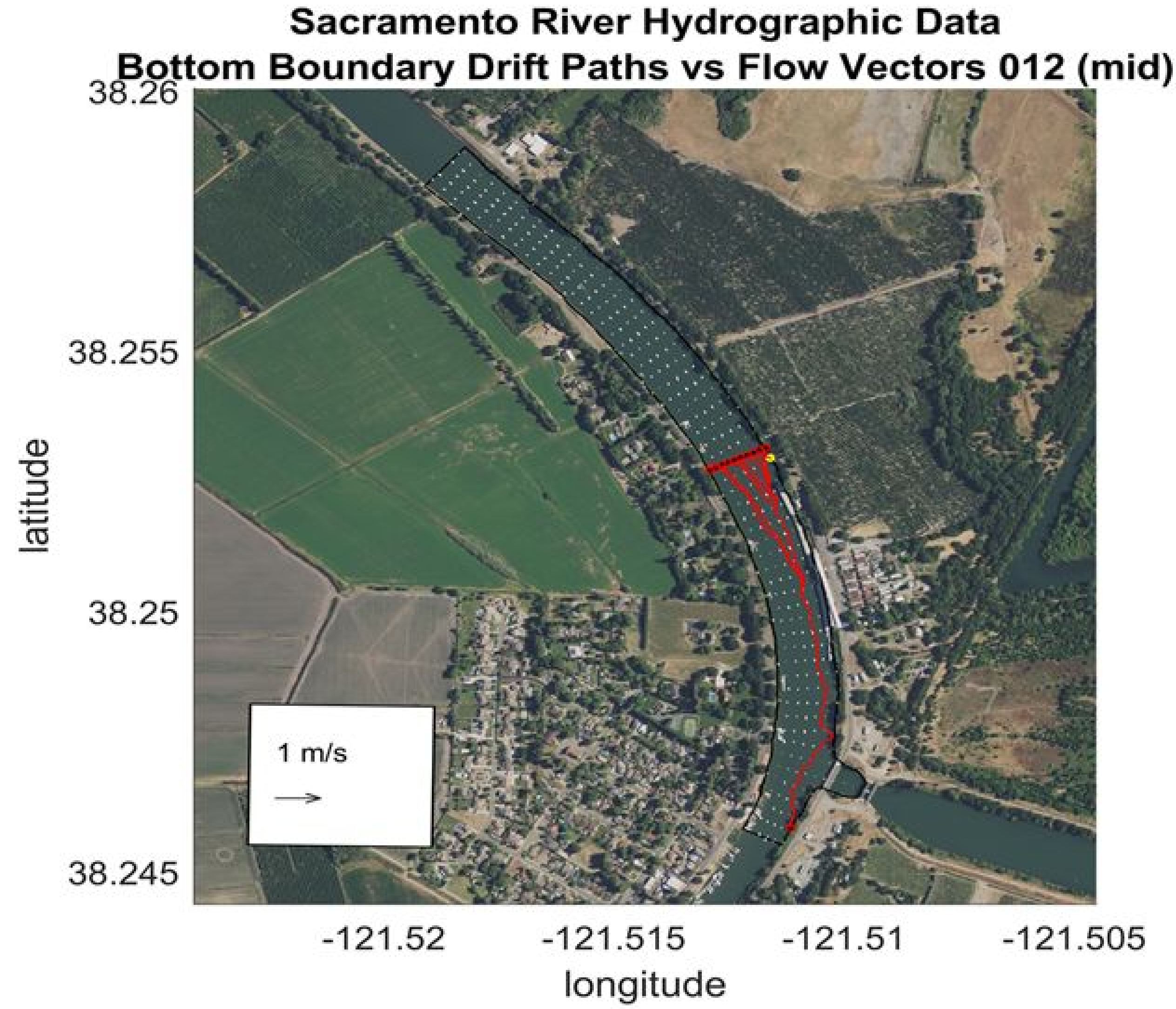

Figure 42. A plot of bottom boundary drift paths (red arrows) relative to the flow vectors (white arrows) for the Sacramento River near the cross-cut channel which was closed (Day 1, 10-17-17). Note that nearly all the flow paths collapse into a narrow path and the deflection of that path near the cross-cut channel. The yellow dot at the top of the drift represents a drift path stalled in very low to zero velocity flow.

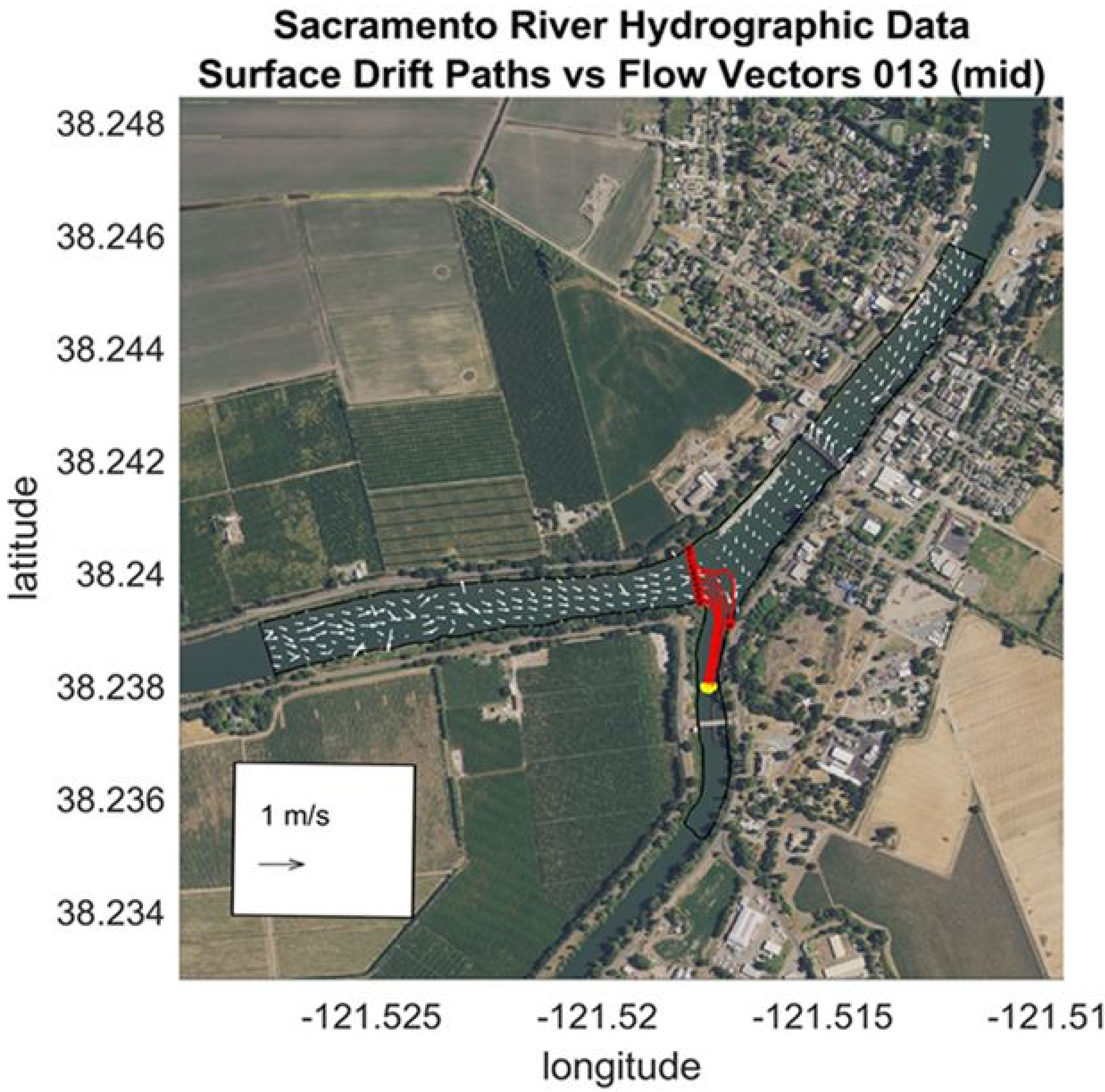

Figure 43. A plot of surface water drift paths (red arrows) relative to the flow vectors (white arrows) for the Sacramento River near Georgiana Slough. Note that the flow vectors above Georgiana Slough are pointing downstream while the flow vectors below Georgiana Slough are both chaotic and pointing upstream. The tide shifted from slack to flood tide at the time data was collected in this location.

