

1 **Response to the Reviewers:**

2 **Reviewer 1:**

3 Thank you very much for the detailed review and comments to improve this work. We will
4 update the manuscript with the following responses.

5 The responses to questions 1a,c will be added in the model description chapter, section 2.1 as
6 additional paragraphs.

7

8 **1. Does the work apply novel numerical/conceptual techniques?**

9

10 **(a) New numerical techniques (e.g. polyhedral mesh) and their advantage**

11

12 The advantages of the numerical method are addressed by Kernkamp (Kernkamp et al., 2010).
13 In this paper, for the first time a real-world case is run with the new model. With a personal
14 computer it is possible to address challenging morphologies combining rectangular and
15 triangular mesh. The advantage of this approach is the reduced number of cell since it is not
16 compulsory for the entire mesh to be triangular, hence less cells and lower computational
17 time.

18

19 Another advantage is the possibility of directly converting Delft3D grids and settings to
20 DFlow-FM. Delft3D is commonly used models for coastal engineering applications, and
21 DFlow-FM will allow coupling existing Delft3D models with inland models and complex
22 geometry estuaries (van der Wegen and Roelvink, 2012; Guo et al., 2015; Dastgheib et al.,
23 2012; Roelvink, 2006; Lesser et al., 2004).

24

25 **(b) novel algorithms for fast or parallel processing (please note that a computational**
26 **focused paper would be more suited for a journal like Computers Geoscience rather**
27 **than HESS)**

28

1 The algorithm is developed by a partner group, and the publication of computational
2 developments and new schemes is more suitable to them than us. The publication about the
3 grid and solvers is published by Kernkamp (Kernkamp et al., 2010).

4

5 **(c) novel transport equations and couplings.**

6

7 The transport equations are the same one used in many other models, the advective-diffusion
8 equation, and for the cohesive sediment Krone-Parteniades.

9

10 The novelty here is that the flexible mesh model is directly coupled with water quality,
11 sediment transport and habitat model. In this sense the exchange of model input/output
12 between the hydrodynamics, sediment and ecology model is facilitated. For habitat model
13 having SSC as input improves results of light attenuation therefore better primary production
14 and habitat definition.

15

16 -----

17 The responses to question 2 will be added in the end of the introduction on page 4. We agree
18 that the choice of the specific site was not discussed enough.

19

20 **2. What insight can be obtained from choosing this specific field site?**

21

22 **(a) Is the field site characteristic end member case of transport?**

23

24 The Sacramento San-Joaquin Delta is a typical case of a highly impacted estuary. Being able
25 to numerically simulate and determine sediment transport, budget and turbidity levels in this
26 type of environment open possibilities to better informed political, ecological and
27 management decisions including how to respond to climate change and sea level rise. This
28 type of model is an important management tool that is applicable to other impacted estuaries
29 such as Guanabara Bay (Rio de Janeiro, Brazil) and the Hudson estuary (New York, USA).

30

1 **(b) Is the field site very well suited for calibration/model output comparison due to high quality**
2 **available flow/topographic data?**
3

4 As you already posed, the field site is very well suited for calibration. The Delta and Bay has
5 a big survey network. There is a big data base of freely available data on river stage, discharge
6 and suspended sediment concentration among other parameters, maintained by USGS. The
7 continuous sediment in suspension measurement stations are periodically calibrated by water
8 collection in situ, filtered and weighted in the laboratory.

9
10 The Bay-Delta system has high resolution bathymetry (10m) for all the channels and bays.

11
12 **(c) Is the field site of specific importance, especially with respect to the ecological focus of the**
13 **paper's title.**
14

15 The focus of the paper is to improve the connection between physical and ecological
16 numerical models. In this sense the ecological importance of the Delta is discussed below.

17 Starting from the bottom of the food web, the Delta is the most important area for primary
18 production in the San Francisco Estuary. The Delta is one order of magnitude more
19 productive than the rest of the estuary (Jassby et al., 2002;Kimmerer, 2004).

20 The Delta is an area for spawning, breeding and feeding for many endemic species of fishes
21 and invertebrates, including some endangered species like delta smelt (Brown et al., 2013),
22 Chinook salmon, spring run salmon and steelhead.

23 Several projects for marshes restoration in the Delta are planned and the success of these
24 projects depends on sediment availability (Brown, 2003).

25
26 **3. What general conclusions can be drawn from the analysis besides comparing (calibrated)**
27 **simulation with field observations?**
28

29 Here we present the first real case application of the flexible mesh model DFlow-FM. The
30 good agreement with data and reproducibility of the main events gives us confidence in the
31 model. The mesh flexibility makes a perfect model for estuaries and complex geometry areas.

1 DFlow-FM was developed with the possibility of a direct coupling with ecological and water
2 quality models speeding the knowledge interchange between the two areas (physical and
3 biological).

4

5 Sediment is a key-factor to estuaries water quality and ecology. The already calibrated model
6 generates high quality input for the ecological models and is ready for forecast scenarios.

7

8

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37

1

2 Answering the more specific comments:

3

4 **P2, Line 24- P3, Line 16 What do the anthropogenic impacts mentioned here have to do**
5 **with the presented results? Please clarify how this paragraph contributes to the**
6 **understanding of context of the presented analysis.**

7

8 The idea behind these 2 paragraphs is to put the work in a broader context, in terms of world
9 sediment budget (P2 line 24) and the importance of numerical models to forecast scenarios
10 because the conditions and forcing are constantly changing.

11

12 **P2, Line 6: "A robust sediment model ..." Do the authors mean sediment transport?**
13 **Please clarify. Also 'chain of models' as the authors describe several.**

14

15 Corrected to: "A robust sediment transport model is the first step towards a chain of
16 models...".

17 Regarding the explanation about the chain of models, we will modify P2 Line6-7 to:

18 "The chain of model means that each model provides input to the next model. For example
19 the sediment transport model output is the input to contaminants, phytoplankton and habitat
20 numerical models."

21

22 **P2, Line 20: "...are subject..." should be "are subjected"**

23

24 The sentence was corrected in the manuscript.

25

26 **P4, Line 3-7: Please explain shortly what the "2DH process based model" physically is?**
27 **I suppose it integrates height averaged Saint-Vernant type equations, together with**
28 **some transport equations for sediment as mentioned three pages later. However a**

1 (short) physical explanation should be given when the modeling framework is
2 introduced in the text. For example adding a phrase like "...solves the 2d height
3 integrated shallow water equations coupled with advective diffusive transport ..." would
4 help a lot to understand the physics behind the 2DH process based model.

5

6 We will include the sentence in P4, Line 3-7.

7 "The 2DH model solves the 2D vertical integrated shallow water equations coupled with
8 advective-diffusive transport."

9

10 **P4 Line 6 "sediment budgets [..] in time (days)" seems to contradict line 8 "... yearly
11 sediment budget ...". Please clarify.**

12

13 In P4 Line 6 we were aiming to explain the several time scales, as we present in the results the
14 yearly budget and seasonal analysis the sentence will be rephrased as:

15 " This process-based model will be able to quantify high resolution sediment budgets and
16 SSC, both in time (~ monthly/yearly) and space (~10s-100s of m)."

17

18 **P6 Line 8: Pumping keeps salinity constant. How does this justify the height integrated
19 modeling approach? The (possible) justification for this, (limited saltwater-freshwater
20 interaction in the Delta) is given only 2 pages later. The authors should justify their
21 statements at the point where these are made rather than assuming that the reader has
22 already advanced several paragraphs in the text.**

23

24 In this case we assumed that it is clearer to remove the sentence "allowing the 2-DH
25 modeling approach." from P6 line 8.

26 And modify P7 line 10 as:

27 " We assume that the main flow dynamics in the Delta are 2D with no vertical stratification.
28 This assumption is supported by the lack of salt-fresh water interactions in the Delta due to

1 the pumping operations. We also assume that temperature differences do not govern flow
2 characteristics."

3

4 **P10 Line 10-15: Please explain abbreviations at first usage.**

5

6 All the abbreviations in these lines are the stations names. They will be written as:

7 " The river water flow hourly input data are from the following stations, at Sacramento River
8 at Freeport (FPT), San Joaquin River near Vernalis (VNS) and Yolo Bypass (YOLO) were
9 obtained from California Data Exchange Center website (cdec.water.ca.gov/) (Fig 2). The
10 sediment input data, for both input stations FPT and VNS, and calibration stations S
11 Mokelumne R(SMR), N Mokelumne R (NMR), Rio Vista (RVB), Mokelumne (MOK), Little
12 Potato Slough (LPS), Middle River (MDM), Stockton (STK), Mallard Island (MAL) (Fig 2),
13 was obtained by personal communication from USGS Sacramento; this data is part of a
14 monitoring program (<http://sfbay.wr.usgs.gov>). Since 1998, USGS has continuous measuring
15 stations for sediment concentration which is derived from optical backscatter sensors (OBS)
16 measurements every 15 minutes, and nearly monthly calibrated with bottle samples (Wright
17 and Schoellhamer, 2005)."

18

19 **Equation 3 and 4 are confusing. The index over which the sum runs is "i" and the
20 summation is from "i-1" to "N". I suppose it should be "i=1" under the sum.**

21

22 You are right, there was a typo error. I was already corrected.

23

24 **Fig. 2 The labels and the location points of the calibration stations are too small. Please
25 increase the font size.**

26

27 Figure updated.

28

1 **Fig. 3: It is hardly visible that the blue line is dashed. The authors may increase the dash**
2 **spacing or simply plot a blue line.**

3

4 Figure updated.

5

6 **Fig.4: Same problem with red dashed line as in Fig. 3. Increasing the dash spacing and**
7 **plotting the dashed line on top of the solid line may also improve the visibility where**
8 **both lines overlap considerably.**

9

10 Figure updated.

11

12 **Fig.8: The 3D flow effects mentioned in the caption are not discussed in the main text.**
13 **Please update the manuscript accordingly.**

14

15 I will add a line in the manuscript as follow:

16 "Seawards from MAL, figure 8 shows preliminary sediment flux for the bay in dashed line,
17 because we don't have confidence on them. The model here presented is 2DH, seawards from
18 MAL stratification takes place in the water column due to salinity intrusion, meaning that 3D
19 effects become important and they are not capture by a 2DH model. "

20

21 **Figure A1: The figure is too small**

22 Figure updated.

23 The manuscript will be updated accordingly. We hope to have properly addressed your
24 comments.

25

1 **Reviewer 2:**

2 Thank you very much for the detailed review and comments to improve this work. We will
3 update the manuscript with the following responses.

4 The responses to questions 1 will be added in the model description chapter, section 2.1 as
5 additional paragraphs.

6

7 1) Calibration/validation of the numerical model. I understand that the technical
8 details on the numerical method and validation/comparison with other schemes have
9 been given in Kernkamp et al. (2010), but it would be helpful to comment on
10 alternative methods for this specific site.

11

12 Are there other numerical models done for the Delta, e.g. just the hydrodynamic
13 part? For example, Delft3D in the depth-averaged mode seems to be a close
14 competitor which handles both hydrodynamic and morphodynamic transport. A few
15 comments would be nice, such as:

16 a) how many grid cells are involved in the calculation of the model setup presented in
17 this work, versus how many grid cells would have to be used for the total triangular
18 mesh?

19

20 b) How much time would it take for other methods to reach the same level of
21 accuracy with the same computation power (only one desktop)?

22

23

24 Structured grid models as Delft3D and ROMS (Regional Oceanic Modeling System) have
25 been widely used and accepted in estuarine hydrodynamics and morphodynamics modeling
26 including San Francisco Estuary (Ganju and Schoellhamer, 2009; Ganju et al., 2009; van der
27 Wegen et al., 2011). In all these cases of San Francisco estuary modeling efforts, the Delta
28 was schematized as 2 long channels since the grid is not flexible to have a 2D modeling of the
29 rivers, channels and flooded island of the system.

30

31 There are three widely known unstructured mesh models the TELEMAC-MASCARET
32 (Hervouet, 2007), the UnTRIM (Casulli and Walters, 2000; Bever and MacWilliams, 2013)
33 and D-Flow FM (Kernkamp et al., 2010). The two first models are purely triangle based and
34 are not coupled with sediment transport and/or water quality and ecology model.

35 DFlow-FM allows for a combination of curvilinear grid and triangles, in the present model
36 DFlow-FM grid has 63.844 cells, from which about 80% are rectangles. In the case of only
37 triangle grid all the rectangles would be 2 triangles summing up to 114.920 grid cells. Not
38 counting the triangular grid orthogonality and circumscription issues, in the case of entirely
39 triangular grid the running time for a 1 year simulation would increase from ~72 clock hours
40 to ~192 hours.

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The responses to questions 2 will be added partly in the discussion description chapter, section 4.2 as additional paragraphs, and partly in the conclusion (chapter 5).

R: (2) Insights of the specific field site. As the authors stated, the Delta provides critical habitats for ecological purposes. I can see how this model and its predictions become handy for a chain of models.

R: Could the author use the model results to inform more into the monitoring and data collecting practice?

R: For example, what data set should be collected to help the model make better predictions? And where could be a good location for building a new monitoring station?

Addressing issues like these, or even in a discussion of future work, will expand the scope of this work and gives a higher scientific impact.

A: The Delta is already very well measured in terms of observation stations. However, this work show that the substantial sediment is exported trough the pumping stations at the Southern Delta where no data in SSC is available.

The connections between Sacramento and San-Joaquin River (DCC and GLS) are currently is being surveyed.

The present model opens the possibility for forecast and operational modeling. Forecasting the time frame of high levels of SSC (turbidity) allows planning of measurements campaigns for ecologists, as well as the possibility of tracking potentially contaminated sediment and be able to make a contingency plan. The forecast could also be a tool to guide management decisions concerning seasonal barriers as well as pumping operations.

The 2D model is a step towards the 3D model. The 2D model allows faster runs facilitating sediment parameter definition and understanding of sediment dynamics in the Delta. However, for the fully Delta-Bay coupling it is necessary fully 3D model, which is the next step of this work.

The responses to questions 3 will be added in conclusion chapter (chapter 5) as additional paragraphs.

1 R: (3) Information on suitable systems for model application.

2

3 R: The Delta is a relatively well-surveyed region. What should be taken into account
4 for potential users of this model, when applying to a different region with less
5 available data?

6

7

8 A: As a well surveyed area the Delta offers the chance of testing how much data it is
9 necessary to define sediment budget. This work shows with simple sediment settings as one
10 fraction at the input boundary and simple distribution of bed sediment availability, it is
11 possible to reproduce seasonal variations as well as define yearly sediment budget with more
12 than 90% of accuracy. It shows also that it is extremely important to have discharge and SSC
13 measurements at least in the input boundaries and close to the system output in order to be
14 able to calibrate the model settings applied for hydrodynamics and suspended sediment.

15

16

17 R: Also, it seems that the configuration of the channel network does play a role
18 determining the SSC level (the effects of closing/opening DCC). Would the authors
19 give more insights into how changing the configuration of the network affects the
20 distribution of fluxes?

21

22 A: The channel network influence in sediment budget and deposition is the topic of the work
23 in development right now.

24

25 As for from this work results, we note that the Sacramento San-Joaquin River connecting
26 channels DCC and GLS are important bridges to export sediment from Sacramento to Eastern
27 Delta. On the other hand the smaller channels of the network play a minor role in the Delta
28 sediment budget, since the discharges in these channels are considerably smaller than in the
29 rivers.

