Modeling morphodynamic development in the Alviso Slough system, South San Francisco Bay, California

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Abstract

Alviso Slough area, South San Francisco Bay, California, is the site of an ongoing effort to restore former salt production ponds to intertidal habitat. As restoration proceeds and the levees surrounding the former salt production ponds are breached, the increase in tidal prism and associated sediment scour in the sloughs will remobilize legacy mercury deposits. A numerical model that is able to assess patterns of sediment transport, erosion, and the fate of remobilized sediments can improve mercury remobilization estimates and inform management actions.

The goals of the current research are to (1) validate a 2D geomorphic model for Alviso Slough using bathymetric surveys and to (2) apply the validated model for Alviso Slough to investigate scenarios of sea level rise and levee breaching on the long-term scour in Alviso Slough. The 2D geomorphic numerical model applies the Delft3D Flexible Mesh (software by Deltares) that describes detailed interaction between hydrodynamics, sediment transport, and geomorphic change on a high resolution mesh.

The morphodynamic modeling exercise shows that observed erosion and sedimentation patterns can be reproduced with skill. The associated suspended sediment concentrations are more difficult to reproduce. The model reveals tide residual flow patterns that are difficult to measure. These residual flow and transport patterns are the result of subtle, tide residual transport trends so that their effect becomes visible in multi-year simulations. Scenario model simulations show possible, illustrative impacts of sea level rise and potential management interventions (additional levee breaches).

Cover picture: breach of Pond A6 levee looking towards pond interior, by Mick van der Wegen, 2014

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1. Introduction

1.1. Background

Alviso Slough, South San Francisco Bay, California, is the site of an ongoing effort to restore former salt production ponds to intertidal habitat. The restoration project is complicated by the fact that: (1) the study area is located downstream of the decommissioned New Almaden mercury mines and bed sediments within Alviso Slough and the surrounding ponds contain elevated mercury concentrations, and (2) the ponds are deeply subsided as a result of excessive groundwater withdrawal in the mid-to-late 1900s. As restoration proceeds and the levees surrounding the former salt production ponds are breached, the increase in tidal prism and associated sediment scour will remobilize legacy mercury deposits.

Since understanding fine-sediment transport is key to understanding contaminant transport, numerical modeling can help inform restoration managers and minimize adverse environmental effects resulting from restoration activities. A numerical model that is able to assess patterns of sediment transport, erosion, and the fate of remobilized sediments under both present-day conditions as well as hypothetical breach scenarios can improve mercury remobilization estimates and inform management actions. Since no such model exists, we develop and validate a full geomorphic coupled numerical model (2D) of hydrodynamics, sediment transport, and geomorphic change of Alviso Slough. This full geomorphic model (2D) updates morphology, which in turn affects hydrodynamics, allowing long-term simulations.

Simulations using this model ultimately can answer questions such as whether the system will reach equilibrium, which would reduce or eliminate mercury remobilization. This modeling also can be used to assess the fate of remobilized Hg. Where this Hg is transported to and deposited is key to understanding potential impacts on birds and fish because of the relationships of depositional environment and mercury methylation. In addition, a validated morphodynamic model can act as a basis for testing scenario simulations of alternative breach configurations and longer term morphodynamic developments of the system including sea level rise.

1.2. Goals of this research

The goals of the current research are twofold: (1) validate a full geomorphic model (2D) for Alviso Slough developed in 2016 using bathymetric surveys (Foxgrover et al. 2011, 2014, 2015, 2018), Guadalupe River discharge data (USGS station 11169025), and new data from the USGS California Water Science Center (CA-WSC) flux stations in mid-slough and near the A8 Notch; and (2) apply the validated geomorphic model (2D) for Alviso Slough to investigate scenarios of breach locations and sea level rise on the long-term scour in Alviso Slough. We put special emphasis on the effect of breaching the historic salt ponds and the resulting morphodynamic effects on the slough's bathymetry.

1.3. Site description

The Alviso Slough system is located in the southernmost area of South San Francisco Bay. The system consists of two major tributary inputs draining flow from the hinterland during storms, i.e. Alviso Slough draining flow from Guadalupe River and Coyote Creek. A third slough, Guadalupe Slough, has little river flow. The slough flows are governed by tidal motion with occasional high river flow events lasting from a day to a week from storms occurring several times per the year. The suspended sediments in the sloughs are mainly fine (silty to muddy) and originate from the Bay, but also from the watershed during peak river flows. Sediments that deposited in the sloughs and Bay during past decades are contaminated with mercury originating largely from the now decommissioned New Almaden mines located in the upstream watershed. Historically these mines were the largest mercury producers in North America and mining waste and contaminated sediments that traveled downstream since the mid-1800s have resulted in elevated mercury concentrations within the bed sediments of Alviso Slough and the surrounding ponds.

Former commercial salt production ponds are located adjacent to the sloughs. The salt pond restoration project is a major effort to restore the former salt ponds to ecologically viable and valuable areas. However, these ponds subsided beneath mean tide level as a result of excessive groundwater withdrawal in the mid-to-late 1900s and will require sediment input to reach elevations that could sustain marsh vegetation. Beginning in 2010 levees separating the salt ponds from the sloughs were breached in a controlled manner to allow tides to enter the ponds. As a result, sediment will deposit in the subsided ponds and ultimately lead to the development of intertidal marsh habitat.

Opening of the pond levees over the past decade has led to morphodynamic development within the slough system. Conveying an increase of the tidal prism, the sloughs have eroded between the Bay and the levee breach. Deposition occurred landward of the breach, although some parts of the slough also showed erosion. The ponds have begun to fill with sediment (Callaway et al., 2013). Shoals in the Bay had considerable deposition as well. Part of this deposition may have originated from the erosion of the sloughs although deposition volumes, approximately 600 million cubic meters, far exceed the erosion volumes, approximately 90 million cubic meters, meaning that most of the deposited sediment must have originated from the Bay.

1.4. Methodology

The Alviso Slough system is complex to model due to a limited and confined area conveying large parts of the tidal flow (the sloughs) adjacent to large areas with limited flow velocities but having considerable water storage during a tidal cycle (the ponds). As a result, a flexible mesh and advanced numerical methods describing the flow, sediment transport and morphodynamics are required. This study applies the Delft3D Flexible Mesh (D3D FM) software that is being developed exactly for this kind of circumstance (Deltares, 2017a, b). The software calculates flow patterns and sediment transports on a high resolution mesh at typical time steps of 15 s. The bed level is updated as frequently as every time step, depending on the spatial gradients in sediment transport.

The model was first calibrated against morphodynamic developments derived from bathymetric surveys collected in January, September and December 2010 and October 2012 (Figure 1). Calibration consisted of varying critical shear stress, the erosion parameter, and sediment fall velocity to reproduce patterns of deposition and erosion and magnitude of erosion near the mouth of Alviso Slough. A second sediment fraction was added to calibrate against observed suspended sediment concentration (SSC) measured mid Alviso Slough (Shellenberger et al., 2015). A key parameter that was varied in this second phase of calibration was D_{eff}, the fraction of sediment that deposits on the bed. After calibration, we then ran the model until March 2017 and derived a sediment budget for the entire system. Finally, we ran two other scenarios for the same period, i.e. Scenario 1 including a 0.5 m higher mean water level, mimicking sea level rise, and Scenario 2 including additional breaches in the ponds, mimicking possible future management interventions.

The software is open source and the model setup will be made publicly available at the community model website http://www.d3d-baydelta.org/. The software, which was being developed during this project, is state-of-the-art. This is the first validated D3D FM application to include fine sediment morphodynamics.

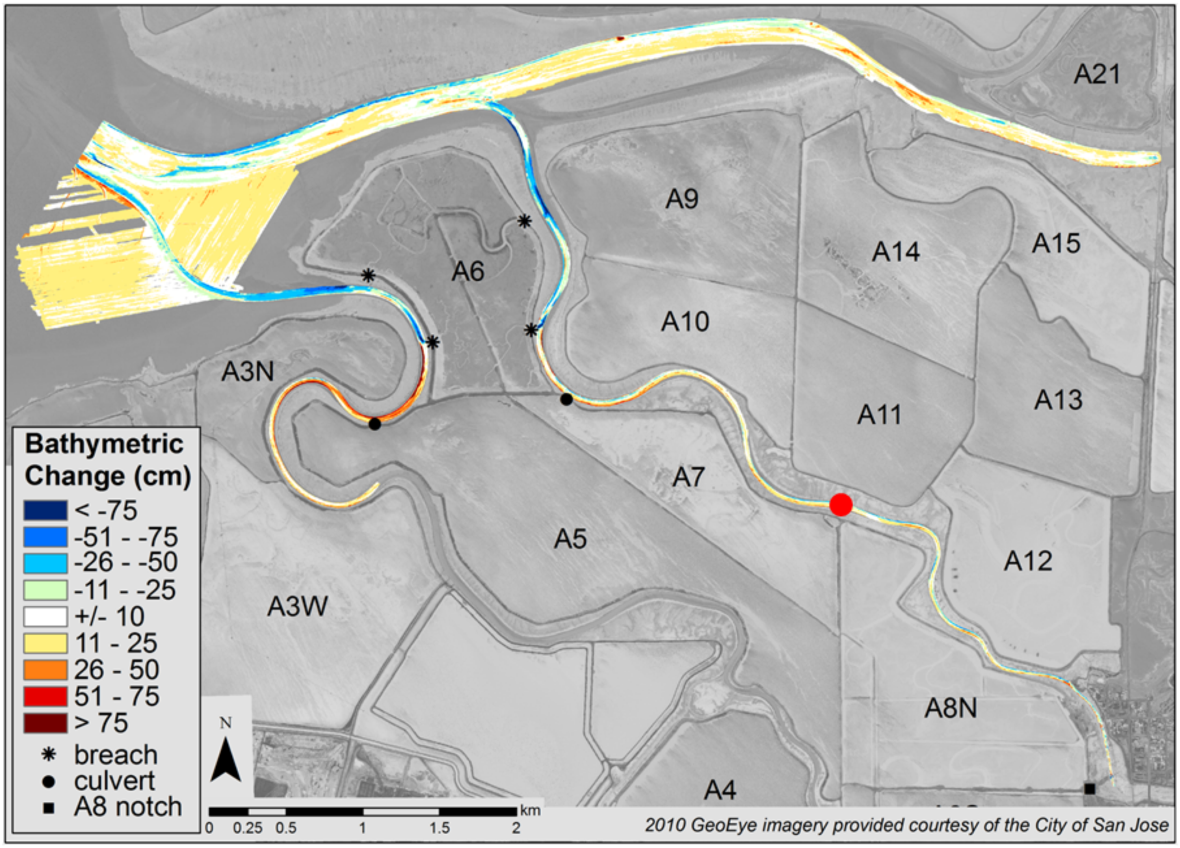


Figure 1. Erosion and sedimentation patterns in the Alviso Slough system from 2010 – Oct 2012. Names of ponds shown for reference (modified from Foxgrover et al., 2015). Red dot indicates SSC measurement location USGS station # 11169750.

