Effect of Submerged Aquatic Vegetation on Chesapeake Bay Water Quality

Carl F. Cerco[1] and Richard Tian[2]

[1]Attain, Inc. 1750 Forest Drive, Suite 130, Annapolis, Maryland 21401
(769) 230-5543 carlcerco@outlook.com

[2]University of Maryland Center for Environmental Studies (UMCES) 1750 Forest Drive, Suite 130, Annapolis, Maryland, Maryland 21401 (410) 295-1328 rtian@chesapeakebay.net

Abstract

The relationship between submerged aquatic vegetation (SAV) and Chesapeake Bay water quality is examined by employing the 2017 version of the Chesapeake Bay Water Quality and Sediment Transport Model. The model indicates SAV enhances nutrient transfer from bottom sediments to overlying water. The enhanced transfer is equivalent to 1.67% of the watershed nitrogen load and 4.72% of the watershed phosphorus load under 1991-2000 conditions. The recycled nutrients stimulate phytoplankton production and concurrent dissolved oxygen (DO) production in surface waters. Enhanced algal biomass settles to the deep water and the deep channel of the Bay, stimulating respiration in the water and bottom sediments and subsequently diminishing DO. The DO diminishment varies in magnitude but is primarily less than 0.05 g m^{-3}.

Introduction

Restoration of submerged aquatic vegetation (SAV) is a key management goal in the overall restoration of Chesapeake Bay. SAV provides numerous environmental benefits to the Bay, especially as habitat for desirable invertebrate and vertebrate species. The primary production of SAV carbon results in multiple interactions and material exchanges with the surrounding water column and benthic sediments. Production and respiration produce and consume dissolved oxygen (DO) while sloughing and similar processes release organic carbon which may be subsequently oxidized. Production and respiration also influence nutrient cycling in the adjacent water column and sediments. Production requires inorganic nutrients, primarily nitrogen and phosphorus, which are taken up by leaves and roots. Respiration and mortality return nutrients to water and sediments in various dissolved and particulate forms.

Hypoxia abatement is another key management goal. Reduction of hypoxia is largely achieved through control of nutrient loads to the Bay from the surrounding watershed. Nutrient load reduction reduces phytoplankton production and subsequent respiration of phytoplankton carbon in bottom waters of the Bay. Nutrient cycling in the water column and benthic sediments is the subject of multiple research and modeling studies of the Bay. The large-scale impact of nutrient fluxes through SAV on eutrophication processes including bottom-water hypoxia remains largely unknown, however. Investigation of this impact is especially important since Bay restoration plans include extensive increases in the area covered by SAV beds.

A process-based SAV sub-model (Cerco and Moore, 2001) is incorporated in the primary eutrophication model package (Cerco and Noel, 2019) used to guide management in meeting restoration goals. The sub-model and the larger Water Quality and Sediment Transport Model (WQSTM) provide the opportunity for an initial investigation of the present and future role of SAV in Bay nutrient cycling. The investigation addresses the following questions:

- What is the influence of SAV on nutrient cycling in the adjacent water column and benthic sediments?
- How does the SAV influence compare in magnitude to external nutrient loading to the system?
- What is the influence of SAV nutrient cycling in DO and chlorophyll concentration in adjacent waters?
- What is the influence of SAV nutrient cycling in management efforts to meet DO criteria?

The Water Quality and Sediment Transport Model

The WQSTM simulates eutrophication processes throughout Chesapeake Bay and the tidal portions of its tributaries. The model solves the three-dimensional conservation of mass equation for multiple state variables on a computational grid of 50,000 elements, roughly 1 km x 1 km x 1.7 m. State variables include multiple forms of carbon, nitrogen, phosphorus and suspended solids as well as dissolved oxygen. The model has undergone a continuous cycle of application and development for more than 30 years and has been extensively documented. Recent, relevant publications include application of the model to guide development of Total Maximum Daily Loads for the Bay (Cerco et al. 2010) and guidance for 2017 Mid-Point Reassessment of the 2010 TMDL (Cerco and Noel, 2019). This last reference describes the model employed here.

