Impacts of Submerged Aquatic Vegetation on Water Quality In Cache Slough Complex, Sacramento-San Joaquin Delta: A Numerical Study

Nicole Cai, Joseph Zhang, Jian Shen

Jun 07, 2021

A story of a fish

Delta Smelt (endangered)

- Endemic and indicator species for the health of the Delta ecosystem
- It is functionally extinct in the wild, which coincides with substantial changes in Delta ecosystem

Egeria densa (invasive)

- Displaced most of the native SAV species within Delta
- Form canopies in slow-flowing or still water
- Stems can grow from 1.8 m to 3 m, or even to the water surface
- Delta Smelt Resiliency Strategy calls for enhanced control and study of the effects of removal by herbicide.

Impacts of SAV

1)

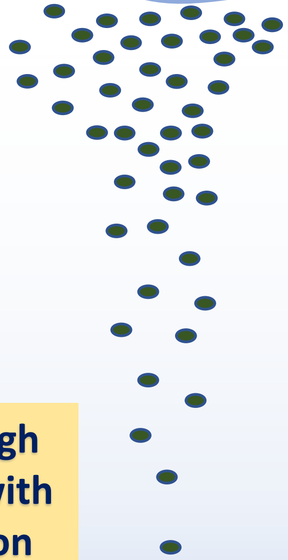
Direct Impact

- Nutrient uptake/release
- Oxygen production/consumption

2)

Impact through Interactions with Phytoplankton

- Nutrient competition
- Light shading

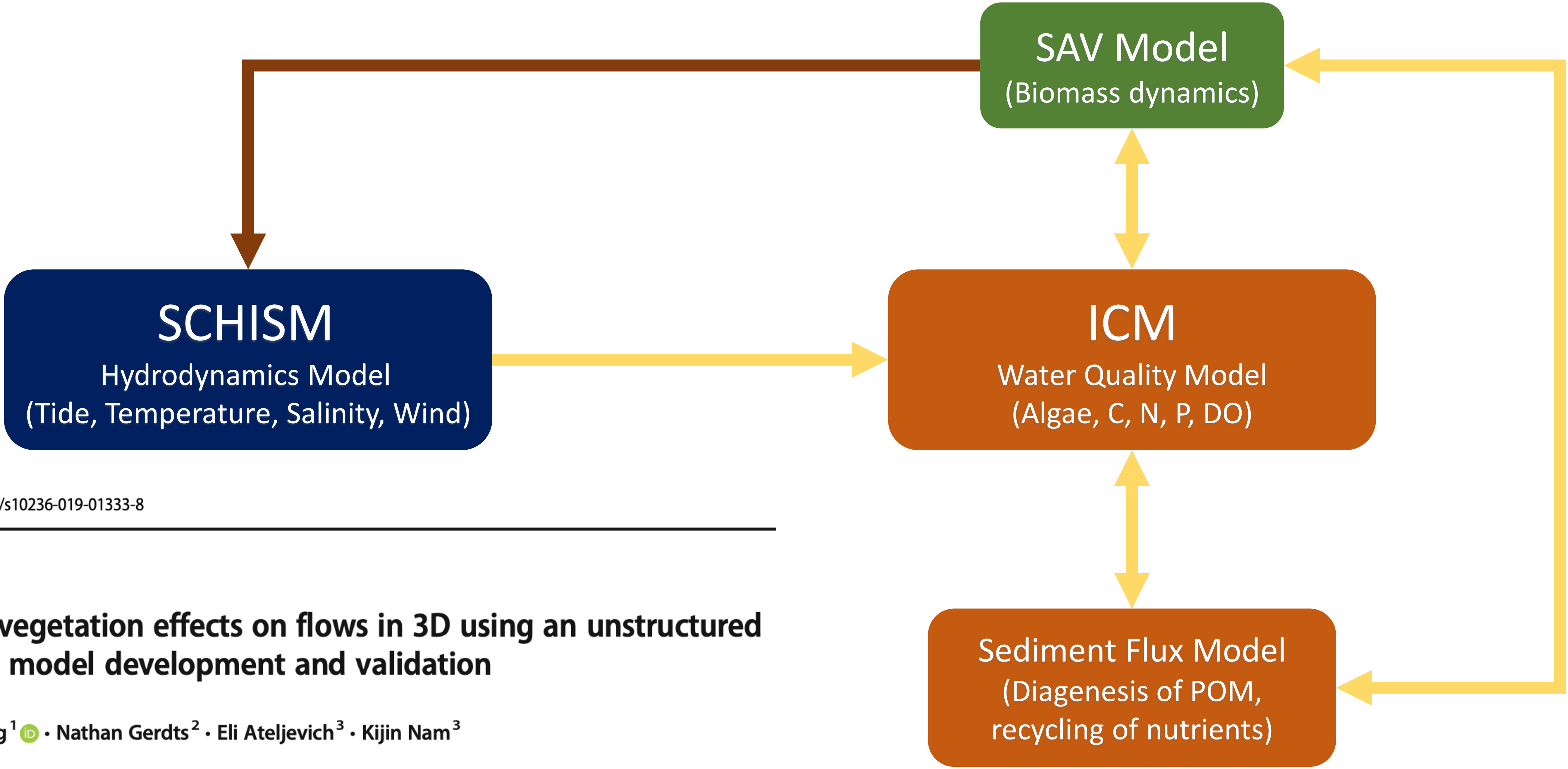


3)

Impact through Feedback Effects on Hydrodynamics

- Decreased local velocity
- Prolonged residence time
- Altered material transport

SCHISM-ICM-SAV



Ocean Dynamics
https://doi.org/10.1007/s10236-019-01333-8

Simulating vegetation effects on flows in 3D using an unstructured grid model: model development and validation

Yinglong J. Zhang[1] · Nathan Gerdts[2] · Eli Ateljevich[3] · Kijin Nam[3]

Received: 26 June 2019 / Accepted: 28 November 2019

Vegetation impacts on hydrodynamics in SCHISM

Continuity equation: $\nabla \cdot \mathbf{u} + \frac{\partial w}{\partial z} = 0$

Transport equation: $\frac{\partial C}{\partial t} + \nabla \cdot (\mathbf{u}C) = \frac{\partial}{\partial z}\left(\kappa \frac{\partial C}{\partial t}\right) + F_h$

Momentum equation: $\frac{D\mathbf{u}}{Dt} = \frac{\partial}{\partial z}\left(\nu \frac{\partial \mathbf{u}}{\partial z}\right) - g \cdot \nabla\eta(x,y,t) + \mathbf{f} + \mathbf{F_{veg}}$

where $\mathbf{f}$ is forcing terms in momentum treated explicitly in the numerical formulation – Coriolis force, baroclinic gradient, atmospheric pressure, earth tidal potential, horizontal viscosity and other forces.

$$\mathbf{F_{veg}} = 0.5 \cdot D_v \cdot N_v \cdot C_{D_v} \cdot \mathbf{u}|\mathbf{u}| \cdot L(x,y,z)$$

SAV-induced drag force

Turbulence closure equations:

SAV-induced additional source term

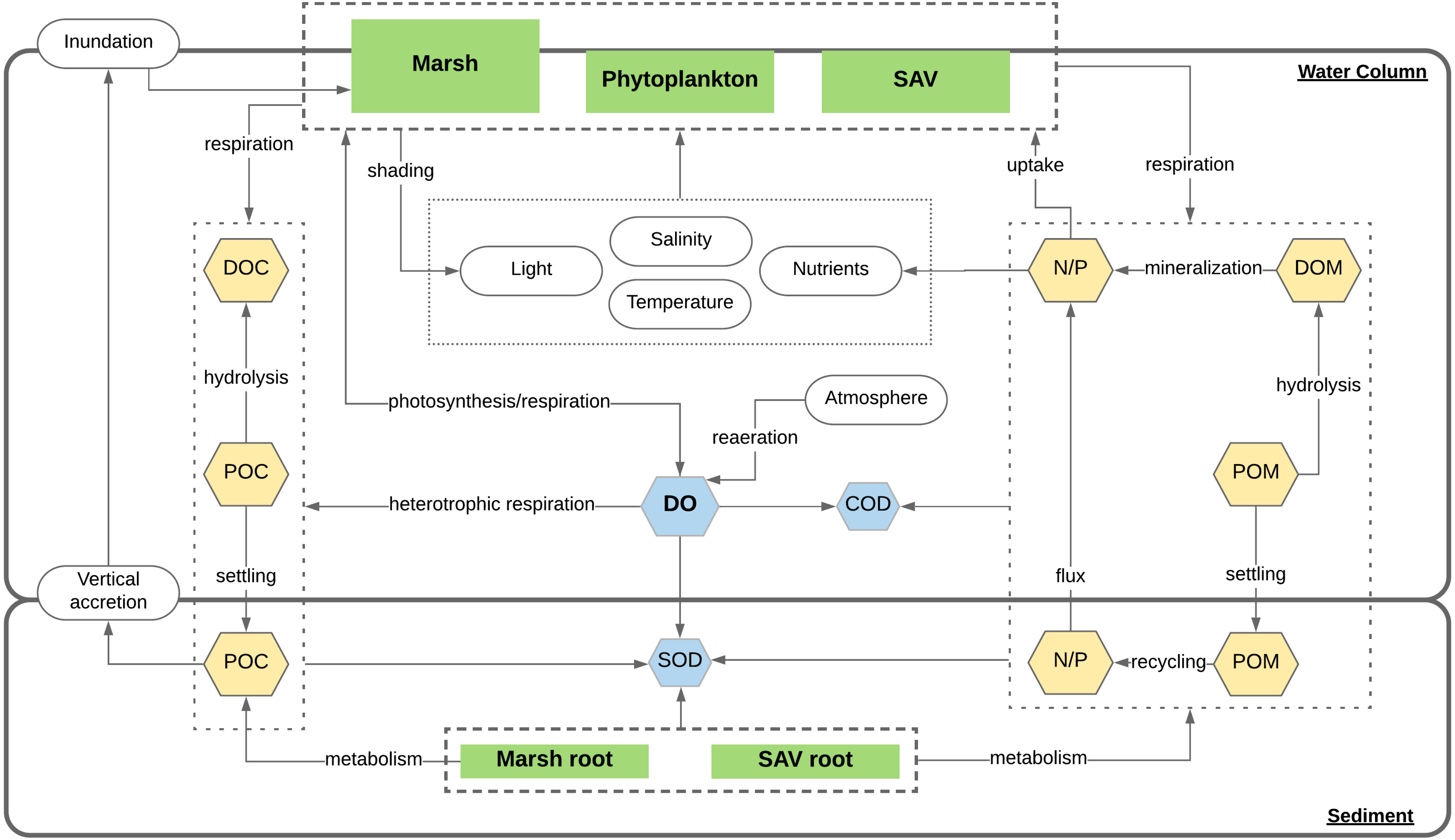
turbulent kinetic energy K: $\frac{DK}{Dt} = \frac{\partial}{\partial z}\left(\nu_k^{\psi} \frac{\partial K}{\partial z}\right) + \nu M^2 + \mu N^2 - \varepsilon + c_{fk} \cdot 0.5 \cdot D_v \cdot N_v \cdot C_{D_v} \cdot |\mathbf{u}|^3 \mathcal{H}(z_v - z)$

generic length-scale variable ψ: $\frac{D\psi}{Dt} = \frac{\partial}{\partial z}\left(\nu_\psi \frac{\partial \psi}{\partial z}\right) + \frac{\psi}{K}(c_{\psi 1}\nu M^2 + c_{\psi 2}\mu N^2 - c_{\psi 3}F_w\varepsilon) + \frac{\psi}{K}(c_{f\psi} \cdot 0.5 \cdot D_v \cdot N_v \cdot C_{D_v} \cdot |\mathbf{u}|^3 \mathcal{H}(z_v - z))$

where $\mathrm{D_v}$ is the stem diameter (m), $\mathrm{N_v}$ is vegetation density (number of stems per m^2), $\mathrm{C_{D_v}}$ is a bulk drag coefficient with a typical value of 1.13 (Garcia et al. 2004; Nepf and Vivoni, 2000) and L is a step function.