1.5. Model setup

The model mesh (Figure 2) consists of 2316 cells, roughly ranging in size from 20 m in the sloughs to 150 m in the ponds Sloughs and channels were meshed with curvilinear quadrilaterals securing numerically efficient and accurate results, while intertidal and storage area (ponds) were meshed with triangles allowing flexible and irregular shapes in areas with flow velocities. About 3-5 cells covered the sloughs in width, which is considered a minimum to reflect proper friction effects and morphodynamic development. Higher resolutions would make the model slower. Model run time was about 1.5 days for a single year on an 8 core Windows workstation (Intel i7-3930K CPU @ 3.2 GHz, 32 Gb RAM).

Figure 2. Model mesh.

1.5.1. The sediment transport model

We assume that the sediments responsible for morphodynamic development are fine, cohesive sediments (Marvin-DiPaquale et al., 2018). The erosion and deposition of cohesive mud is modeled by the Partheniades-Krone formulations (Krone 1962, 1993; Ariathurai 1974).

$$\begin{aligned} E &= MS_e(\tau_{cw}, \tau_{cr,e}) \\ D &= D_{eff} w_s c_b S_d(\tau_{cw}, \tau_{cr,d}) \end{aligned} \quad (1)$$

where

E erosion flux [kg/m^2/s]

M erosion parameter [kg/m^2/s]

D deposition flux [kg/m^2/s]

D_{eff} fraction of sediment that deposits [-]

w_s sediment fall velocity [m/s]

c_b near bottom concentration [kg/m^3]

τ_{cw} maximum shear stress due to currents [N/m^2], (wave induced shear stress is not considered in this study)

$\tau_{cr,e}$ critical shear stress for erosion [N/m^2]

$\tau_{cr,d}$ critical shear stress for deposition [N/m^2]

S_e erosion step function

S_d depositon step function

and

$$\begin{aligned} S_e(\tau_{cw}, \tau_{cr,e}) &= \left(\frac{\tau_{cw}}{\tau_{cr,e}} - 1 \right) \quad for\ \tau_{cw} > \tau_{cr,e} \\ &= 0 \qquad\qquad\quad for\ \tau_{cw} \le \tau_{cr,e} \end{aligned} \quad (2)$$

$$S_d(\tau_{cw},\tau_{cr,d}) = \left(1-\frac{\tau_{cw}}{\tau_{cr,d}}\right) \; for \; \tau_{cw} < \tau_{cr,d} \qquad (3)$$
$$= 0 \qquad for \; \tau_{cw} \geq \tau_{cr,d}$$

The factor D_{eff} accounts for hindered settling, so that only part of the depositing sediment leads to bed level change while the remaining parts remain in suspension. Delft3D Flexible Mesh applies an advection-diffusion equation to account for the transport of suspended sediments.

The bed sediment model applies a fluff layer concept (Van Kessel et al., 2011), indicating that the bed consists of a lower layer with high critical shear stress and a thin upper layer that is more easily eroded, the so-called fluff layer. Exchange is possible between the lower and upper layer. The model thus assumes that the upper layer of the bed consists of easily erodible material with a low critical shear stress. This material is freshly deposited, e.g. during low water slack, and may eventually 'consolidate' into the lower layer. The fluff layer concept has been successfully applied to reproduce SSC levels in tidal environments (e.g. Van Kessel et al., 2011). ParFluff0 is the 0th order erosion parameter of the fluff layer, whereas ParFluff1 is the 1st order erosion parameter, used when the mass in the fluff layer < ParFluff0/ParFluff1. TCrFluff is the critical bed shear stress for erosion of the fluff layer and IniFluffMass is the initial sediment mass in the fluff layer.

It was difficult to validate the model against SSC and morphodynamic development at the same time. This is a known phenomenon in morphodynamic modeling (personal communication from E. Elias, Deltares). Applying a single sediment fraction, sediment1, led to good morphodynamic predictions, but modeled SSC was about one order of magnitude smaller than the observed SSC. We therefore added a second sediment fraction, sediment2, that would erode at a much lower critical shear stress and that would minimally deposit. Extensive sensitivity analysis led to the applied values described in Table 1.

Parameter	***Value Sediment1***	***Value Sediment2***	***Unit***
Fall velocity (w)	0.5	0.05	mm/s
Erosion parameter (M)	$0.5*10^{-5}$	$0.5*10^{-4}$	$kg/m^2/s$
Critical erosion shear stress ($\tau_{cr,e}$)	0.35	0.025	N/m^2
Dry bed density	700	700	kg/m^3
Fraction of sediment deposited, (D_{eff})	0.3	0.05	-
ParFluff0	10^{-4}	10^{-4}	$kg/m^2/s$
ParFluff1	10^{-5}	10^{-5}	1/s
TCrFluff	0.05	0.05	N/m^2
IniFluffMass	25	25	kg/m^2

Table 1 Sediment characteristics applied in the model

1.5.2. Input

Tidal components derived from measured water levels and constant SSC prescribed the boundary condition at the seaward side. The constant SSC was set at 0.035 kg/m^3 (sediment1) and 0.1 kg/m^3 (sediment2), which were based on prevailing SSC observed at Dumbarton Bridge. Measured river flow and SSC from Coyote Creek and Guadalupe River flow defined landward boundary conditions, although measured SSC levels in Coyote Creek were not available at the time the model was set up (winter 2017).

(These SSC values are now available (i.e., summer 2018) for periods of high river flow in 2010, 2011, 2012 and 2013 via https://ca.water.usgs.gov/projects/baydelta/). As a result, we derived an empirical river flow (Qr)-SSC relationship based on the Alviso Slough data and applied this equation to Coyote Creek (Figure 3). We applied a uniform Manning roughness of 0.026 $s/m^{1/3}$. We did not include Guadalupe Slough inflow since these flows were considered minor. Other impediments to including Guadalupe Slough boundary conditions are that flow and SSC data were not available and accurate bathymetry of a large part of Guadalupe Slough was missing.

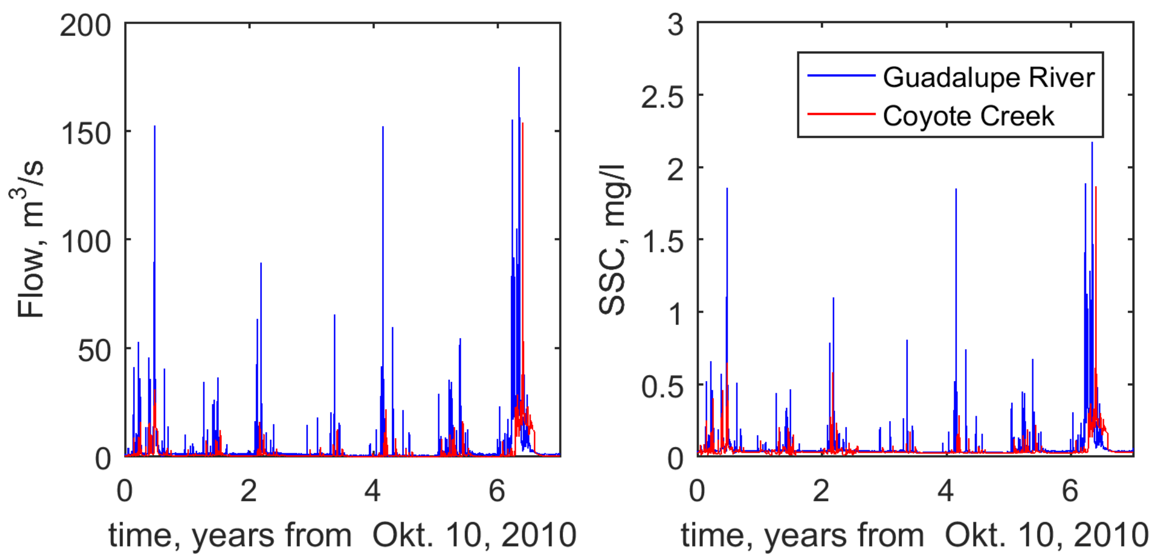


Figure 3. Landward boundary conditions for Guadalupe River entering Alviso Slough and for Coyote Creek.

Table 2 shows the source of input parameter values applied in the model. Bathymetry is from 2010 and 2012 (Foxgrover et al., 2015). Polygons defining the location of levees were developed from the S_GEN_Structure layer, which contains the location and attributes for flood control structures. These structures are part of the 2012 Federal Emergency Management Agency (FEMA) National Flood Hazard Layer that incorporates all digital flood insurance rate maps (DFIRM) databases published by FEMA (2013). Lines delineating the levee crest were edited to ensure they were in the correct location using 2014 high resolution satellite images provided by Esri's ArcGIS online image catalog (Esri, 2011). Elevation values were derived by querying the Topobathymetric Model of San Francisco Bay, California (2013).

The A6 breaches were modeled as 30 m openings in the levee system. A5, A7 (Figure 4) and A8 (Figure 5) openings (actually 2 bi-directional syphons and gates at the A8 Notch) were modeled via gate routines (Deltares, 2017b) with sill heights at 1 m NAVD88 (North American Vertical Datum of 1988) and variable opening widths as a function of time as defined in Table 3 and Table 4. Opening heights (from sill) were 1.2 m for A5 and A7 (siphons) and 2 m for the A8 Notch (implying a free water surface not obstructed vertically by a door during the entire model run).

Parameter	Model location	website	Station id
River flow (Qr) and SSC	Alviso Slough inflow (Guadalupe river)	www.waterdata.usgs.gov	11169025
River flow	Coyote Creek inflow	www.waterdata.usgs.gov	11172175
Tidal water level (measured tidal components) wrt GMT	Western Boundary	www.tidesandcurrents.noaa.gov	9414575
SSC (constant, based on measured concentrations)	Western Boundary	https://ca.water.usgs.gov/projects/baydelta/	373015122071000
Bathymetry	Alviso Slough system	Foxgrover et al. (2015)	
Levee locations and heights	Alviso Slough system	Locations modified from FEMA (2013) using Esri (2011); elevations from USGS (2013)	
Gate openings	Breaches and A8 Notch	Personal communication L. Valoppi (USGS)	

Table 2 Input parameter sources

Date	*Opening A5 (m)*	*Opening A7 (m)*
10/10/10	0.6096	0.6096
21/12/10	0.6096	0.254
01/18/11	0.6096	0
03/28/11	0.889	0.889
06/06/11	0.4572	0.4572
07/01/11	0.254	0.4572
07/14/11	1.2192	1.2192
09/27/11	0.508	1.2192
12/15/11	0	1.2192
01/03/12	0.6096	0.6096
05/18/12	1.2192	0.6096
09/06/12	1.2192	1.2192
12/11/12	0.6096	0.6096
03/11/13	1.2192	1.2192
08/25/14	0.9144	0.9144
11/03/15	1.2192	1.2192

Table 3 A5 and A7 gate operations from personal communication, Laura Valoppi (USGS)

Operation	*Open date*	*Close date*
1 A8 gate open	06/01/2011	12/01/2011
3 A8 gates open	06/01/2012	12/01/2012
3 A8 gates open	06/06/2013	12/06/2013
3 A8 gates open	03/06/2014	09/28/2014
5 A8 gates open	09/29/2014	N/A
8 A8 gates open	06/02/2017	N/A
each A8 gate is 5ft (1.5m) wide and there are a total of 8 gates		

Table 4 A8 Notch gate operations from personal communication, Laura Valoppi (USGS)

Figure 4. Syphon from Alviso Slough to pond A6 in 2014.