Transport processes for the WQSTM are provided by the Computational Hydrodynamics in Three Dimensions (CH3D) hydrodynamic model (Johnson et al., 1993). CH3D solves the three-dimensional equations of motion, via finite difference algorithms, on the same computational grid as the WQSTM. Integration time step is roughly 5 seconds. Volumetric transport and diffusivity are stored at hourly intervals for subsequent use by the WQSTM.

The Submerged Aquatic Vegetation Sub-Model

The SAV sub-model (Cerco and Moore, 2001) incorporates three carbonaceous state variables: shoots (aboveground biomass), roots (belowground biomass), and epiphytes (attached growth). Epiphytes and shoots exchange nutrients with the water-column component of the WQSTM while roots exchange nutrients with a sediment diagenesis sub-model (DiToro and Fitzpatrick, 1993). Light available to the shoots and epiphytes is computed via a series of sequential attenuations by color, fixed and volatile solids in the water column, and by self-shading of shoots and epiphytes.

SAV Composition and Nutrient Cycling

A fundamental assumption of the model is that plants have uniform, constant composition. Dissolved inorganic nutrients, nitrogen and phosphorus, are taken up in stoichiometric relation to net production (Figure 1). The fraction of nutrient uptake from each pool is a weighted combination of nutrient concentrations and a half saturation constant for uptake from each pool (Madden and Kemp, 1996). For the sediments:

$$FNsed = \frac{Khw \cdot Ns}{Khs \cdot Nw + Khw \cdot Ns} \qquad (1)$$

in which FNsed = fraction of total nutrient uptake removed from sediments; Ns = nutrient concentration in sediments; Nw = nutrient concentration is water column; Khs = half-saturation concentration for nutrient uptake from sediments; and Khw = half-saturation concentration for nutrient uptake from water. The remaining fraction of nutrient uptake, 1 – FNsed, is from the water column.

Nutrients produced by shoot mortality are routed to the dissolved inorganic, dissolved organic, and particulate organic nutrient pools in the water column. Nutrients produced by root mortality are routed to the particulate organic pools in the sediments.

SAV Communities

The model considers three exclusive SAV communities: a freshwater community characterized by Valisneria; a saltwater community characterized by Ruppia, and a saltwater community characterized by Zostera. The characteristic species and their distributions (Figure 2) are based on Moore et al., 2000. A unique property of the freshwater community is the nearly complete sloughing of above-ground biomass in late fall (Figure 3). Aboveground biomass of the Ruppia (Figure 4) and Zostera (Figure 5) communities diminishes in winter but does not disappear. The freshwater community also has the greatest above-ground density (biomass per unit area) in summer. Summer densities of the Ruppia and Zostera communities are similar although, as modeled, Zostera has a greater proportion of root biomass than Ruppia.

SAV Area

The location and area of SAV beds in the Bay varies on an inter-annual basis. The dominant determinant of SAV area is light availability although soil type, annual recruitment, and propagation are influential as well. In the model, SAV cells are placed at locations where SAV has been historically observed. Each SAV cell adjoins a single cell in the WQSTM computational grid. The area of each SAV cell is specified on an annual basis. For the model application years, SAV cell areas are derived from annual aerial surveys (Virginia Institute of Marine Science, 2022). For projections of the restored Bay, SAV cell areas are based on the greatest observed historical extent.

Epiphytes

Epiphytes are quantified as carbonaceous biomass per unit SAV leaf area. The primary role of epiphytes in the SAV model is attenuation of light passing through the water column to the above-ground SAV. Epiphyte kinetics are largely based on the phytoplankton kinetics of the WQSTM. Epiphyte production removes dissolved inorganic nutrients from the water column while mortality returns nutrients in dissolved inorganic, dissolved organic, and particulate organic form.

Sediment Diagenesis Sub-Model

The sediment diagenesis sub-model (DiToro and Fitzpatrick, 1993) interacts with the model representation of the water column and SAV (Figure 1). The primary purpose of the model is to compute sediment-water fluxes of dissolved oxygen, dissolved inorganic nitrogen (ammonium and nitrate), and dissolved inorganic phosphorus. Diagenesis is fueled by net deposition of particulate organic carbon, nitrogen, and phosphorus. In the sediments, the model computes bulk concentrations of three reaction classes of particulate organic carbon, nitrogen, and phosphorus. The model also computes sediment concentrations of ammonium, nitrate, and dissolved inorganic phosphorus. Sediment-water fluxes of these nutrients are determined by the difference between concentrations in the sediments and overlying water.