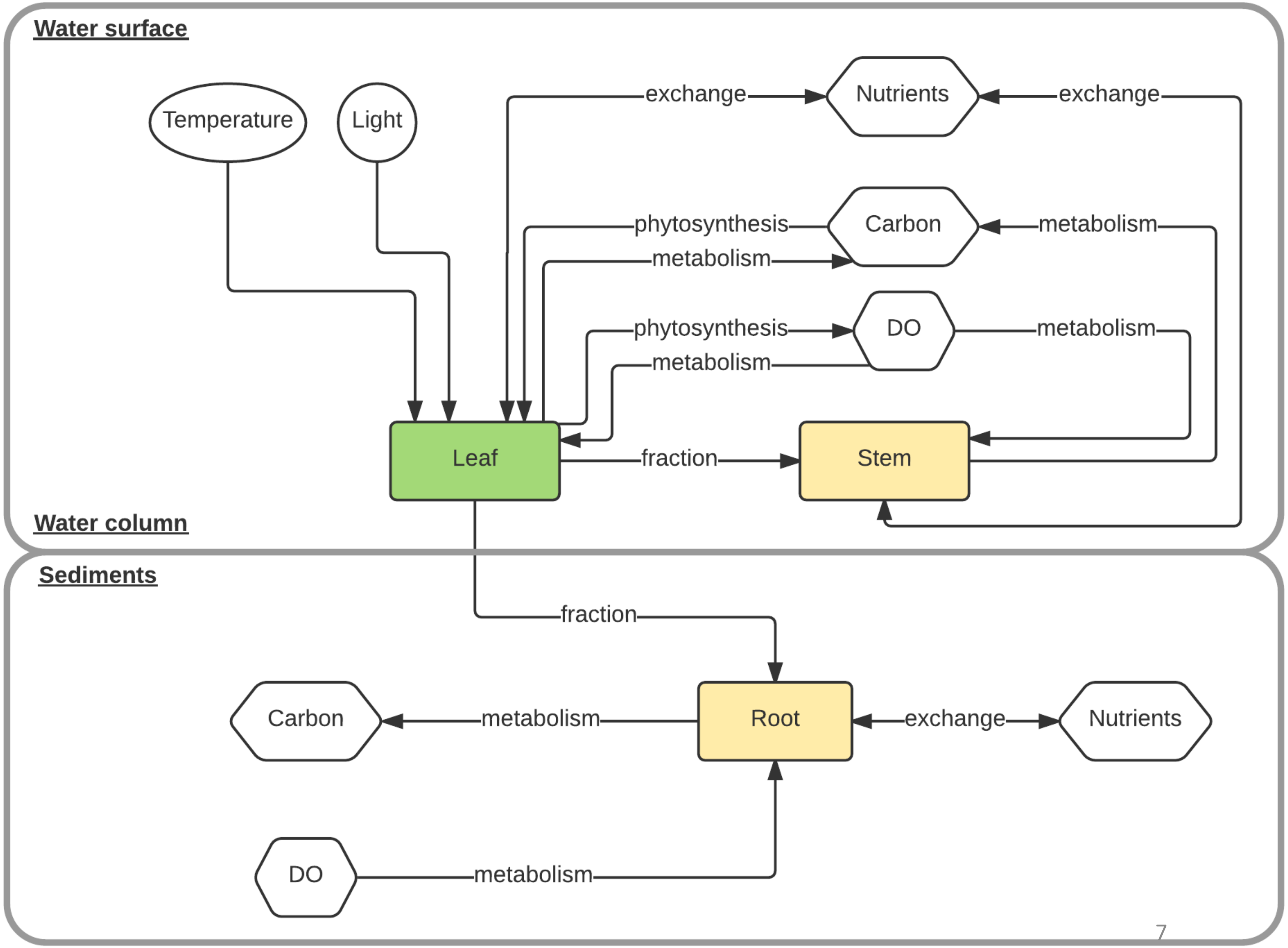
SAV impact on hydrodynamic is incorporated **implicitly** into the SCHISM hydrodynamics part by *Zhang et al. (2019)*, in order to avoid the stringent stability constraints associated with this term.

Fully-coupled ICM-VEG model



SAV component

- Three components of SAV biomass: leaf, stem and root.
- Leaf is the photosynthetic portion of the above-ground plant biomass.
    - Growth of leaf is a function of temperature, light and nutrient limitation.
- Stem is the structural, non-photosynthetic portions of the above-ground plant biomass.
- Root is the below-ground portions of the plant biomass associated with anchoring the plant and with nutrient uptake



Formulations of the SAV biomass

$$\frac{dLF}{dt} = Plf \cdot (1 - Fam) \cdot FPlf \cdot LF - BMlf \cdot LF$$

$$\frac{d\,ST}{dt} = Plf \cdot (1 - Fam) \cdot FPst \cdot LF - BMst \cdot ST$$

$$\frac{d\,RT}{dt} = Plf \cdot (1 - Fam) \cdot FPrt \cdot LF - BMrt \cdot RT$$

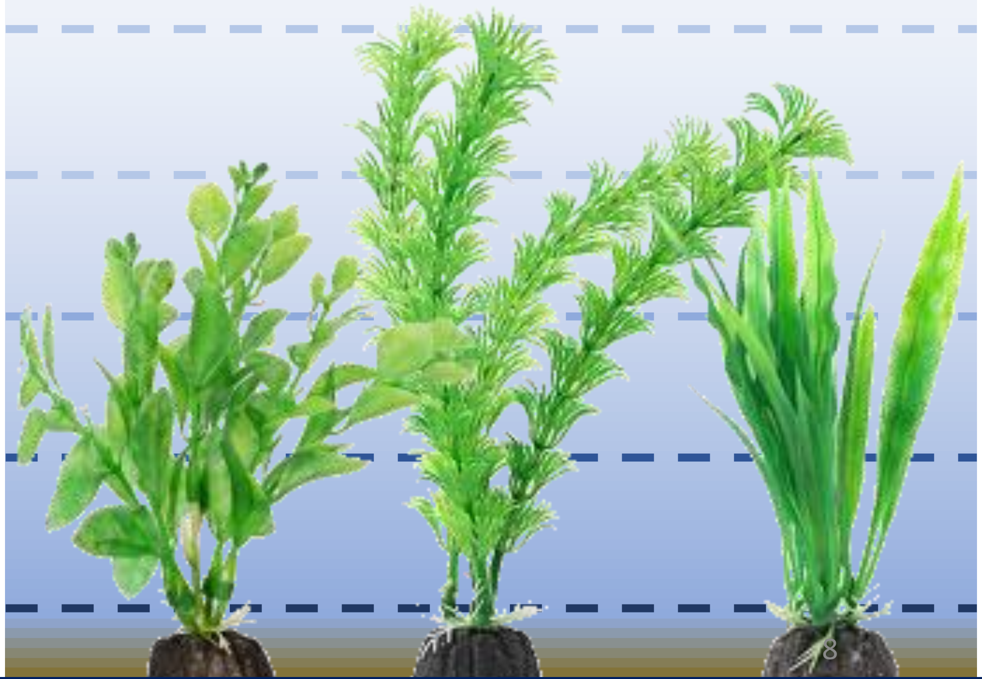
$$Hcan = \min(wdep, rlf \cdot LF + rst \cdot ST + rrt \cdot RT + hcansav0)$$

Parameters:

- $Plf\ and\ Pep$ are leaf production rate (d^{-1}).
- $Fam, FPlf, FPst, FPrt$ are fractions of production devoted to active metabolism, routed to leaf, stem, and root biomass.
- $BMlf, BMst, BMrt$ are basal metabolism (d^{-1}).
- $rlf, rst, rrt, hcansav0$ are coefficients to transfer SAV biomass to canopy height. $wdep$ is water depth.

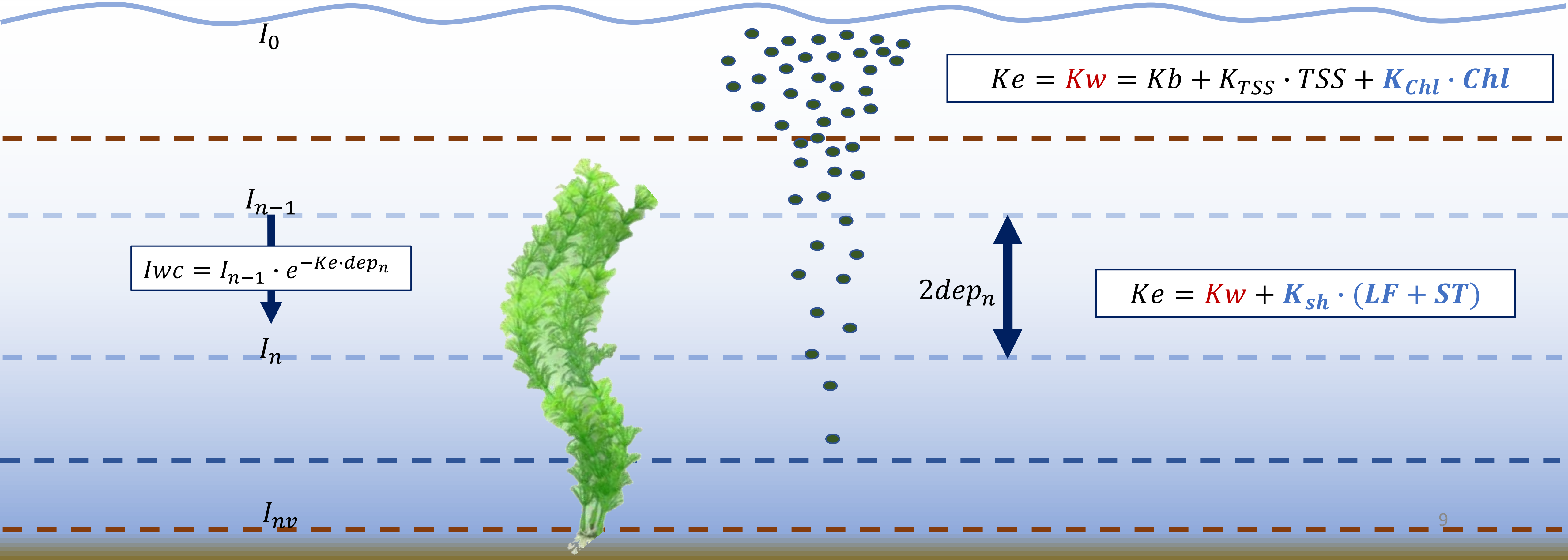
State variables:

LF, ST, RT are biomasses of leaves, stems, and roots ($g\ C\ m^{-3}$);