Figure 5. A8 Notch gates in 2014.

2. Model results

2.1. Water level and velocities

The tide propagates and dissipates through Alviso Slough leading to an 80-cm higher low water near the A8 Notch compared to the Alviso Slough mouth, whereas the high water levels have a much smaller difference of about 20 cm (Figure 6 and Figure 1 for locations). Flow velocities associated with tides are about 50% lower at the A8 Notch than at the mouth (Figure 7). The 80-cm water level difference holds during both peak flow (left panel Figure 6) and low water flow (right panel Figure 6). Different tidal forcing is responsible for the difference in water levels. The flow direction is consistently seaward during high river flow near Notch A8 (Figure 7, left panel). However, timing of the river flow with respect to tidal characteristics (neap and spring) is crucial to draw further conclusions on the impact of river flow on water levels and velocities. That impact may be different under spring or neap tidal conditions.

Figure 8 and Figure 9 show comparison of measured and modeled water levels and velocities at USGS station # 11169750 (see Figure 1 for location). Although tidal phasing is correct, the model slightly under predicts observed tidal variations while tidal velocities are over predicted. Water level performance could be improved by a lower roughness, but that would lead to even higher velocities. Velocities are sensitive to location. Velocity performance could subsequently be improved by a higher channel grid resolution enabling a match with the exact location of the measurements.

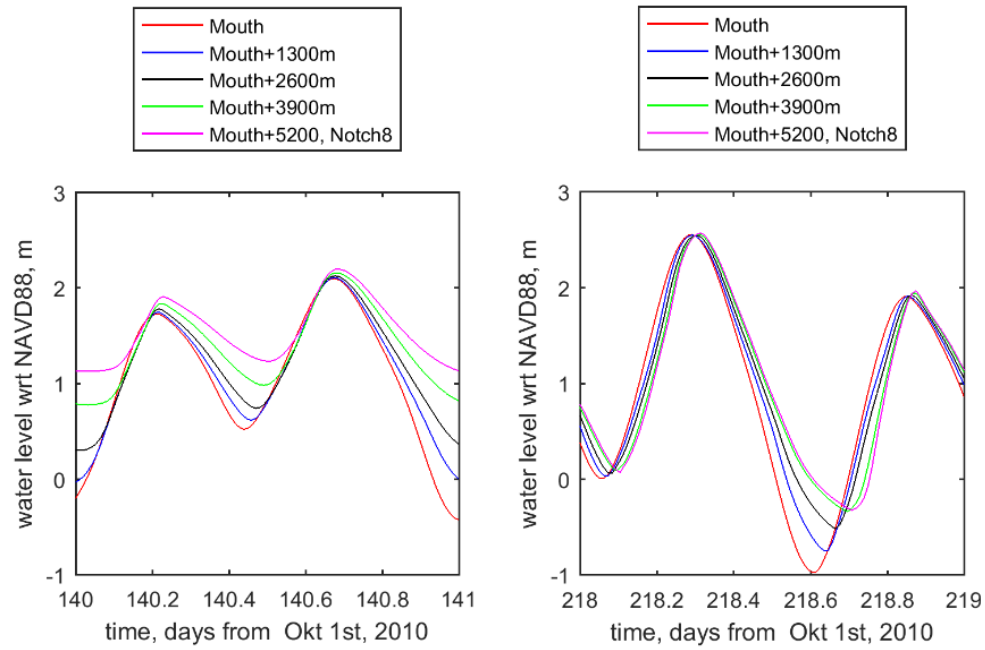


Figure 6. Water levels relative to NAVD88 along Alviso Slough during high river flow (left panel) and low river flow (right panel). See Figure 1 for locations.

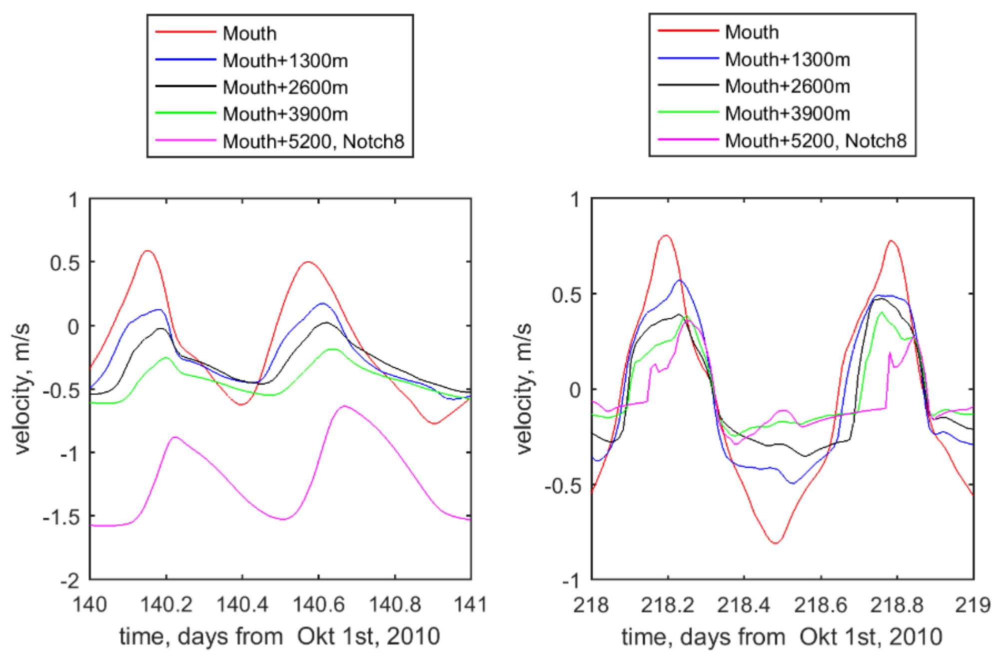
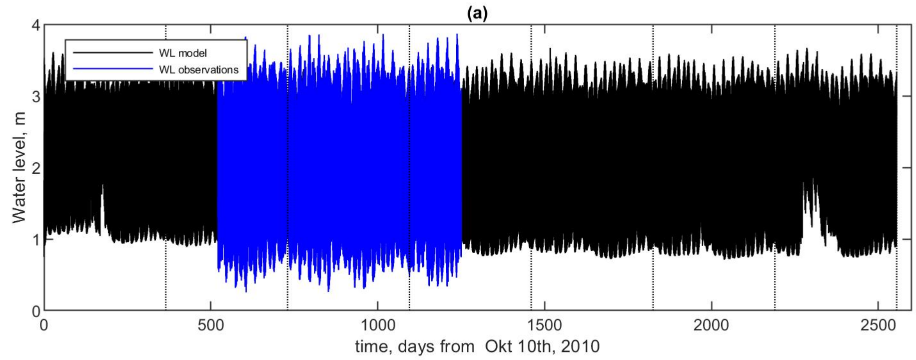


Figure 7. Cross-section averaged velocities along Alviso Slough during high river flow (left panel) and low river flow (right panel). Negative values indicate seward transport. See Figure 1 for locations.



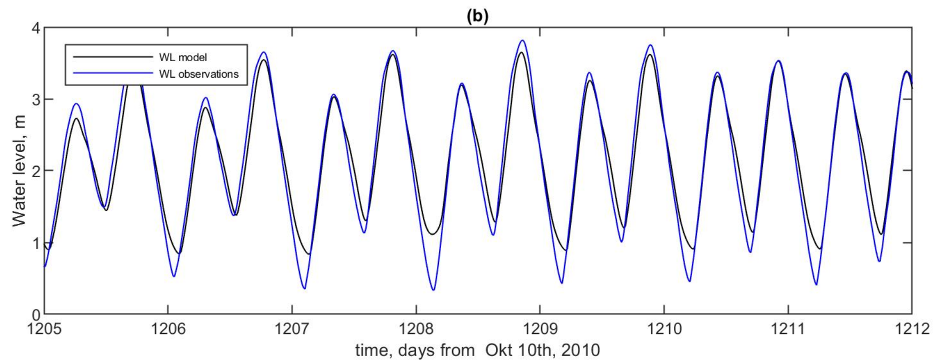


Figure 8. (a) Comparison of measured and modeled water level at USGS station # 11169750 (see Figure 1 for location) over 2010-2017 period; (b) detail of (a). Vertical reference of water level data was not clear. The calculated mean water level from the data was corrected by the known local relation between mean water level and NAVD88.

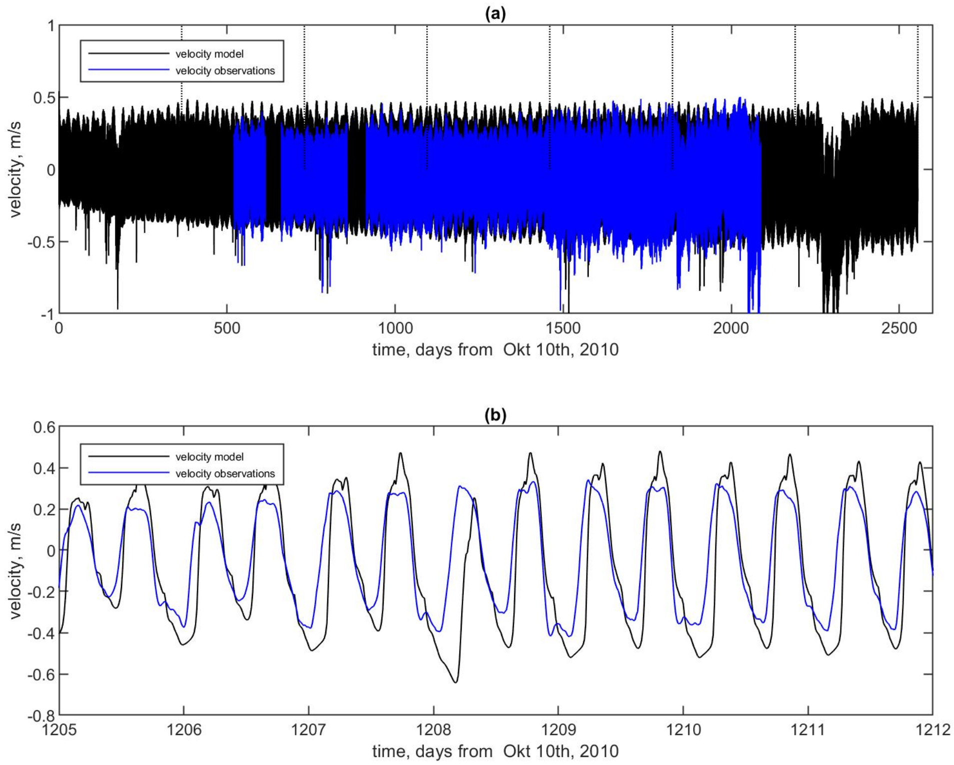


Figure 9. (a) Comparison of measured and modeled velocity at USGS station # 11169750 (see Figure 1 for location) over 2010-2017 period; (b) detail of (a).