30

31

32

33

34 Below are some minor comments:

35 R: Page 1514, Eq. (2): "M" is also used later as the subscript for "Model".

36 A: We changed the from M to m in the other equations

37

38 R: Page 1515, Line 3: Winterwerp (2006) is missing in the reference list.

39

1 A: It will be included
2
3 (Winterwerp et al., 2006)
4 Winterwerp, J. C., Manning, A. J., Martens, C., de Mulder, T., and Vanlede, J.: A heuristic
5 formula for turbulence-induced flocculation of cohesive sediment, *Estuarine, Coastal and*
6 *Shelf Science*, 68, 195-207, 10.1016/j.ecss.2006.02.003, 2006.
7
8
9 R: Page 1515, Line 5: sentence is not complete, “the second term in equation (Eq.
10 1): is close to zero?”
11
12 A: Thanks for the remark, already added. It is indeed close to zero.
13
14 R: Page 1515, Line 20-25: will changing the 5m threshold for mud/sand affect the
15 results?
16
17 A: The 5 meter threshold is not fixed, what we observed is a big change when considering
18 available mud in the entire channel as presented in session 3.4.
19 We did some test varying the 5m threshold. From 3 to 10 meters the final results are quite
20 similar to the one showed. Considering no mud availability also does not disturb the final
21 results for more than 10 days. However, considering mud availability in the channels deeper
22 than 10 meters starts to disturb the SSC levels.
23
24 I will include this analysis in the session 3.4 and as discussion as well.
25
26 R: Page 1519, Line 15-20: uRMSe given by Eq.(3) cannot give negative values.
27 Seems that it needs to be multiplied by the sign of the difference between modeled
28 and observed SD (see Eq. (7) in Bever and MacWilliams, 2013).
29
30 A: Yes, you are right, I forget the signal difference. Proper changes will be done in figure 6
31 and analysis.
32
33 R: Page 1519, Line 23: “Willmott, 1981” is missing in the reference list.
34
35 A: It will be included
36 (Willmott, 1981)
37 Willmott, C. J.: ON THE VALIDATION OF MODELS, *Physical Geography*, 2, 184-194,
38 10.1080/02723646.1981.10642213, 1981.

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R: Page 1524, Eq.(7): Why is the term “[A’C’][U]” eliminated?

A: We use the same methodology as suggested by (Morgan-King and Schoellhamer, 2013). The combination of the advective, dispersive and Stokes Drift already account for more than 97% of the flux.

R: Page 1542, Fig. 5: The values of the parameters are vague by presenting them as multiples of the standard run (e.g., $w*0.5$, $E*100$). I personally prefer the form in Fig. 6 with absolute values.

A: Figure 5 x axis will be updated according with the axis presented in figure 6.

R: Page 1544, Fig. 7: the black rectangle is missing in the left panel.

A: Figure 7 updated.

References:

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8 10.1080/02723646.1981.10642213, 1981.

9 Winterwerp, J. C., Manning, A. J., Martens, C., de Mulder, T., and Vanlede, J.: A heuristic
10 formula for turbulence-induced flocculation of cohesive sediment, *Estuarine, Coastal and*
11 *Shelf Science*, 68, 195-207, 10.1016/j.ecss.2006.02.003, 2006.

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2 **A 2D Process-Based Model for Suspended Sediment** 3 **Dynamics: a first Step towards Ecological Modeling**

4

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11

12 **Abstract**

13 In estuaries Suspended Sediment Concentration (SSC) is one of the most important
14 contributors to turbidity, which influences habitat conditions and ecological functions of the
15 system. Sediment dynamics differ depending on sediment supply and hydrodynamic forcing
16 conditions that vary over space and over time. A robust sediment transport model is the first
17 step towards a chain of models connecting models on contaminants, phytoplankton and
18 habitat.

19 This works aims to determine turbidity levels in the complex-geometry Delta of San
20 Francisco Estuary using a process-based approach (Delft3D Flexible Mesh software). Our
21 approach includes a detailed calibration against measured SSC levels, a sensitivity analysis on
22 model parameters, ~~the~~and the determination of a yearly sediment budget as well as an
23 assessment of model results in terms of turbidity levels for a single year (Water Year 2011).

24 Model results show that our process-based approach is a valuable tool in assessing sediment
25 dynamics and their related ecological parameters over a range of spatial and temporal scales
26 and which may act as the base model for a chain of ecological models assessing the impact of
27 climate change and management scenario ~~forecasting~~. Here we present a modelling approach
28 with limited data producing trustworthy predictions, useful findings for less monitored

1 | [estuaries. With plenty of available data it was possible to analyze the strictly necessary data](#)
2 | [for the simulations which are water level, discharge and SSC for the input and output](#)
3 | [boundaries.](#)

5 | **1 Introduction**

6 | Rivers transport water and sediments to estuaries and oceans. Sediment dynamics will differ
7 | depending on sediment supply and hydrodynamic forcing conditions varying over space and
8 | over time. Many river basins are subjected to slow morphodynamic adaptation due to
9 | (gradually) changing forcing conditions, ranging from sea level rise and climate change to
10 | anthropogenic developments such as reservoir construction in the watershed.

11 | The human impact on sediment production dates from 3000 years ago, and has been
12 | accelerating over the past 1000 years due to considerable engineering works (Syvitski and
13 | Kettner, (2011). Milliman and Syvitski (1992) estimate that the budget of sediment delivered
14 | to the coastal zone varies between 9.3 and 58 Gt per year. Estimating the world sediment
15 | budget is still a challenge either due to lack of data or detailed model studies in this field
16 | (Vörösmarty et al., 2003). Adding to that, there is considerable uncertainty in hydraulic
17 | forcing conditions and sediment supply dynamics due to variable adaptation timescales over
18 | seasons and years (such as varying precipitation and river flow), decades (such as engineering
19 | works) and centuries to millennia (sea level rise and climate change).

20 | Examples of anthropogenic changes in sediment dynamics in river basins and estuaries are
21 | manifold, e.g. San Francisco Bay-Delta (Schoellhamer, 2011), Yangtze Estuaries (Yahg,
22 | 1998) and Mekong Delta (Manh et al., 2014). These three systems present similar conditions
23 | of anthropogenic forced sediment supply. After an increase in sediment supply (due to
24 | hydraulic mining and deforestation respectively) each had a steep drop in sediment discharge
25 | (30%) due to reservoir building and further estuarine clearance after depletion of available
26 | sediment in the bed. This implies a) continuous change in sediment dynamics and hence
27 | sediment budget in the estuary; b) change in sediment availability leading to change in
28 | turbidity levels.

29 | Turbidity is a measurement of light attenuation in water and it is a key ecological parameter.
30 | Fine sediment is the main contributor to turbidity. Therefore suspended sediment
31 | concentration (SSC) can be translated into turbidity applying empirical formulations. Besides

1 SSC, algae, plankton, microbes and other substances may also contribute to turbidity levels
2 (ASTM International, 2002). High turbidity levels limit photosynthesis activity by
3 phytoplankton and microalgae, therefore decreasing associated primary production (Cole et
4 al., 1986). Turbidity levels also define habitat conditions for endemic species (Davidson-
5 Arnott et al., 2002). We can cite the Delta Smelt as an example seeking for regions where the
6 turbidity is between 12-18NTU to hide from predators (Bakersville-Bridges, 2004;(Brown et
7 al., 2013).

8 Examples of other ecological impacts related to SSC are for vegetation stabilization (Morris
9 et al., 2002;Whitcraft and Levin, 2007), and salt marsh survival under sea level rise scenarios
10 (Kirwan et al., 2010;Reed, 2002).

11 To assess the aforementioned issues, the goal of this work is to provide a detailed analysis of
12 sediment dynamics concerning a) SSC levels, in the Sacramento-San Joaquin Delta (Delta)
13 area, b) sediment budget and c) translate these results in turbidity levels, by means of a two
14 dimensions in the horizontal, averaged in the vertical dimension (2DH), process-based,
15 numerical model. [The 2DH model solves the 2D vertical integrated shallow water equations](#)
16 [coupled with advective-diffusive transport](#). This process-based model will be able to quantify
17 high resolution sediment budgets and SSC, both in time (~ [days/monthly/yearly](#)) and space
18 (~10s-100s of m). We selected the Delta area as a case study, since the area has been well
19 monitored so that detailed model validation can take place, it hosts endemic species, and
20 allow us to use a 2DH model approach.

21 [The Delta and Bay are covered by a large survey network, offering freely available data on](#)
22 [river stage, discharge and suspended sediment concentration \(SSC\) amongst other parameters,](#)
23 [and maintained by USGS \(\[nwis.waterdata.usgs.gov\]\(http://nwis.waterdata.usgs.gov\)\), by Californian Department of Water](#)
24 [Resources \(<http://cdec.water.ca.gov/>\) and National Oceanic and Atmospheric Administration](#)
25 [\(<http://tidesandcurrents.noaa.gov/>\). The continuous SSC measurement stations are](#)
26 [periodically calibrated by water collection in situ, filtered and weighted in the laboratory. On](#)
27 [top of that, the Bay-Delta system has a high resolution bathymetry available \(10m\) for all the](#)
28 [channels and bays \(<http://www.d3d-baydelta.org/>\).](#)

29 [Regarding ecological value, starting from the bottom of the food web, the Delta is the most](#)
30 [important area for primary production in the San Francisco Estuary. The Delta is one order of](#)
31 [magnitude more productive than the rest of the estuary \(Jassby et al., 2002;Kimmerer, 2004\).](#)
32 [It is an area for spawning, breeding and feeding for many endemic species of fishes and](#)

1 [invertebrates, including some endangered species like delta smelt \(Brown et al., 2013\),](#)
2 [Chinook salmon, spring run salmon and steelhead. Additionally, Several projects for marshes](#)
3 [restoration in the Delta are planned and the success of these projects depends on sediment](#)
4 [availability \(Brown, 2003\).](#)

5 The SSC model results are compared to in situ measured SSC data. The calibration process
6 assesses the sensitivity of sediment characteristics such as fall velocity (w), critical shear
7 stress (τ_{cr}) and erosion coefficient (E). The model outputs are the spatial and temporal
8 distribution of SSC (turbidity), yearly sediment budget for different Delta regions, and the
9 sediment export to the bay.

10 For the first time, a detailed, process-based model is developed for San Francisco Bay-Delta,
11 to focus on the complex Delta sediment dynamics (MacWilliams, 2015). From this model it is
12 possible to describe the spatial sediment (turbidity) distribution and deposition patterns that
13 are important indicators to assess habitat conditions. Analyzing seasonal and yearly variations
14 in sediment dynamics and translating these into turbidity levels to be used as indicators for
15 ecological modeling (Janauer, 2000), this work fills gap the between the physical aspects
16 (hydrodynamic and sediment modeling) and ecology modeling. Previous work focused on
17 understanding the San Francisco Bay-Delta system through data analysis (Barnard et al.,
18 2013;Manning and Schoellhamer, 2013;McKee et al., 2006;McKee et al., 2013;Morgan-King
19 and Schoellhamer, 2013;Schoellhamer, 2011;Schoellhamer, 2002;Wright and Schoellhamer,
20 2004, 2005), while similar work in other estuaries around the world does not give the direct
21 link to ecology (Manh et al., 2014).

22 **2 Background**

23 San Francisco Estuary is the largest estuary on the U.S. West Coast. The estuary comprises
24 San Francisco Bay and the inland Sacramento-San Joaquin Delta (Bay-Delta system), which
25 together cover a total area of 1235 km² with a mean water depth of 4.6 meter (Jassby et al.,
26 1993). The system has a complex geometry consisting of interconnected sub-embayments,
27 channels, rivers, intertidal flats, and marshes ([Fig 1](#)). The Sacramento-San Joaquin Delta
28 (Delta) is a collection of natural and man-made channel networks and leveed islands, where
29 the Sacramento River and the San-Joaquin River are the main tributaries followed by
30 Mokelumne River (Delta Atlas, 1995). San Francisco Bay has 4 sub-embayments. The most
31 landward is Suisun Bay followed by San Pablo Bay, Central Bay (connecting with the sea
32 through Golden Gate) and, further southward, South Bay.

1 Tides propagate from Golden Gate into the Bay and most of the Delta up to Sacramento
2 (FPT) and Vernalis (VNS) when river discharge is low. Suisun Bay experiences mixed
3 diurnal and semidiurnal tide that ranges from about 0.6 m during the weakest neap tides to 1.8
4 m during the strongest spring tides. During high river discharge the 2psu isohaline is located
5 in San Pablo bay while during low river discharge it can go landwards of Chipps Island
6 (westernmost reach of the black rectangle, [Fig 1](#)). The topography highly influences the wind
7 climate in the Bay-Delta system. Wind velocities are strongest during spring and summer
8 presenting afternoon north-westerly gusts of about 9 ms^{-1} (Hayes et al., 1984).

9 San Francisco estuary collects 40% of the total Californian fresh water discharge. It has a
10 Mediterranean climate, with 70% of rainfall concentrated between October and April (winter)
11 decreasing until the driest month September (summer) (Conomos et al., 1985). The
12 orographic lift of the Pacific moist air linked to the winter storms and the snowmelts in early
13 spring govern this wet (winter) and dry (summer) season variability. This system leads to a
14 local hydrological 'Water Year' (WY) definition from 1st October to 30th September, including
15 a full wet season in one WY.

16 It is important to notice that Sacramento and San Joaquin Rivers, together, account for 90% of
17 the total fresh water discharge to the estuary (Kimmerer, 2004). The daily inflow to the Delta
18 follows the rain and snowmelt seasonality, with average dry summers with discharges of 50-
19 $150 \text{ m}^3\text{s}^{-1}$ and wet spring/winter reaching peak discharges of $800\text{-}2500 \text{ m}^3\text{s}^{-1}$. The geographic
20 and seasonal flow concentration leads to several water issues related to agricultural use,
21 habitat maintenance and water export. On a yearly average $300\text{m}^3\text{s}^{-1}$ of water is pumped from
22 South Delta to southern California. The pumping rate is designed to keep the 2psu (salinity)
23 line landwards of Chipps Island avoiding salinity intrusion in the Delta. [5-a](#) Allowing the 2DH
24 modeling approach.

25 The hydrological cycle in the Bay-Delta determines the sediment input to the system, thus
26 biota behavior. McKee (2006) and Ganju and Schoellhamer (2006) observed that a large
27 volume of sediment passes through the Delta and arrives to the Bay in a yearly pulse. They
28 estimated that in 1 day approximately 10% of the total sediment volume could be delivered
29 and in extremely wet years up to 40% of the total sediment volume can be delivered in 7 days.
30 During wet months more than 90% of the total sediment inflow is supplied to the Delta.

31 The recent Delta history is dominated by anthropogenic impacts. In the 1850`s hydraulic
32 mining started after placer mining in rivers became unproductive. Hydraulic mining

1 remobilized a huge amount of sediment upstream of Sacramento. By the end of the nineteenth
2 century the hydraulic mining was outlawed leaving approximately $1.1 \times 10^9 \text{ m}^3$ of remobilized
3 sediment, which filled mud flats and marshes up to 1 meter in the Delta and Bay (Wright and
4 Schoellhamer, 2004;Jaffe et al., 2007b). At the same time of the mining prohibition, civil
5 works such as dredging and construction of levees and dams started, reducing the sediment
6 supply to the Delta (Delta Atlas, 1995;Whipple et al., 2012).