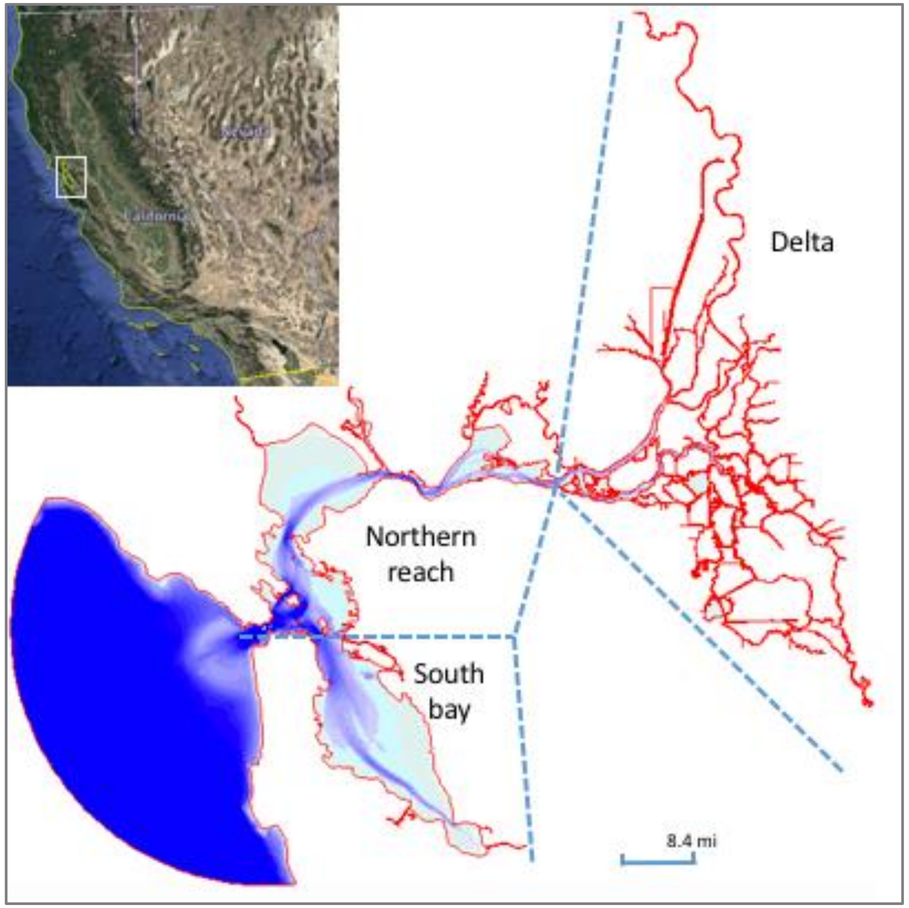


Interactions of SAV and light

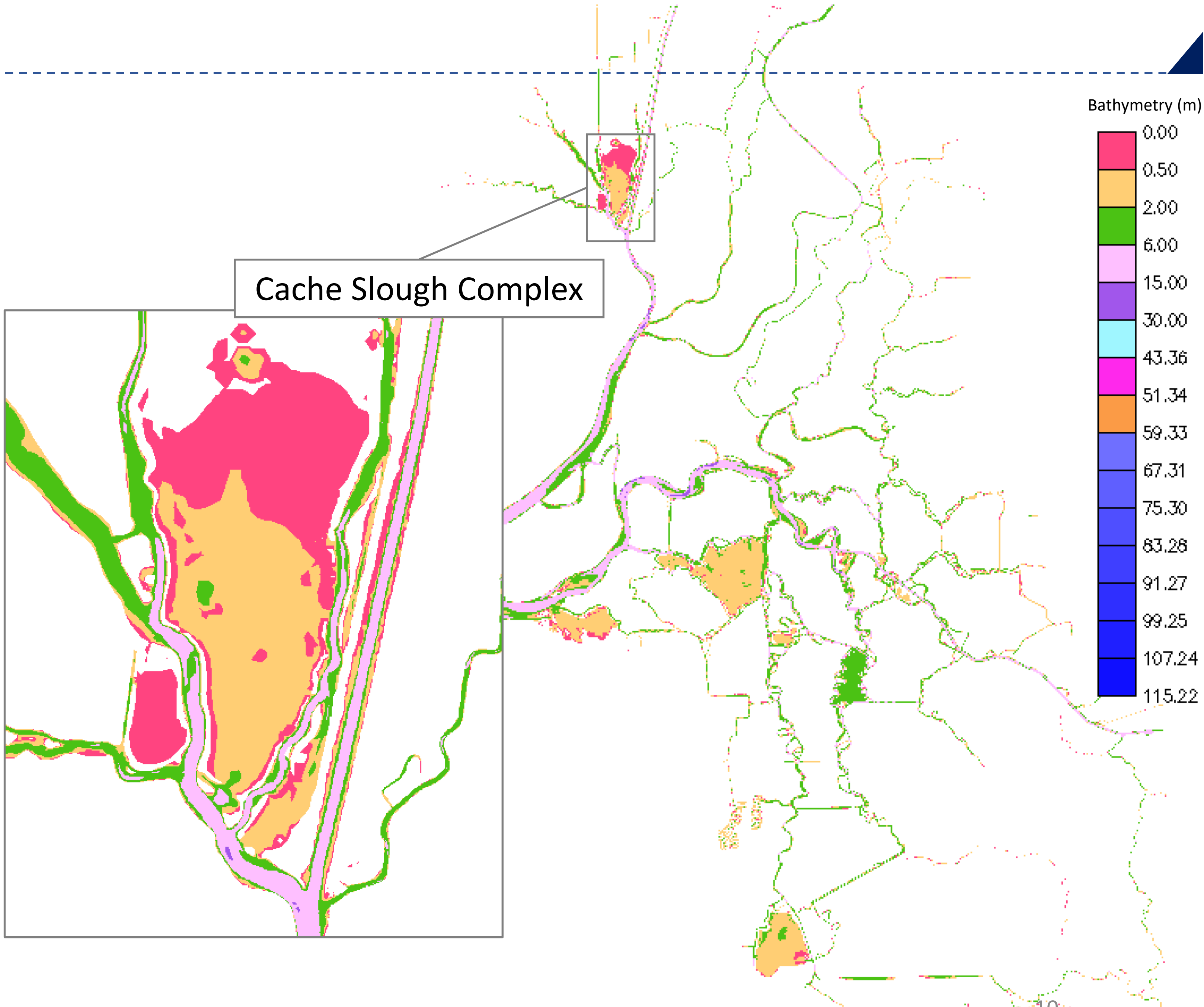
- Iwc is the irradiance at certain layer ($\mathrm{E\ m^{-2}\ d^{-1}}$); I_0 is surface irradiance; I_n is irradiance at the bottom of vertical layer n.
- Ke is total diffuse light attenuation ($\mathrm{m^{-1}}$); Kw is diffuse light attenuation in layers without SAV ($\mathrm{m^{-1}}$); Ksh is light attenuation by SAV absorption ($\mathrm{m^2\ g^{-1}\ C}$).



Study area

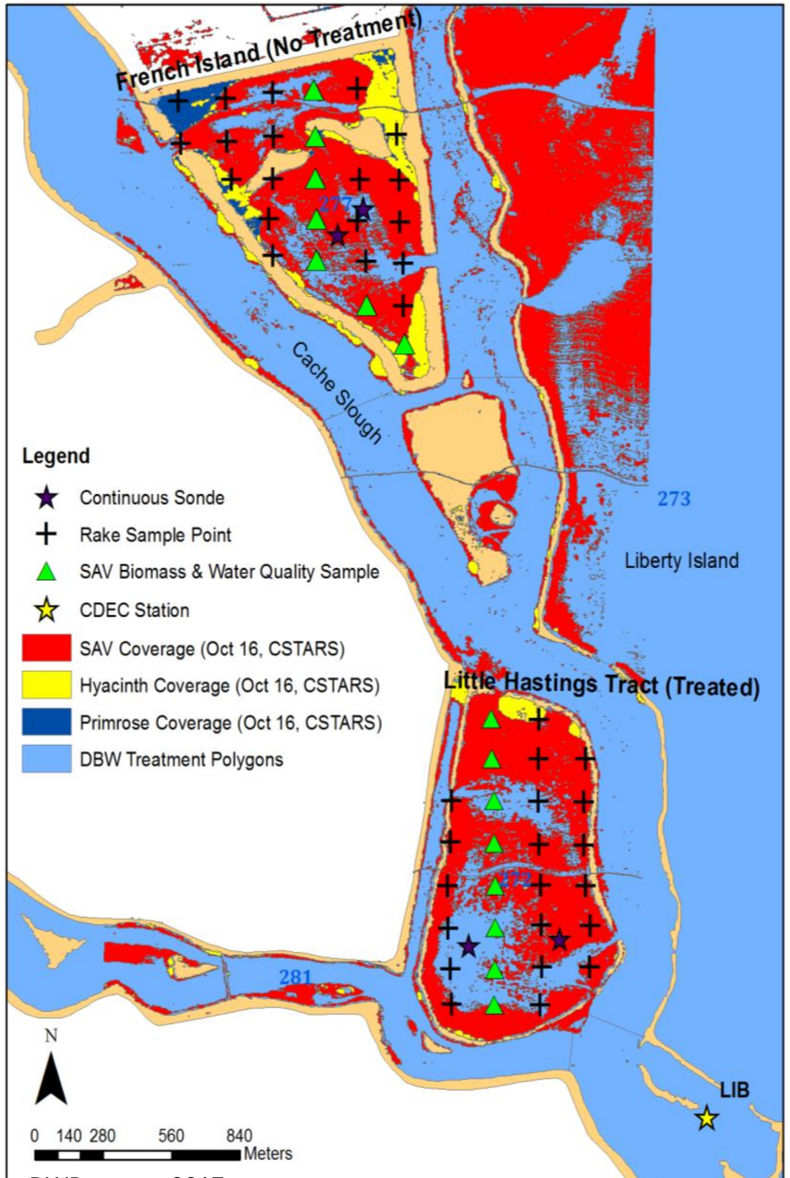


- Cut out from the Bay-Delta grid.
- Complex geometry with large shallow habitat and deep channels
- Influence by both tide and flow discharges