2.2. Sediment concentrations

The application of the fluff layer concept improved model skill compared to simulations without the fluff layer, to the extent that SSC levels are within the same order of magnitude. As in the 2D model, the observed SSC is presented here as cross-sectionally averaged values. The modeled base SSC levels are similar to observed values (Figure 10 and Figure 11). The spring-neap cycle is reflected in both observations and model results, although observed spring tidal SSC levels far exceed the modeled values. Also, timing and phasing are not reproduced well. Fine tuning the fluff layer model could probably increase model skill.

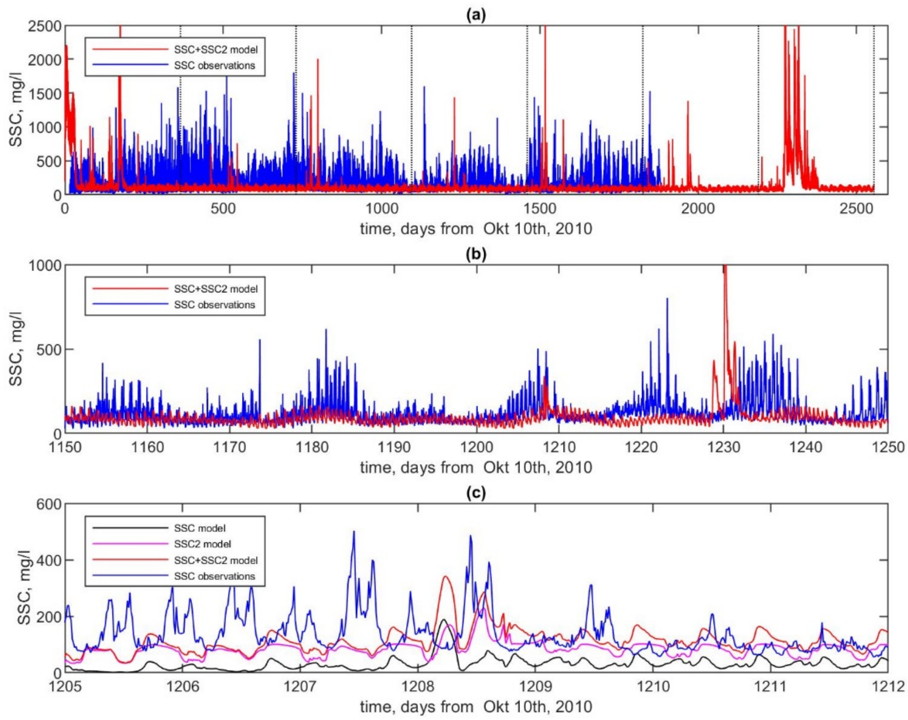


Figure 10. Comparison of modeled and observed SSC at USGS station #11169750 at different durations where (c) is a detail of (b) and (b) is a detail of (a). SSC model is the concentration of the fine sediment fraction. SSC2 model is the concentration of the coarser sediment fraction and SSC+SSC2 is the combined concentration of both the fine and coarser sediment fractions.

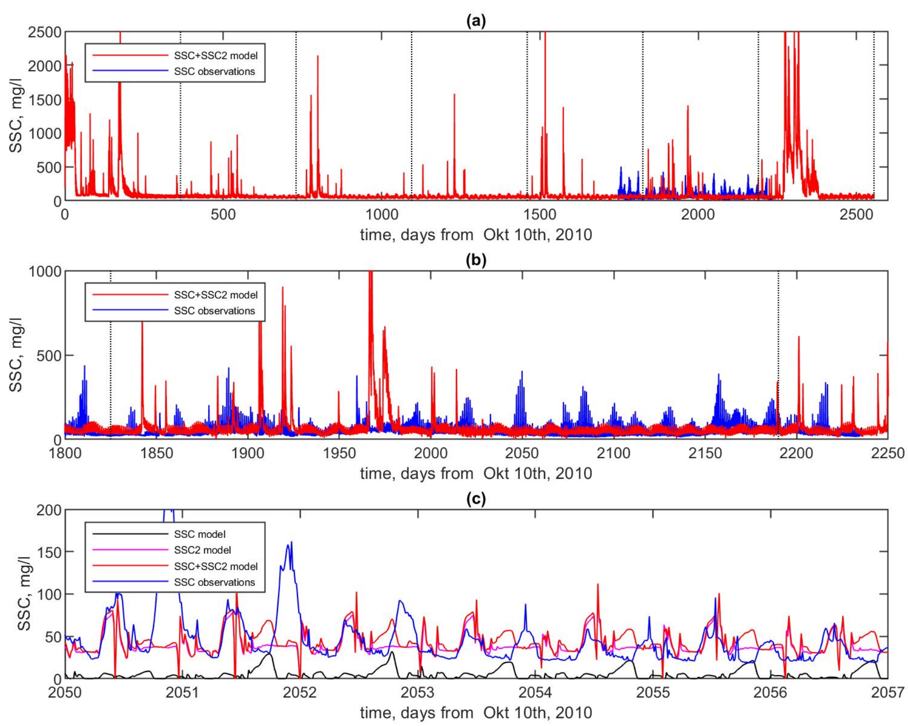


Figure 11. Comparison of modeled and observed SSC at Alviso Slough and A8 feeder channel at different durations where (c) is a detail of (b) and (b) is a detail of (a). SSC model is the concentration of the fine sediment fraction. SSC2 model is the concentration of the coarser sediment fraction and SSC+SSC2 is the combined concentration of both the fine and coarser sediment fractions.

2.3. Morphodynamics

There are substantial similarities between observed and modeled patterns and volumes of erosion and sedimentation for the 2010-2012 and 2010-2017 periods (Figure 12**Error! Reference source not found.**). Mudflats in South Bay and Coyote Creek show accretion, while channels connecting Guadalupe Slough and Alviso Slough with South Bay show erosion in the reach of the pond A6 breaches. The modeled erosion in that reach is about 0.2 m more than the observed erosion. Deposition occurs landward of these breaches, although both sloughs also show regions with (limited) erosion. A detailed view shows that the modeled channel erodes (as observed) but that the channel side slopes and parts of the shallows adjacent to the channel accrete. A more landward detailed view of Alviso Slough (Figure 12 e, f) shows that the channel is depositional near Alviso Marina County Park, while measurements show a net erosion over the 2010-2017 period (last figure in Appendix, data from Foxgrover et al., 2018).

The modeled deposition within the slough upstream of the A6 breaches and on the intertidal flats in the Bay is greater than the observed deposition, particularly for the 2010-2017 timespan. All ponds show deposition, although the majority of the sediment deposits in A6 and much less in A5, A7 and A8. This process basically continues until 2017 with erosion and sedimentation patterns becoming more pronounced.

The origin of the deposited material is also difficult to determine. The modeled deposition may originate both from sea and the river. It is also possible that sediment deposited seaward during a flow event are later transported landward during low flow conditions. Layering of the bed by subsequent deposition events (low flow versus high flow) further complicates analysis. This may be solved by adopting a bed layering in the model, a feature that became available in March 2018.

Figure 13 and Figure 14 and the Appendix figures show bed levels and erosion and sedimentation in more detail. Figures in the Appendix compare measured and modeled erosion and sedimentation patterns at the approximate half-yearly survey intervals conducted between 2010 and 2017. There appear to be seasonal patterns for measured data; during the wet season from October of any given year to April of the following year erosion dominates along the slough but during the dry season from April to Oct of the same year, deposition trends dominate. Such seasonal variation is not evident in the modeling results. During the period from October 16 to March 17, a very wet season modeling shows deposition trends. Clearly, the 2017 river pulse has a large impact.

For the 2015-2017 period, the model produces deposition in Alviso Slough whereas erosion is measured. We are uncertain what the underlying reason is for this discrepancy. This difference may be caused by interpolation of the high resolution (1 m) data on the lower resolution (20 m in the sloughs) model mesh. Another reason may be seasonal effects on sediment erodibility, for example by bioturbation. Variations in sediment supply and SSC from the Bay boundary could be another reason for differences between the modeled and measured bed level changes. Closer analysis should reveal the cause. Preliminary simulations varying SSC levels at the seaward boundary (e.g., decreasing by 50% during half a year of observed erosion in the sloughs) did show decreased SSC levels in the sloughs, but the increase in erosion was minimal.