7 Typical SSC in the Delta ranges from 10 to 50 mg L⁻¹, except during high river discharge
8 when SSC can exceed 200 mg L⁻¹ reaching values over 1000mgL⁻¹ (McKee et al.,
9 2006;Wright and Schoellhamer, 2005). A sediment budget reflects the balance between
10 storage, inflow and outflow of sediment in a system. Studies based on sediment inflow and
11 outflow, estimated that about two-third of the sediment entering the system deposits in the de
12 Delta (Schoellhamer et al., 2012;Wright and Schoellhamer, 2005). The remaining third is
13 exported to the Bay, and represents on average 50% of the total Bay sediment supply (McKee
14 et al., 2006), the other half comes from smaller watershed around the Bay (McKee et al.,
15 2013).

16 Several studies have been carried out to determine sediment pathways and to estimate
17 sediment budgets in the Delta area (Schoellhamer et al., 2012;Jaffe et al., 2007a;Gilbert,
18 1917;McKee et al., 2013;McKee et al., 2006;Wright and Schoellhamer, 2005). These studies
19 were based on data analysis and conceptual hindcast models. Although the region has a
20 unique network of surveying stations, there are many channels without measuring stations.
21 This might lead to incomplete system understanding and knowledge deficits for the
22 development of water and ecosystem management plans. The monitoring stations are located
23 in discrete points hampering spatial analysis. Also, the impact of future scenarios related to
24 climate change (i.e. sea level rise and changing hydrographs) or different pumping strategies
25 remains uncertain.

26 **2.1 Model description**

27 [Structured grid models such as Delft3D and ROMS \(Regional Oceanic Modeling System\)](#)
28 [have been widely used and accepted in estuarine hydrodynamics and morphodynamics](#)
29 [modeling including San Francisco Estuary \(Ganju and Schoellhamer, 2009;Ganju et al.,](#)
30 [2009;van der Wegen et al., 2011\).](#) In all these cases the Delta was schematized as 2 long

1 [channels since the grid is not flexible to have a 2D modeling of the rivers, channels and](#)
2 [flooded island of the system ~~together~~ with the Bay.](#)

3 [In case of complex geometry unstructured grids or finite volume model is more suitable.](#)
4 [There are three widely known unstructured grid models the TELEMAC-MASCARET](#)
5 [\(Hervouet, 2007\), the UnTRIM \(Casulli and Walters, 2000;Bever and MacWilliams, 2013\)](#)
6 [and D3D FM \(Kernkamp et al., 2010\). The two first models are purely triangle based and are](#)
7 [not coupled \(~~yet~~\) with sediment transport and/or water quality and ecology model.](#)

8 The numerical model applied in this work is Delft3D Flexible Mesh (D3D FM). D3D FM
9 allows straightforward coupling of its hydrodynamic modules with water quality model,
10 Delft-WAQ (DELWAQ), which gives flexibility to couple with the habitat (ecological)
11 model. D3D FM is a process-based unstructured grid model developed by Deltares (Deltares,
12 2014). It is a package for hydro- and morphodynamic simulation based on a finite volume
13 approach solving shallow-water equations applying a Gaussian solver. The grid can be
14 defined in terms of triangles, (curvilinear) quadrilaterals, pentagons and hexagons, or any
15 combination of these shapes. It is important to note that (orthogonal) quadrilaterals are the
16 most computationally efficient cells. Kernkamp (2010) and the D3D FM manual (Deltares,
17 2014) describe in detail the grid aspects and the numerical solvers.

18 The Bay area and river channels are defined by consecutive curvilinear grids (quadrilateral).
19 Different resolution grid, the river discharging in the Bay, and channel junctions are
20 connected by triangles ([Fig 2](#)). The average cell size ranges from 1200m x 1200m, in the
21 coastal area, to 450x600m in the Bay area down to 25x25m in the Delta channels. In the
22 Delta, each channel is represented by at least 3 cells in the across-channel direction ([Fig 2](#)).
23 The grid flexibility allows including the entire Bay-Delta in a single grid [containing 63.844](#)
24 [cells from which about 80% are rectangles, ~~but still~~ keepings](#) the computer run times at an
25 acceptable level. It takes 6 real days to run 1 year of hydrodynamics simulation and 12 hours
26 to run the sediment module on an 8 cores desktop computer. [Not counting the triangular grid](#)
27 [orthogonality and circumscription issues, in the case of entirely triangular grid the running](#)
28 [time for a 1 year simulation would increase from ~72 clock hours to ~192 hours.](#)

29 [The advantages of the numerical method are addressed by Kernkamp \(2010\). With a personal](#)
30 [computer it is possible to address challenging morphologies combining rectangular and](#)
31 [triangular mesh. The advantage of this approach is the reduced number of cells since it is not](#)

1 [compulsory for the entire mesh to be triangular](#), leading to [less cells and lower computational](#)
2 [time](#).

3 We assume that the main flow dynamics in the Delta are 2D [no vertical stratification](#), ~~since~~
4 ~~no~~ salt-fresh water interactions occur in the Delta [due to the pumping operations](#) and we
5 assume that temperature differences do not govern flow characteristics. D3D FM generates
6 hydrodynamic output for off-line coupling with water quality model DELWAQ (Deltares,
7 2004). Off-line coupling enables faster calibration and sensitivity analysis. DFlow-FM
8 generates time series of the following variables: cell link area; boundary definition; water
9 flow through cell link; pointer file gives information concerning neighbors' cells; cell surface;
10 cell volume; and shear stress file, which is parameterized in DFlow-FM using Manning's n.
11 Given a network of water levels and flow velocities (varying over time) DELWAQ can solve
12 the advection-diffusion-reaction equation for a wide range of substances including fine
13 sediment, the focus of this study. DELWAQ solves sediment source and sink terms by
14 applying the Krone-Parteniades formulation for cohesive sediment transport (Krone,
15 1962; Ariathurai and Arulanandan, 1978) (Eq.1, Eq.2).

$$16 \quad D = w_s * c * (1 - \tau_b / \tau_d) \quad (1)$$

$$17 \quad E = M * (\tau_b / \tau_e - 1) \quad (2)$$

18 Where; D Deposition flux of suspended matter ($\text{mg m}^{-2}\text{s}^{-1}$), w_s settling velocity of suspended
19 matter (ms^{-1}), c concentration of suspended matter near the bed (mg m^{-3}), τ_b bottom shear
20 stress (Pa) τ_d critical shear stress for deposition (Pa), E erosion rate ($\text{mg m}^{-2}\text{s}^{-1}$), M first order
21 erosion rate ($\text{mg m}^{-2}\text{s}^{-1}$), τ_e critical shear stress for erosion (Pa).

22 Note: Following Winterwerp (~~{Winterwerp, 2006 #402}2006~~) we assume that deposition
23 takes place regardless of the prevailing bed shear stress. τ_d is thus considered much larger
24 than τ_b and the second term in equation (Eq. 1) [is close to zero](#).

25 **2.2 Initial and Boundary Conditions**

26 The Bay-Delta is a well measured system; therefore all the input data to the model are in situ
27 data. Initial bathymetry has 10m grid resolution, which is based on an earlier grid (Foxgrover
28 et al., <http://sfbay.wr.usgs.gov/sediment/delta/>), modified to include new data by Wang and
29 Ateljevich
30 (<http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/modelingdata/DEM.cfm>) and

1 further refined. The bathymetry is based on different data sources including bathymetric
2 soundings and LiDAR data. The hydrodynamic model includes real wind, which results from
3 the model described by (Ludwig and Sinton, 2000). The wind model interpolates hourly data
4 from more than 30 meteorological stations into regular 1km grid cells. Levees and temporal
5 barriers are included in the model considering their deployment time
6 (http://baydeltaoffice.water.ca.gov/sdb/tbp/web_pg/tempbsch.cfm).

7 The hydrodynamic model has been calibrated for the entire Bay-Delta system (see appendix
8 A and <http://www.d3d-baydelta.org/>). Initial SSC was set at 0mgL^{-1} over the entire domain.
9 The initial bottom sediment availability defined available mud at places shallower than 5
10 meters below Mean Sea Level (MSL) including intertidal mud flats, and sand at places deeper
11 than 5 meter below MSL, which are primarily channel regions. This implies that the main
12 Delta channels such as, Sacramento, San Joaquin, Mokelumne are defined as sandy with few
13 mud patches. The smaller channels and the flooded islands such as Franks Tract are initialized
14 with a muddy bottom. DELWAQ does not compute morphological changes or bed load
15 transport.

16 In this study we applied 5 open boundaries. Seaward we set hourly water level time series
17 derived from Point Reyes station (tidesandcurrents.noaa.gov/). The other four landward
18 boundaries are river discharge boundaries at Sacramento River (Freeport), Yolo Bypass
19 (upstream water divergence from Sacramento River), San Joaquin River and Mokelumne
20 River. Studies show that Sacramento River accounts for 85% of the total sediment inflow to
21 the Delta, while San Joaquin accounts for 13% (Wright and Schoellhamer, 2005), so it is
22 reasonable to apply 2 sediment discharge boundaries at Sacramento and San Joaquin River.
23 All river boundaries present unidirectional flow, excluding tidal influence.

24 The river water flow hourly input data [are from the following stations](#), at-Sacramento River at
25 Freeport (FPT), San Joaquin River near Vernalis (VNS) and Yolo Bypass (YOLO) were
26 obtained from California Data Exchange Center website (cdec.water.ca.gov/) (**Fig 2**). The
27 sediment input data, for both input ~~(stations FPT and VNS,)~~ and calibration [stations S](#)
28 [Mokelumne R \(SMR\)](#), [N Mokelumne R \(NMR\)](#), [Rio Vista \(RVB\)](#), [Mokelumne \(MOK\)](#),
29 [Little Potato Slough \(LPS\)](#), [Middle River \(MDM\)](#), [Stockton \(STK\)](#), [Mallard Island \(MAL\)](#)
30 (**Fig 2**), was obtained by personal communication from USGS Sacramento; this data is part of
31 a monitoring program (<http://sfbay.wr.usgs.gov>). Since 1998, USGS has continuous
32 measuring stations for sediment concentration which is derived from backscatter sensors

1 (OBS) measurements every 15 minutes, and nearly monthly calibrated with bottle samples
2 (Wright and Schoellhamer, 2005).

3 The SSC data that is used to compare to model results are derived from optical backscatter
4 sensors (OBS). This type of sensor converts scattered light from the particles in photocurrent,
5 which is proportional to SSC. To define the rating curve it is necessary to sample water, filter
6 and weight the filter. However, in some locations the cloud of points when correlating
7 photocurrent and filtered weight shows a large scatter. Large scatter leads to errors in
8 translating photocurrent to SSC. These errors are due to (amongst others) particle size,
9 desegregation (cohesiveness, flocculation, organic-rich estuarine mud); shape effects;
10 sediment-concentration effect (Kineke and Sternberg, 1992; Downing, 2006; Sutherland et al.,
11 2000; Gibbs and Wolanski, 1992; Ludwig and Hanes, 1990). Wright and Schoellhamer (2005)
12 showed that for the Sacramento-San Joaquin Delta these errors can sum up to 39%, when
13 calculating sediment fluxes through Rio Vista.

14 In this work we modeled the 2011 water year - 1st October 2010 until 30th September 2011.
15 First, we ran D3D FM for this year to calculate water level, velocities, cell volume and shear
16 stresses. Then, the 1 year hydrodynamic results were imported in DELWAQ which calculated
17 SSC levels.

18 **3 The next five centuries**

19 Our focus is to represent realistic SSC levels capturing the peaks, timing and duration, and to
20 develop a sediment budget to assess sediment trapping in the Sacramento-San Joaquin Delta,
21 (Fig 1, highlighted by the black rectangle). Throughout the following sections the results are
22 analyzed in terms of tide averaged results, meaning that the data and model results are filtered
23 to frequencies lower than 2 days. We applied a Butterworth filter with cut off frequency of
24 $1/30\text{h}^{-1}$ as presented in Ganju and Schoellhamer (2006).

25 **3.1 Calibration**

26 The results shown below are the derived from an extensive calibration process where the
27 different sediment fractions, w , τ_{cr} and E were tested. The first attempt applied multiple
28 fraction settings presented in previous works (van der Wegen et al., 2011; Ganju and
29 Schoellhamer, 2009). However, tests with a single mud fraction proved to be consistent with
30 the data, representative of the sediment budget, and allow a simpler model setting and better

1 understanding of the SSC dynamics. The choice of one mud fraction follows (Beven et al.,
2 2011) argument that it is better to keep a model simple in order to understand the processes.
3 In addition, with a single fraction it was possible to reproduce more than 90% of the sediment
4 budget for the Delta.

5 After defining for 1 fraction runs, the sensitivity analysis and metrics helped to choose the
6 standard run presented below, the fraction selected has w of 0.25mms^{-1} , τ_{cr} of 0.25Pa and E of
7 $10^{-4}\text{kgm}^{-2}\text{s}^{-1}$. The same applies to the bed sediment availability defined by 1 mud (shoals) and
8 1 sand (channels) fraction.

9 **3.2 Suspended Sediment Dynamics (water year 2011)**

10 The 2011 simulation reproduces the SSC seasonal variation in the main Delta regions such as
11 the North (Sacramento River) represented by Rio Vista station (RVB); the South (San Joaquin
12 River) represented by Stockton (STK); Central-East Delta represented by Mokelumne station
13 (MOK) and Delta output represented by Mallard Island (MAL) (Fig 4).

14 All stations clearly reproduce SSC peaks during high river flow periods during November to
15 July and lower concentrations during the remainder of the year (apart from MAL during the
16 July-August period). The good representation of the peak timing indicates that the main Delta
17 discharge event is reproduced by the model as well as the periods of Delta clearance. These
18 two periods are critical for ecological models, and a good representation generates robust
19 input to ecological models. The differences found between the model and data are further
20 discussed in appendix B.

21 **3.3 Sensitivity analysis**

22 **3.3.1 Sediment fraction analysis**

23 We considered one fraction for simplicity and because it reproduces more than 90% of the
24 sediment budget throughout the Delta as well as the seasonal variability of SSC levels.
25 Although more mud fractions considerably increase running time, several tests with multiple
26 fractions were done to explore possibilities for improving the model results.

27 Including heavier fractions changes the peaks timing and also lowers the SSC curve.
28 Comparing the standard run ($w=0.25\text{mm s}^{-1}$, $T=0.5\text{Pa}$, $E=10^{-4}\text{ kg m}^{-2}\text{s}$ and bottom
29 composition with mud available shallower than 5 meters) to another run considering 15% of

1 heavier fraction ($w=1.5\text{mm s}^{-1}$) and 30% of a lighter fraction (fall velocity of 0.15mm s^{-1}),
 2 showed that the peak magnitudes were underestimated but the first peak timing is closer to the
 3 data and the spurious peak mid May is lower.

4 To be able to find the best parameter setting a sensitivity analysis was done varying the main
 5 parameters in the Krone-Parteniades formulation ([Table 1](#)).

6 Regarding sediment flux, these tests show that some stations, such as RVB and MAL, are
 7 more sensitive to parameter change than others, such as STK ([Fig 5](#)). The model results are
 8 most sensitive to the critical shear stress and least sensitive to the erosion coefficient.

9 Analyzing the time series, one concludes that in stations where the fluxes are higher, the
 10 change in critical shear stress is less important, since during most of the time the shear stress
 11 is already higher than any given critical shear stress.