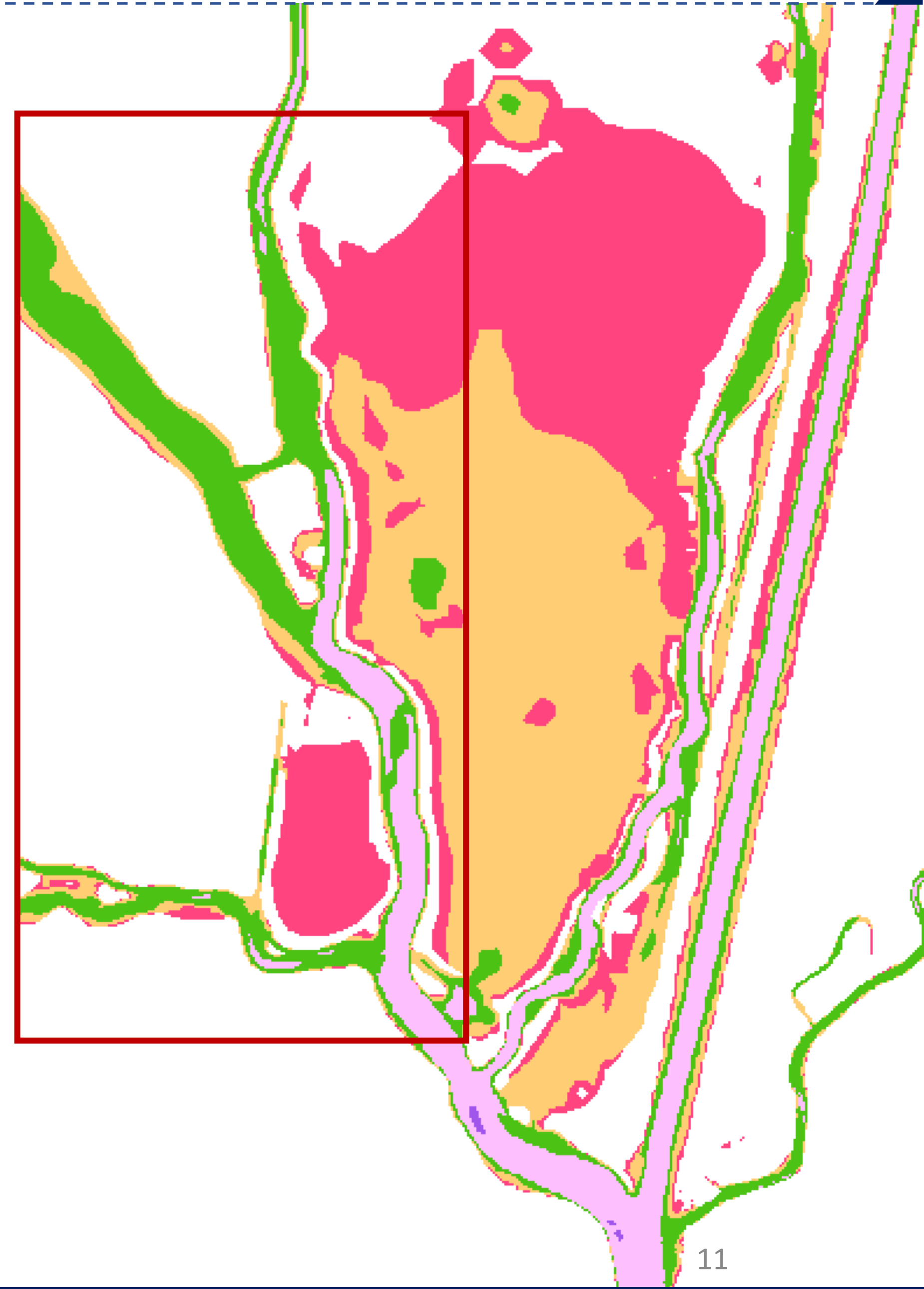


Study area

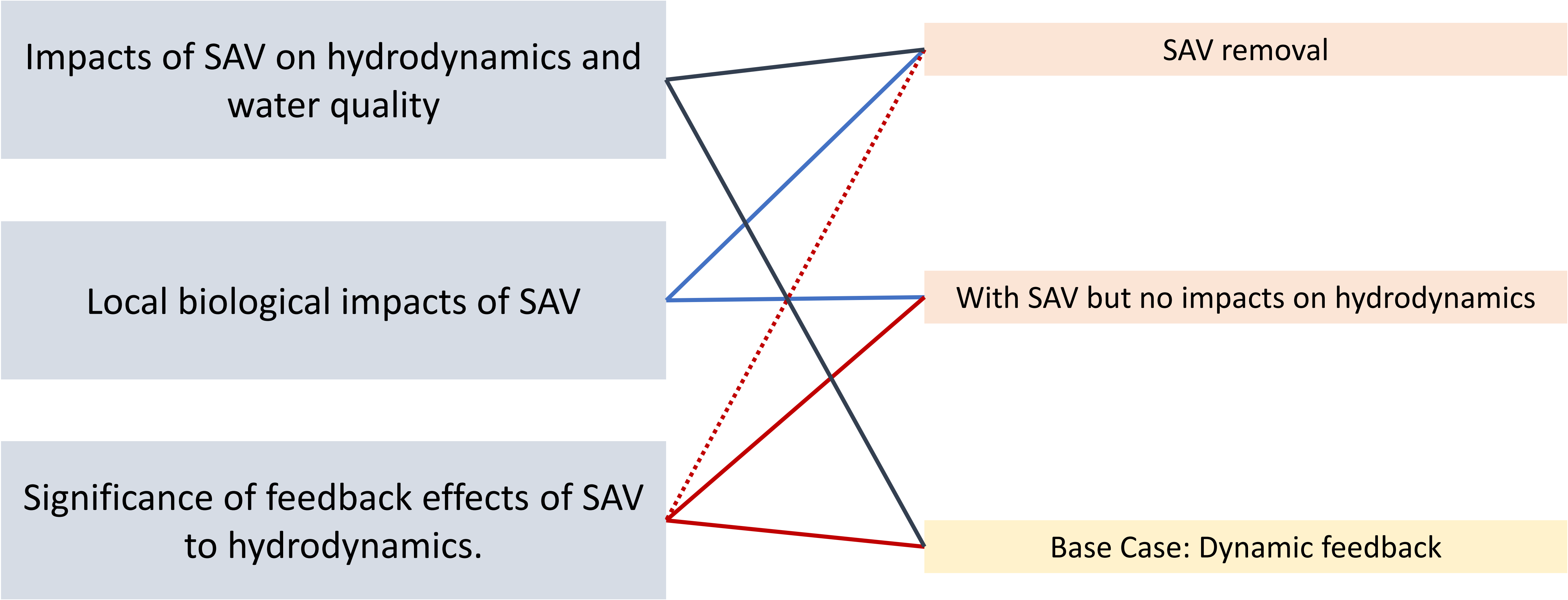
- Little Hastings Tract and French Island, two of the selected locations for this study, are hydrologically connected to Liberty Island and have been consistently infested with SAV in recent years (Shruti Khanna, CDFW).
- For model initiation and validation, we mostly use the observed SAV distributions.
- French Island (no herbicide treatment) and Little Hastings Tract (treated) are chosen for comparison. But French Island is not included in the current model domain.



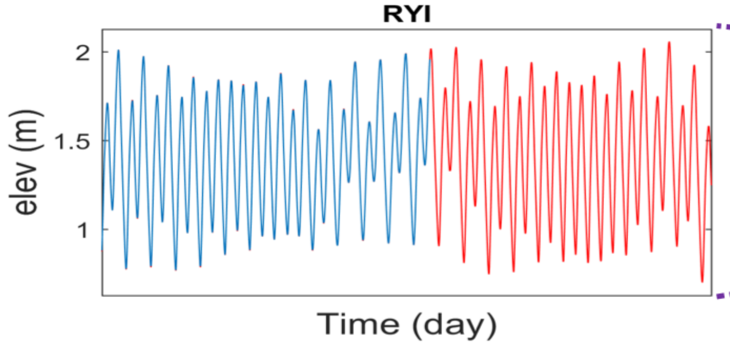
DWR report, 2017

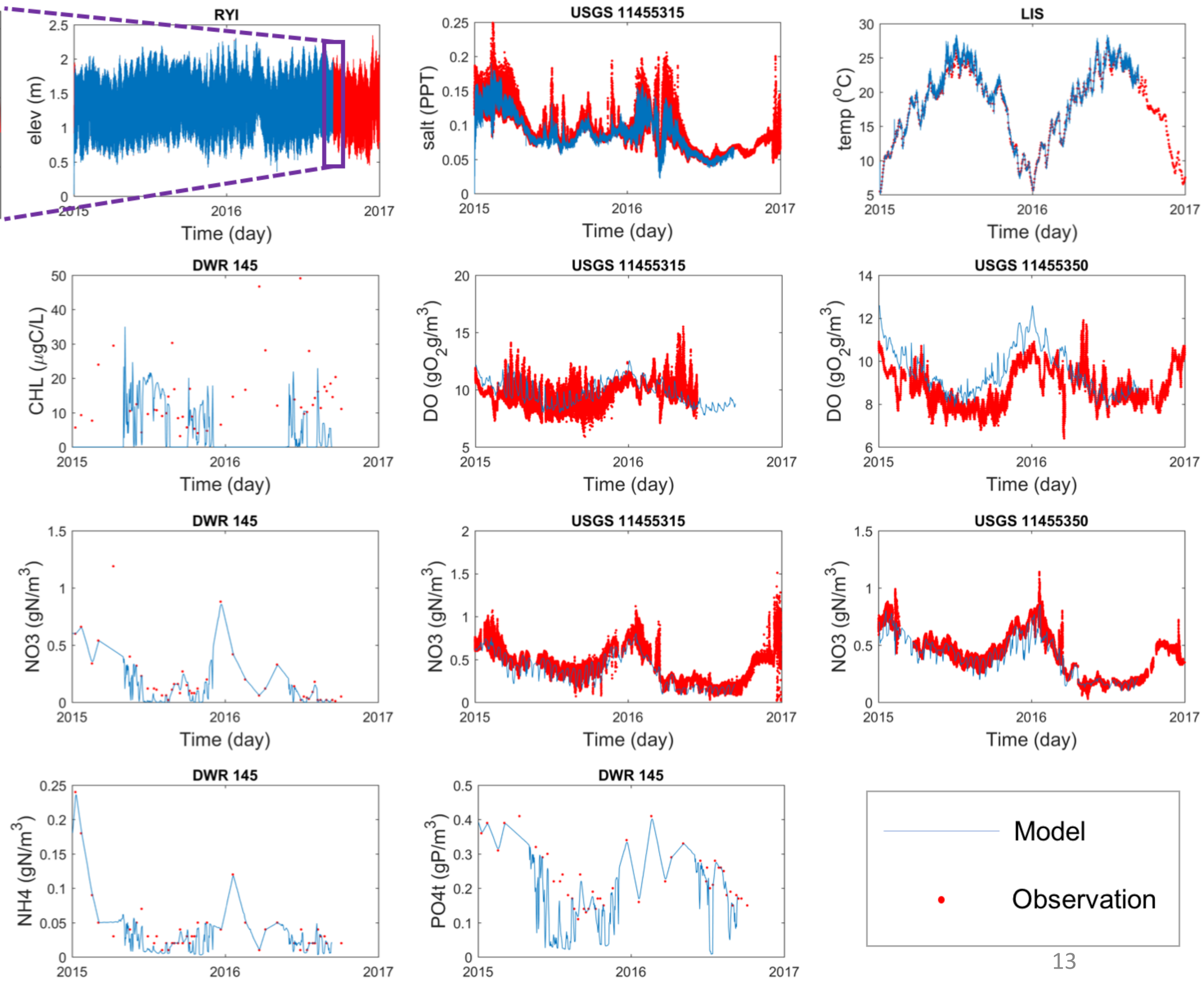


Model experiments



Model calibrations





- The elevation is mainly controlled by the boundary condition and fits the observation in Cache Slough.
- Salinity is low in this area and the model simulation matches the observed temporal variations. The modelled temperature agrees with the observations.
- Overall, the model catches the magnitude of the chlorophyll-a concentration.
- It matches both the pattern and magnitude of the dissolved oxygen.
- The nutrient concentrations agree well with the observations well in terms of temporal variations and values.

SAV biomass and distributions

French Island (No Treatment)

- Start from uniform biomass 100 g/m^2.

Not in model domain

Channel

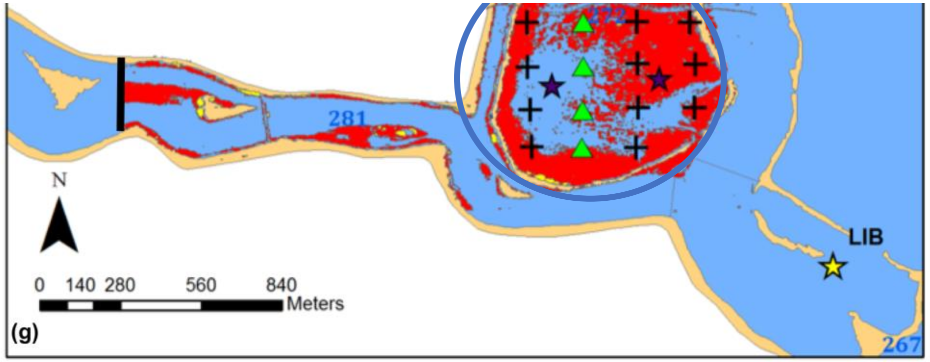
- Declines by half in 60 days in channels.
- Almost completely disappears in 180 days.