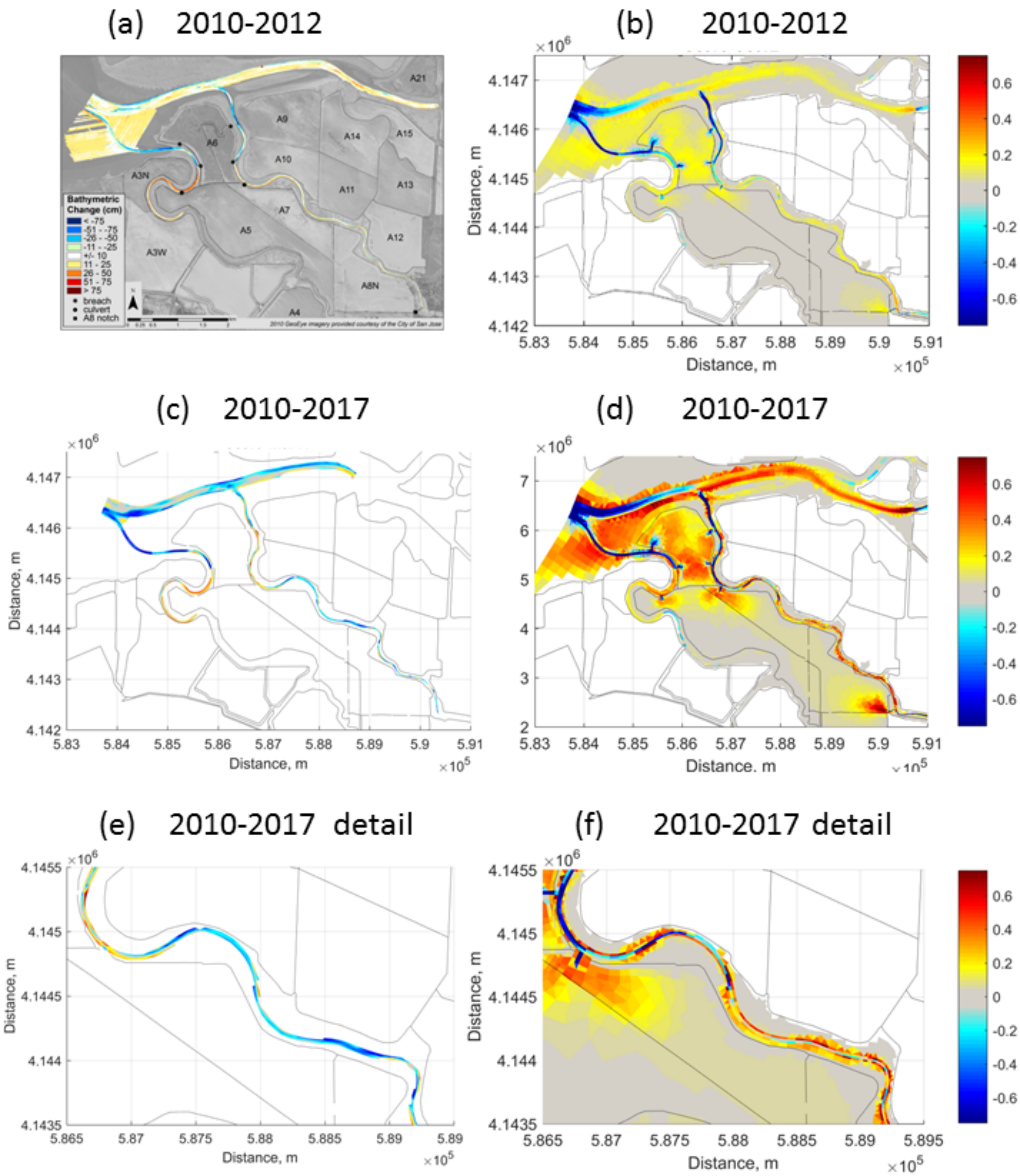


Figure 12. Erosion and sedimentation patterns between 2010 and 2012 (a, b) and 2010 and 2017 (c, d) with detail (e, f) in meters. Left column shows observations and right column shows model results. Black lines denote levees. Color bar indicates net deposition (positive values in meters, yellow and red colors) and erosion (negative values in meters, blue colors) over the modeled period.

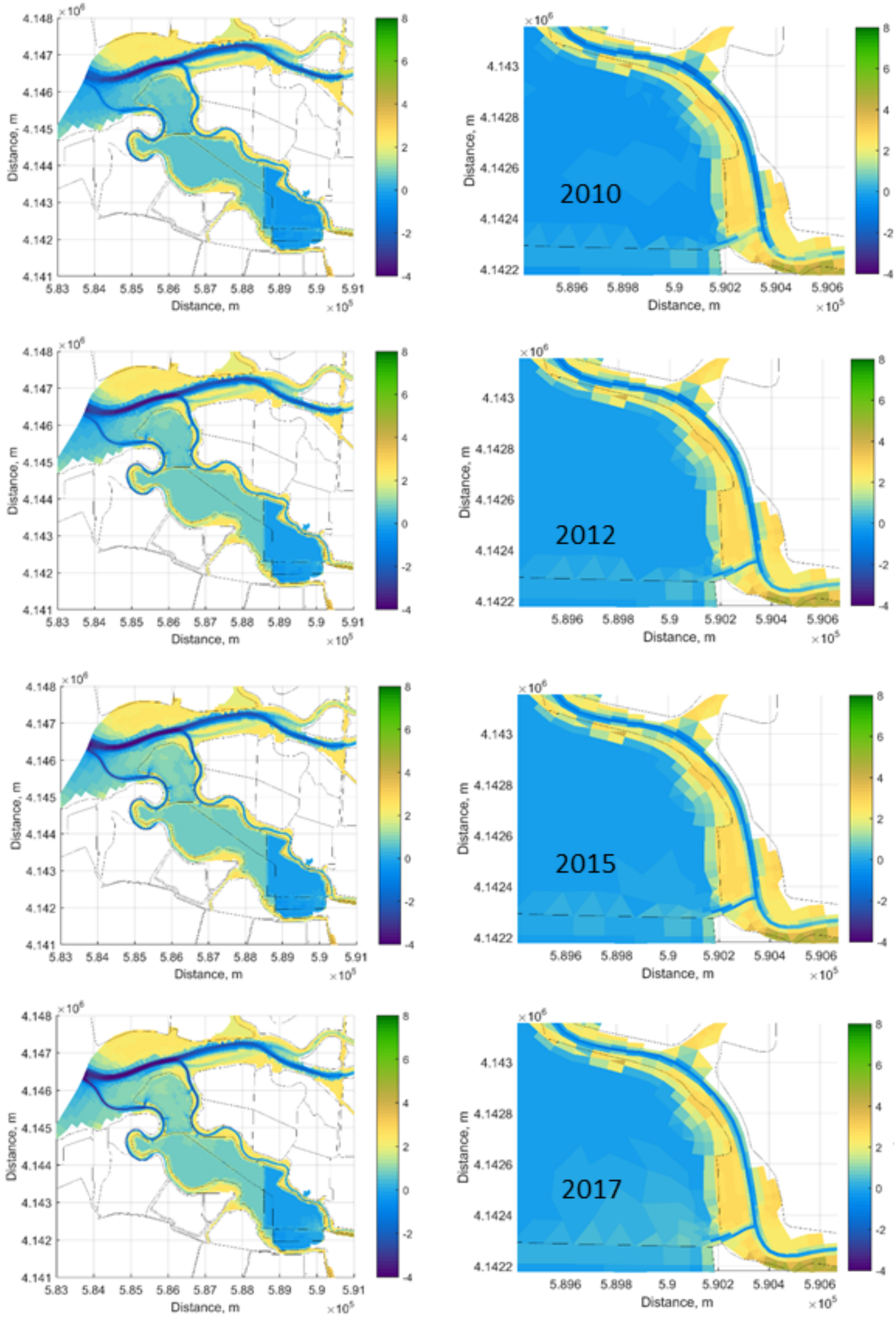


Figure 13. Modeled 2010, 2012, 2015 and 2017 bed levels (left column), with details near Alviso Marina County Park, near the A8 Notch (right column). Black lines denote levees. Color bar indicates elevation in meters above NAVD88.

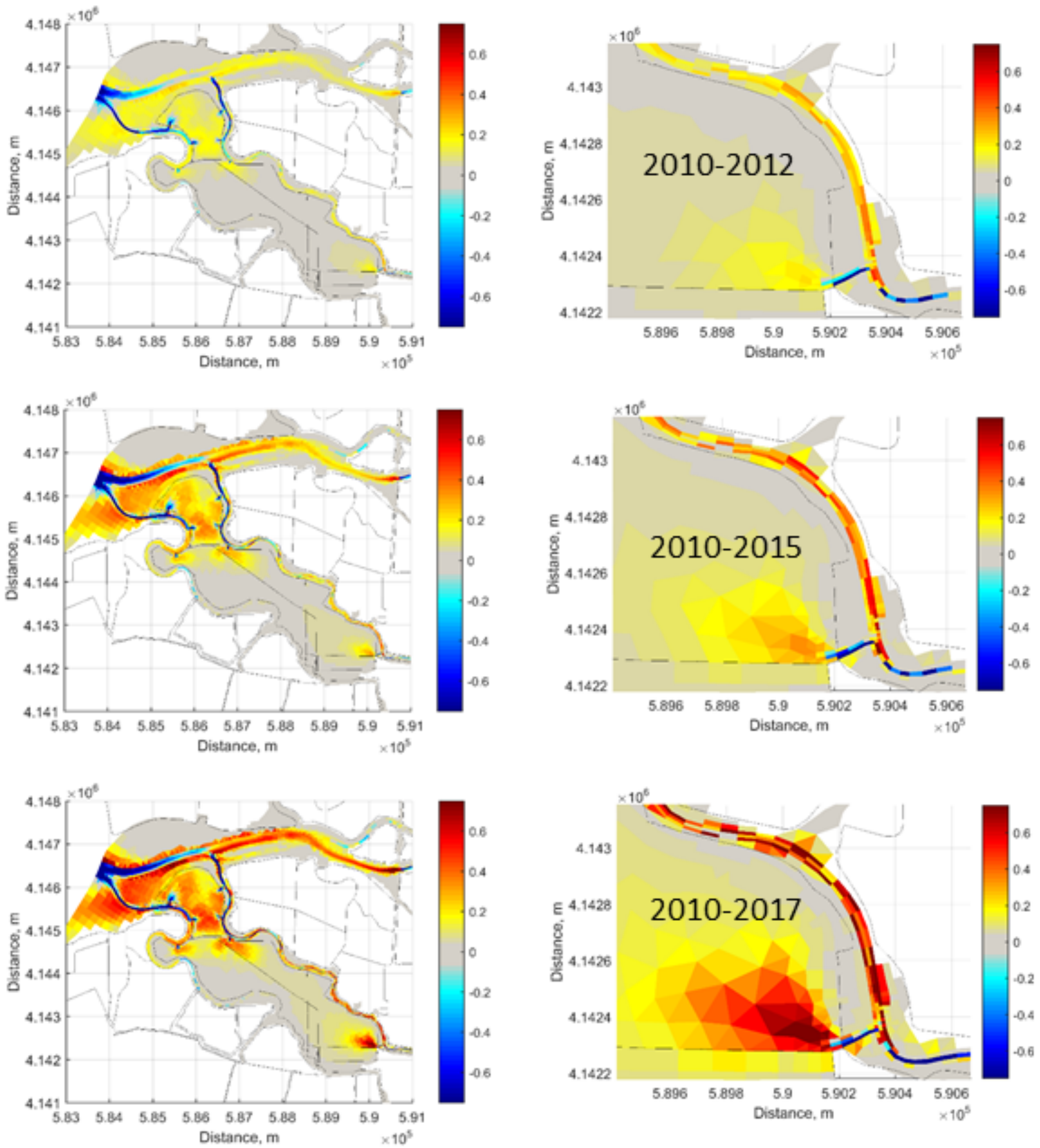


Figure 14. Modeled erosion and sedimentation patterns between 2010-2012, 2010-2015 and 2010-2017 (left column), with details near Alviso Marina County Park, near the A8 Notch (right column). Black lines denote levees. Color bar indicates net deposition (positive values in meters, yellow and red colors) and erosion (negative values in meters, blue colors) over the modeled period.