12 It is important to note that reaching a perfect fit for one station does not mean reaching it for
 13 the others. We are analyzing two metrics, the unbiased Root Mean Square Error (uRMSe, [Fig](#)
 14 [6](#)) and Skill (Skill, [Fig 6](#)) (Bever and MacWilliams, 2013). The uRMSe analyzes the
 15 variability of the model relative to the data, in this case 0 is the case when the model and data
 16 have equal variability, positive values indicate more model variability and negative values
 17 indicate less model variability.

$$18 \quad uRMSe = \left(\frac{1}{N} \sum_{i=-1}^N [(X_{Mmi} - \overline{X_{mM}})(X_{Oi} - \overline{X_O})]^2 \right)^{0.5}$$

19 (3)

20 Where N is the time series size, X is the variable to be compared, in this case SSC, and \overline{X} is
 21 the time-averaged value. Subscript $M-m$ and O represent modeled and observed values,
 22 respectively.

23 Skill is a single quantitative metric for model performance (Willmott, 1981). When skill
 24 equals 1 the model perfectly reproduces the data. The 2 metrics were evaluated at RVB,
 25 STK and MAL, representing respectively Sacramento River, San Joaquin River and Delta
 26 output.

$$27 \quad Skill = 1 - \left[\sum_{i=-1}^N |X_{mMi} - \overline{X_{Oi}}|^2 \right] / \left[\sum_{i=-1}^N (|X_{mMi} - \overline{X_O}| + |X_{Oi} - \overline{X_O}|)^2 \right]$$

28 (4)

1 One notices that changing a parameter can lead to better results in one station but worse in
2 other stations ([Fig 6](#)). The choice of the standard run analyzed throughout the paper comes
3 from this analysis as well as the budget analysis. Following the argumentation from (Beven et
4 al., 2011) statistical analyses are needed in order to make a better choice of the model
5 settings. We note that both uRMSE and Skill varies up to 50% over the different runs.

6 **3.4 Initial bottom composition**

7 To study the importance of initial bottom sediment availability we considered 2 cases; one
8 excluding sediment (concrete bed) and the other by defining available mud at places
9 shallower than 5 meters below Mean Sea Level (MSL) including intertidal mud flats and sand
10 at places deeper than 5 meter below MSL being mainly channel regions (standard run).

11 [We did some test varying the 5m threshold. From 3 to 10 meters the final results are quite](#)
12 [similar. However, considering mud availability in the channels deeper than 10 meters starts to](#)
13 [disturb the SSC levels.](#) Time series of SSC comparing the 2 cases and data show that bottom
14 composition has virtually no influence on SCC after the first couple of days. This result also
15 applies for different mud fractions availability and opens horizons for modeling less measured
16 estuaries where virtually no bottom sediment data is available.

17 Another test shows that it is better to initialize the model with a 'concrete' bed than with mud
18 available in the entire domain. Initializing the channels with loose mud generates
19 unrealistically high SSC levels through the years, which can take up to 5 years to be
20 reworked.

21 **4 Discussion**

22 In the previous section we presented the model calibration, a normal practice in the modeling
23 process. In this section we discuss the new insights that were derived from the model results.
24 Although these insights are specific to the San Francisco Bay-Delta system, the same
25 approach can be applied to other estuaries and deltas. The model shows detailed sediment
26 dynamics and the main paths that sediment is transported in the Delta. Sediment flux
27 calculations define the sediment dynamics while gradients in sediment describe the sediment
28 distribution and deposition pattern in the Delta. We also discuss daily and seasonal variation
29 of turbidity levels.

1 4.1 Spatial sediment distribution

2 Starting the analysis with the general Delta behavior, during dry periods SSC in the entire
3 Delta is low ($<20\text{mgL}^{-1}$) and the Delta water is relatively clear. The current model results
4 confirm and compile data showing that the Sacramento River is the main sediment supplier
5 into the Delta (Wright and Schoellhamer, 2004; Schoellhamer et al., 2012). Sacramento River
6 peak flow fills the north and partially fills the central/east Delta with sediment. However, the
7 rest of the Delta keeps quite low levels ($\sim 20\text{mgL}^{-1}$) of SSC all year long. Passing Vernalis
8 (VNS), San Joaquin River main branch flows to the east, however the SSC peak reaches no
9 much further than STK. The west branch goes toward the water pumping stations where to the
10 sediment is pumped out of the system. This behavior reflects in very low SSC in the South
11 Delta (Old River and Franks Tract) region, which are deposition areas.

12 Three Mile Slough (TMS) and the Delta Cross Channel (DCC) connect the Sacramento River
13 with the central and eastern Delta. Model results show that together they carry 60Kton per
14 year of sediment southward. DCC operation defines SSC levels in the eastern/central Delta to
15 a large extent. To show the importance of DCC we run the model twice, one with DCC
16 always open and one always closed. When DCC is open, high SSC Sacramento river water
17 ($\sim 150\text{mgL}^{-1}$) flows towards Mokelumne River and Eastern Delta increasing the overall SSC
18 in the area. When it is closed SSC levels in central and eastern delta are about 30mgL^{-1} lower
19 than in the previous case (Fig 7). The effect of opening DCC can be observed in the SSC level
20 at the San Joaquin River from MOK station seawards. In the Sacramento River, the opening
21 decreases SSC levels, by about 10mgL^{-1} . It affects the river SSC all the way to Mallard Island
22 (Fig 7).

23 During peak river discharge, Sacramento River sediment reaches Mallard Island in
24 approximately 3 days, Carquinez Straight in 5 days, and the Golden Gate Bridge in
25 approximately 10 days. This timing is proportional to river discharge. However from Mallard
26 Island seawards it is a rough estimate due to the 2D approximation. The San Joaquin River
27 sediment remains largely trapped in the southern Delta. The flooded islands, breached levees
28 like Franks Tract, present a different behavior. During the entire year the SSC levels are
29 below 15mg L^{-1} , the river peak discharge signal does not affect them.

30 Sediment flux is a useful tool for a quantitative and qualitative analysis of the sediment path
31 and its derivative gives sedimentation/erosion patterns. It is defined by the product of water
32 velocity (U), times Cross-sectional area (A) times SSC (C) (Eq. 5).

$$F_{sed} = U * A * C \quad (5)$$

The yearly sediment flux through FPT from model results is 1132Kt yr⁻¹ (thousand metric tons per year) against 1096Kt yr⁻¹ from data, following Sacramento River we have RVB with 832Kt yr⁻¹ (994Kt yr⁻¹, data), then MAL with 617Kt yr⁻¹ (654 Kt yr⁻¹) (Fig 8). We calculate that 30Kt yr⁻¹ of Sacramento River sediment flows to the eastern Delta through DCC, 30 Kt/yr through TMS and 20Kt yr⁻¹ from Georgina Slough. San Joaquin River carries 490Kt yr⁻¹ (498) through VNS, heading to STK with 205Kt yr⁻¹ (190Kt yr⁻¹). It was estimated that 100Kt yr⁻¹ was exported through pumping. To close the system in central Delta, the flux through JPT is 126Kt yr⁻¹ (no data) and DCH approximately 0 (no data) (Fig 8).

Seaward from MAL considerable salt-freshwater stratification takes place in the water column. These 3D effects are not captured by our 2DH approach so that the model results in this region are disregarded. Therefore, Fig 8 shows preliminary sediment flux to the Bay by a dashed line.

4.2 Sediment budget

From the previous section one can see that more sediment enters (~1600 Kt yr⁻¹) than leaves (~600 Kt yr⁻¹) the Delta. So by mass conservation law, the difference between inflow and outflow deposits in the Delta. Jaffe et al.(2007b) developed a box model based on bathymetry data to define sediment budget of the Delta and Bay to define sediment availability for ecology purposes. The model results agree with data estimations that about two third of the sediment input is retained in the Delta (Schoellhamer et al., 2012;Wright and Schoellhamer, 2005), and it is consistent throughout the years (Cappiella et al., 1999;Jaffe et al., 1998;Wright and Schoellhamer, 2004). Because of the detailed description of the sediment path, it is possible to further understand and describe the sediment budget in Delta sub-regions (north, central and south), comparing our results to data when available (Morgan King, 2012, personal communication).

Besides the overall trend, different parts of the Delta present different trap efficiency. Model results show that Northern Delta (the least efficient) traps ~ 23%; Central/Eastern Delta traps 32%, Central/Western 65%, and the most efficient is the Southern Delta region trapping 67% of the sediment input. The highest trapping efficient regions correspond to islands inundated through levee breaching (Wright and Schoellhamer, 2005).

1 From the total Sacramento River sediment input 40% stays in the northern Delta and about
2 40% is exported to Bay area. The remaining 20% deposits in the central/eastern Delta and
3 only 2% travel all the way to South Delta. About 70% of San Joaquin sediment deposits in the
4 southern Delta, 10% go to central Delta, 15% is exported via Clifton Court pumping facilities
5 and 5% is exported to the Bay. This transport is reflected in the bottom composition of the
6 Delta, Sacramento River sediment dominates the Northern and Central Delta and San Joaquin
7 River sediment dominates the Southern Delta bottom composition ([Fig 9](#)).

8 It is possible to divide the sediment budget analysis for the wet and the dry season, since the
9 Delta presents different dynamics for each season. Water year 2011 was a wet year, with the
10 wet season lasting from mid-January until the end of May. During the wet period 60% of the
11 yearly sediment input budget entered the Delta through FPT and VNS and 70% of the yearly
12 budget was exported through MAL. In the wet season the high river water discharges and
13 SSC pulses flushes the entire Delta with sediment. In this season high SSC gradients are
14 observed in the plume fronts leading to rapid changes in habitat conditions for many species.
15 After the front the high SSC level can last for more than a month, indicating changing in
16 habitat conditions

17 During the dry season the Delta experiences lower river discharges and SSC levels thus the
18 sediment transport is lower as well. In the dry season SSC levels are more uniform not
19 presenting peaks, at this time the water is clear and the advective flux is lower, which is going
20 to be discussed in the next section.

21 **4.3 Sediment flux analysis**

22 SSC peaks at FPT can be tracked down the estuary. At the RVB station the SSC peak follows
23 the same dynamic as observed at FPT; however, this behavior does not apply for the entire
24 Delta. Schoellhamer and Wright (2005) observed that the river signal is attenuated through
25 the estuary. This attenuation can be understood by analyzing changes in the dominant
26 sediment flux component.

27 Dyer (1974) decomposed the tidally averaged fluxes in three main components: tidal mean,
28 the advective term; tidal fluctuation, the dispersive term; and the Stokes Drift. This
29 decomposition was possible considering that the measured value is the sum of a tidally mean
30 component $[x]$, and a fluctuating component x' , so $x = [x] + x'$ (Eq.6), substituting in Eq 5
31 and simplifying the small contribution terms, three main terms remain (Eq.7). The first term

1 of Eq7 is the advective term, it is the river flow as it is calculated by the mean discharge, area
2 and concentration; the second one is the dispersive term that accounts for tidal pumping,
3 which is the compensation flow for the inward transport of the tidal wave the 2 first terms
4 already account for more than 95% of the flux and the Stokes Drift which is the transport due
5 to a variation in the cross-sectional area.

$$6 \quad [F] = [U][A][C] + [[U' C']][A] + [[U' A' [C]]] \quad (7)$$

7 The model allows for a detailed temporal and spatial analysis of the three flux components.
8 The temporal analysis are done in 3 steps, the first one considering the whole year and then
9 splitting in the wet and dry season. For the spatial analysis, we defined 4 stations for each
10 river where the first station is dominated by the river flux and the last experience a mix of
11 tidal and river fluxes. The stations were determined following Sacramento River, starting with
12 FPT, followed by RVB down to Mallard Island the delta output and following San Joaquin
13 River from VNS, to STK and MOK. Three Mile Slough (TMS) and San Joaquin Junction
14 (SJJ) represent the Delta smaller channels.

15 Sacramento River at FPT, the most landward station, experiences no tidal influence so the
16 flux is purely advective. RVB, seaward, experiences tidal fluctuations and the dispersive flux
17 is responsible for 22% of the total flux; however no Stokes drift flux is present ([Fig 10](#)). On
18 the other hand, Stokes Drift component accounts for 33% of the total flux in MAL station
19 implying that tides have a bigger influence in this region.

20 An analogue can be drawn to San Joaquin branch, where VNS and STK experience only
21 advective terms. In MOK and SJJ dispersive (20% and 63% respectively) and Stokes flux
22 start (5 and 11%) to change the total flux ([Fig 10](#)). The analyses of the 3 different flux
23 components in smaller Delta channels show that river and tidal signals are equally important.
24 In other words the river peak signal is less important inside smaller channels than in rivers. At
25 TMS, the dispersive flow accounts for 60% of the total flux.

26 The fluxes analysis shows that there is no change in the Delta net circulation when comparing
27 wet and dry seasons. In other words, there is not a major signal change in the flux signal
28 direction when comparing the seasons. However, there is a change in importance of each flux
29 component.

30 [Fig 10](#) shows that dispersive flux and Stokes Drift relative contributions vary seasonally:
31 when river discharge is high the relative contribution of dispersive flux and Stokes Drift is

1 lower than during low flow conditions. This pattern is better observed in stations where the
2 river signal is stronger. At RVB the dispersive flux contribution is about 15% during the wet
3 season and 26% in the dry season, the same applies for MAL and STK. In smaller channels,
4 like TMS and SJJ, The dispersive flux seasonal variation is milder, varying about 10%, from
5 55% in the wet season and 65% in the dry. In the dry season the change in fluxes contribution,
6 from advective to dispersive and Stokes Drift, leads to a lower net export of sediment from
7 the Delta, even though the concentrations in the Delta about 30mg L^{-1} .

8 **4.4 Sediment deposition pattern**

9 The flux change from completely advective to dispersive and Stokes drift sheds some light on
10 the Delta deposition areas. The places where the dispersive flux starts to play a role, near
11 RVB and MOK areas, are the same places where net deposition is observed ([Fig 11](#)). Other
12 locations where considerable sedimentation takes place are in flooded islands areas, such as
13 Frank Tract and the Clifton Court. The 2D model allows determining such areas ([Fig 11](#)).

14 The San Joaquin River downstream of Stockton experiences high deposition. This finding is
15 confirmed by constant dredging works need to maintain Stockton navigation channel. The
16 river discharge modulates the deposition pattern in the main channels. In the Sacramento
17 River, Rio Vista area (RVB), a rapid deposition takes place just after the peak discharge.
18 Later this deposited sediment is gradually washed away and transported to the mud flats at the
19 channel margins, until the next peak.

20 At flooded island the sedimentation process is gradually and steady, and is not transported
21 again. The deposition pattern does not change from wet to dry season, except for some small
22 bends in the Sacramento River that goes from eroding (wet) to depositing areas (dry). The
23 deposition pattern provides insight into the best areas for marsh restoration.

24 **4.5 Turbidity**

25 So far the discussion was presented in terms of SSC levels, budgets and fluxes, while
26 ecological analysis is often based on turbidity levels. SSC and turbidity are correlated by
27 rating curves as $\log_{10}(\text{SSC}) = a \cdot \log_{10}(\text{Turb}) + b$, where a and b are local parameters
28 empirically defined for each Delta area. The Northern area $a=0.85$ and $b=0.35$;
29 Central/Western area $a=0.91$ and $b=0.29$, Central/Eastern $a=0.72$ and $b=0.26$; Southern

1 a=1.16 and b=0.27; Eastern a=0.914 and b=0.29 (USGS Sacramento, personal communication
2 2014).