The diagenesis sub-model interacts with the root component of the SAV model. SAV production removes dissolved inorganic nutrients from the sediments via the roots. Root mortality returns particulate organic nutrients to the sediments. By altering the concentrations of dissolved inorganic and particulate organic nutrients, SAV production and mortality indirectly influence the sediment-water nutrient exchange.

Influence of SAV on Sediment-Water Nutrient Fluxes

SAV influences sediment-water nutrient fluxes by altering the concentrations of interstitial dissolved inorganic nutrients and by producing particulate organic nutrients subject to subsequent sediment diagenesis. The magnitude of the SAV influence depends on the life cycle of the SAV community, on the SAV biomass, and on conditions in the water column and sediments. Multiple pathways may contribute to the same effect. For example, the quantity of diagenetic material in the sediments is influenced by root mortality and by settling of material released to the water column by mortality of shoots and epiphytes (Figure 1). Each potential interaction between SAV and the surrounding water and sediments is quantified in the model code. For reporting purposes, the interactions are summarized into the following mass fluxes:

BENNH4 – sediment-water ammonium flux (positive from sediments to water)

BENNO3 – sediment-water nitrate flux (positive from sediments to water)

BENPON – sediment-water particulate organic nitrogen flux (positive from sediments to water)

SAVNFL – combined net nitrogen exchange of SAV and epiphytes with the water column (positive from SAV to water column)

NETNFL – Combined effect of all processes on sediment-water nitrogen flux (positive from sediments to water)

BENPO4 - sediment-water dissolved inorganic phosphorus flux (positive from sediments to water)

BENPOP - sediment-water particulate organic phosphorus flux (positive from sediments to water)

BENPIP - sediment-water particulate inorganic phosphorus flux (positive from sediments to water)

SAVPFL – combined net phosphorus exchange of SAV and epiphytes with the water column (positive from SAV to water column)

NETPFL – Combined effect of all processes on sediment-water phosphorus flux (positive from sediments to water)

Nutrient Fluxes by SAV Communities

The ten-year model calibration, 1991-2000, was run with and without the SAV component activated. The influence of SAV on sediment-water fluxes was illustrated through examination of an individual model cell from each community (Figure 2).

Nitrogen Fluxes

The sediment-water nitrogen fluxes in the Vallisneria cell (Figure 6) are influenced by the nitrogen loads from the nearby Susquehanna River. Large diffusive flux of nitrate into the sediment occurs, accompanied by settling of particulate nitrogen. The flux of particulate organic nitrogen to the sediments produces large diagenetic flux of ammonium back to the water column. All of these fluxes are magnified in the presence of SAV. The enhanced nitrate flux to the sediments reflects nitrate uptake by roots. The enhanced deposition results from mortality of SAV leaves and stems, especially during the fall die-off (Figure 3). Enhanced deposition results in enhanced diagenetic ammonium flux. SAV releases nitrogen to the water column through respiration and mortality. The net effect is that less nitrogen is retained in the sediments in the presence of SAV.

The largest net nitrogen fluxes occur in March through June (Figure 7). The fluxes are into the sediments and the influence of SAV is relatively small, suggesting that the fluxes are largely the result of loading from spring runoff events. The SAV effect is pronounced in the months of July through November, however. The autumn die-off of above-ground biomass and the release of this material to the water column diminishes net flux to the sediments and contributes to the long-term average disparity in conditions with and without SAV (Figure 6).

The Ruppia cell is located far from major external nutrient sources. As a result, the sediment-water nitrogen fluxes (Figure 8) are an order of magnitude smaller than the fluxes in the Valisneria cell. The major fluxes are deposition of particulate nitrogen and recycling of nitrogen back to the water column by SAV. As a result of the recycling, the retention of nitrogen in the sediments with SAV is less than half the retention in the absence of SAV.