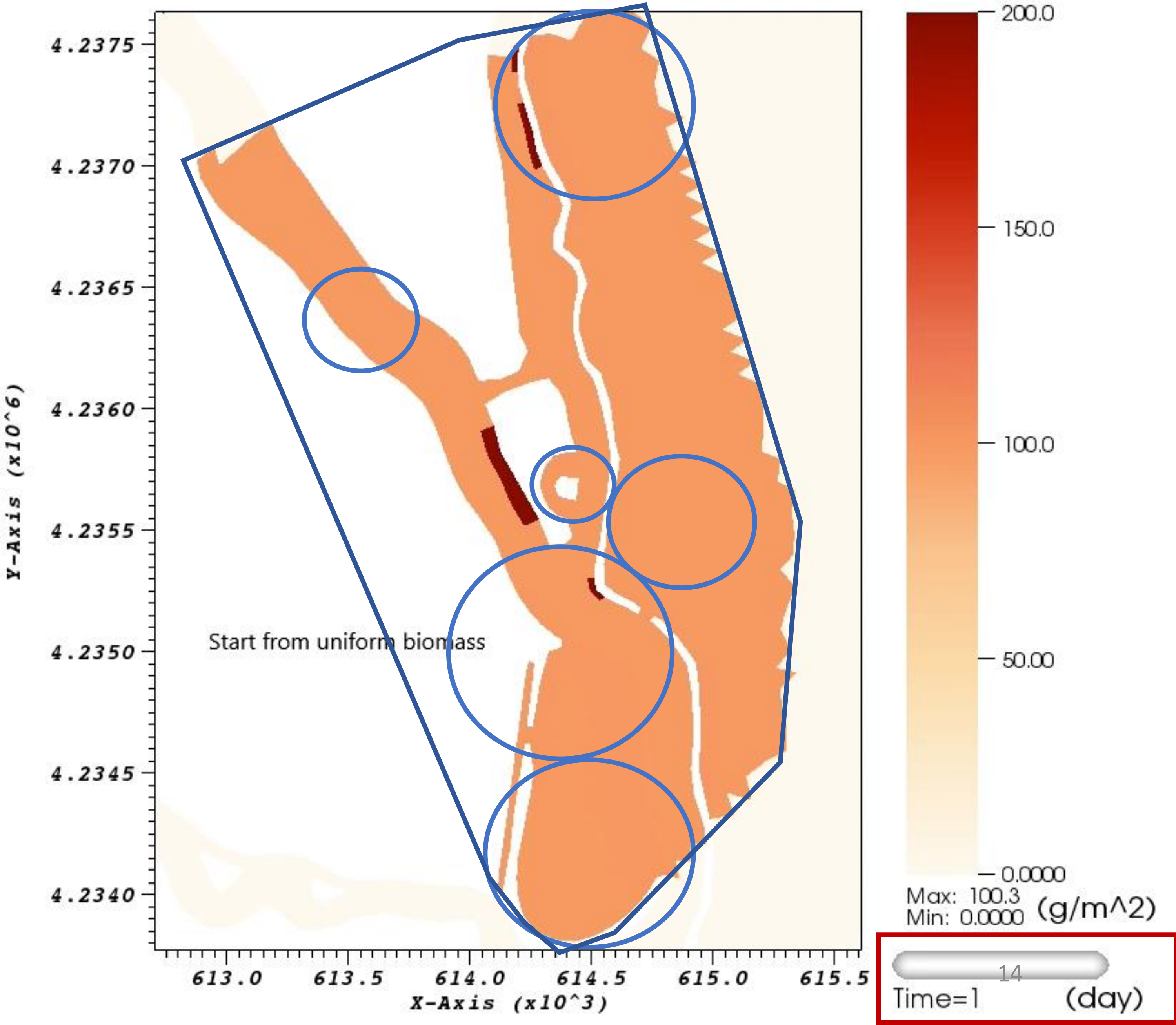
SAV Biomass & Water Quality Sample

Liberty Island

Shoal

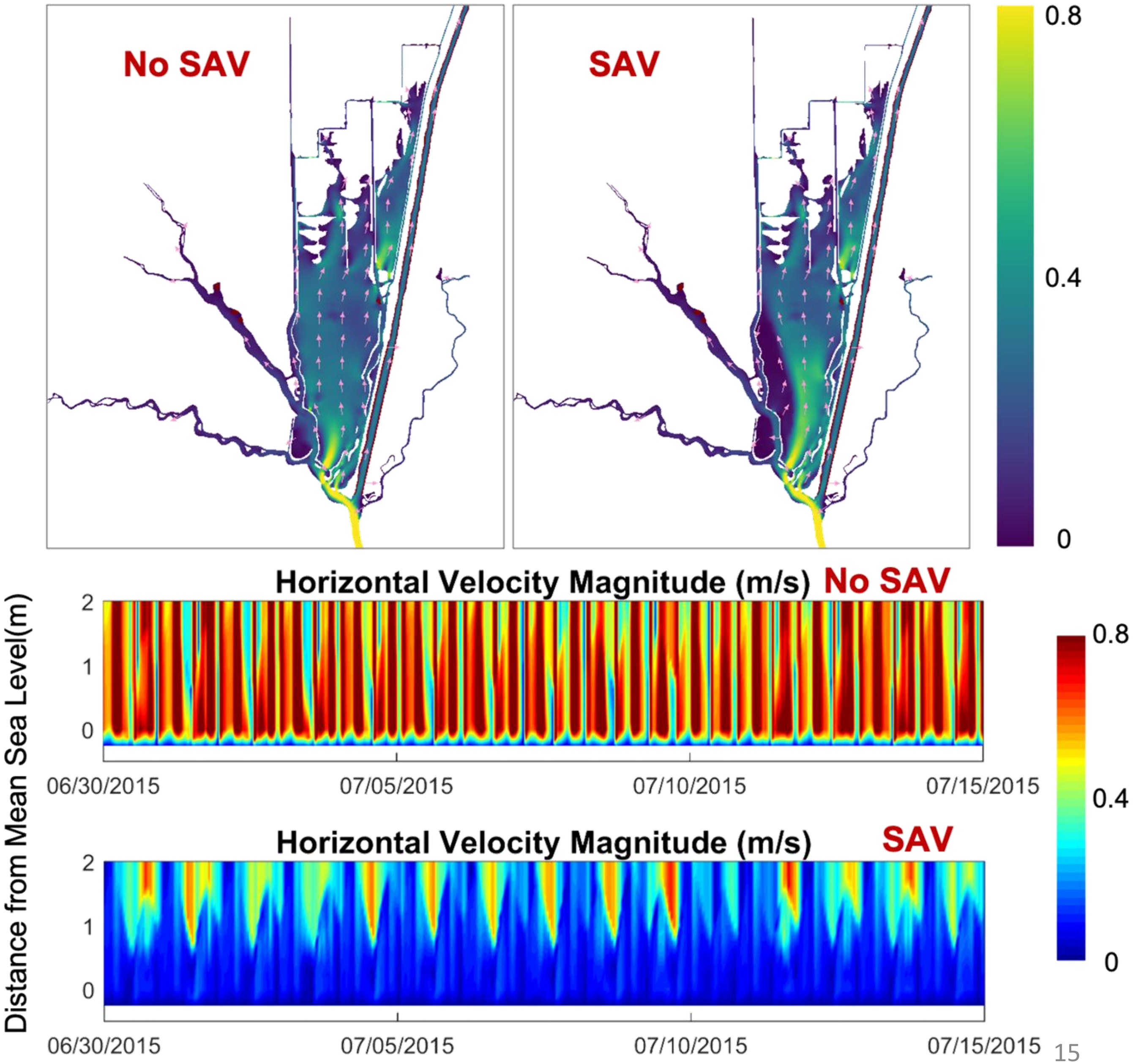
- Growth in shallow regions
- Clear summer-fall bloom pattern





Impacts of SAV on flow fields

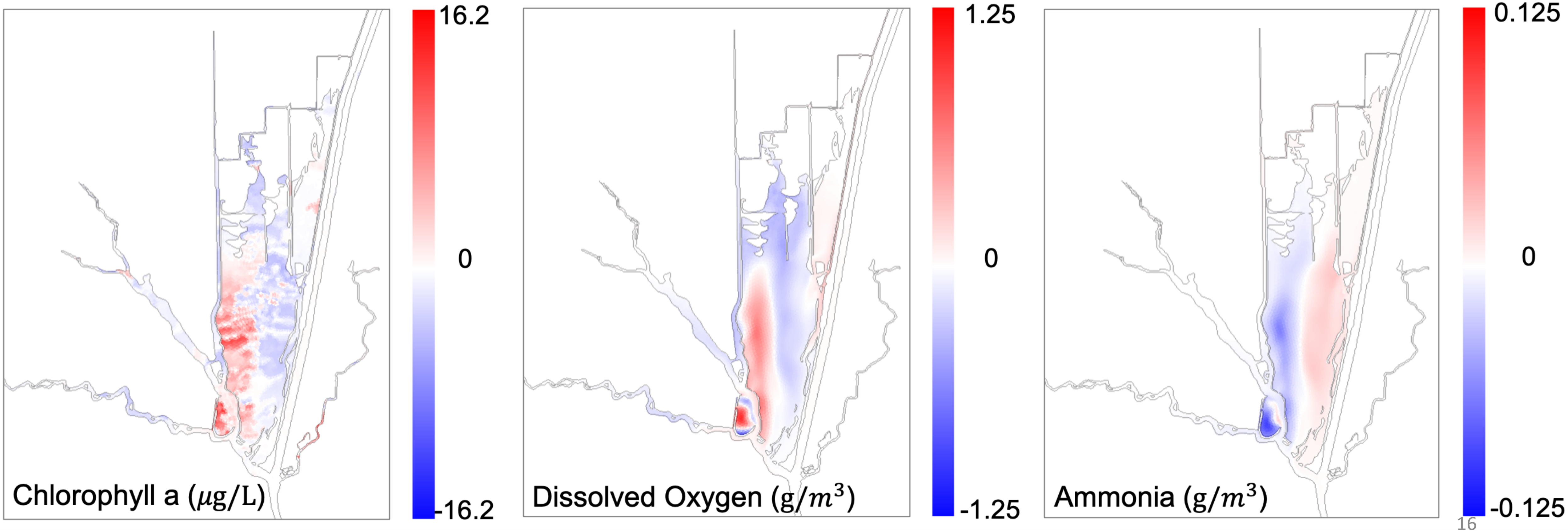
- Flow is more channelized
- Flow velocity is larger in areas without SAV
- Flow velocity is largely reduced over SAV beds
- The difference of velocity magnitude can be 0.2 m s^{-1}



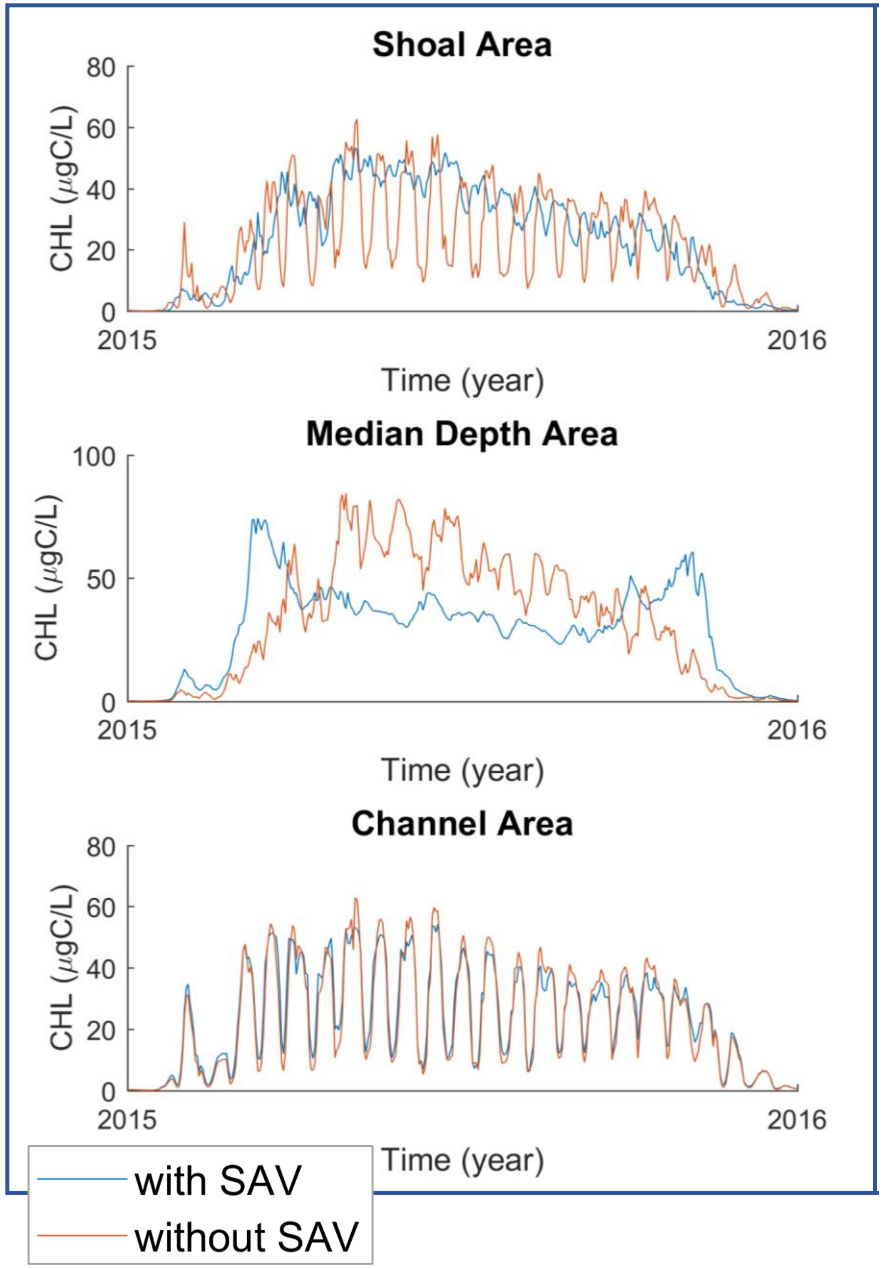
Impacts of SAV on water quality

- Chl-a increases in local SAV beds while decreases in the rest area
- SAV increases DO locally from production of both SAV and increased phytoplankton
- NH_4^+ decreases due to local uptake in the SAV beds, while increases outside the SAV beds

[With SAV impacts on hydrodynamics] - [no SAV]



Phytoplankton Biomass VS. SAV Canopy Height



Shoal Area:

With the presence of SAV, fluctuation of phytoplankton concentration is greatly reduced.