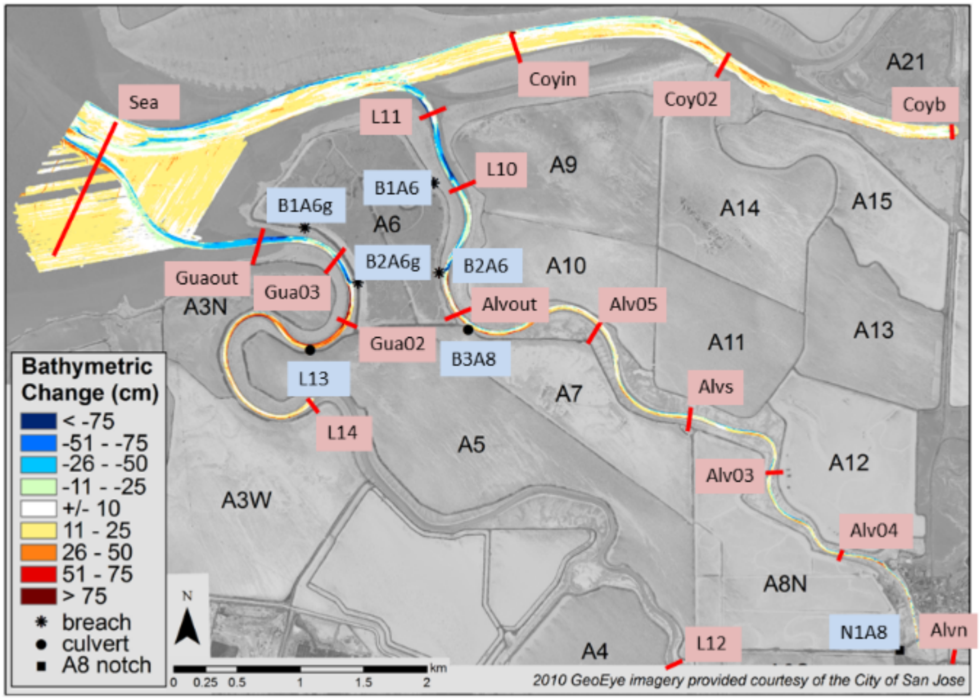


Figure 15 Location of model cross sections and observation points. Blue boxes denote breaches, while red boxes denote cross sections.

2.4. Flow budget

Figure 16 and Figure 17 show the cumulative flow volumes through the ponds and sloughs, and Figure 15 indicates names and locations of the applied cross sections and observation points. The trend looks almost gradual and is only interrupted by river flow pulses. The trend is formed by tide-residual flow of yearly cumulative flow volumes that are much larger than the exchange volumes during a single tidal cycle.

Pond A6 experiences the largest flow volumes initially from Alviso Slough breaches towards Guadalupe breaches. As the pond fills with sediments, water starts to flow out via B2A6alv while the other breaches are still filling pond A6. The pond A8-A5-A7 system imports water from the A8 Notch while water leaves the systems initially via B3A8. Later, probably as the result of morphodynamic developments in Alviso Slough, water leaves the system via L13 and B3A8 also becomes flow importing. Flows into the ponds are hardly influenced by river flow pulses except for the 2017 flow pulse.

During limited river flow, Alviso Slough exports water that enters pond A6 via B1A6 (Figure 17). More landward, water from pond A6 enters Alviso Slough via B2A6. Residual flows are directed landward through Alvout and enter A7 via B3A8. Differences in tide residual flows between Alv05 and Alv03 remain limited. Alvn shows seaward flow that mainly enters A8 via N1A8. Figure 17 clearly shows that river flow pulses make Alviso Slough fully flow exporting over the entire reach. Large river pulses make the entire slough export water towards the Bay.

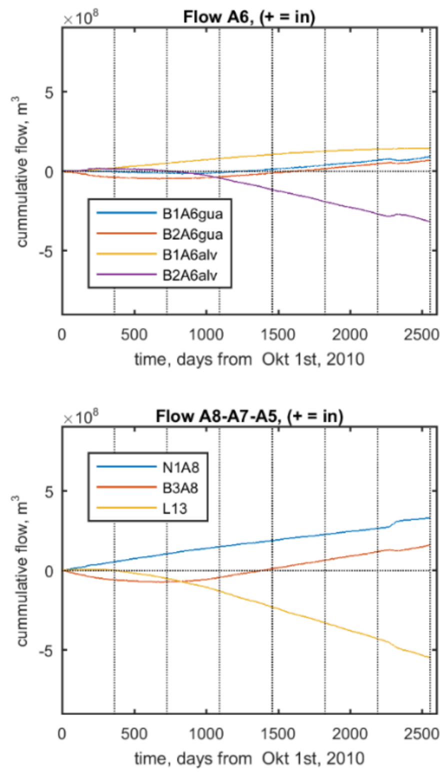


Figure 16 Cumulative flows through breaches and the A8 Notch into different ponds. Vertical black lines indicate days from Oct 1st, 2010. See Figure 15 for locations of breaches.

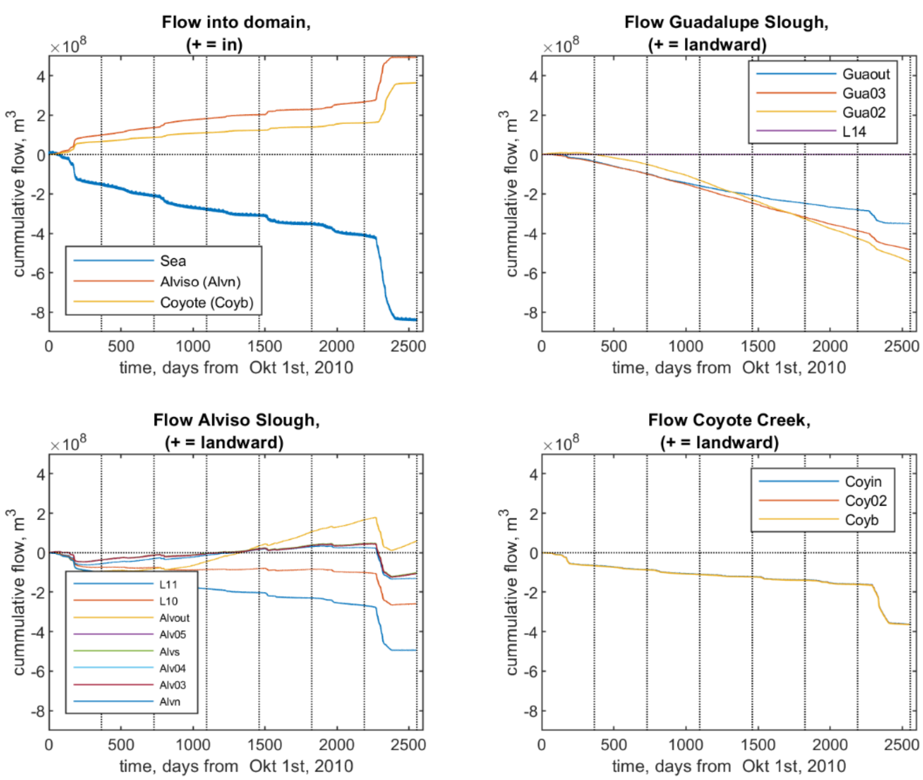


Figure 17 Cumulative flows through different slough cross sections. See Figure 15 for locations of cross sections.

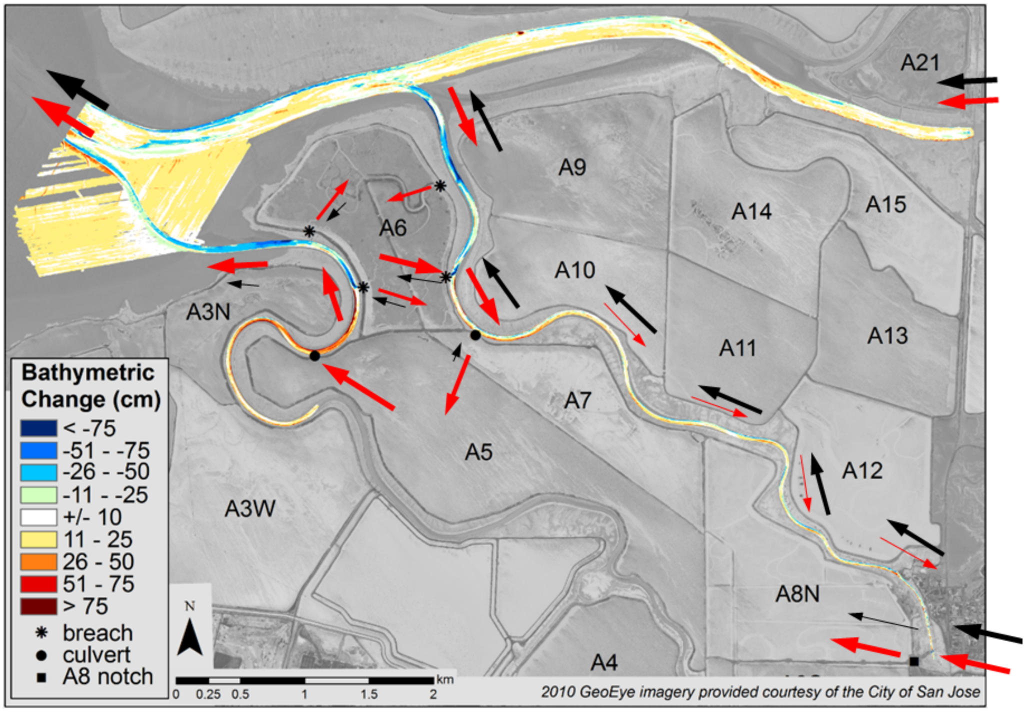


Figure 18 Residual flows during 2012-2016 low river flow conditions (red) and during 2017 river flow pulse (black). Arrow size approximates flow volumes.

2.5. Sediment budget

Tide residual sediment transport trends show different behavior from flow patterns (Figure 19, Figure 20 and Figure 21). During the entire period, the ponds import sediment through most of the breaches. The A8-A5-A7 system imports sediments, although a sediment export from pond A5 develops through L13 after two years. The same holds for B2A6alv in the A6 pond, although the net sediment transport remains positive (import) for that cross section due to the 2017 flow pulse.

Figure 20 shows that the major amount of sediment enters the model domain via the seaward boundary during periods of low river flow, despite an initial and short-duration export due to the sudden opening of the A6 breaches. Flow pulses temporarily provide more sediments to the domain, but the importing trend from the sea eventually dominates sediment supply over a year. The 2017 flow pulse was an exception that provided more sediments during the pulse than the importing trend from the sea. Guadalupe Slough continuously imports sediments apart from an initial export at the mouth. There is no flow boundary condition added to Guadeloupe Slough; the residual sediment transports at L12 are landward but negligible to the other cumulative transports. Residual transport at L14 is seaward but also negligible. During low river flow, Alviso Slough imports sediments at the downstream cross sections near pond A6 and (slightly) exports sediments at all cross sections landward of Alv05. River flow pulses lead to a sudden export of sediments to the extent that sediment imported during the 6 previous years are flushed out during a substantial (2017) river flow pulse.