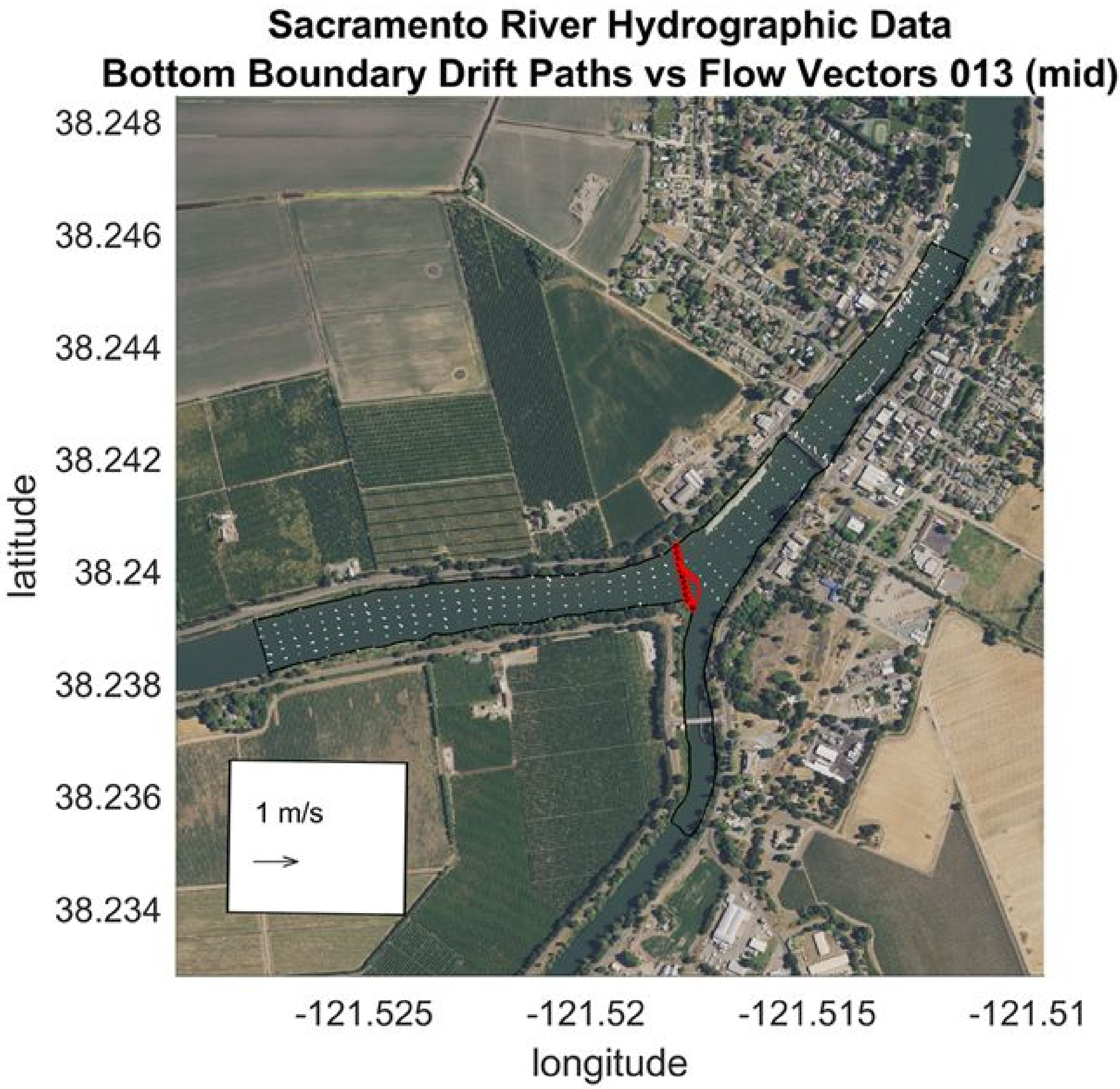

Figure 44. A plot of bottom boundary drift paths (red arrows) relative to the flow vectors (white arrows) for the Sacramento River near Georgiana Slough. Note that the drift paths do not enter Georgiana Slough. The tide shifted from slack to flood tide at the time the data was collected in this location.

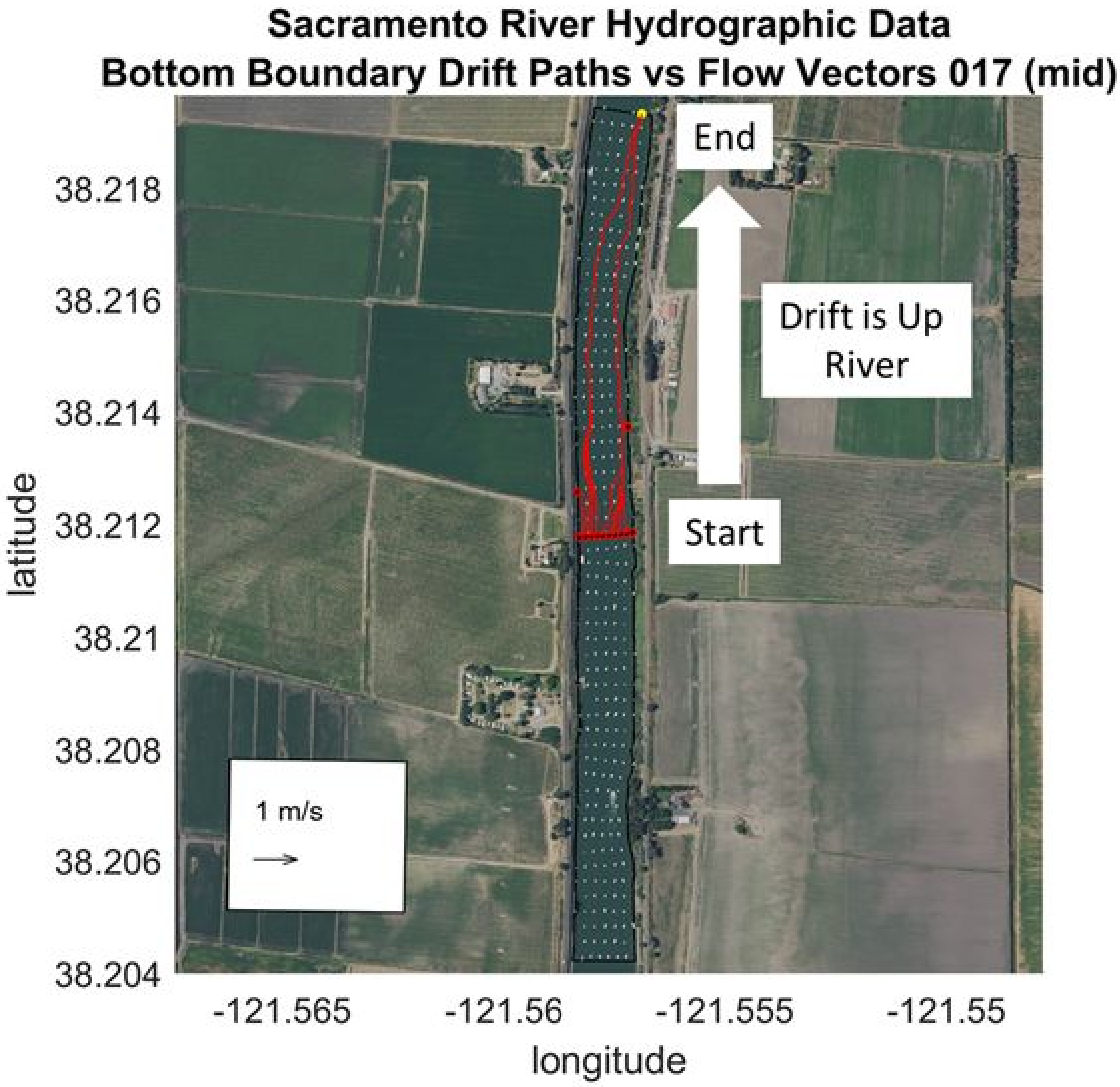

Figure 45. A plot of bottom boundary drift paths (red arrows) relative to the flow vectors (white arrows) for the Sacramento River below Ryde. Note that all of the flow and drift is upstream. At the time the data was collected in this location, several km downstream of data plotted in figures 44, the tide is in full flood stage.

8. Cross-Sectional Flow Mapping

So far in this technical report we have examined flow from a map-view perspective looking at the spatial variance of flow in terms of magnitude and direction. In this section we will take a more traditional cross-sectional transect view of flow by looking at slices of the 3D data set. We did this in the bathymetry section when we combined the channel bathymetry with the levee topography to create a DEM where a user can extract slices anywhere along the study reach (Fig. 25). In this section we will show how this analysis enables the user to look at the 3D flow field in terms of flow velocity, whether that flow is going downstream or upstream, and how tide influences flow patterns. With this view we can see the extent of the bottom boundary layer and the complexity of flow in the vertical. We have extracted 11,187 cross-sectional flow slices from three datasets on the Sacramento River and two in Elk Slough; one during a flood tide phase and the other during the ebb tide phase over the length of the entire slough. These slices are arranged by river segment corresponding to the particle drift analysis discussed above. The slices are arranged into .avi movies for easy viewing of each segment.. Each slice is also saved as an individual .png file.

Each of these cross-sectional flow slices allows the user to examine the complexity of the flow coupled to the complexity of the channel bathymetry. This information is critical for examining the bottom boundary habitat available within the delta. Bottom boundary habitat is vital to all organisms that live in the benthic environment as well as those that use it to migrate through the delta. For example, adult fish of many different species may rest and feed in the low-flow lee of sand bars, which we imaged with the sonar, making the abundance and distribution of that microhabitat of vital importance. This lee-habitat itself will have a hierarchy of value with some habitat providing both a place to rest and a place with high food availability. Competition between fish for those spots will be high and changes in water flow will impact both the abundance of such habitat and where it is spatially located. Clearly, crawdads and fish that live entirely on the bottom will seek out benthic habitat that best suites their life cycle needs from reproduction to feeding, protection, growth depend on bottom boundary conditions.