In the absence of SAV, net nitrogen fluxes to the sediments demonstrate a symmetrical seasonal pattern with a maximum in the summer months (Figure 9). The summer maximum suggests deposition from primary production in the water column. The presence of Ruppia destroys the symmetry and produces a net nitrogen release to the water column in autumn due to die-off of above-ground biomass.

The diffusive fluxes on ammonium and nitrate in the Zostera cell (Figure 10) are mid-way in magnitude between the Valisneria and Ruppia cells. The magnitude and direction of the fluxes perhaps indicate a source of nitrogen from coastal waters adjacent to the Bay. Ammonium and nitrate fluxes are into the sediments and are greater in the presence of SAV indicating uptake by the SAV roots. SAV release to the water column is a major flux and, as a result, nitrogen retention in the sediments with SAV is roughly a third the value in the absence of SAV.

In the absence of SAV, the greatest net fluxes to the sediments occur from May to October (Figure 11). These fluxes consist predominately of diffusive flux of ammonium and nitrate. The mechanism behind the seasonality of the diffusive fluxes is not apparent. One hypothesis is that warmer temperatures result in enhanced nitrification/denitrification in the sediments. The nitrification produces a deficit of ammonium which enhances diffusion from overlying water. The denitrification produces a nitrate deficit which also enhances diffusion. Recycling to the water column by SAV diminishes net flux to the sediments and, in the months of July and August, results in net flux to the water column.

Phosphorus Fluxes

The major sediment-water phosphorus fluxes in the Valisneria cell (Figure 12) are deposition of particulate organic phosphorus and recycling of phosphorus to the water column by SAV. Deposition is greater in the presence of SAV due to mortality from leaves and stems. The recycling by SAV reduces the sediment retention of phosphorus to a small fraction of the value in the absence of SAV. The influence of SAV recycling is most evident in the late summer and fall when the net phosphorus flux is to the water column, the reverse of net flux in the absence of SAV (Figure 13).

As with nitrogen, the sediment-water phosphorus fluxes in the Ruppia cell are an order of magnitude smaller than the fluxes in the Valisneria cell (Figure 14). The settling of particulate inorganic phosphorus exceeds the settling of particulate organic phosphorus, perhaps indicating a source from local shoreline erosion. Phosphorus recycling from SAV to the water column reduces retention in the sediments to a value roughly one-third the value in the absence of SAV.

The greatest net fluxes are to the sediments in the months of September and October (Figure 15). The origin of these fluxes is not apparent. They may indicate the presence of an external load source. Fluxes to the sediments in these two months represent a large fraction of the total annual load. The fluxes are diminished in the presence of SAV due to SAV recycling of phosphorus back to the water column.

The major phosphorus fluxes in the Zostera cell are diffusion of dissolved inorganic phosphorus into the sediments and recycling back to the water column by SAV (Figure 16). The diffusive flux is greater in the presence of SAV indicating phosphorus uptake by SAV roots. As a result of SAV recycling, phosphorus retention in the sediments is a small fraction of the value in the absence of SAV.

The seasonal pattern of net phosphorus flux (Figure 17) resembles the net nitrogen flux. In the absence of SAV, the greatest fluxes are into the sediments in the months of May through October. The flux into the sediments is primarily diffusion of dissolved inorganic phosphorus (Figure 16). Although the diffusion is greater in warmer months, the rate should not be greatly influenced by temperature. The seasonal pattern perhaps reflects seasonal abundance of dissolved inorganic phosphorus in the water column. As with nitrogen, recycling to the water column by SAV diminishes net phosphorus flux into the sediments. For two months, July and August, recycling is sufficient to reverse the direction of net phosphorus flux into the water column from the sediments.

Relative Magnitude of Net Fluxes

The preceding analyses indicate that the net impact of SAV on sediment-water nutrient transfer is diminished nutrient retention in the sediments (Figures 6, 8, 10, 12, 14, 16). Diminished nutrient retention in the sediments is equivalent to an increased nutrient load to the water column. The significance of these equivalent loads was determined by comparing the difference in net sediment-water nutrient flux, with and without SAV, to the total watershed nutrient load. SAV nutrient releases to the water column and SAV impact on net sediment-water nutrient fluxes were summed over salinity regimes and systemwide (Tables 1, 2). Under calibration conditions, the SAV nitrogen release to the water column is 3.52% of the annual nitrogen load from the watershed. A portion of the release settles and diffuses to the sediments, however, so the equivalent net nitrogen load from SAV is 1.67% of the watershed load. Interestingly, when the entire tidal fresh salinity regime is considered, rather than a single example cell, SAV increases sediment nitrogen retention in this regime. SAV phosphorus release to the water column is 9.91% of the annual watershed load. After consideration of transfer to the sediments, the equivalent net phosphorus load from SAV is 4.72% of the watershed load.