Median Depth Area:

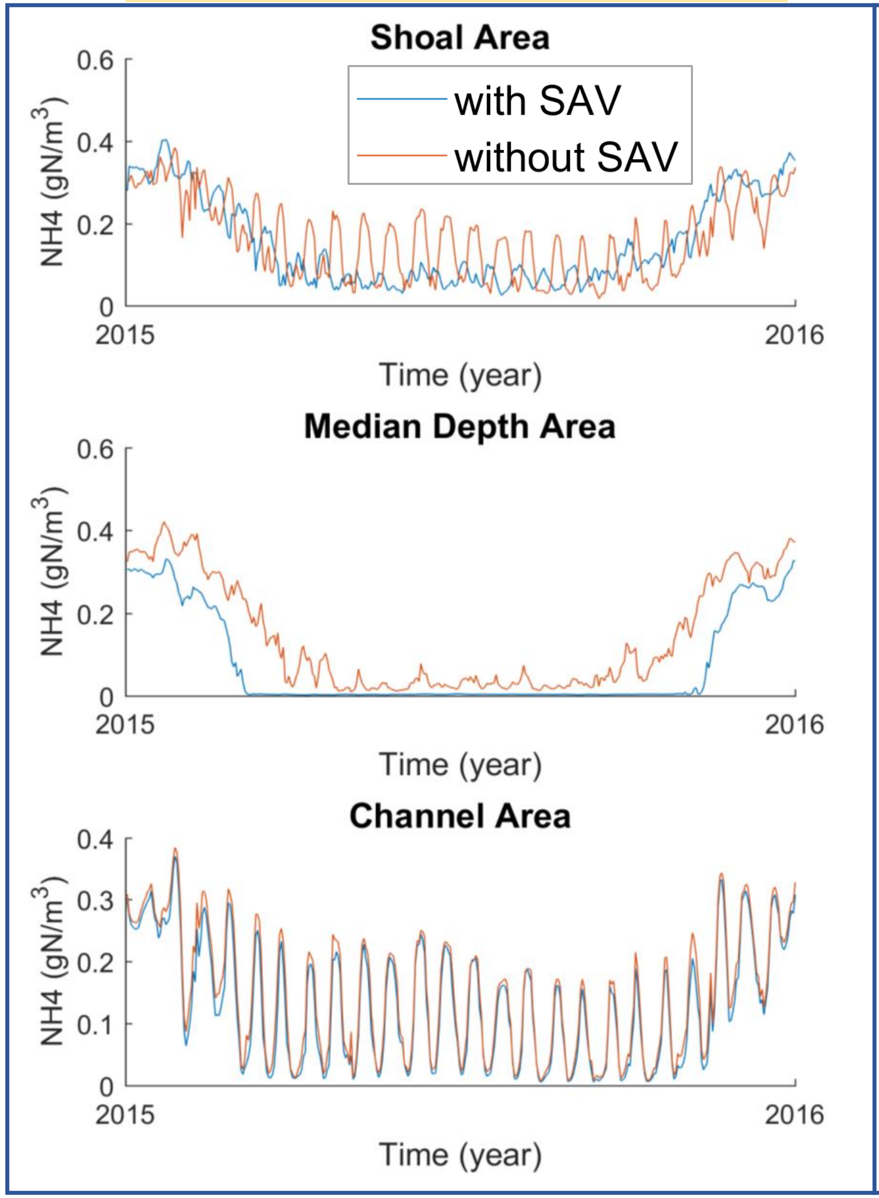
In the presence of SAV, the phytoplankton has double blooms in early spring and late fall, while its concentration is lower in summer.

Deep Channel Area:

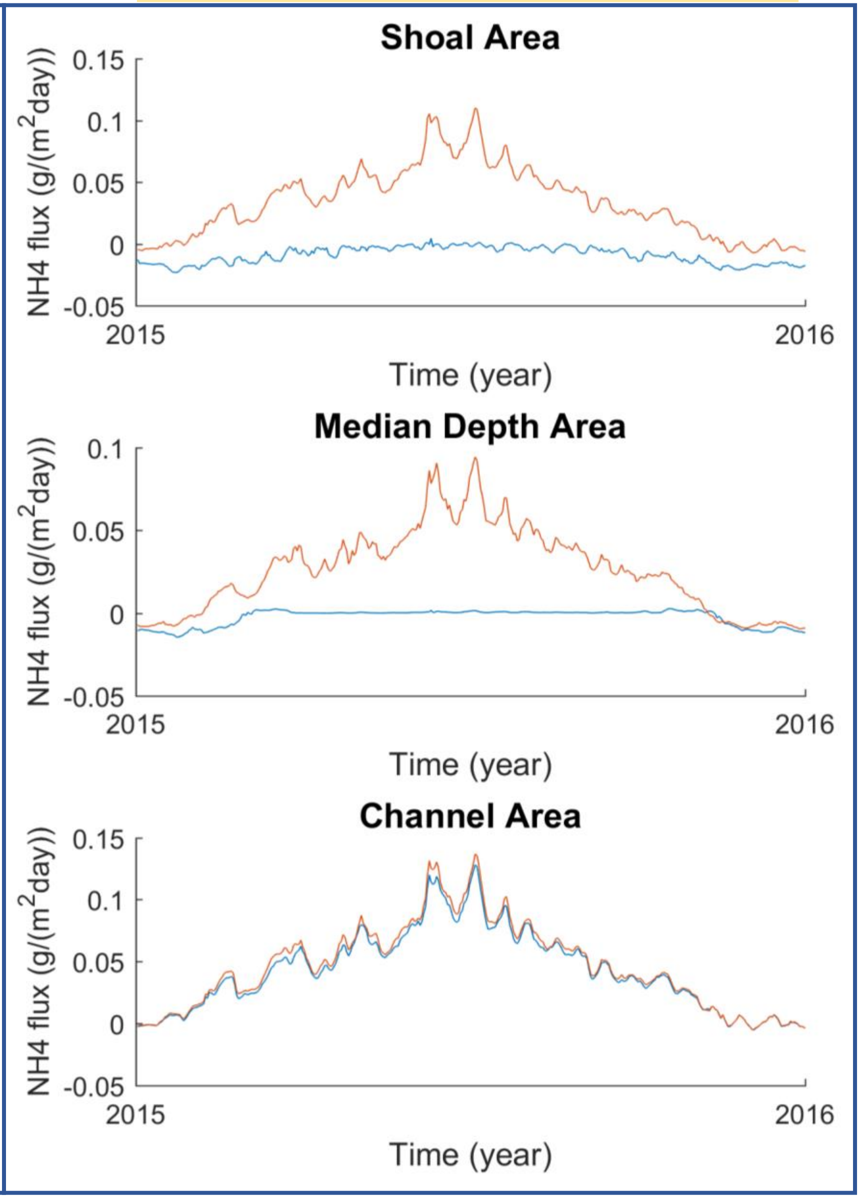
There is a small decrease in the phytoplankton concentration with same fluctuation.

Nutrient Concentration and Bottom Flux

Ammonia Concentration



Ammonia Bottom Flux



Shoal Area:

- With SAV nutrient has smaller fluctuations but is not limited for the growth of phytoplankton or SAV.
- SAV plays a significant role in decreasing the recycling inorganic nutrients.

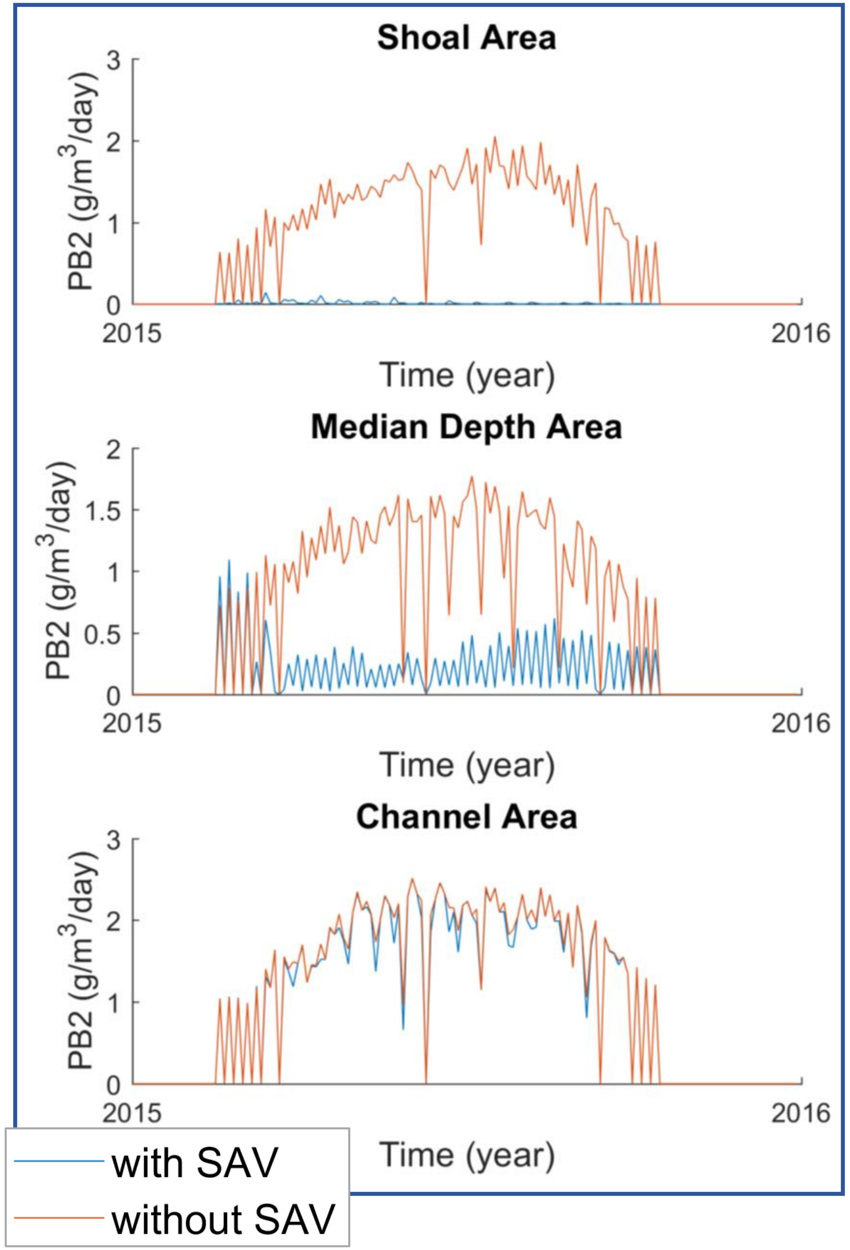
Median Depth Area:

- With SAV the nutrient is lower in winter but still unlimited for the phytoplankton bloom, while in summer, the nutrient is used up.
- Nutrient supply limits the growth of both SAV and phytoplankton since late spring to late fall.

Deep Channel Area:

- There is slight decrease of nutrients.

Phytoplankton Local Growth Rates



Green Algae Local Growth Rate

Shoal Area:

- With SAV, local growth rate decreases to almost zero.
- Light limitation is the main reason while nutrient is not limited.