3 In this section we present average values for turbidity within a specific Delta region as well
4 as its seasonal and daily variations ([Fig 12](#)). Generally, the mean turbidity levels and spatial
5 variations are higher during the wet season than during the dry season. During the wet season,
6 the Southern area presents the highest mean value (50 ntu), and deviation (15ntu), caused by a
7 combination of large sediment supply and low flow velocities. The Northern region is the
8 second most turbid area (45 ± 10 ntu), where sediment transported by Sacramento River flows
9 in the channels, increasing the turbidity levels. The Central Eastern region is the least turbid
10 area (5 ± 2 ntu) and, as previously shown, it presents the highest trapping efficiency of the
11 entire Delta. In the dry season the mean turbidity daily variation decreases in the whole Delta,
12 excepting the Central/Eastern region. The opening of the DCC during the dry season lets
13 sediment from the Sacramento River entering these areas, increasing the mean turbidity level.
14 The spatial distribution of the most turbid areas is the same as in the wet season. The daily
15 deviation is mostly proportional to the turbidity level and to the distance from the sea. In the
16 Southern and Western areas the daily variation is higher during the dry season. It shows that
17 there is a strong tidal signal in these parts of the Delta.

18 As for from this work results, we note that the Sacramento [to San- Joaquin River connecting](#)
19 [channels DCC and GLS are important bridges to export sediment from Sacramento to Eastern](#)
20 [Delta. On the other hand the smaller channels of the network play a minor role in the Delta](#)
21 [sediment budget, since the discharges in these channels are considerably smaller than in the](#)
22 [rivers.](#)

23 **4.6 Data input discussion**

24 [As a well surveyed area, combining with a complex process-based model, the Delta offers the](#)
25 [chance of testing how much data it is necessary to develop a robust model to sediment](#)
26 [dynamics and budget. The model offers the possibility of having high temporal and spatial](#)
27 [resolution, as well as considers multiple physical processes as bottom friction, sedimentation](#)
28 [and erosion. The available data allows calibration and validation of model results.](#)

29 [As presented before, with simple settings as 1 mud fraction and simple bed sediment](#)
30 [availability the model is capable of representing the main sediment dynamics processes, the](#)
31 [peak timing and duration, as well as sediment budget. The necessary data to a trustworthy](#)

1 modeling and further forecasting is a fine resolution bathymetry to correctly reproduce
2 hydrodynamics, SSC and discharge in the inflow and outflow boundaries as well as in 1-
3 2stations in the domain in order to properly calibrate the model. The results from the
4 calibrated model using these few data can be extrapolated for the entire domain, allowing
5 closing the sediment budget for the whole system.

6 The 2D model results output are available in high temporal (~hours) and spatial (~20 meters)
7 resolution, allowing to translate model results in water quality parameters for modeling or for
8 descriptive purposes. In other words, with limited input data we can come to a detailed system
9 description with considerable forecast capacity, expanding the applicability of this work to less
10 measured estuaries.

11

12 **5 Conclusions**

13 In this work we make a step towards the understanding and simulating sediment dynamics
14 from source to sink in a complex estuary. This work shows that it is possible to reproduce the
15 main system sediment dynamics as well as a detailed budget for complex areas such as the
16 Delta using a 2D process based numerical model coupled with a water quality model.

17 Overall, the model reproduces the SSC peaks and event timing and duration (wet season) as
18 well as the low concentration in dry season throughout the Delta, except at Mallard where
19 water column is stratified due to salt intrusion. Stratification issues are not solved in a 2D
20 model. For this reason we are working on a 3D model in order to include the Bay area,
21 leading to a unique model from source to sink.

22 The Delta is well covered by observation stations. However, this work shows that the
23 substantial sediment is exported trough the pumping stations (100kt yr⁻¹) at the Southern
24 Delta where no data in SSC is available. The sediment exporting needs further investigation,
25 since it is possible that has being deposited in the channels before the pumps.

26 We show that with simple sediment settings as one fraction at the input boundary and simple
27 distribution of bed sediment availability, it is possible to reproduce seasonal variations as well
28 as define yearly sediment budget with more than 90% of accuracy. It shows also that it is
29 extremely important to have discharge and SSC measurements at least in the input boundaries
30 and close to the system output in order to be able to calibrate the model settings applied for

1 [hydrodynamics and suspended sediment. This methodology now can be applied in less](#)
2 [measured estuaries.](#)

3 [Sediment is a key-factor to estuaries water quality and ecology. The D3D FM software allows](#)
4 [direct coupling to water quality, sediment transport and habitat modeling. Our work provides](#)
5 [the basis to a chain of models, which goes from the hydrodynamics, to suspended sediment, to](#)
6 [phytoplankton, to fish, clams and marshes. The turbidity and deposition pattern analysis may](#)
7 [guide ecologists in future works to define areas of interest and/or venerable areas to be study,](#)
8 [as well as guide data collecting efforts. The present model opens the possibility for forecast](#)
9 [and operational modeling. Forecasting the time frame of high levels of SSC \(turbidity\) allows](#)
10 [planning of measurements campaigns for ecologists, as well as the possibility of tracking](#)
11 [potentially contaminated sediment and be able to make a contingency plan as well as](#)
12 [temporary barriers and pumping operations.](#)

13 [The Sacramento San-Joaquin Delta is a typical case of a highly impacted estuary. Being able](#)
14 [to numerically simulate and determine sediment transport, budget and turbidity levels in this](#)
15 [type of environment open possibilities to better informed political, ecological and](#)
16 [management decisions including how to respond to climate change and sea level rise. This](#)
17 [type of model is an important management tool that is applicable to other impacted estuaries](#)
18 [worldwide.](#)

19 **Appendix A: Hydrodynamic Calibration**

20 The hydrodynamic calibration was carried out for 3 month high river flow conditions
21 (December 16, 1999 until March 16, 2000) and a 3 month period of low river flow conditions
22 (July 16, 2001 until October 16, 2001). All presented data is with respect to NAVD88
23 (vertical datum), UTM 10 (horizontal datum) and GMT (time reference).

24 Hourly measured water levels at Point Reyes (tidesandcurrents.noaa.gov/) were used as
25 seaward boundary condition. Landward boundary conditions for the Sacramento River were
26 obtained from daily measured river flow data at Freeport (FPT) and for the San Joaquin River
27 near Vernalis (VNS) (cdec.water.ca.gov/). The inflow from the Yolo Bypass was
28 approximated by (Derived after curve fitting data relationship between Qyolo and Qrsac.)

29 Measured data for the Bay area were derived from tidesandcurrents.noaa.gov/, for part of the
30 Delta from the California Data Exchange Centre cdec.water.ca.gov/ and for station with
31 numbers from direct contact with the Department of Water Resources (DWR).

1 Calibration was carried out by systematically varying the value of the Manning's coefficient
2 for different sub-areas of the Bay-Delta system. The calibration data analysis includes (local
3 and time varying) influence of air pressure and wind in the definition of the boundary
4 condition as well as in the calibration data inside the modeling domain. These may account
5 for (part of) the error between measurements and modeling results. Also, the NAVD88
6 reference is not known for all measurement stations, although tidal water fluctuations may be
7 modeled properly. To circumvent these distortions a better method to assess the model
8 performance is to focus on water level amplitude and phasing of the different tidal
9 constituents. Boundary conditions, calibration data and model results are thus decomposed by
10 Fourier transformation into tidal components which are then compared. The following table
11 gives the results of this analysis for 34 tidal constituents at Golden Gate (GGT) for high river
12 flow conditions. By far, the main tidal constituents at (GGT) are O1, K1, N2, M2 and S2,
13 with M2 being the largest. The model represents their values quite well. The difference in
14 amplitude is 1.3 % for M2, up to 14% for O1, but the phasing shows a maximum of only 3%
15 (O1)).

16 The Fig A1 gives calibration results for the high and low river flow. The largest (extreme)
17 deviations are explained by the fact that the measured water levels did not have a known
18 reference to NAVD88 (<http://www.d3d-baydelta.org/>).

19

20 **Appendix B: SSC Calibration**

21 All stations clearly reproduce SSC peaks during high river flow periods and lower
22 concentrations during the remainder of the year (apart from MAL during the July-August
23 period). The good representation of the peak timing means that the main Delta event is
24 reproduced by the model as well as the periods of Delta clearance. These two periods are
25 critical for ecological models, and a good representation generates robust input to ecological
26 models. A closer look at [Fig 4](#) reveals differences between model results and data. Following
27 these differences is discussed station by station in this appendix.

28 One observes that at RVB, SSC levels are directly proportional to Sacramento River
29 discharge (Fig B3), and that the model properly represents the water discharge peak intensity
30 and duration. However, in the model, the first peak remobilizes sediment faster than observed

1 in the data. Analyzing the raw data, it is possible to observe a trend of SSC increase which the
2 model overestimates. A probable explanation lies on the initial sediment composition of the
3 bed. Defining the bottom sediment composition does not account for consolidation processes;
4 so the first peak comes after the dry season when the mud in the banks has consolidated. In
5 the simulation case, when river discharge increases, it remobilizes non-consolidated
6 bottom/bank sediment causing an earlier peak than in the data; similar behaviour is observed
7 in STK in December. Sediment trapped in subaquatic vegetation and marshes could be
8 another explanation for the slower increase of the first peak as the model discharges for both
9 stations agree with data ([Fig 4](#)).

10 Another difference between the data and the model results in RVB is the peak in May (second
11 rectangle, [Fig B1](#)), which is not observed in the data. SSC level at RVB station is directly
12 proportional to water discharge in FPT ([Fig B3](#), RVB). The May peak is observed in FPT
13 and so should have been transported towards RVB just as the two preceding peaks. However,
14 the data set does not reproduce this peak. One of the possible explanations is errors in data
15 measurements, since it comes after a major event and the equipment might be damaged.
16 Other explanations could be a different composition of the suspended sediment properties
17 and/or flocculation.

18 The model underestimates the first and second SSC peaks at MOK. However, the data SSC
19 signal is not consistent with the local water discharge signal. First, we checked that modeled
20 water discharge is reproducing the local conditions, where data is available from mid-
21 February onwards. The last peak in [Fig](#) (mid-March) shows that water discharge, in situ and
22 modeled SSC have the same range of variation. Therefore the SSC levels are proportional to
23 the local water discharge. Backwards in time, the January SSC data peak is much higher than
24 the water discharge and the SSC level calculated in the model. The same happens in mid-
25 February when no water discharge peak is observed but there is a peak in the SSC data. Again
26 the peaks in SSC could be derived from an error in the measurements or local, diffuse input of
27 sediment such as from local farm waste water or biological activity remobilizing the substrate.

28 The model represents well the wet season SSC peaks at MAL; however, during the three drier
29 periods of the year the model underestimates SSC levels ([Fig B2](#)). From the scatter plot water
30 discharge versus SSC ([Fig B3](#)**Error! Reference source not found.**), it is possible to explain
31 the weaker performance of the model during low river flow at MAL. These graphs represent
32 river water discharge in FPT lagged by 2 days to SSC in RVB and MAL. Several time lags

1 were tested, as MAL does not present a reasonable correlation with any of the time lags; it is
2 presented here with the same time lag as the one for RVB. RVB station reflects a positive
3 correlation between river discharge and SSC derived from in situ data and model results. The
4 correlation coefficient (R), statistically shows how two variables are correlated, in RVB
5 $R=0.58$.

6 In MAL station $R=0.26$, showing that there is almost no correlation between river discharge
7 and SSC levels. The low correlation is due to high SSC level in low water discharge periods,
8 when the model underestimates SSC levels. Under low river discharges conditions, salt water
9 intrudes into Suisun Bay leading to considerable stratification between fresh and salt water
10 and shifting of the ETM landward (<http://sfbay.wr.usgs.gov/access/wqdata/>) (Brennan et al.,
11 2002). In order to better model SSC levels at these conditions a 3D model would be needed to
12 reflect conditions at MAL adequately. With this results we are still able to calculate sediment
13 export, since most of the sediment export occurs in the wet period (McKee et al., 2006),
14 when the model reproduces SSC levels.

15

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20 in this work is freely available on the USGS website (nwis.waterdata.usgs.gov). The model
21 applied in this work will be freely available from <http://www.d3d-baydelta.org/>.

22

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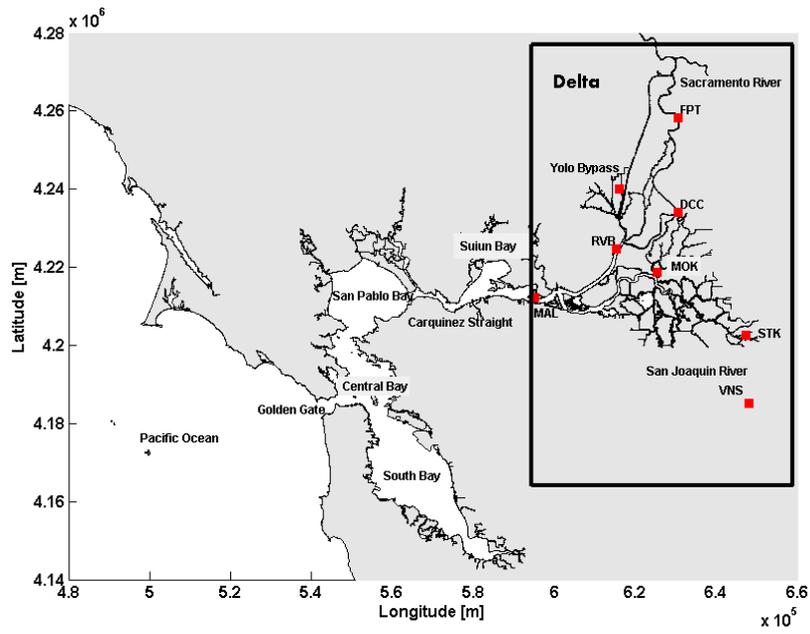
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1 Table 1: Parameters set of sensitivity analysis.