Our measurements allow discrimination of bottom boundary flow conditions as well as mid column flow conditions that are vital to assessing many life cycle stages for ESA listed species in the delta. With these data and images of the flow, biologists can begin to assess juvenile salmonid fish drift, delta smelt drift, embryo drift for both white and green sturgeon, and fish behavior from prediation to reproduction. Moreover, this information is critical for evaluating ecological modeling for the delta. The ePTM juvenile fish model, the CASM-LTL food web model and the ELAM fish movement simulation model can all greatly benefit from the analysis and results of these data sets (Fig. 3).

Perhaps the most important first-order benefit from the cross-sectional flow mapping comes from spatial discharge analysis. For each slice we can determine the discharge and with that information begin to assess, on a broad spatial scale, the net delta outflow of freshwater relative to consumptive use and net channel loss (seepage which is also linked to levee integrity) through slicer discharge measurements. That topic is examined in section 10 of this report. What follows here is a discussion of the methodology behind Slicer together with examples relative to tidal differences impacting flow.

The Slicer module in RA performs linear interpolation between adjacent data ensembles and exponentially (log) from the deepest accurate velocity measurement to the river bottom and horizontally to the river bank. This provides a 3D set of interpolated data points for every 2.5 m^2 of the river surface. River Analyzer simply performs a linear interpolation between data ensembles and a logarithmic interpolation to the bed and bank (Fig. 46). This approach is a standard method by which all discharge measurements are completed using ADP data. We apply it on a very broad spatial scale and in a new and novel way to create a complete 3D view of the river linked to its bank and floodplain. It is like putting the river through a cat-scan to reveal the inner complexity of flow.

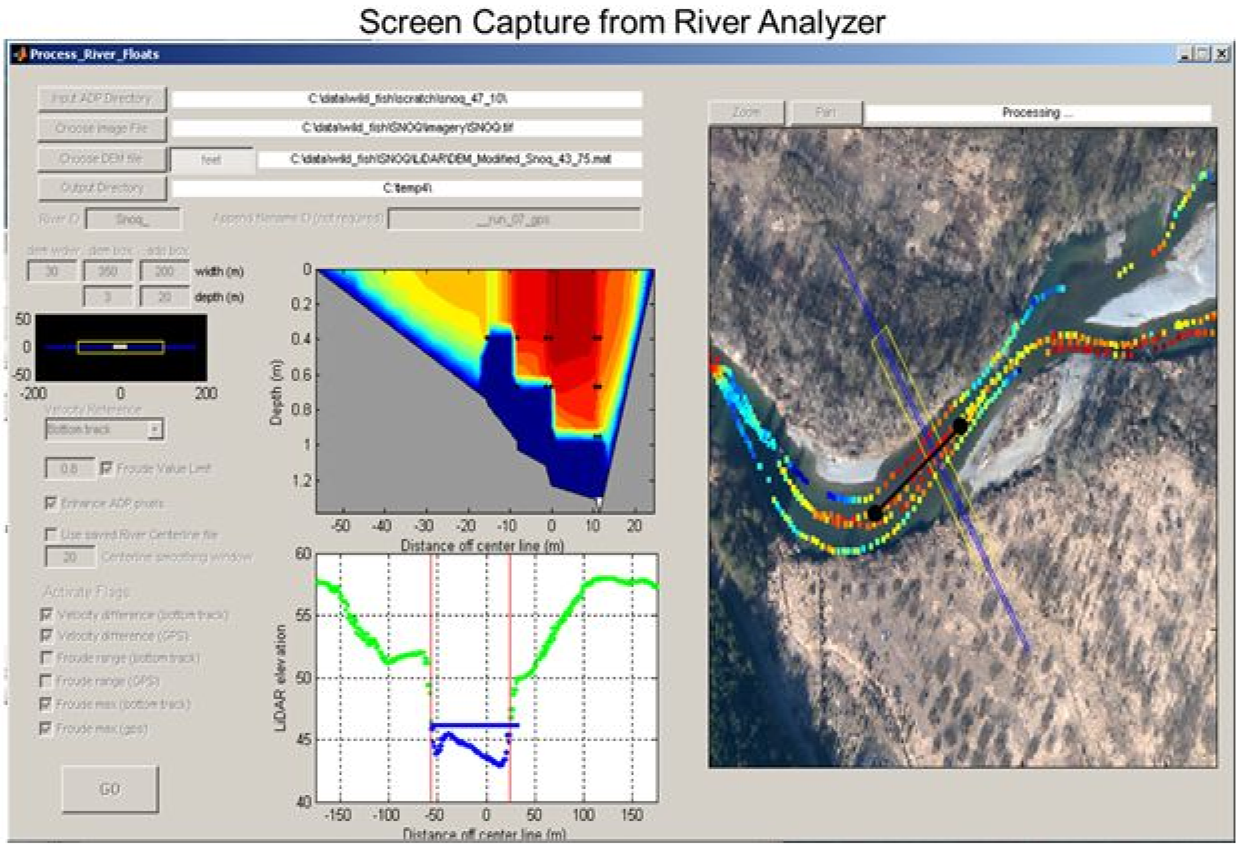

Figure 46. A screenshot of River Analyzer creating transect slices of the ADP data.

All the cross-sectional slices are plotted in a format where the left panel is scaled from 0 to maximum flow conditions and the right panel is scaled to emphasize the negative upstream velocity values which are plotted as cool blue hues and downstream values as warm red hughes with each view looking downstream to conform to river right and left orientations (Figs 47-50 and 55). This way a quick look at the left panel gives an overall look at the downriver flow velocity and the right panel provides a quick look at flow direction whether upstream or down as well as velocity. The middle panel for each diagram shows the location of each particular cross-sectional slice.

Flow in the upper Sacramento River near Clarksburg was dominated by river discharge and an ebb tidal condition hence all of the water was flowing down river (Fig, 47). Bottom boundary layer conditions and thicknesses are clearly visible as in the left panel as well as the location of maximum flow and turbulent complexities. Flow and bottom bathymetry is quite complex in the Sacramento River at the confluence with Georgiana Slough (Fig. 48). Water is flowing downstream in Georgiana and upstream in the Sacramento River. Further downstream most of the Sacramento River is slow flowing upstream with localized jets of flow downstream located near the surface on the river left bank and mid-column on the right bank (Fig. 49). By the time the river team reached the Isleton Bridge flood tide was ending with most of the flow moving downstream but with jets of flow upstream and complexities around bridge piers (Fig. 50).

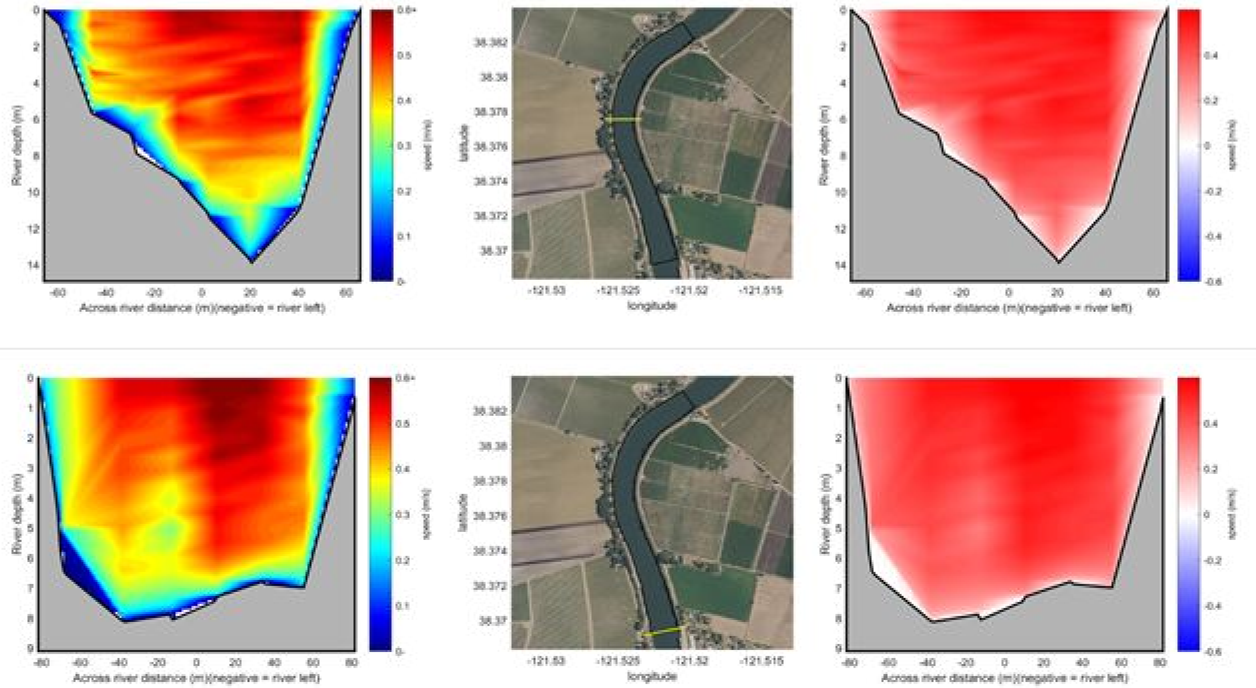

Figure 47. Slicer output from river segment one just below the put-in at Clarksburg. The left panel shows flow velocity scaled from 0 to maximum positive values (i.e. flow in the downstream direction). The panel on the right is scaled relative to the maximum negative value creating an easy to read plot where water flowing downstream appears red and water flowing upstream appears blue. Both plots are viewed from the perspective of looking downstream corresponding to river-right and river-left orientation. The middle panel shows the location of the transect with a yellow line.