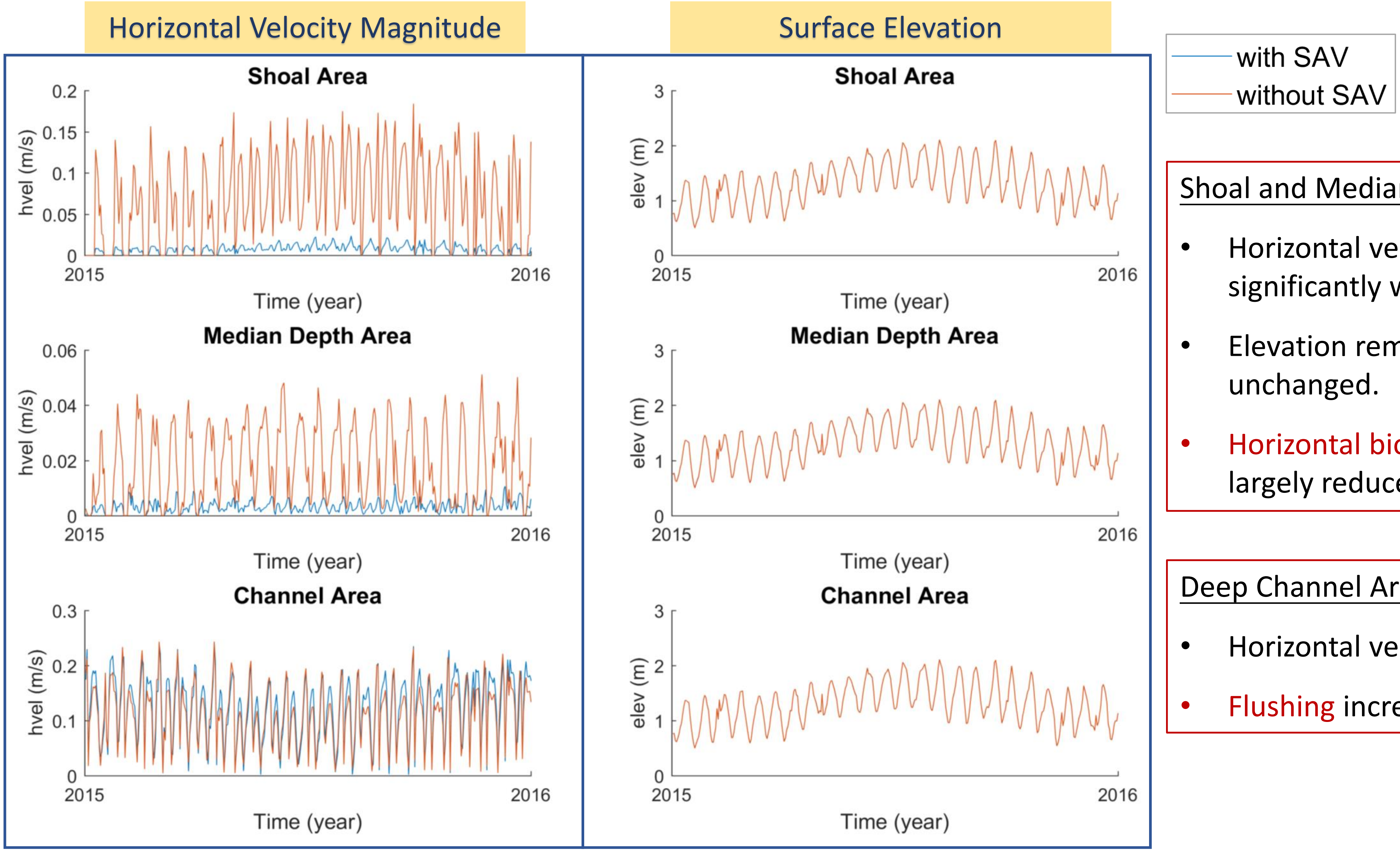
Median Depth Area:

- With SAV, local growth rate is reduced from late spring.
- Nutrient limitation is dominant.

Deep Channel Area:

- Similar local growth rates with or without SAV

Horizontal Phytoplankton Transport



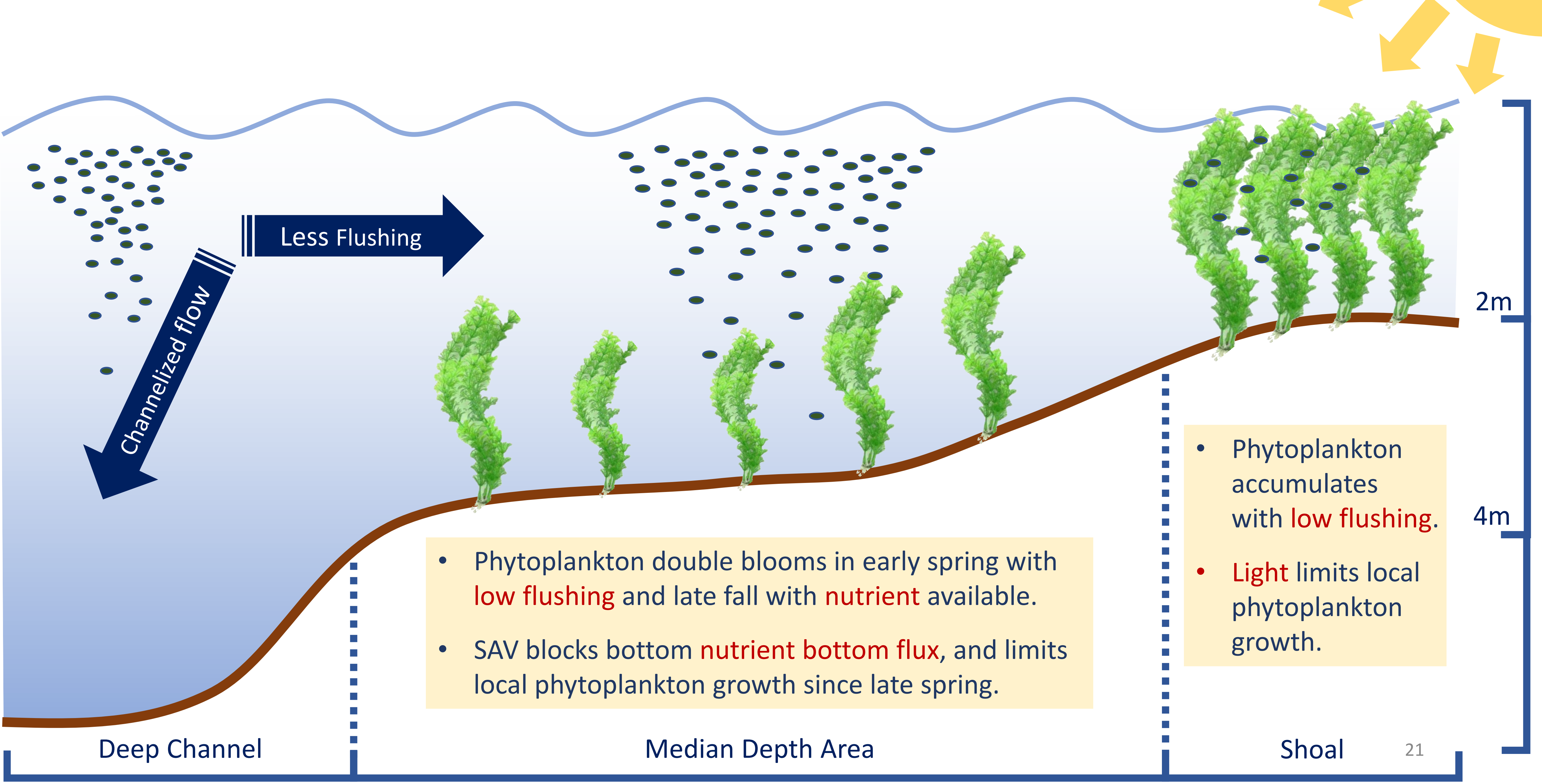
Shoal and Median Depth Areas:

- Horizontal velocity decreases significantly with SAV.
- Elevation remains almost unchanged.
- Horizontal biomass transport is largely reduced in these areas.

Deep Channel Area:

- Horizontal velocity increases.
- Flushing increases in this areas.

Pattern of SAV-phytoplankton interactions



- Phytoplankton double blooms in early spring with low flushing and late fall with nutrient available.
- SAV blocks bottom nutrient bottom flux, and limits local phytoplankton growth since late spring.

- Phytoplankton accumulates with low flushing.
- Light limits local phytoplankton growth.

Local biological impacts of SAV on water quality

Phytoplankton:

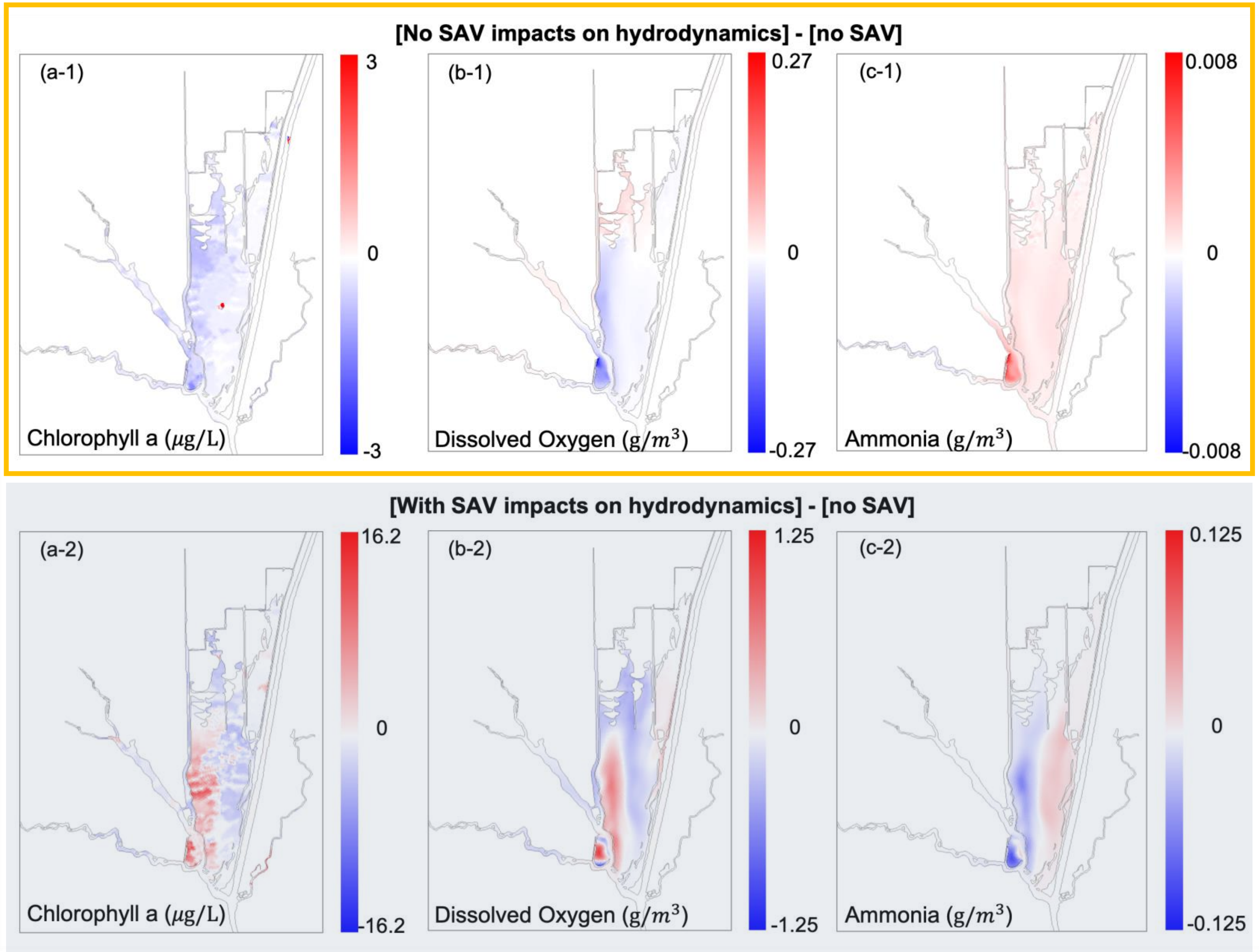
- SAV decrease phytoplankton biomass.
- Less than 18.5% of the difference compared to the total change.

Dissolve Oxygen:

- SAV decrease DO by increasing heterotrophic respirations
- Less than 21.6% of the difference compared to the total change.
- Differences are minor due to supersaturation.