An identical analysis was performed for WIP3 conditions. WIP3 conditions are based on actions the Bay jurisdictions intend to implement between 2018 and 2025 to meet Chesapeake Bay restoration goals. The WIP3 conditions included an increase in SAV extent and a reduction in watershed nutrient loads. Under WIP3 conditions, the SAV nitrogen flux to the water column and the net sediment nitrogen retention both increase relative to calibration conditions (Table 3). The increased nitrogen fluxes and the reduced watershed loads combine to increase the significance of the SAV nitrogen effects. The SAV nitrogen release to the water column under WIP3 conditions is 5.9% of the watershed load while the equivalent net nitrogen load is 2.71% of the watershed load.

In contrast to nitrogen, the SAV phosphorus load to the water column diminishes under WIP conditions, relative to calibration conditions (Table 4), although the net sediment retention increases, consistent with SAV nitrogen effects. Both fluxes represent an increased fraction of the watershed load, however. The SAV phosphorus load to the water column under WIP conditions is 16.7% of the watershed load while the equivalent net phosphorus load is 10.4% of the watershed load.

Influence of SAV on Water Quality

The primary water quality standards in Chesapeake Bay are based on dissolved oxygen (DO) concentration. Chlorophyll (Chl) standards are also prescribed in limited regions. Standards are prescribed for habitats (Chesapeake Bay Program Office, 2003) including Open Water (OW), Deep Water (DW), and Deep Channel (DC). The OW habitat focuses on surface waters in tidal creeks, rivers, embayments, and the mainstem Bay. The DW habitat includes the deeper transitional water column and bottom waters between the well-mixed surface water and very deep channels. The DC habitat lies beneath DW and experiences low to no dissolved oxygen conditions in summer. Compliance is determined for Chesapeake Bay Program Segments (CBSEG, Figure 18). Segment boundaries are determined based on salinity regime and other factors (Chesapeake Bay Program Office, 2004). Model scenarios conducted to guide compliance with standards are based on results for the period from June through September in the years 1993 – 1995. The period and years were selected based on the annual occurrence of minimum dissolved oxygen and on the broad range of hydrologic events which occurred in the three years. Results for these periods and years are extracted from ten-year simulations of the years 1991-2000.

To examine the influence of SAV on water quality, model runs were completed with and without SAV activated. Runs were completed for calibration (existing) conditions and for WIP3 conditions. Model results from each run were first averaged by month for the years 1993 – 1995. Monthly averages, for appropriate periods, in each computational cell were subsequently averaged by CBSEG and habitat. More than 1000 data points (monthly-CBSEG-habitat averages) resulted for the OW habitat. Fewer data points were produced for the DW (228 averages) and DC (108 averages) habitats due to their limited extent. Next, differences were taken for results from the runs with and without SAV. The population of differences were examined for magnitude, spatial trends, and other insights.

Existing Conditions

Histograms of the DO differences were produced for each habitat. In addition, histograms of chlorophyll differences were produced for the OW habitat. Each occurrence on a habitat histogram represents one monthly-CBSEG average. SAV exhibits both positive and negative influences on DO in the OW habitat (Figure 19). The numbers of positive and negative responses are evenly divided although the negative responses are primarily less than -0.05 g m^{-3} in magnitude while the positive responses are distributed over a greater range to 0.5 g m^{-3} or more. The most negative responses occur in the C&D Canal (segments CMDOH and CDDOH) while the greatest positive responses are in Piscataway tributary of the tidal fresh Potomac River (segment PISTF).