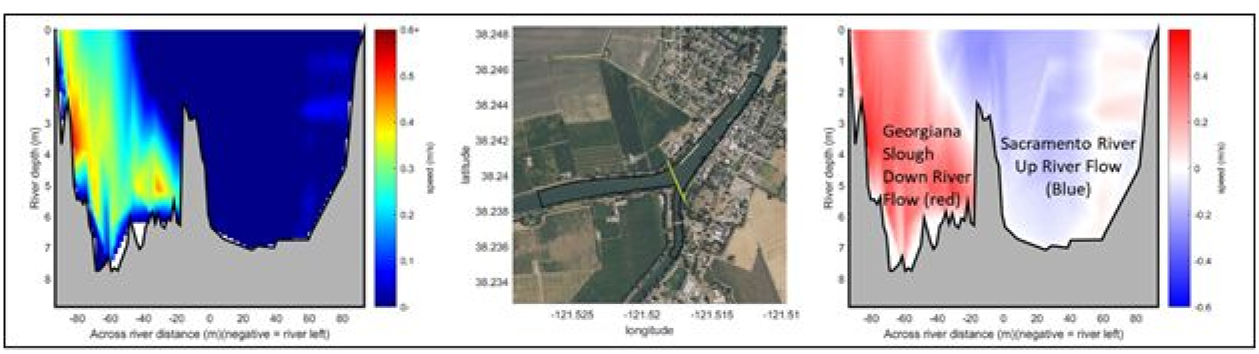

Figure 48. An output of transect slice located at the mouth of Georgiana Slough. The left panel shows flow velocity scaled from 0 to maximum positive values (i.e. flow in the downstream direction). The panel on the right is scaled relative to the maximum negative value creating an easy to read plot where water flowing downstream appears red and water flowing upstream appears blue. Both plots are viewed from the perspective of looking downstream corresponding to river-right and river-left orientation. The middle panel shows the location of the transect with a yellow line. Note the complexity of flow both horizontally and vertically as well as the complexity of the channel bathymetry.

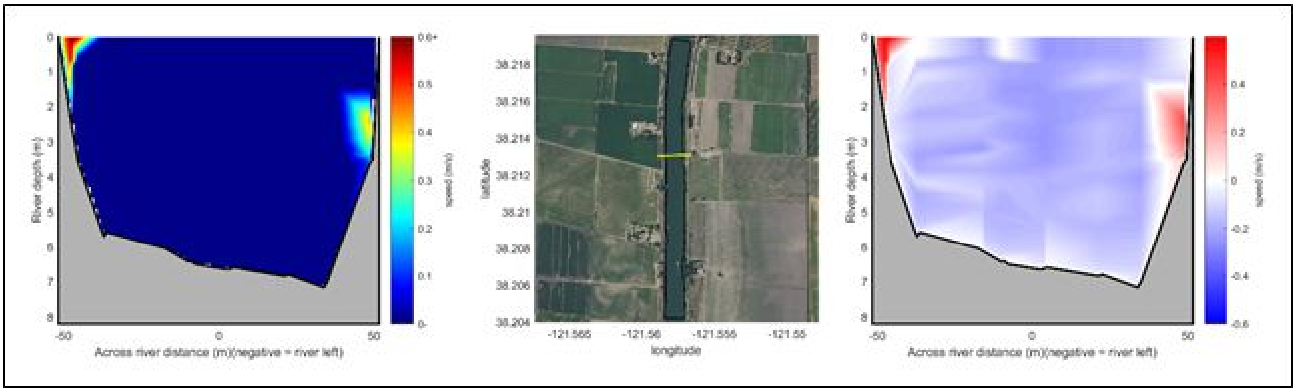

Figure 49. An output of transect slice located in the Sacramento River downstream of Ryde and corresponding to the drift plot shown in figure 43. The left panel shows flow velocity scaled from 0 to maximum positive values (i.e. flow in the downstream direction). The panel on the right is scaled relative to the maximum negative value creating an easy to read plot where water flowing downstream appears red and water flowing upstream appears blue. Both plots are viewed from the perspective of looking downstream corresponding to river-right and river-left orientation. The middle panel shows the location of the transect with a yellow line. Note the complexity of flow both horizontally and vertically contrasting with relatively simple channel geometry relative to the transect slice shown in figure 44. Most of the water column is flowing upstream as is all the bottom boundary water verifying the drift paths plotted in figure 43.

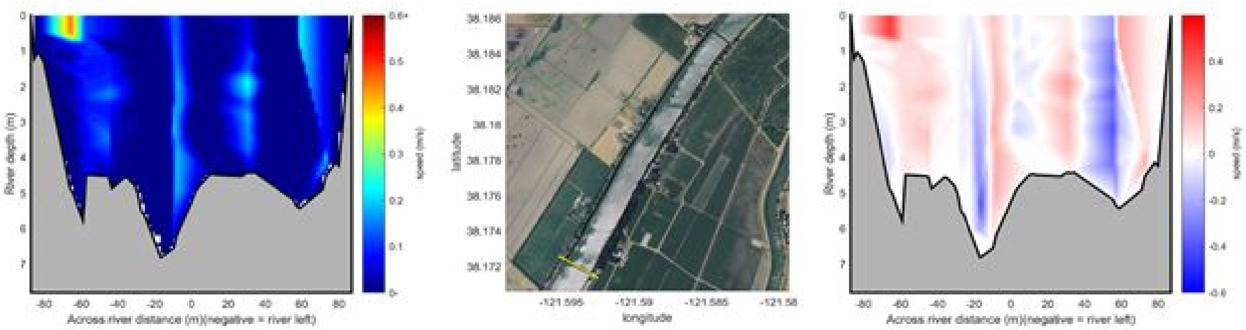

Figure 50. Flow at Isleton Bridge. The left panel shows flow velocity scaled from 0 to maximum positive values (i.e. flow in the downstream direction). The panel on the right is scaled relative to the maximum negative value creating an easy to read plot where water flowing downstream appears red and water flowing upstream appears blue. Both plots are viewed from the perspective of looking downstream corresponding to river-right and river-left orientation. The middle panel shows the location of the transect with a yellow line. Note the complexity of flow and the bottom morphology as influenced by the bridge piers.

9. The Elk Slough Challenge

Mapping Elk Slough was presented as a challenge to determine if we could successfully collect data in a very complex, confined and shallow reach. We agreed to exchange one day of data collection on the Sacramento River for a single pass mapping in Elk Slough. We completed two Elk Slough mapping passes with the ADP river team and one sonar mapping pass.

We completed the data collection and complete suite of analysis on that data set. Those results are presented below. The spatial discharge measurement for Elk Slough is presented with the Sacramento River results in section 10 below. The temperature data for Elk Slough was presented in section 5 (Temperature Mapping) where the most variable water temperatures were measured (Fig. 30). The channel bathymetry and bottom composition were presented in sections 2 & 3 (Figs. 13 & 17). The DEM for Elk Slough is coupled to the Sacramento River with examples of cross-sections shown in figure 25.

The river team started in Sutter Slough at the confluence with the mouth of Elk Slough. The team measured up the slough just after the tide had changed from high slack tide to a falling ebb tide (Fig. 34 and 58) reaching the top of the slough as the low slack tide was approaching. They then turned around and measured back down the slough, motoring against an in-coming flood tide (Fig. 34 and 58). This data collection scheme relative to the timing with the tidal conditions was fortuitous in that it allowed us to examine the same channel but with opposing tidal flow while mapping the slough twice.

Flow complexity was greatest for ebb tide conditions and especially complex for the bottom segment near the confluence with Sutter Slough. This complexity is apparent when comparing the surface water mean flow map with the the bottom boundary flow map (Figs. 51 and 52). The water on the surface is flowing upstream during an ebb tide while the bottom is flowing downstream during the same tidal condition. Elk Slough appears to be draining along the bottom boundary layer during ebb tide conditions.