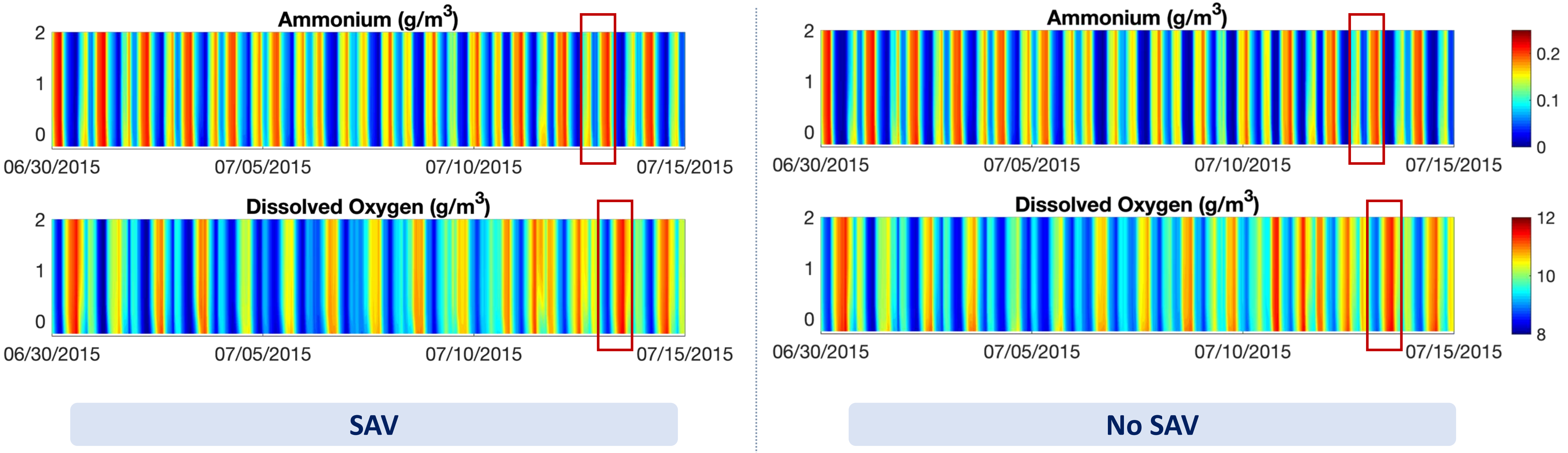
Nutrients:

- SAV beds tends to be a net source of ammonia.
- Less than 6.4% of the difference compared to the total change.



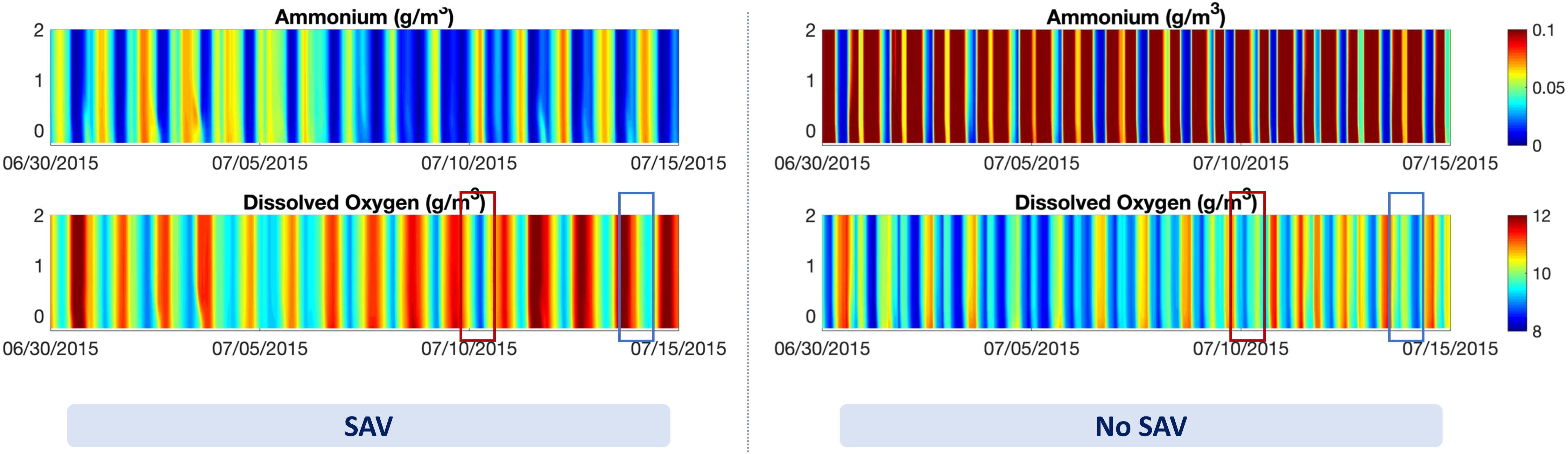
Local biological impacts of SAV on water quality on diurnal scale

- SAV promotes the concentration of ammonia
- SAV increases the daytime DO concentration
- SAV decreases the nighttime DO concentration



Significance of feedback effects to the hydrodynamics

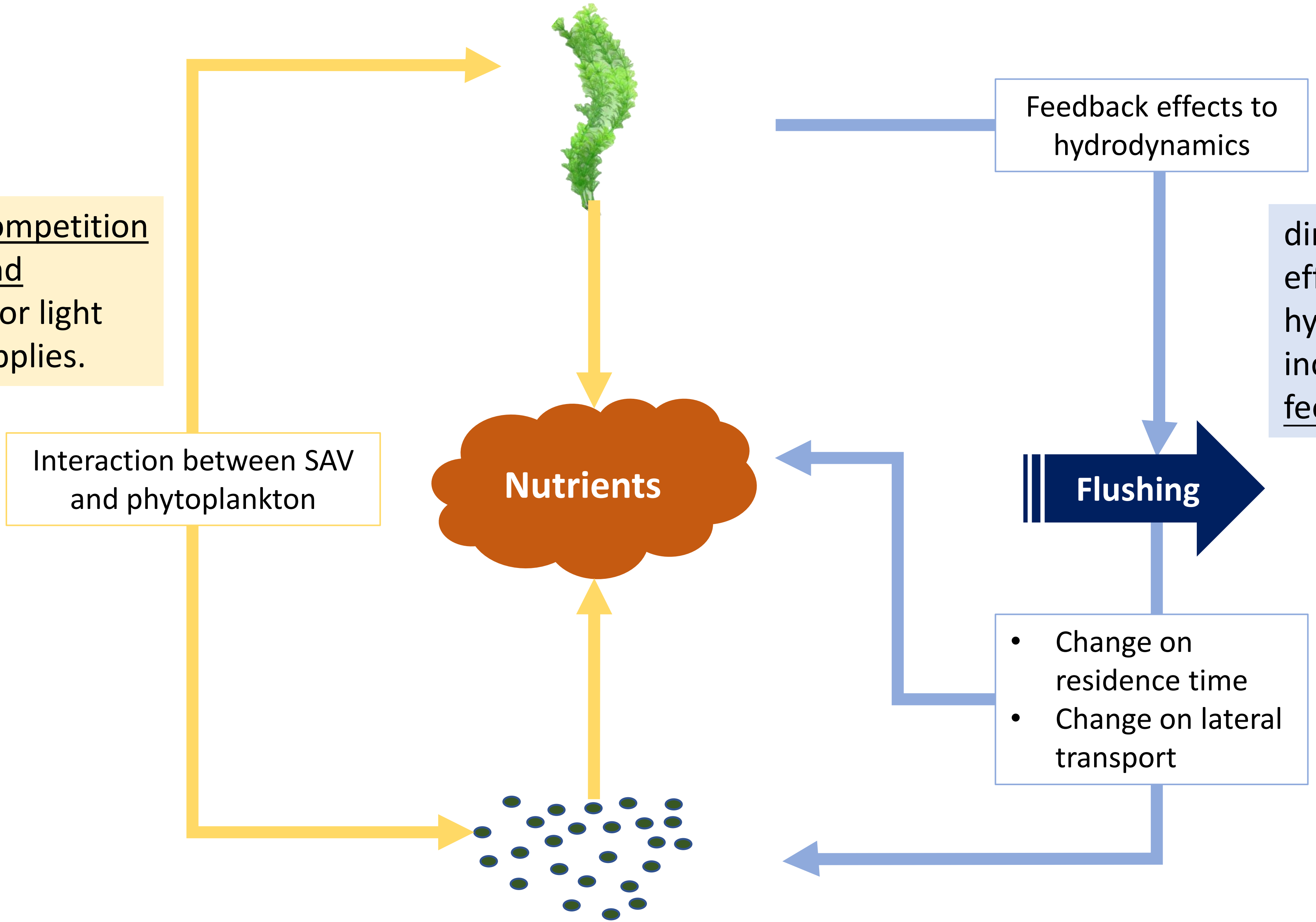
- The concentration of ammonia largely decreases due to uptake by phytoplankton
- Change of DO diurnal dynamics is non-linear considering both the local kinetic processes and transports



Summary

A new version of SAV model SCHISM-ICM-SAV.

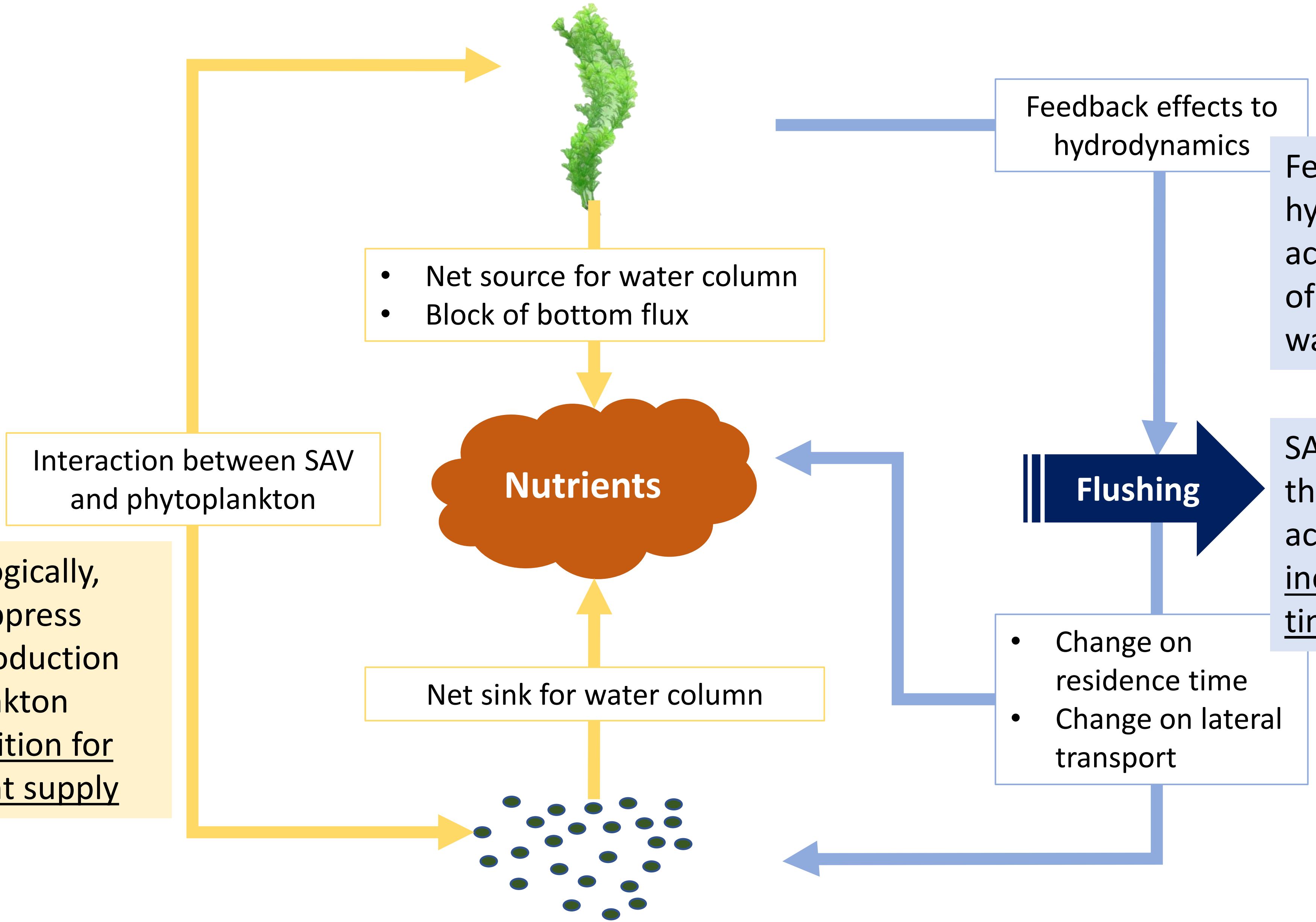
simulates the <u>competition between SAV and phytoplankton</u> for light and nutrient supplies.



directly simulates the effects from SAV on hydrodynamics, and includes the <u>biological feedback to physics</u>

Summary

Overall, SAV tends to increase phytoplankton and dissolved oxygen, and decrease inorganic nutrients.



Feedback on hydrodynamics accounts for up to 80% of the changes of the water quality variables.

SAV tends to encourage the phytoplankton accumulation by <u>increasing the residence time.</u>

Locally and biologically, SAV tends to suppress local primary production of the phytoplankton through <u>competition for light and nutrient supply</u>

Questions?

Nicole Cai: ncai@vims.edu