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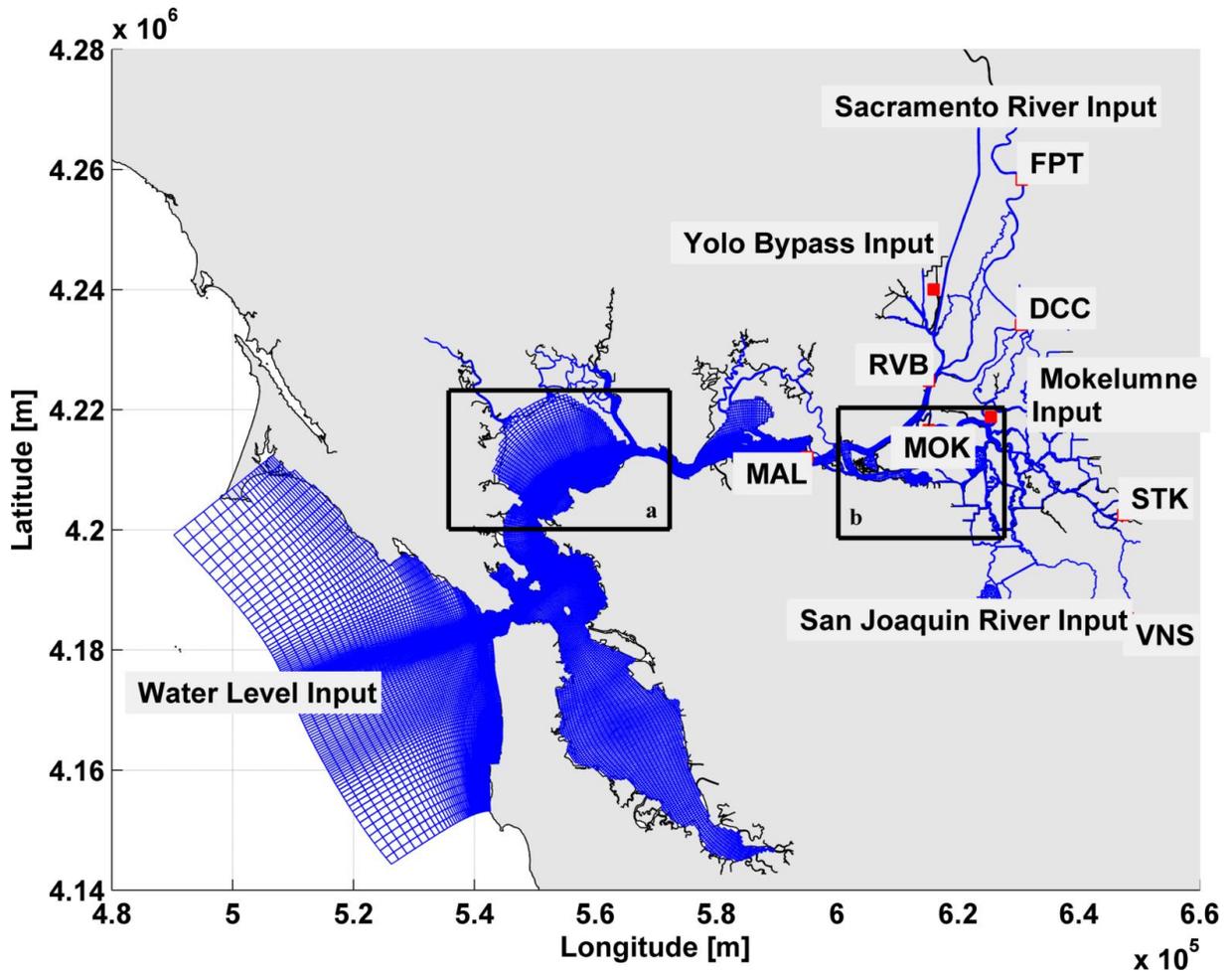
Parameters		Minimum	Maximum
standard		$w = 0.25$; $\tau_{cr} = 0.25$; $E = 1 * 10^{-4}$	
Fall velocity	w (mm s^{-1})	0.15	0.38
Critical shear stress	τ_{cr} (Pa)	0.125	0.5
Erosion Coefficient	E ($\text{kg m}^2\text{s}^{-1}$)	$2.5 * 10^{-5}$	$1 * 10^{-2}$

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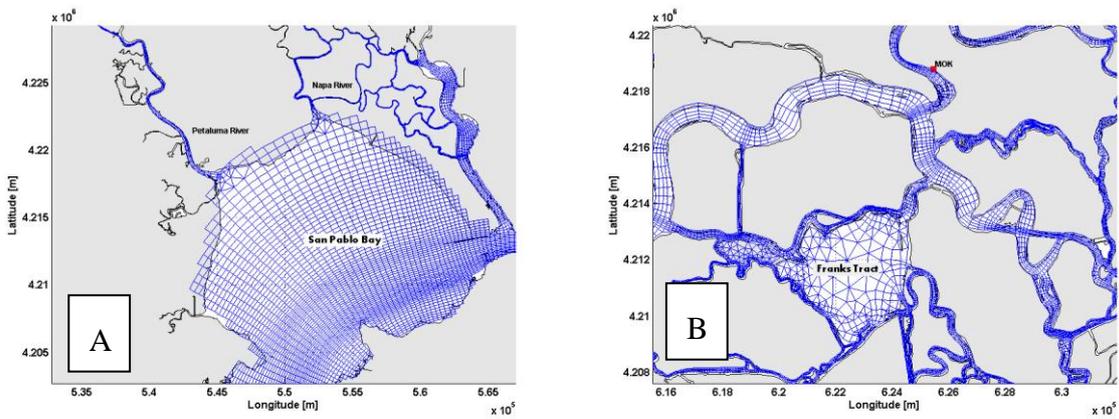


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 2 Fig 1: San Francisco Bay-Delta, the black rectangle highlights the Delta, and the red squares
 3 indicate measurement stations.

4



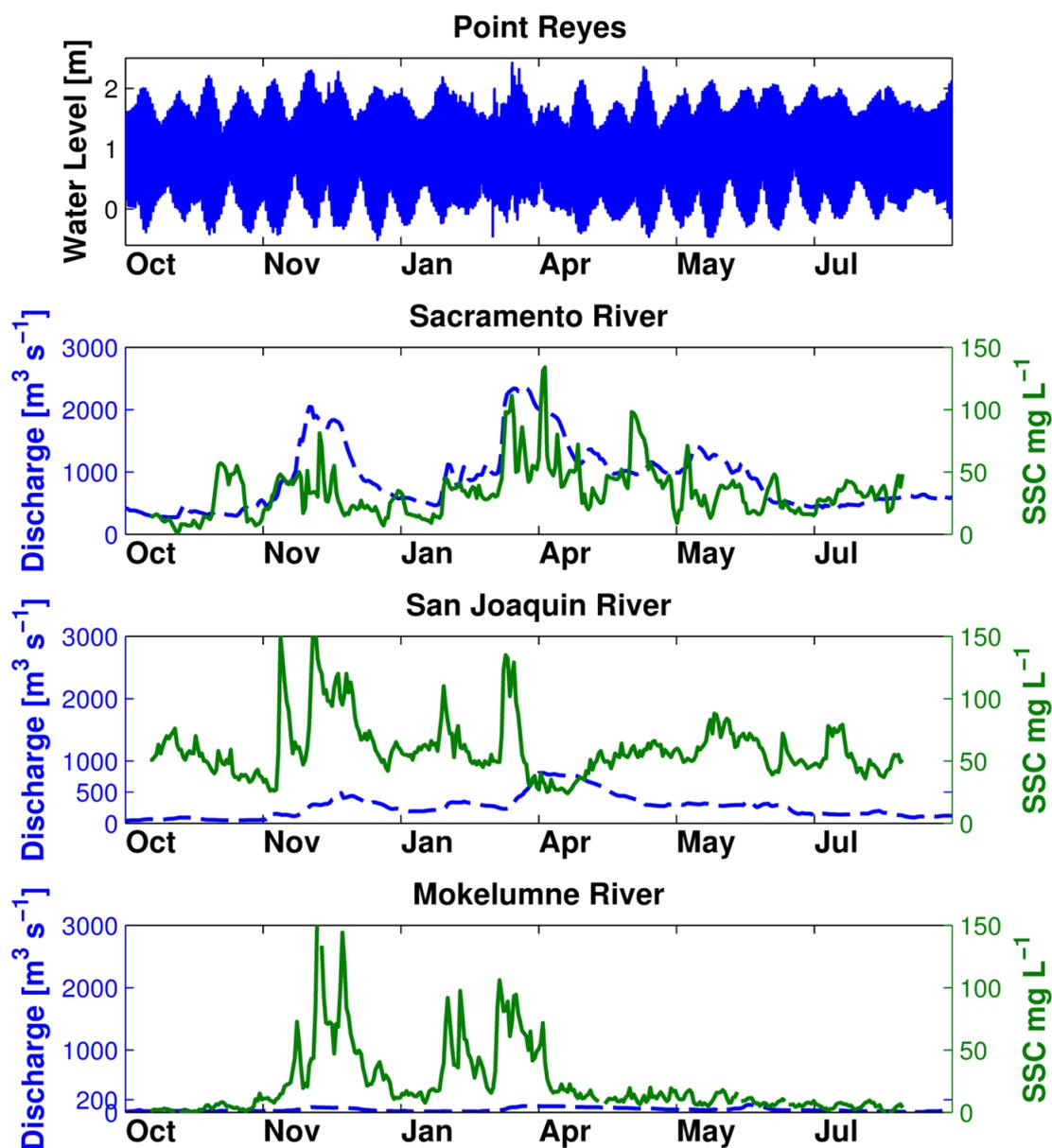
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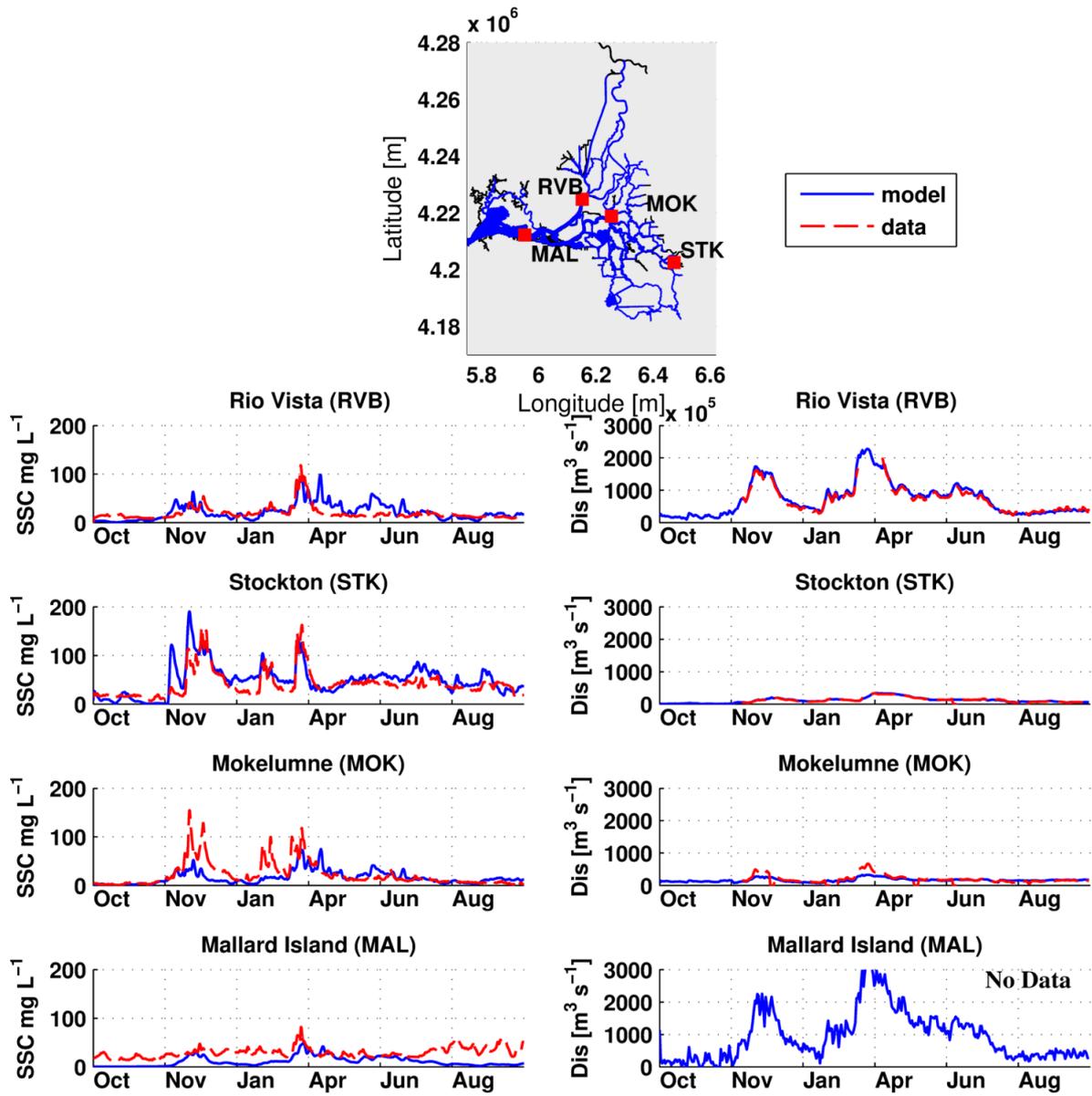
3 Fig 2: Numerical mesh, the red dots indicate the calibration stations. ([http://san-francisco-bay-](http://san-francisco-bay-delta-model.unesco-ihe.org/)
 4 [delta-model.unesco-ihe.org/](http://san-francisco-bay-delta-model.unesco-ihe.org/)). Zoom in the computational grid, A) San Pablo Bay connecting
 5 to Petaluma and Napa Rivers, B) Delta channels and Franks Tract.

6



1
 2 Fig 3: Input boundary condition. Top panel water level at Point Reyes, the following 3 panels
 3 show discharge in dashed blue line and SSC in solid green line for Sacramento River at FPT,
 4 San Joaquin River at VNS and Mokelumne River at Woodbridge respectively.

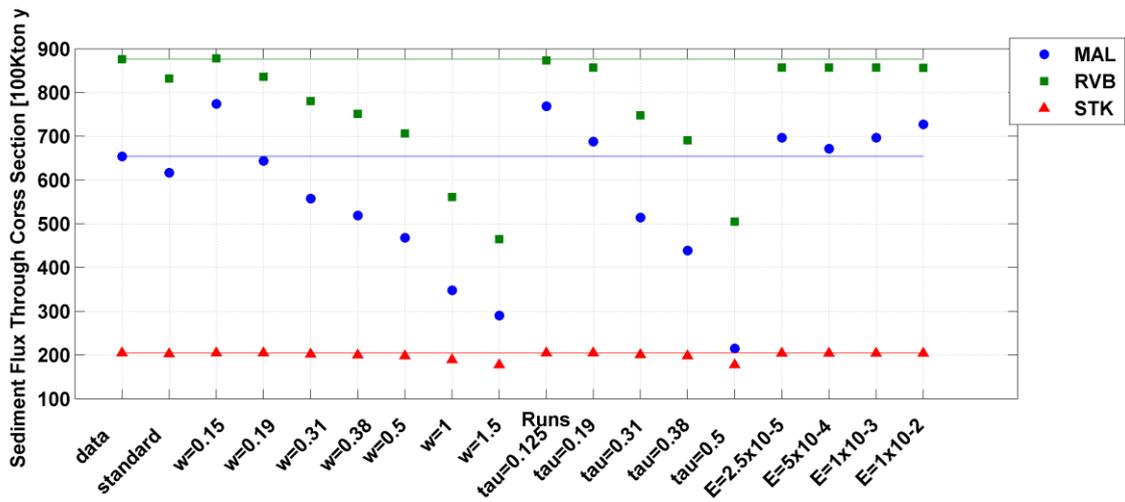
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 2 Fig 4: Calibration stations location top Fig. Left panels show SSC calibration and right panels
 3 show discharge. Data are dashed red lines and model results are solid blue lines. Note that
 4 in the discharge plots of RVB and STK the data line is behind the model line.