When we look at the mean flow and bottom boundary flow vectors and subsequent drift paths we see more detail regarding complexity of flow (Fig. 53). Flow along the river-right bank for both the top and along the bottom is quite strongly directed into the bank (Fig. 53). However, comparing the ebb flow in this segment with flow a few hours later during flood tide conditions reveals a much different and less chaotic pattern of mean flow, bottom boundary flow and patterns of drift with all of the flow moving up slough (Fig. 54). Comparing the vertical cross-sectional slices confirms that during flood tide water throughout the water column flows up the slough (left panel is plotted as flood tide in these slice examples) while the ebb flow is quite complex throughout the water column during an ebb tide (Fig. 55)

The mouth of Elk slough at the conference with Sutter slough is a deep hole (Fig, 17) with calm water (Fig. 36). Given the coupled complexities of bathymetry, substrate, temperature and flow, this location could very well be a “hot spot” for large predacious fish. Indeed we met a fisherman at this precise location that claims, “it always produces strippers and he only keeps 5 pounders or bigger”. Perhaps a fishing tale, but given the confluence of physical complexity at this location it is not a surprising tale. From a boat or an aerial photograph it looks like any other location in the smaller sloughs of the delta.

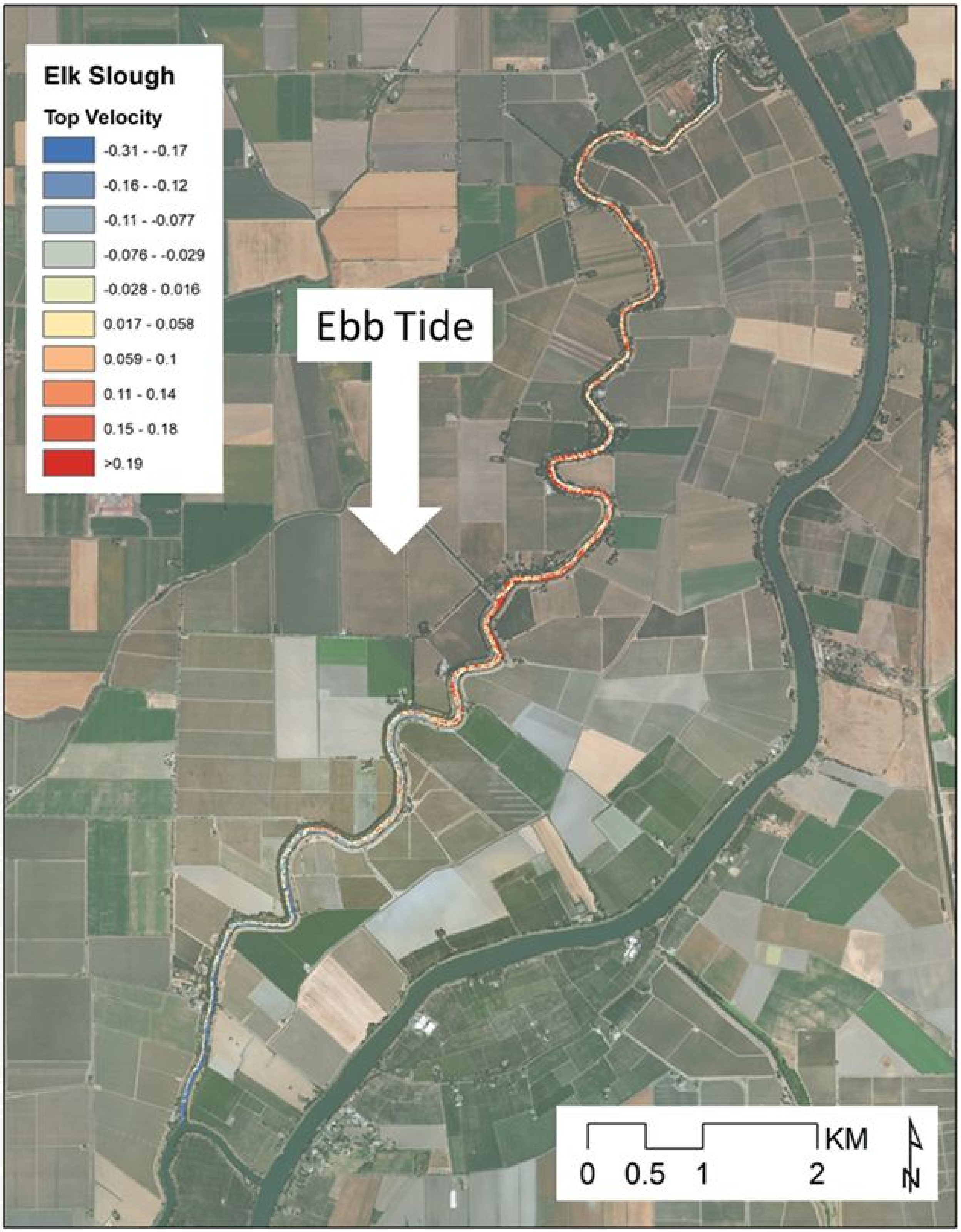

Figure 51. A plot of Elk Slough showing surface-water flow velocity in the top meter of the water column. Note that negative values (green to blue colors) represent flow upstream and red colors downstream flow. The data was collected by the river team starting at the bottom and motoring up the slough against an outflowing ebb tide (see figure 34 for tide data vs collection times).

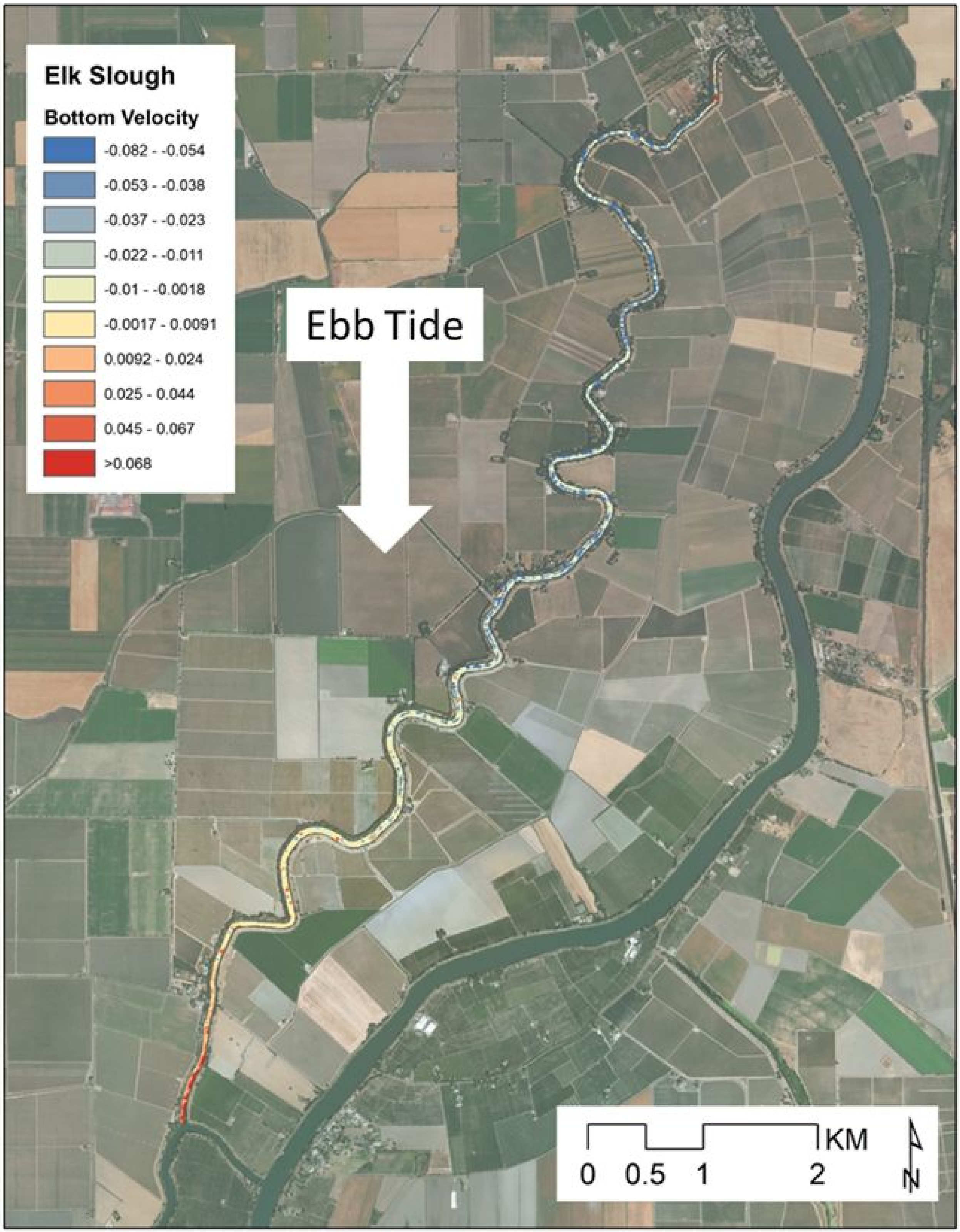

Figure 52. A plot of Elk Slough showing bottom boundary flow velocity. Note that negative values (green to blue colors) represent flow upstream and red colors downstream flow. The data was collected by the river team starting at the bottom and motoring up the slough against an outflowing ebb tide (see figure 34 for tide data vs collection times).