Adding the sediment import through all A6 openings from Figure 19 (upper panel) leads to a total import into pond A6 of about 210 $*10^3$ tons of sediment over 7 years. With a bulk density of 800 kg/m^3 and an A6 area of 1336 $*10^3$ m^2, to the result is an average deposition of 196 mm over 7 years, or 28 mm/year. Callaway (2016) measured an average deposition of 810 mm over 62.7 months, or an average deposition rate of 107 mm/year. Callaway's measured findings indicate that the model underestimates A6 deposition by a factor of approximately 4. This factor corresponds to the SSC underestimation (see Figure 10, Figure 11), comparing mean modeled SSC (about 0.1 g/l) with mean measured SSC (about 0.4 g/l).

Future modeling with time-varying SSC in the Bay may increase deposition in A6 if the Bay is the major source (supported by comparison of slough erosion volumes being substantially less than observed deposition volume in A6) and wind waves increase SSC at times.

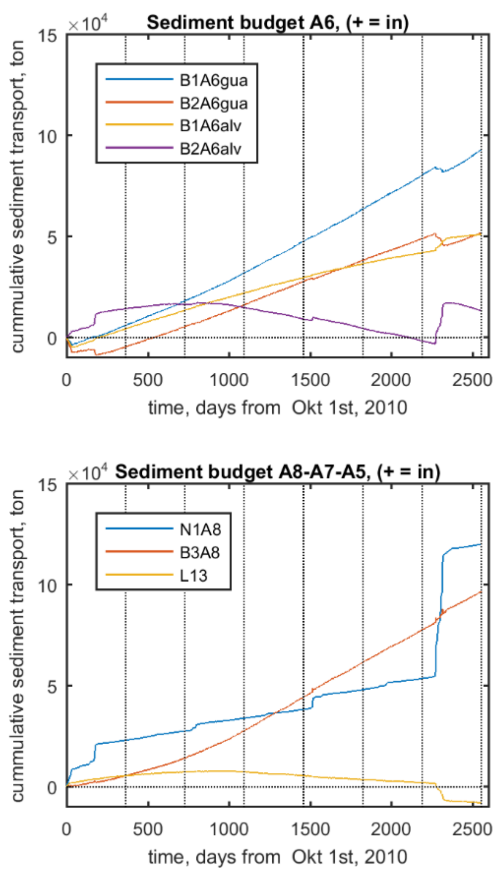


Figure 19 Cumulative sediment transports into the ponds. A positive slope indicates transport into the pond.

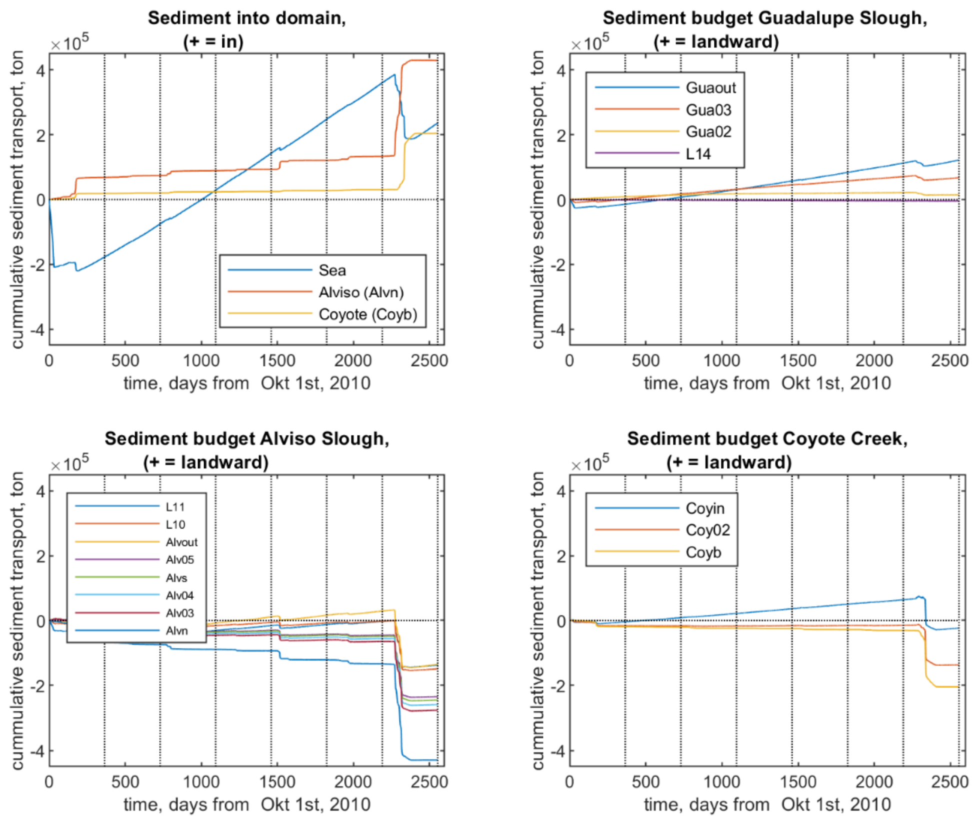


Figure 20 Cumulative sediment transports in the sloughs.

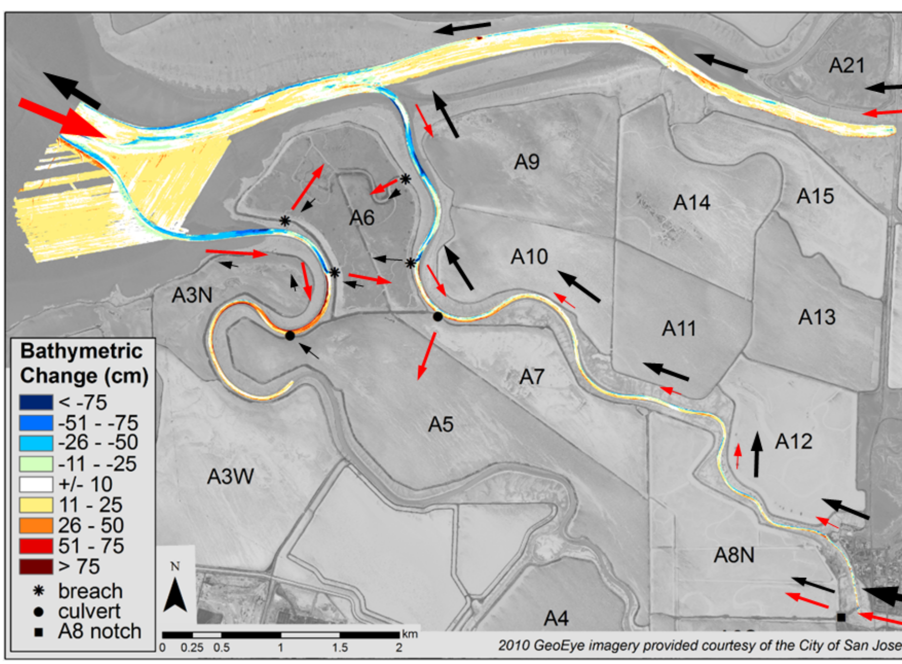


Figure 21 Residual sediment transports during 2012-2016 low river flow conditions (red) and during 2017 river flow pulse (black). Arrow size approximates transport volumes.

2.6. Scenarios

The breach scenario includes 5 breaches of about 30 m in the A5-A7-A8 system (additional to the existing gates and the A8 Notch) as suggested by John Bourgeois (pers. comm.) after vetting likely future breach locations with the Project Management Team Science Subgroup (Figure 22). This breach width is 2 ½ times the A8 Notch width. The sea level rise scenario added 0.5 m of water on the seaward boundary condition. The impact of actual sea level rise would be negligible over a 7-year time frame while runtime of the model for 100 years would exceed weeks. The results of a 0.5-m rise in water levels are thus simply indicating possible developments.

Figure 23 shows that both scenarios lead to substantial infill of the A5-A7-A8 pond system and an increased erosion of Guadalupe Slough and Alviso Slough. The breach scenario developed a single major breach between Alviso Slough and pond A8, while the other breaches hardly developed. The sea level rise scenario regularly flooded large parts of the surrounding levee system and generated major channels in the ponds. Short circuiting occurs in both scenarios where the new channel follows a secondary levee in the pond in the sea level rise scenario and a new channel develops in a defined opening of the secondary levee in the breaching scenario. It may be questionable whether this would really occur since the evolving channel may in reality erode the secondary levees as well. The channel near Alviso Marina County Park filled in with the breach scenario, but eroded in the sea level rise scenario. Most erosion in Alviso Slough is bayward of the most inland breach. A breach landward of the Alviso Marina County Park would likely lead to erosion of the channel near Alviso Marina County Park.

Figure 22 Breach locations.

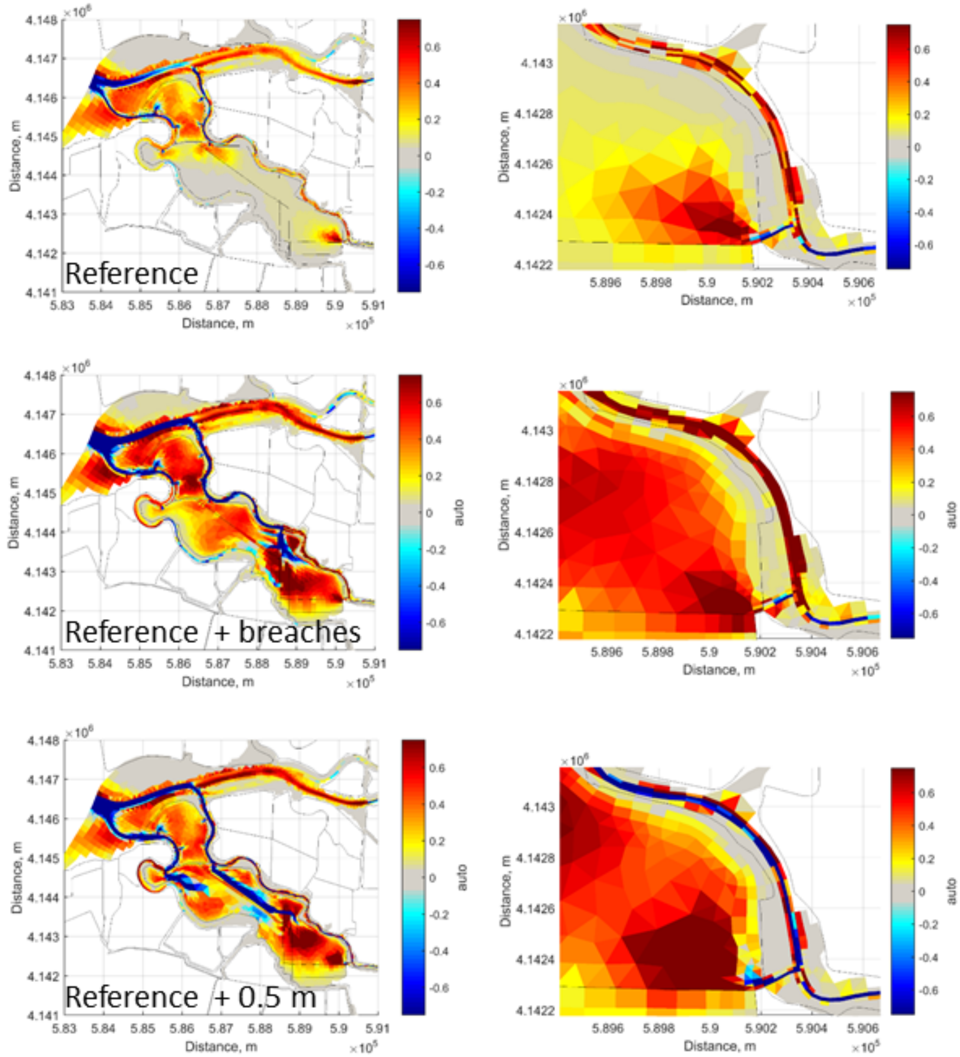


Figure 23 Erosion and sedimentation patterns between 2010 and 2017 for reference case (first row), adding additional breaches (second row), and for the reference case with a 0.5-m rise in mean sea level (third row).