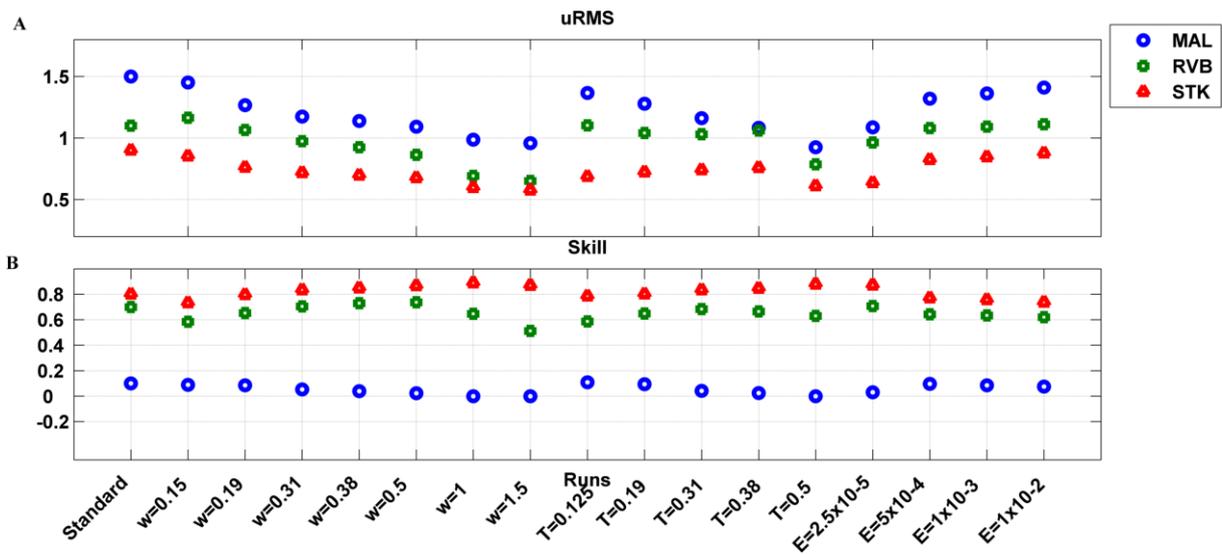
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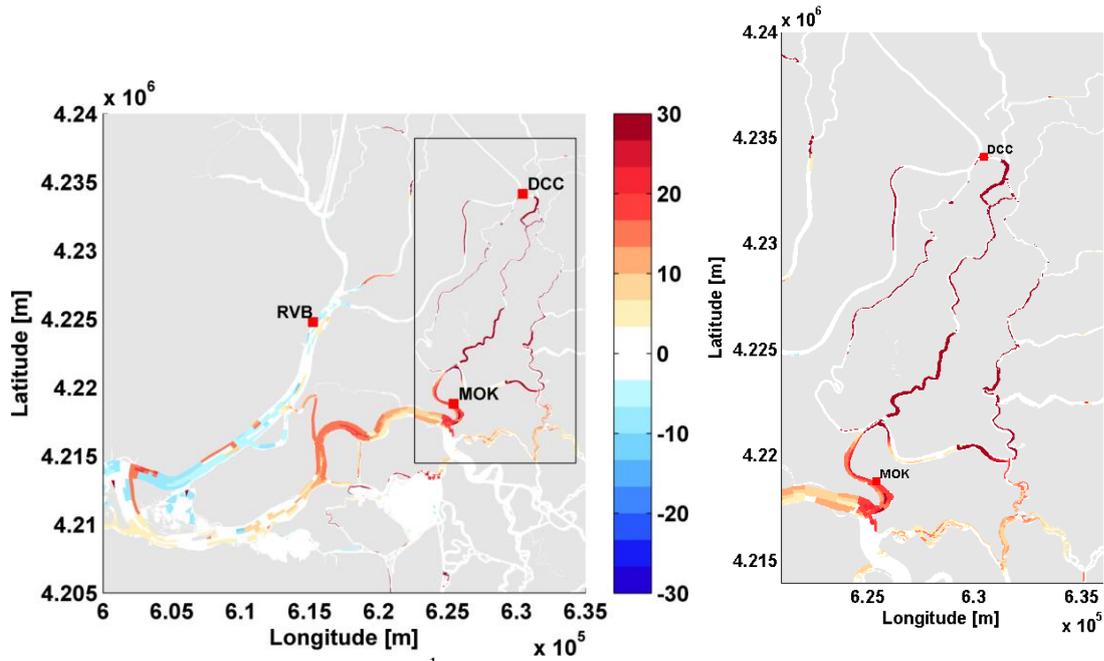
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4 Fig 5: Sensitivity analysis of sediment flux, for 3 stations, RVB in green squares (Sacramento
5 River), STK in red triangles (San Joaquin River) and MAL in blue circles (Delta output). The
6 colour lines indicate the data values.



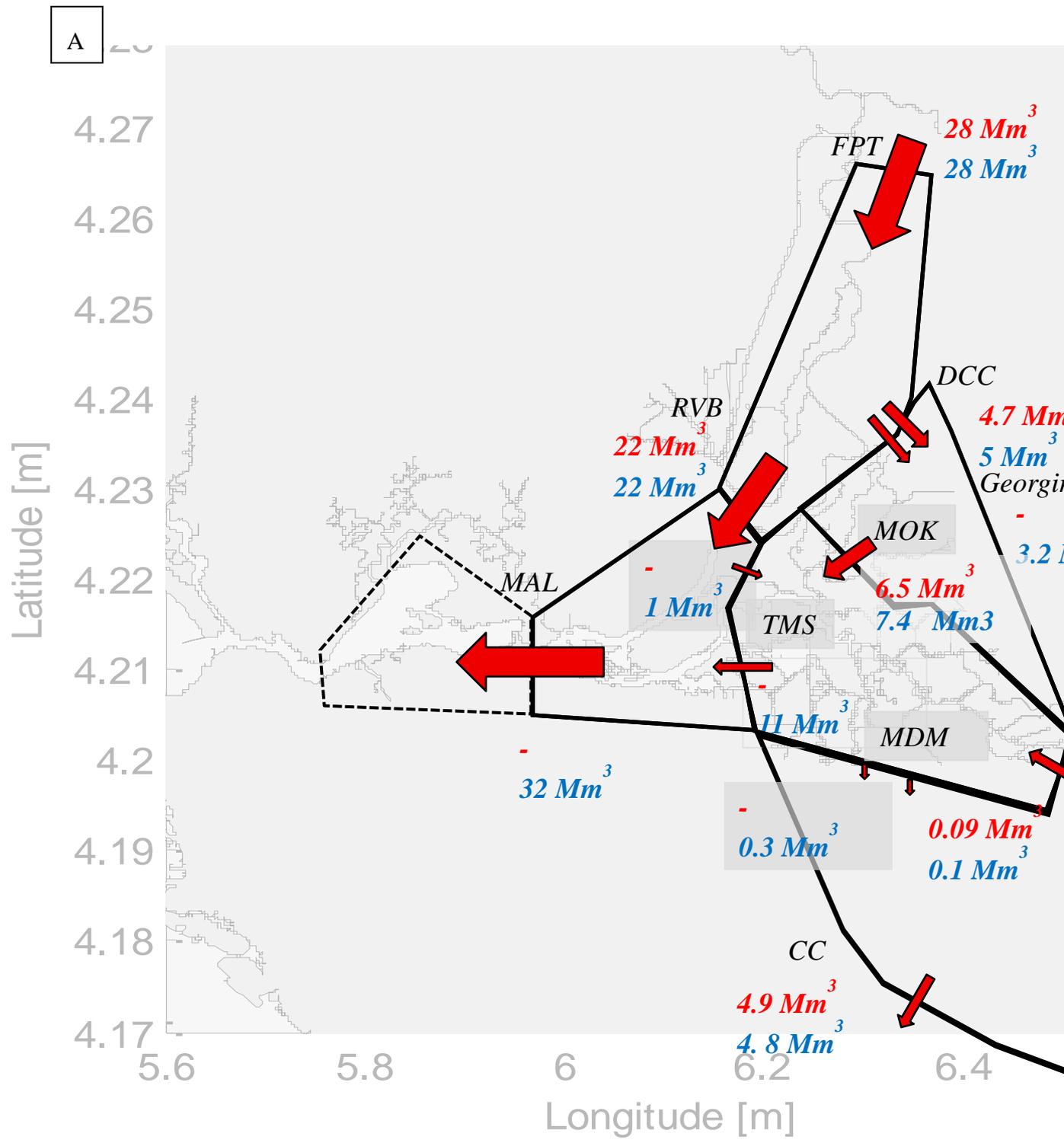
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 2 Fig 6: Statistical metrics in (a) Unbiased Root Mean Square and in (b) Skill. In the x axis are
 3 the different runs and the colors the stations RVB (green square), STK (red triangle) and
 4 MAL (blue circle).

5

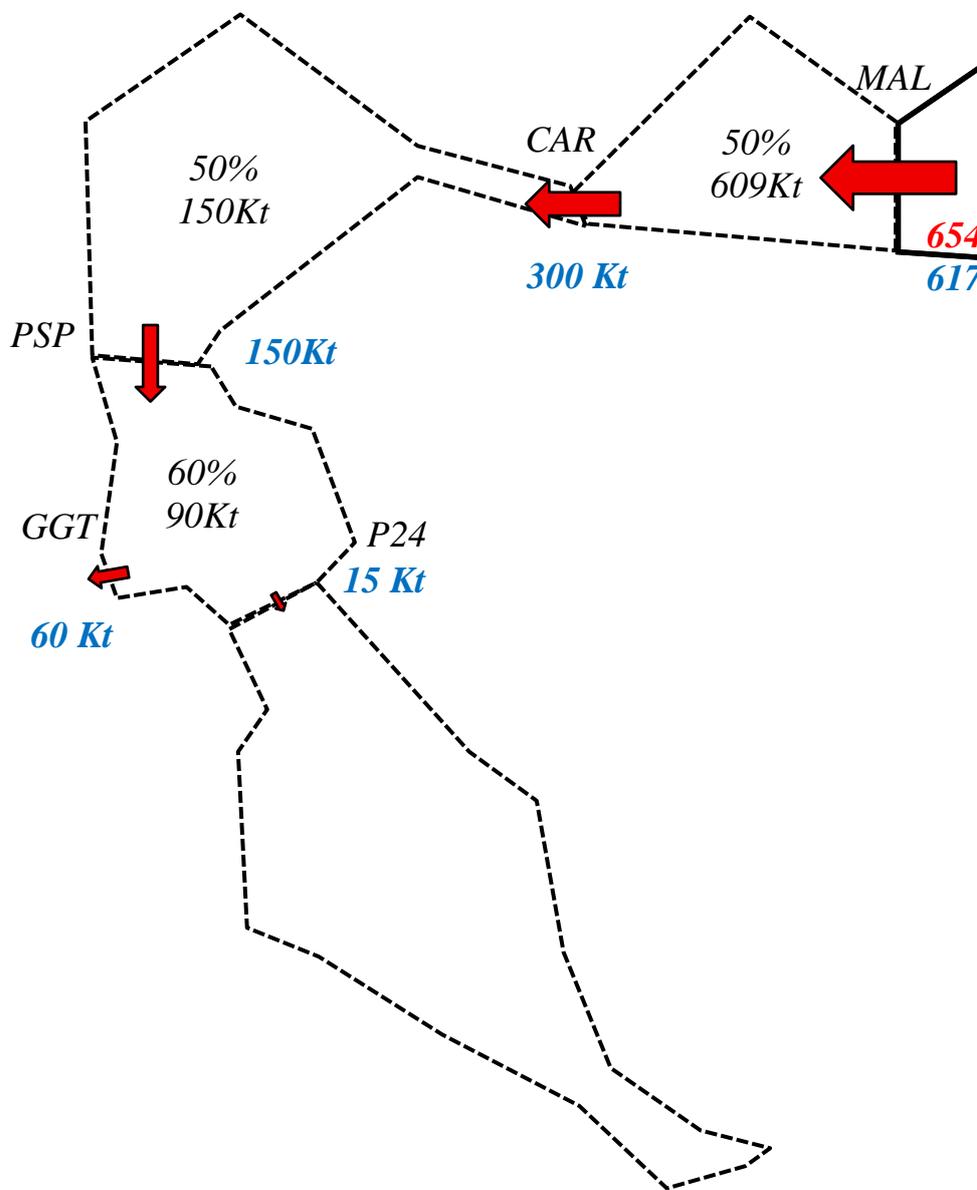


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 2 Fig 7: Anomaly of a SSC (mg L^{-1}) snapshot between a run with open and one with closed
 3 DCC, this pattern is representative in time as well. The right panel is a zoom in between the
 4 DCC and MOK (black rectangle). Red shades represent regions where the SSC level is higher
 5 in the open than the close scenario, the blue shades where it was lower.

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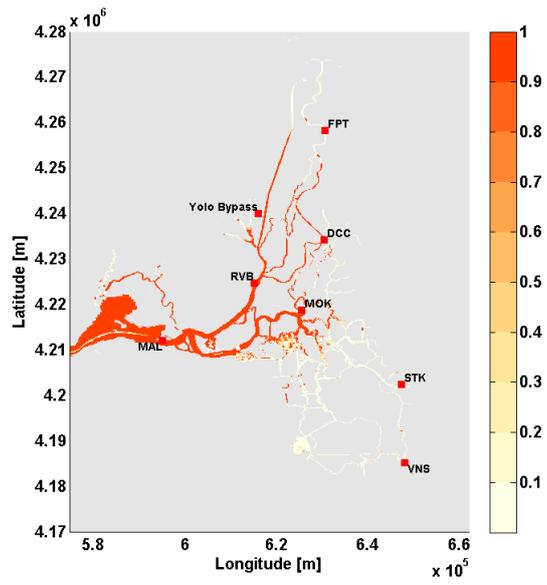


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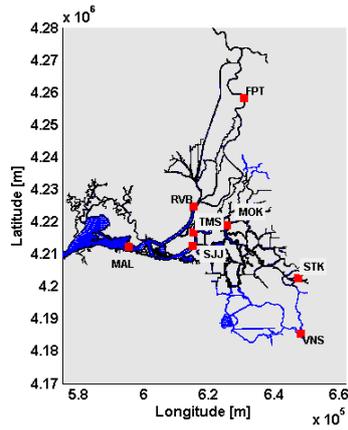
1 Fig 8: Water Discharge (A) and Sediment Flux (B) Path models. The arrows represent the
2 water (A) and sediment (B) fluxes through the cross sections. Area of the arrow is
3 proportional to the flux. Red/blue indicates the sediment (water) fluxes from data/model.
4 Inside each polygon is the sediment budget for the area. The Bay portion is dashed because
5 the model is 2D and 3D processes occur in that region.