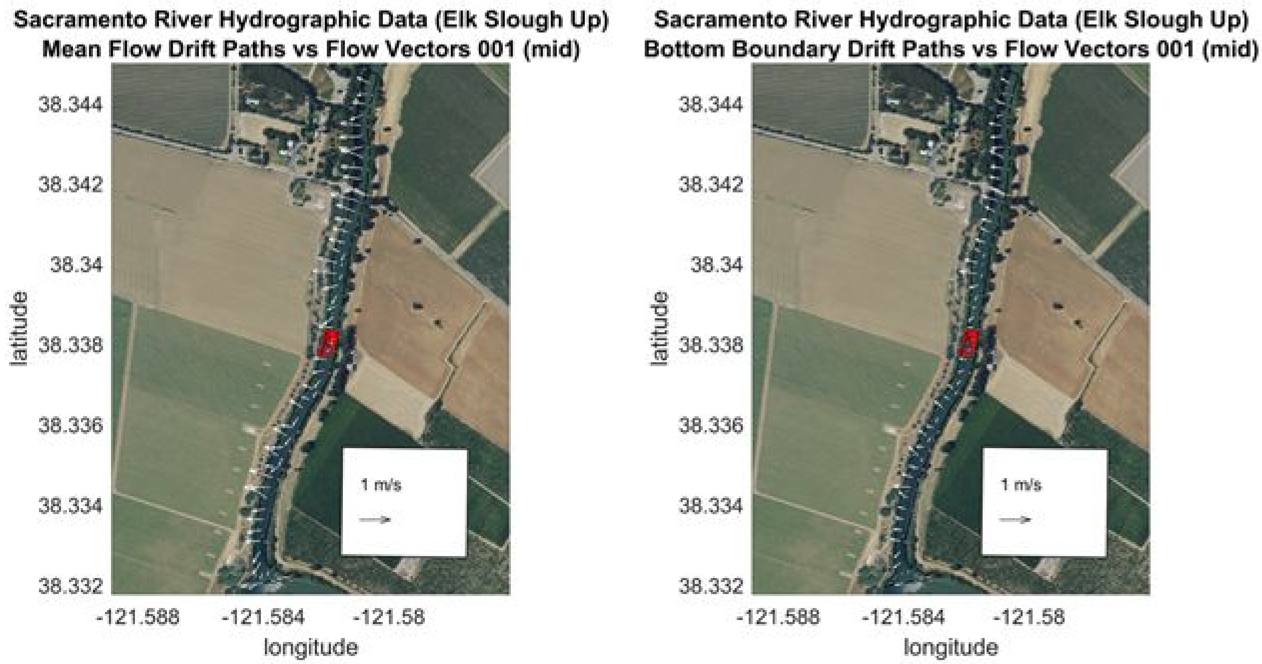

Figure 53. A plot of drift paths (red arrows) relative to the flow vectors (white arrows) for the bottom segment of Elk Slough.

Figure 54. A plot of drift paths (red arrows) relative to the flow vectors (white arrows) for the bottom segment of Elk Slough.

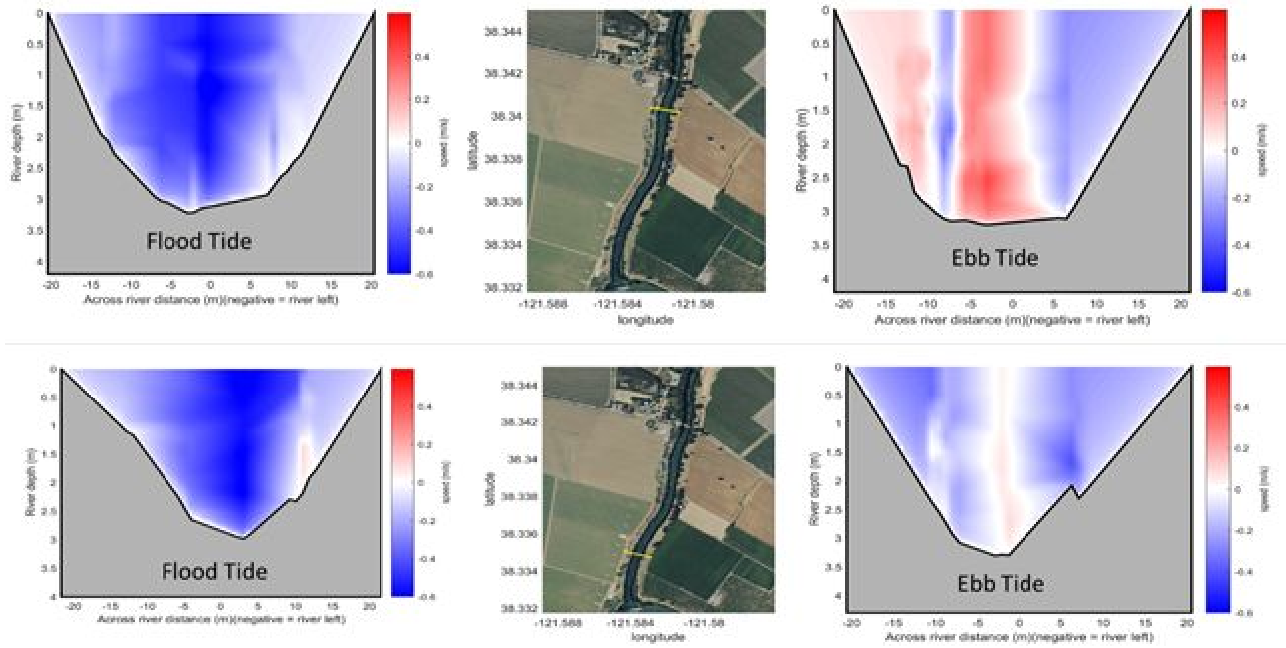

Figure 55. Slicer output from the Elk Slough segment at the confluence with Sutter Slough. The left panels show flow measured during the incoming flood tide and the right panels show the flow during the outgoing ebb tide. scaled from 0 to maximum positive values (i.e. flow in the downstream direction). The middle panels shows the location of the transect with a yellow line.

10. Spatial Measure of Discharge

Determining the volumetric discharge (Q) of water (e.g. cubic feet per second of water) moving past a point on a map) requires measuring cross-sectional area (water depth across the channel) and flow velocity (Fig. 56). This is routinely done at established river gauging stations. If there are enough gauging stations, then the net delta outflow of freshwater could be determined assuming no significant consumptive use or loss due to seepage or evaporation between the gauging stations. However, there are not enough gauging stations to calculate such a water budget and significant consumptive use and seepage loss occurs. The location points of extraction for consumptive use are known and could be easily tabulated but the loss to seepage is unknown. Seepage loss is also directly related to levee integrity and potential zones of levee failure. Hence, high-density spatial measurement of water depth and flow velocity (Q) is necessary to quantify the net delta outflow of freshwater to assess the spatial variance of levee integrity and ultimately to determine the abundance and spatial distribution of aquatic habitat (Fig. 56).