As with DO, SAV exerts both positive and negative influences on chlorophyll although the distribution of occurrences is skewed towards positive responses (Figure 20). Nearly 75% of the occurrences are between -0.2 mg m^{-3} and 0.2 mg m^{-3}. The Mattawoman tributary of the tidal fresh Potomac (segment MATTF) dominates the negative occurrences with multiple instances greater than -4.0 mg m^{-3}. The greatest positive occurrences, 3 to 7 mg m^{-3}, are in the tidal fresh Potomac and the Piscataway tributary (segments PISTF, POVTF, and MDPTF).

More than 95% of the Deep Water DO occurrences are negative (Figure 21) with half of the occurrences in the range 0 to -0.04 g m^{-3}. Negative responses in the range -0.1 to -0.2 occur although no segment predominates in the negative responses. A few positive occurrences up to 0.05 g m^{-3} exist, mostly in the Magothy River, on the upper western shore of the Bay (segment MAGMH).

Deep Channel responses to SAV are exclusively negative (Figure 22) with the majority of occurrences in the range -0.037 to -0.067 g m^{-3}. Maximum negative responses approach -0.1 g m^{-3}. No CBSEG clearly dominates in the magnitude of negative response.

WIP3 Conditions

SAV exhibits both positive and negative influences on DO in the OW habitat (Figure 23). Half the differences are small, ± 0.05 g m^{-3}. SAV exerts a positive effect on DO in two-thirds of the occurrences and differences greater than 1 g m^{-3} occur. The greatest positive influences, from 1 to 5 g m^{-3}, occur in the Piscataway tributary of the tidal fresh Potomac (segment PISTF). The greatest negative differences, nearly -1 g m^{-3}, occur in the C&D Canal (segments CDDOH and CMDOH).

As with DO, SAV induces both positive and negative influences on chlorophyll concentration (Figure 24). More than 80% of the occurrences are positive, however. More than half the occurrences are within the range ± 0.25 mg m^{-3} although positive influences greater than 3 mg m^{-3} occur. The greatest positive changes occur in the tidal fresh Potomac (segments POVTF and MDPTF. Clearly dominant negative segments are difficult to discern although Piscataway Creek occurs repeatedly in the most negative population. The preponderance of positive responses of both chlorophyll and DO to SAV suggest stimulation of chlorophyll via the previously identified SAV nutrient pumping from sediments to the water column. A positive quantitative relationship between increased chlorophyll and increased DO cannot be identified, however.

SAV exerts primarily a negative effect on Deep Water DO (Figure 25). More than 90% of the Deep Water DO occurrences are negative. More than half of the total occurrences are between 0 and -0.1 g m^{-3} although reductions in excess of -0.4 g m^{-3} occur. Mesohaline tributaries of the Chesapeake, including the Patapsco River, the Eastern Bay, and the Chester River, predominate in magnitude of negative occurrences (segments EASMH, PATMH, CHSMH). A small percentage of segments, ≈5%, exhibit positive DO responses up to 0.12 g m^{-3}. The Magothy and the South River tributaries (segments MAGMH and SOUMH) predominate in the positive response population.

SAV exerts exclusively a negative effect of Deep Channel DO (Figure 26). Nearly 40% of the occurrences are between 0 and -0.1 g m^{-3}. The lower Chester River (segment CHSMH) clearly predominates in magnitude of response, greater than -0.4 g m^{-3}.

The modelled impacts of SAV on DO and chlorophyll are similar for both Existing and WIP3 conditions. Perhaps the greatest distinctions are in the DO responses in Deep Water and Deep Channel segments. The maximum negative DO response in Deep Water under Existing Conditions is -0.218 g m^{-3} compared to -0.409 g m^{-3} under WIP3 conditions. The maximum negative DO response in the Deep Channel under Existing Conditions is -0.097 g m^{-3} compared to -0.442 g m^{-3} under WIP3 conditions. The larger response under WIP3 conditions can be partially attributed to the greater SAV extent. The potential DO response is also greater under WIP3 conditions. Under Existing conditions, DO in the Deep Channel is at or near zero. There is minimal space for further declines. The WIP3 conditions increase DO in the Deep Water and Deep Channel, however, providing more potential for DO decreases.