6

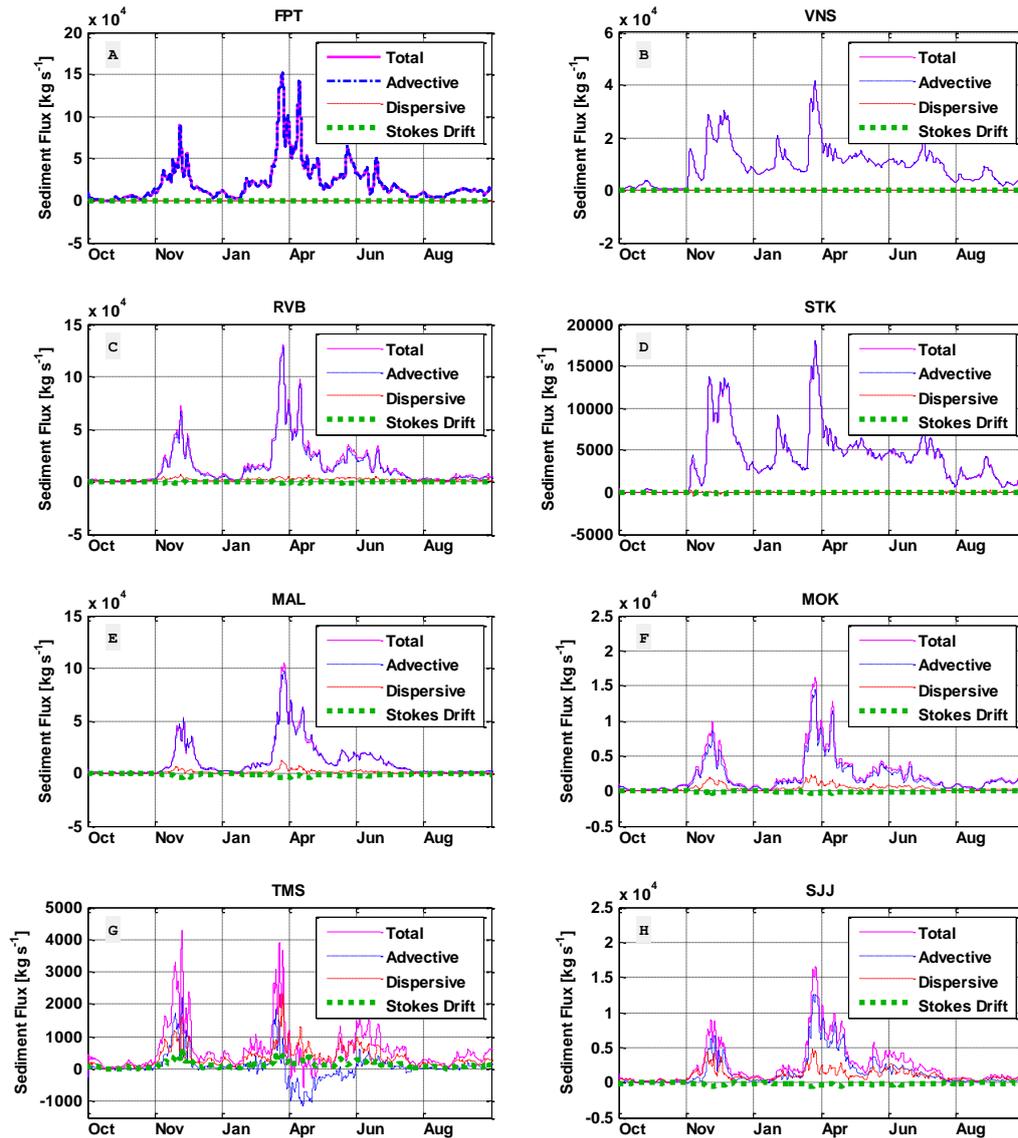


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 2 Fig 9: Sediment bottom composition after one year, starting from concrete bed. In Red shades
 3 region dominated by Sacramento and in white by San Joaquin, the black line highlights this
 4 separation.

5



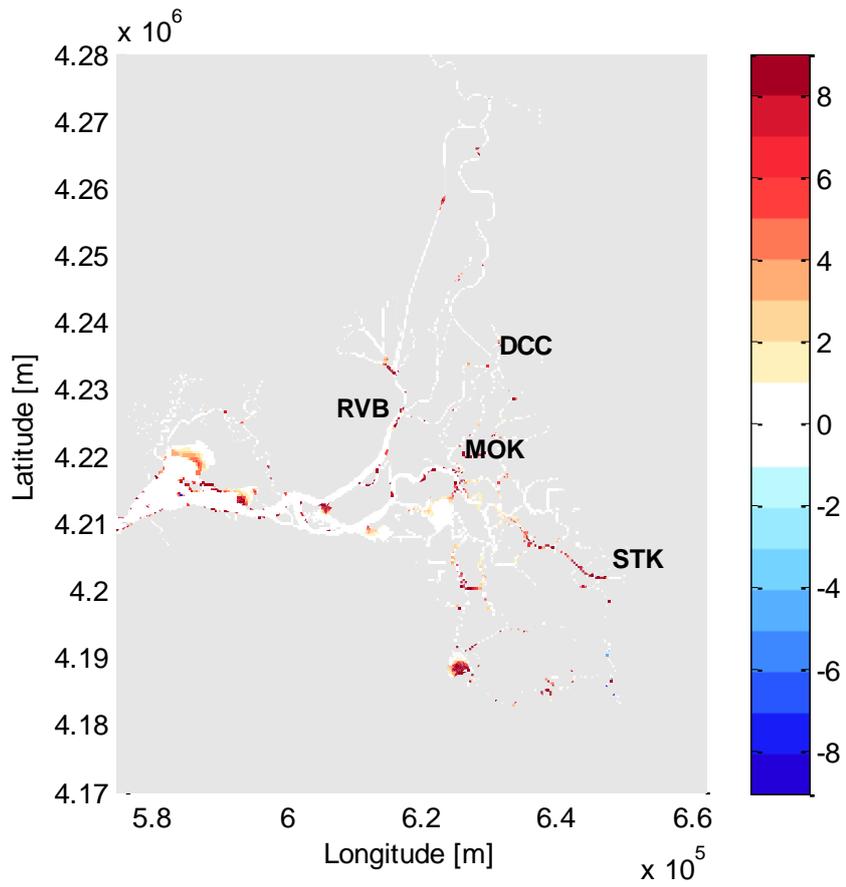
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3 Fig 10: Flux calculation for several stations within the Delta. Figs A, C, E, and G show the
 4 flux change following Sacramento branch and B, C, F and H following San Joaquin branch.
 5 The total flux is represented in magenta (in FPT and VNS the total is the same as the

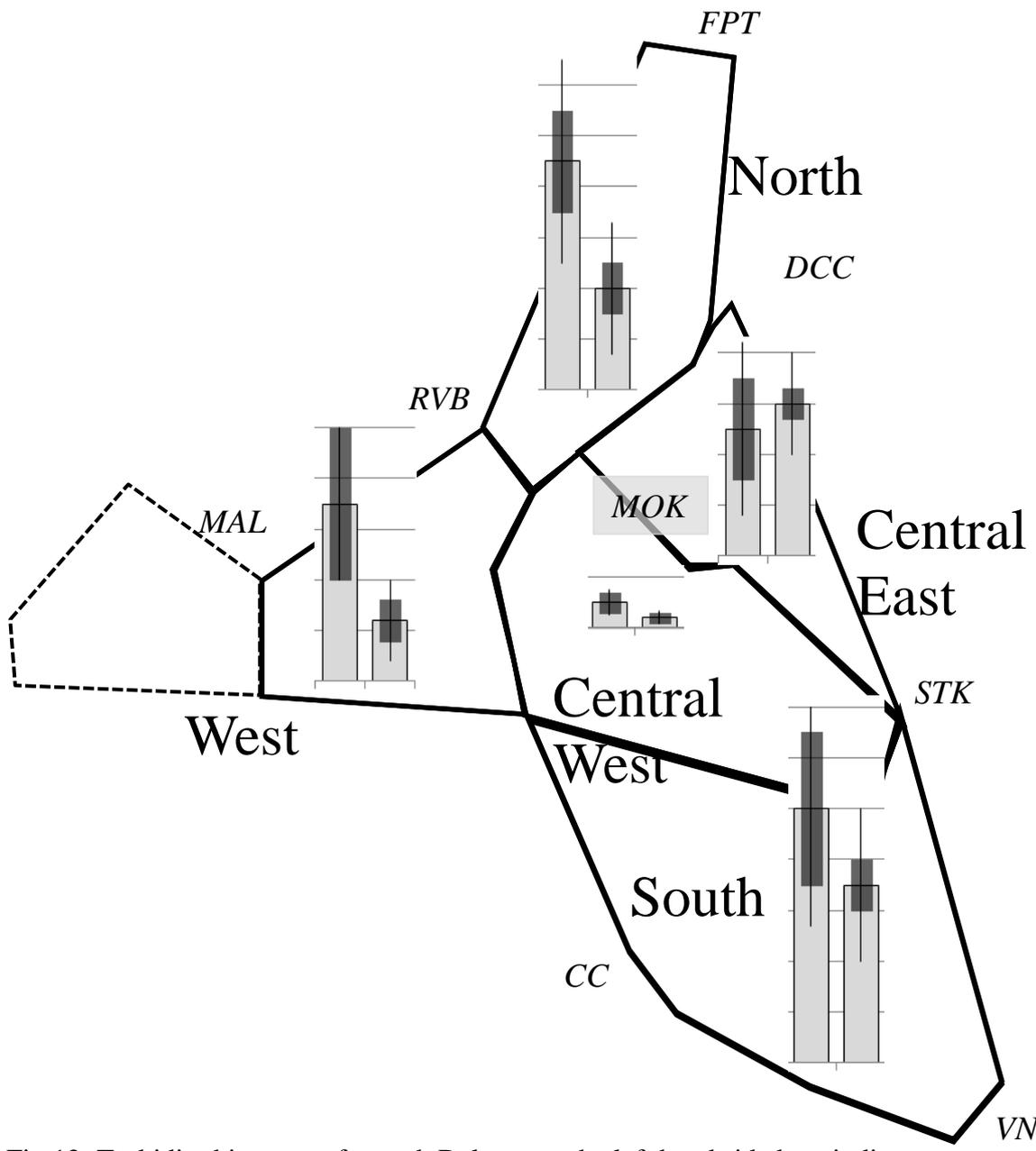
- 1 advective), in blue the advective flux, in red the dispersive flux and in green Stokes drift.
- 2 (Positive is seaward).
- 3



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2 Fig 11: DELWAQ deposition volume translated in bottom sediment deposition in [mm].

3

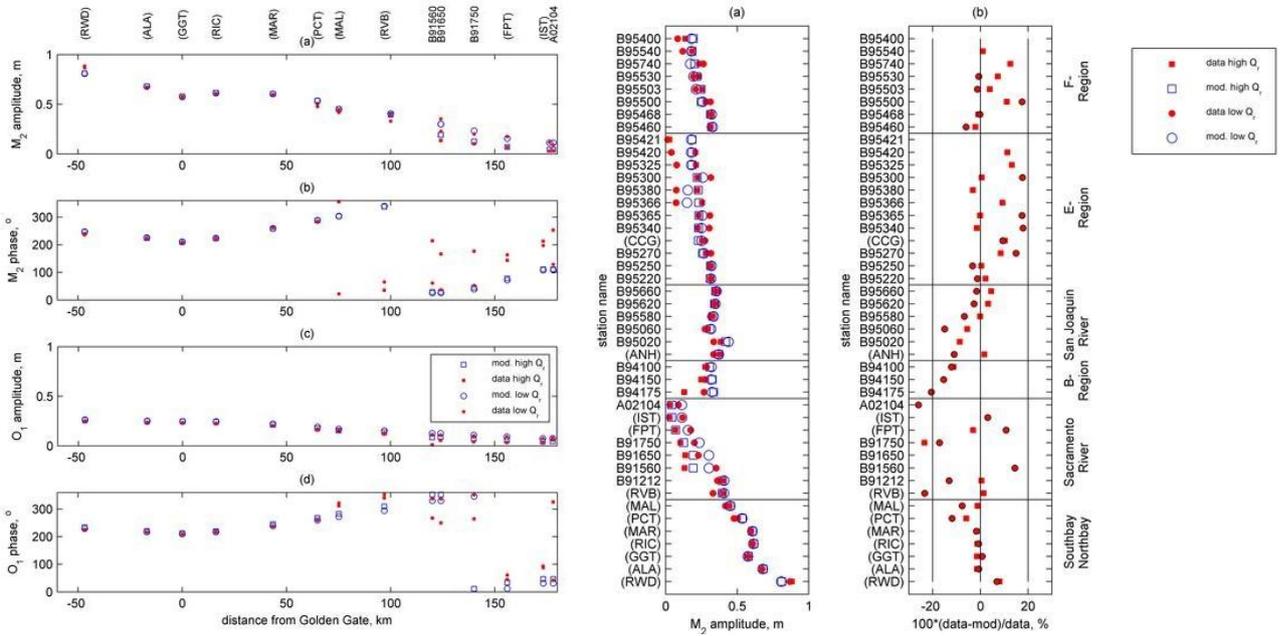


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 2 Fig 12: Turbidity histogram for each Delta area, the left hand side bars indicates wet season
 3 and the ones in the right dry season. The light gray bar indicate the mean turbidity over the
 4 area, the darker bar the spatial deviation and the lines the daily deviation. Each horizontal line
 5 represents 10 ntu.

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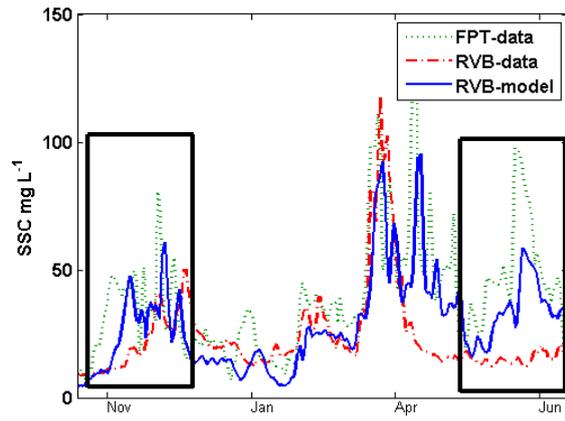
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3 Fig A1: Hydrodynamic calibration example.

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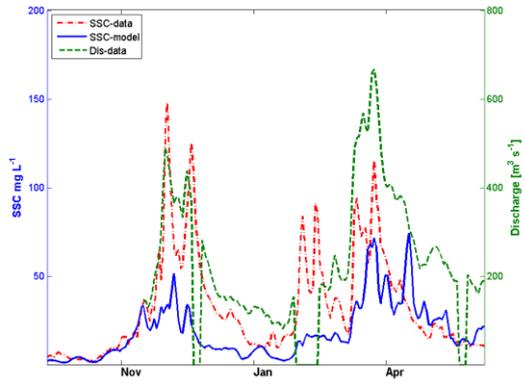


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2 Fig B1: Comparison between SSC levels in RVB station in situ data (dashed red) and model

3 result (solid blue) and FPT station (dotted green).

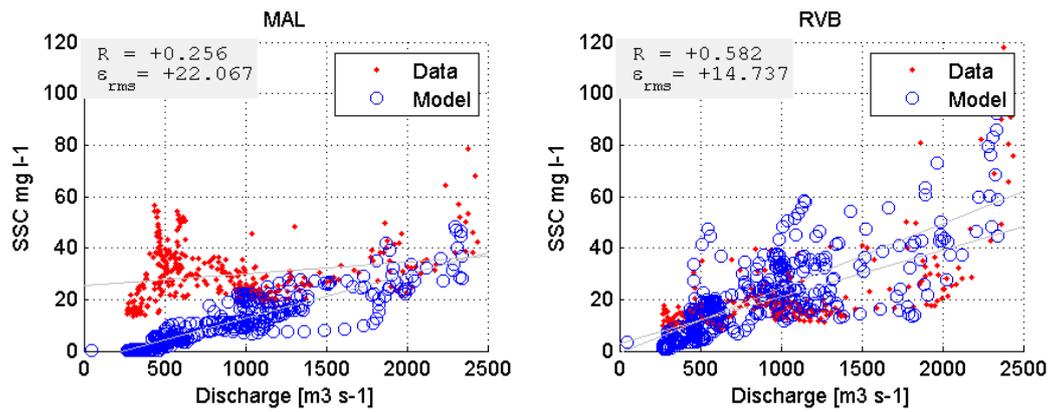
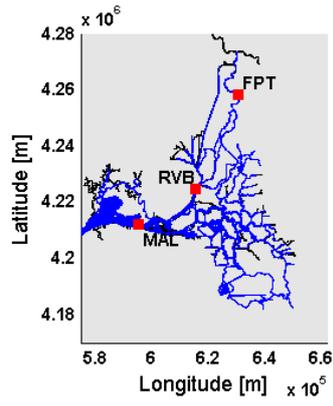
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2 Fig B2: Water discharge (model) and SSC level (data and model) in MOK station.

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Fig B3: Scatter plot Discharge versus SSC. Showing on the left (MAL) for MAL station and on the right hand (RVB) side RVB station. The red dots represent the Data and the blue model results.