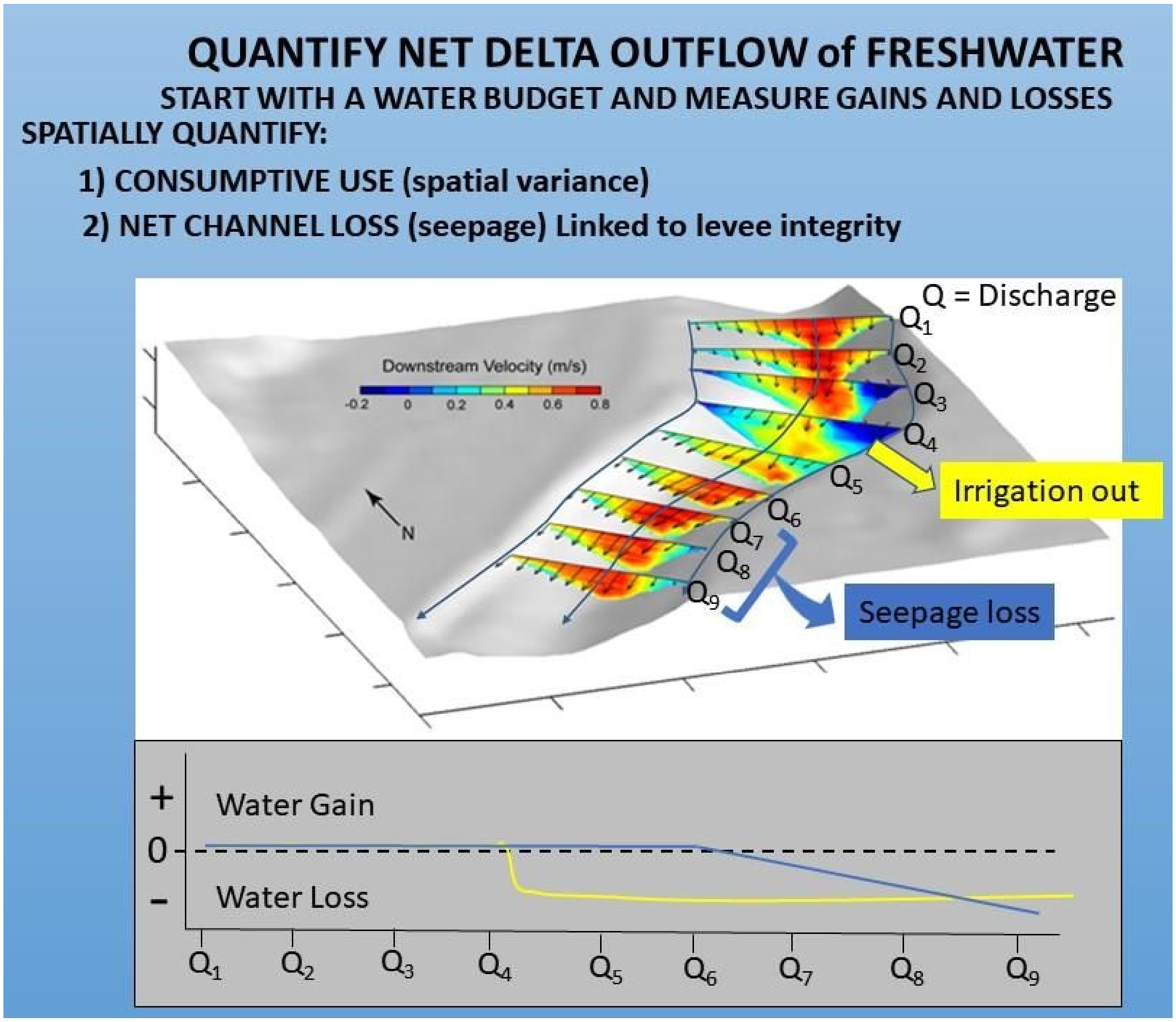

Figure 56. A schematic diagram created from ADP data representing the bathymetry of a channel fused to the topography of the surrounding land (grey area). Cross-sections of flow are shown with ADP measured flow velocity. Discharge (Q) can be calculated for each cross-section. We measure Q every 10 m along the river and slough channels. A water budget can be created from these data where zero change would be represented by the dotted line (bottom graph) and water losses due to consumptive use and seepage are shown by the yellow and blue lines.

Assessments of how much water can be drawn from the delta and how flow alterations within the delta impact aquatic organisms and ecosystem processes can be made with a high-density spatial resolution water budget (Fig. 56). Such a water budget does not currently exist for the entire delta at a sufficient resolution to measure the net outflow of freshwater. The possibility of a successfully negotiated agreement and an adaptive management system on how much water can be extracted from the delta and how much the ecosystem needs is much more likely with this information. Hence, the legislative imperative of co-equal goals more completely met.

We have extracted 11,187 cross-sectional flow slices from three data collections on the Sacramento and two runs in Elk Slough, one during a flood tide phase and the other during the ebb tide phase over the length of the entire slough as explained above in section 8. For each slice we have calculated discharge. Plotting these successive discharge measurements allows a first-order look at net outflow of freshwater (Figs. 57 and 58). These measurements will naturally have much more scatter than traditional approaches to collecting discharge measurements at a single transect location. The advantage of this approach is to get a spatial overview of discharge to examine trends in change over long distances between gauging stations. Data from the Sacramento River was collected over approximately 35 km with a slicer-determined discharge measurement determined every 10 m (Fig. 57). Loss of water at Sutter, Steamboat and Georgiana Sloughs are marked by sharp drops in the discharge trend (Fig. 57). Different slopes in the trend lines are due to either a change in river discharge, loss of water due to seepage or tidal influences. For the Sacramento River below Georgiana Slough tidal influences are apparent. As flood tides are encountered mean velocities are reduced, as we have documented in detail above, resulting in a decrease in discharge as shown by negatively sloping trend lines on days two and three (Fig. 57). Day one shows an increase in discharge towards the end of the day as the tide passed through high slack and into ebb tide, thereby increasing flow velocity and discharge (Fig. 57). These patterns are important for assessing the total flux of suspended and dissolved material in the water, deposition of material due to settling, and provides a surrogate way to look at water quality modeling output from DSM2-GMT.

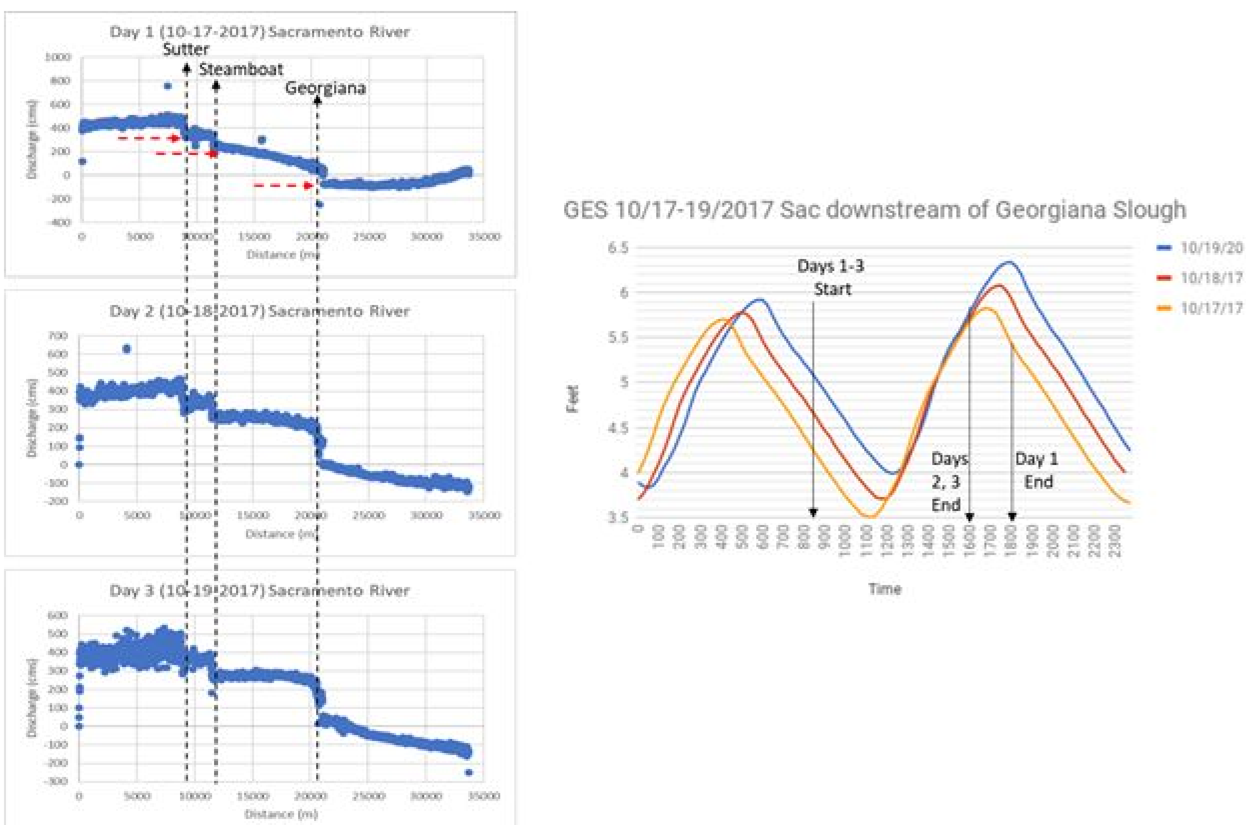

Figure 57. Slicer discharge output for the Sacramento River.

The discharge patterns for Elk Slough are also quite revealing because they were taken during opposing tidal conditions but over the same channel (Fig. 58). One would expect to see decreasing discharge measurements during an incoming flood tide because flow velocity would be, on average, decreasing. One would not expect to see decreasing discharge during an ebb tide, but this is precisely what was measured over the middle section of Elk Slough as depicted by red arrows (Fig. 58, note that the ebb tide plot starts at zero at the confluence with Sutter Slough and the flood tide starts with zero at the top of Elk Slough). This middle section of Elk Slough may very well be losing water due to seepage or pumping or both in the areas marked by red arrows.

Wide variation in these calculations of discharge is expected given time variation in flow and time variation in sampling. Because not all rafts are perfectly abreast at all times and because a flow field that is turbulent has variable velocity over time at a single location, a wide spread in the data from slice to slice is apparent in the measurements. Those areas that have large outliers may very well be due to large boils and complex flow, These areas are typically avoided when measuring discharge using traditional (transects across the river) methods. Hence these anomalies to the trend are interpreted as indicators of areas of high channel and flow complexity and are precisely the areas important to aquatic organisms. These data increase accuracy when mapping large scale spatial variation and help gain further insight into processes that are actively impacting net outflow of freshwater. In addition, these trends show areas of spatial deposition of suspended sediment load that could be impacting ecosystem processes. Actual change in a trend line will require a significant change in discharge as shown in both figures. Large previously unknown changes in discharge, no matter the cause, are revealed with this approach.