Conclusions

A conceptual model can be formed which explains the predominant modelled response of DO and surface chlorophyll to the presence of SAV (Figure 27). SAV diminishes nutrient retention in bottom sediments (Figures 6, 8, 10, 12, 14, 16). Nutrients not retained in the sediments are recycled to the water column. The recycled nutrients stimulate phytoplankton production and concurrent DO production in surface waters. Enhanced algal biomass settles to Deep Water and the Deep Channel, stimulating respiration in the water and bottom sediments and subsequent diminished DO (Figures 21, 22, 25, 26).

Individual CBSEGS occasionally or regularly deviate from the conceptual model. For example, SAV induces diminished chlorophyll and DO in some Open Water segments. The reasons for the non-conforming behavior are not readily apparent. The existence of a single alternate model which explains all non-conforming behaviors is unlikely. More likely multiple combinations of local and temporally-varying conditions explain deviations from the conceptual model. Deviations may also occur due to occasional, anomalous definitions of habitat extent.

References

Cerco, C., and Moore, K. (2001). "System-Wide Submerged Aquatic Vegetation Model for Chesapeake Bay," *Estuaries*, 24(4), 522-534.

Cerco, C., and Noel, M. (2019). "The 2017 Chesapeake Bay Water Quality and Sediment Transport Model," US Environmental Protection Agency, PA Chesapeake Bay Program Office, Annapolis, MD. 2017 Chesapeake Bay Water Quality and Sediment Transport Model

Cerco, C., Kim, S.-C. Noel, M. (2010). "The 2010 Chesapeake Bay Eutrophication Model," US Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, MD. http://www.chesapeakebay.net/publications/title/the_2010_chesapeake_bay_eutrophication_model1

Chesapeake Bay Program Office. (2003). "Technical Support Document for Identification of Chesapeake Bay Designated Uses and Attainability," EPA 903-R-03-004, US Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, MD.

Chesapeake Bay Program Office. (2004). "Chesapeake Bay Program Analytical Segmentation Scheme," EPA 903-R-04-008, US Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, MD. https://www.chesapeakebay.net/content/publications/cbp_13272.pdf

DiToro, D., and Fitzpatrick, J. (1993). "Chesapeake Bay sediment flux model," Contract Report EL-93-2, US Army Corps of Engineers Waterways Experiment Station, Vicksburg MS.

Johnson, B. H., Kim, K., Heath, R., Hsieh, B., Butler, L. (1993). "Validation of a three-dimensional hydrodynamic model of Chesapeake Bay," *Journal of Hydraulic Engineering*, 119, 2-20.

Madden C. and Kemp, W. (1996). "Ecosystem model of an estuarine submersed plant community: Calibration and simulation of eutrophication responses," *Estuaries* 19, 457–474.

Moore, K., Wilcox, D., and Orth, R. (2000). "Analysis of the abundance of submersed aquatic vegetation communities in the Chesapeake Bay," *Estuaries* 23, 115–127.

Virginia Institute of Marine Science, (2022), "SAV Monitoring and Restoration," SAV Data Tables | Virginia Institute of Marine Science (vims.edu)

Salinity Regime	SAV Nitrogen Flux (kg/d)	Net SAV Nitrogen Effect (kg/d)
TFRESH	1593	-167
OLIGOH	1203	485
MESOH	5976	3498
POLYH	2890	1724
Total	11662	5540
% of Watershed Load	3.52	1.67

Table 1. SAV nitrogen flux under calibration conditions.

Salinity Regime	SAV Phosphorus Flux (kg/d)	Net SAV Phosphorus Effect (kg/d)
TFRESH	555	351
OLIGOH	280	137
MESOH	916	333
POLYH	404	205
Total	2155	1026
% of Watershed Load	9.91	4.72

Table 2. SAV phosphorus flux under calibration conditions.

Salinity Regime	SAV Nitrogen Flux (kg/d)	Net SAV Nitrogen Effect (kg/d)
TFRESH	2094	459
OLIGOH	1493	703
MESOH	6019	3029
POLYH	2701	1463
Total	12307	5654
% of Watershed Load	5.90	2.71

Table 3. SAV nitrogen fluxes under WIP3 conditions.