3. Conclusions and recommendations

3.1. Conclusions

This morphodynamic modeling exercise shows that observed erosion and sedimentation patterns can be reproduced with skill. However, the associated suspended sediment concentrations are more difficult to reproduce. We believe that SSC model results can be improved with more sensitivity analysis with respect to the fluff layer model. Also a 3D flow model may improve model results. We stress that there are few studies that are calibrated against both SSC and morphodynamic development.

An advantage of the area model is that it reveals tide residual flow patterns that are difficult to measure. These residual flow and transport patterns are the result of subtle, tide residual transport trends so that their effect becomes visible in multi-year simulations. Extensive sensitivity analysis on sediment characteristics shows similar erosion and sedimentation patterns. Amounts and patterns differ little when changing model parameters, suggesting that this model captures governing processes and that

the interaction of the hydraulic forcing with the planform determines the morphodynamic development to a high degree.
The scenario model simulations show possible illustrative impacts of sea level rise and potential management interventions.

3.2. Recommendations

- Long-term (~decades) model simulations including realistic sea level rise scenarios could inform long-term management decisions.
- Model results may be improved by including wind waves, a feature now available in D3D FM.
- The model could increase understanding of mercury remobilization in Alviso Slough and guide management actions by adding contaminant dynamics to the sediment and assessing the fate of these contaminants. These dynamics may be of increasing complexity ranging from dynamics purely based on sediment attachment (advection) to more sophisticated dynamics like dilution/de-attachment from sediments of contaminants.
- 3D modeling may eventually more accurately simulate the dynamics of flow and sediment transport pathways, especially during peak river flow events. Although D3D FM is a 3D model from a hydrodynamic perspective (including salinity differences and temperature dynamics), the 3D morphodynamic and sediment transport functionality is not yet available (anticipated development in 2018).

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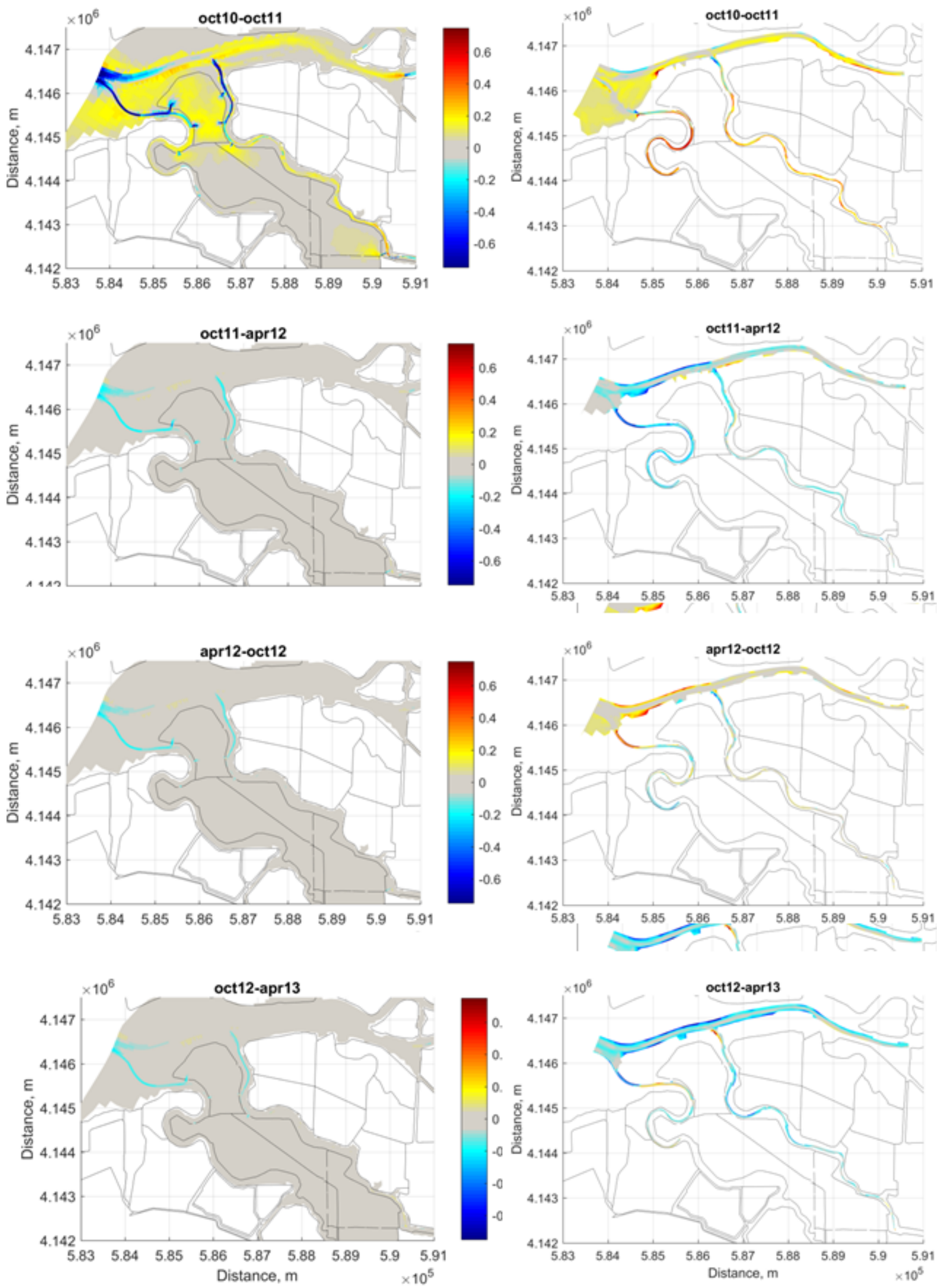
Appendix - Erosion and sedimentation patterns at measurement campaign sequences

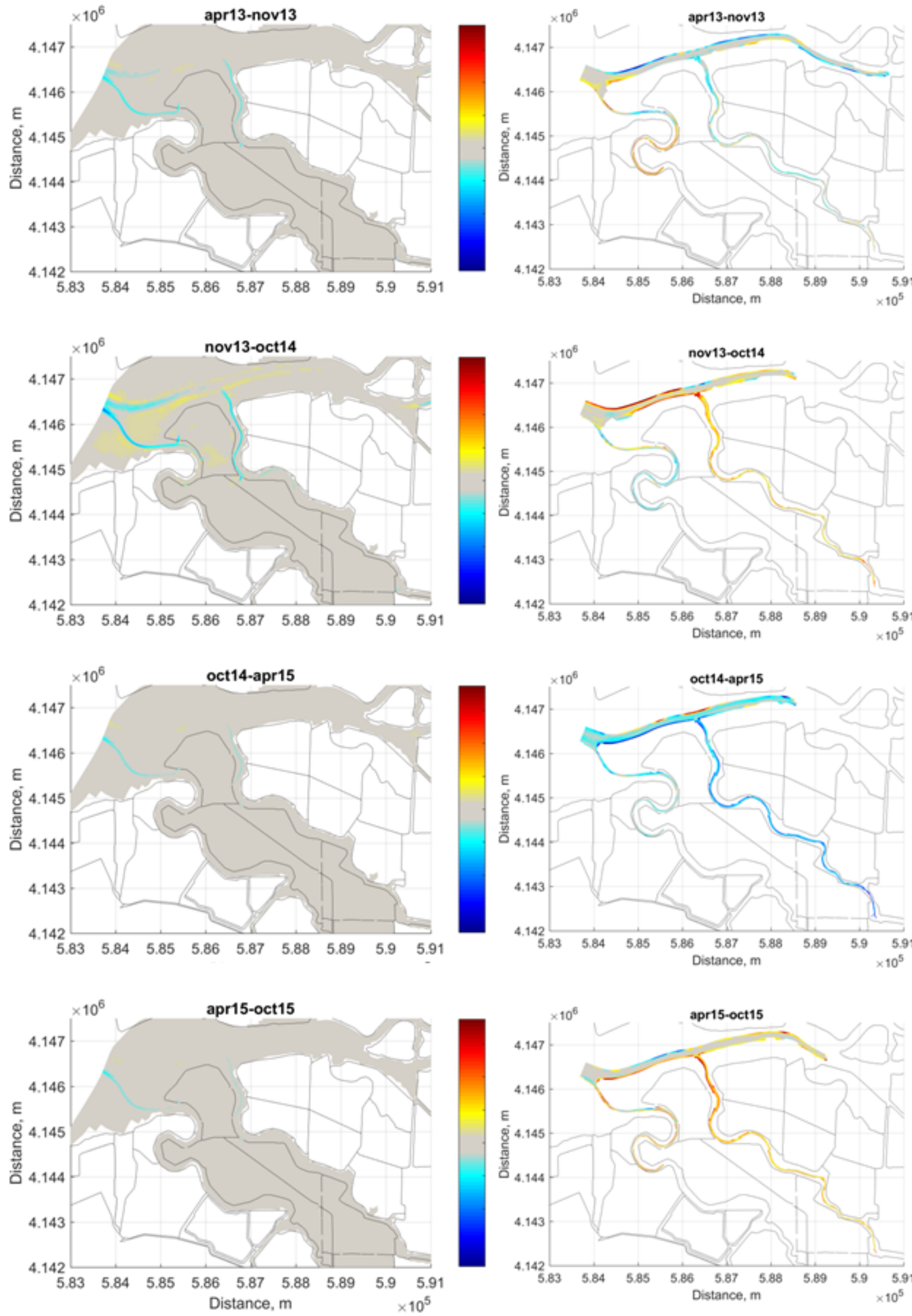
Erosion-sedimentation patterns (in m)

Modeled | Measured



Erosion-sedimentation patterns (in m)

Modeled | Measured



Erosion-sedimentation patterns (in m)