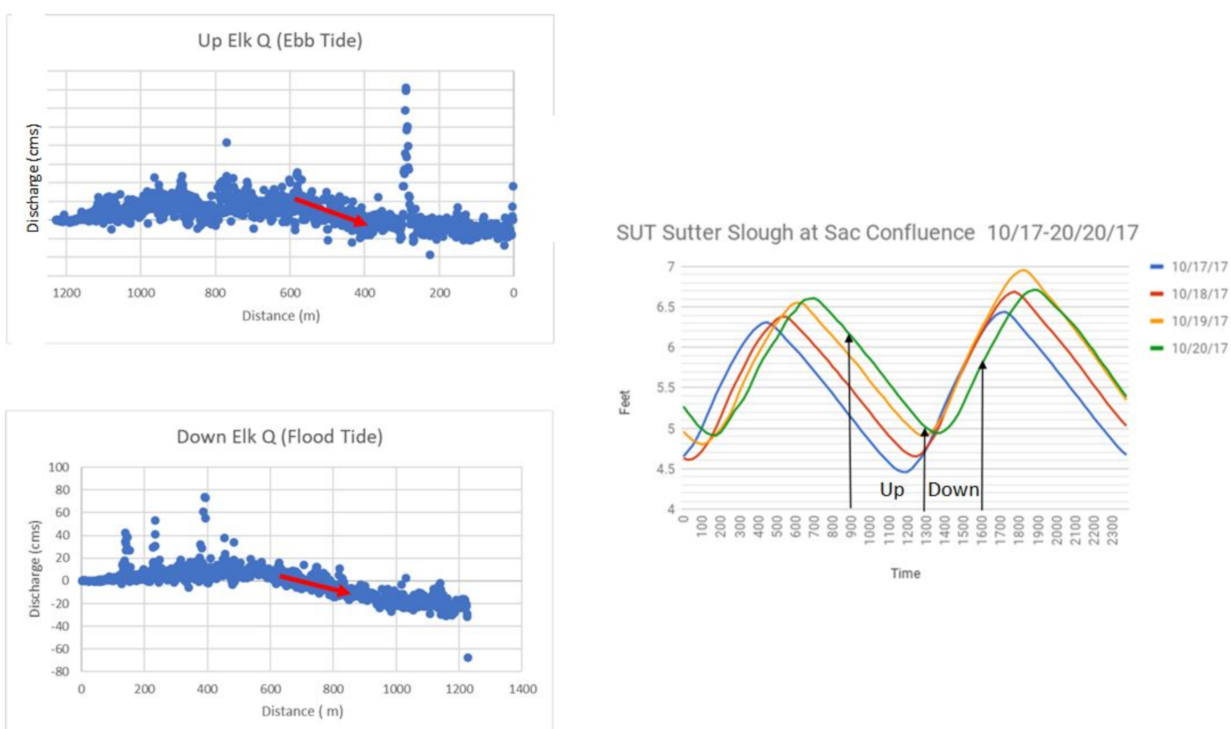

Figure 58. Slicer discharge output for Elk Slough. Red arrows indicate a section of the slough that appears to be losing water due to seepage.

11. Summary

CO-EQUAL GOALS AND FUNDAMENTAL QUESTIONS:

The objective of this phase-1 project was to demonstrate, to a broad audience, how our high-resolution, hydro-acoustic, river-mapping services could help people working toward water resource solutions for the delta. The overarching goal for the State of California is to balance human needs for freshwater with an ecological healthy river-delta system under the "co-equal goals" legislation.

The fundamental question being addressed by all stakeholders is: how much water can be drawn from the delta and still maintain a healthy delta-wide ecosystem? There is no agreement yet on how much the ecosystem needs or how a multitude of uses and flow regulation impacts both humans and the ecosystem.

The data analysis presented in this technical report is a first pass summary of how the depth and flow data coupled to the sonar imagery can be used to help reach delta-wide agreement over water resource management.

NET DELTA OUTFLOW of FRESHWATER

We are able to use the data we collected to assess, over a very broad scale (35 miles of river), a first look at how to approach assessing the net outflow of freshwater (Figs. 57 and 58). By looking at broad scale trends much insight can be gained as to the spatial distribution of physical processing related to the flux of freshwater through the delta. It is a method to map out physical "hotspots" delta-wide. It appears Elk Slough is losing significant water throughout its middle section. It would be worthwhile to investigate this area in greater detail to look for signs of water seeping from the slough. The local landowners probably know exactly where to look. This section of delta levee may very well be vulnerable to levee failure and was, in fact, under repair during our time in the field. The loss looks to be on the order of 100 cfs over about a half a mile of levee. It may also be wise to conduct a precise water surface budget by collection highly accurate discharge transects over this section of slough and over a range in tidal conditions.

THE BOTTOM BOUNDARY LINK

The bottom boundary is the interface between freshwater use for humans and ecosystem needs, hence the ability to measure bottom boundary conditions is essential to finding agreement in delta-wide water resource management. For example, pumping major amounts of water from the delta into the California Aquaduct for human consumptive use changes flow patterns in the delta, as does many other current standard and proposed operations including: operation of the cross-cut channel, placement of rock dikes in sloughs, and diverting water from the Sacramento River across the delta to pumping stations as proposed by the "Twin Tunnels Project". All of these human manipulations of water impact the bottom boundary layer of the entire delta. The total abundance and spatial distribution of bottom boundary layer water provides two KEYSTONE metrics that we can measure very accurately and quickly on the scale required to assess impacts to the delta-wide ecosystem. We can measure the thickness of the bottom boundary layer and, coupled with the spatial area, can determine the total volume. Quantifying changes in the total volume of bottom boundary water throughout the delta due to natural processes, as demonstrated in this pilot project, and changes in water resource management (e.g. open and closing the cross-cut channel) are measurable and reflected in the bottom boundary metric.

Indeed, the entire delta ecosystem depends on bottom boundary conditions. Assessing these condition depends on measuring the thickness, area, range in velocity, substrate composition, large wood and other water column structures coupled with water temperature, and suspended solid concentration. These are the variables that control much of the primary production related to aquatic vegetation growth, all of the benthic invertebrate secondary production and the food web for fish. Bio-geo-chemical processes related to the deposition and decay of organic material including microbial, viral and bacteria related process that all occur in this critical life zone of the delta are affected by bottom boundary conditions.. Knowledge of the abundance and distribution of the volume of bottom boundary water and how it changes relative to natural processes (tidal action, season discharge) and human water use is required before co-equal legislative goals can be agreed upon and met.

OUR DATA

Our approach to the collection and analysis of hydroacoustic data is based on the fundamental principle referred to as Tobler's Law: "Values of missing data will be like the values of its neighbors in space and time". Missing values can be interpolated using existing measurements. The higher the density of those data, the higher the accuracy of the interpolated values. Computational hydrodynamic modeling is used to "fill in" data collected at transects that are 100s of meters apart. This limits model estimates to spatial scales of a few kilometers. Whereas our transects are spaced at a maximum of 20 meters apart and is collected over tens to hundreds of kilometers. This significant increase in data density can be used to initialize standard models at a much greater frequency than currently affordable. Output from these models will result in more complex and accurate estimates to more efficiently and completely understand the delta system and predict outcomes of proposed changes to the system.

Our analysis is very robust. We take high density 3D data and analyze it through three independent and well established interpolation methods.

1) **ArcGIS: Topo to Raster** which interpolates a hydrologically correct raster surface from point data.
2) **Kriging** which uses the raw data ensembles to interpolate or fill in data onto a Cartesian coordinate plane,
3) **Linear interpolation** between velocity measurement from data ensembles and logarithmic interpolation to the channel bottom and bank.

HOW OUR DATA HELPS

The fusion of channel bathymetry with levee topography is a valuable outcome of this delta pilot project. Any stakeholder can now easily and cheaply extract cross-sectional information and data from the DEM that is normalised to the NGVD88 datum. This product is useful to many engineering related applications. The ability to then overlay the sonar imagery enables a look at the channel bottom and its bedforms, substrate composition and occurrence of large wood. More than simply pictures of the bottom, the imagery is georectified which enable accurate measurement directly from the image. In addition the 3D flow field can be added to the information mix through map views of flow, particle drift paths, and cross-sectional views of the vertical flow field. These results will strengthen existing models by improving the initialization of boundary conditions required by all models and by providing validation data to assess predictions of flow between transects used for model calibration. A suite of computer models has been developed and refined over the past two decades to address fundamental water resource questions (Fig. 1). These models were developed to help guide resource decisions related to management of freshwater in the delta. The data that we collect can help initialize, validate and greatly enhance many of these models (Fig. 1).

DELTA WIDE MAPPING: HOW IT CAN BE DONE

It took our river team 4 days to collect the exhaustive data set presented in this report. These data and analysis provide valuable information to help improve resource management decisions and to help negotiate agreement on the co-equal goals of balancing human demand for water and ecosystem needs. Delta-wide data collection field measurements would take a matter of weeks with processing and analysis to generate actionable information requiring a few months.

The first step would be to complete a delta-wide bathymap and fuse that data to the delta wide LiDAR data set. Specific study areas and their respective research questions could then be addressed with more specific analysis.