Salinity Regime	SAV Phosphorus Flux (kg/d)	Net SAV Phosphorus Effect (kg/d)
TFRESH	533	319
OLIGOH	289	144
MESOH	908	656
POLYH	378	199
Total	2108	1317
% of Watershed Load	16.70	10.43

Table 4. SAV phosphorus fluxes under WIP3 conditions.

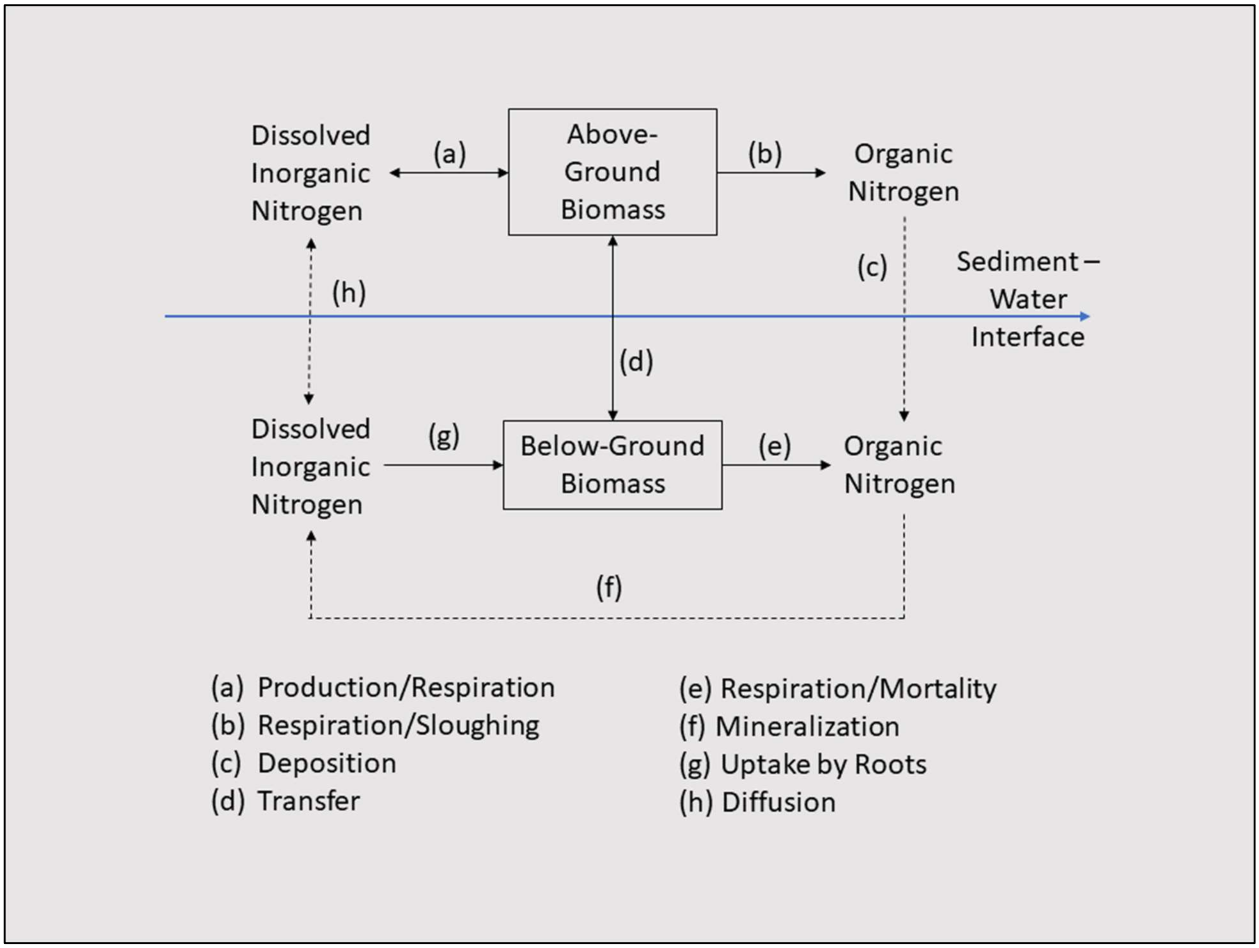


Figure 1. The role of SAV in the model nitrogen cycle. The role of SAV in the phosphorus cycle is analogous.

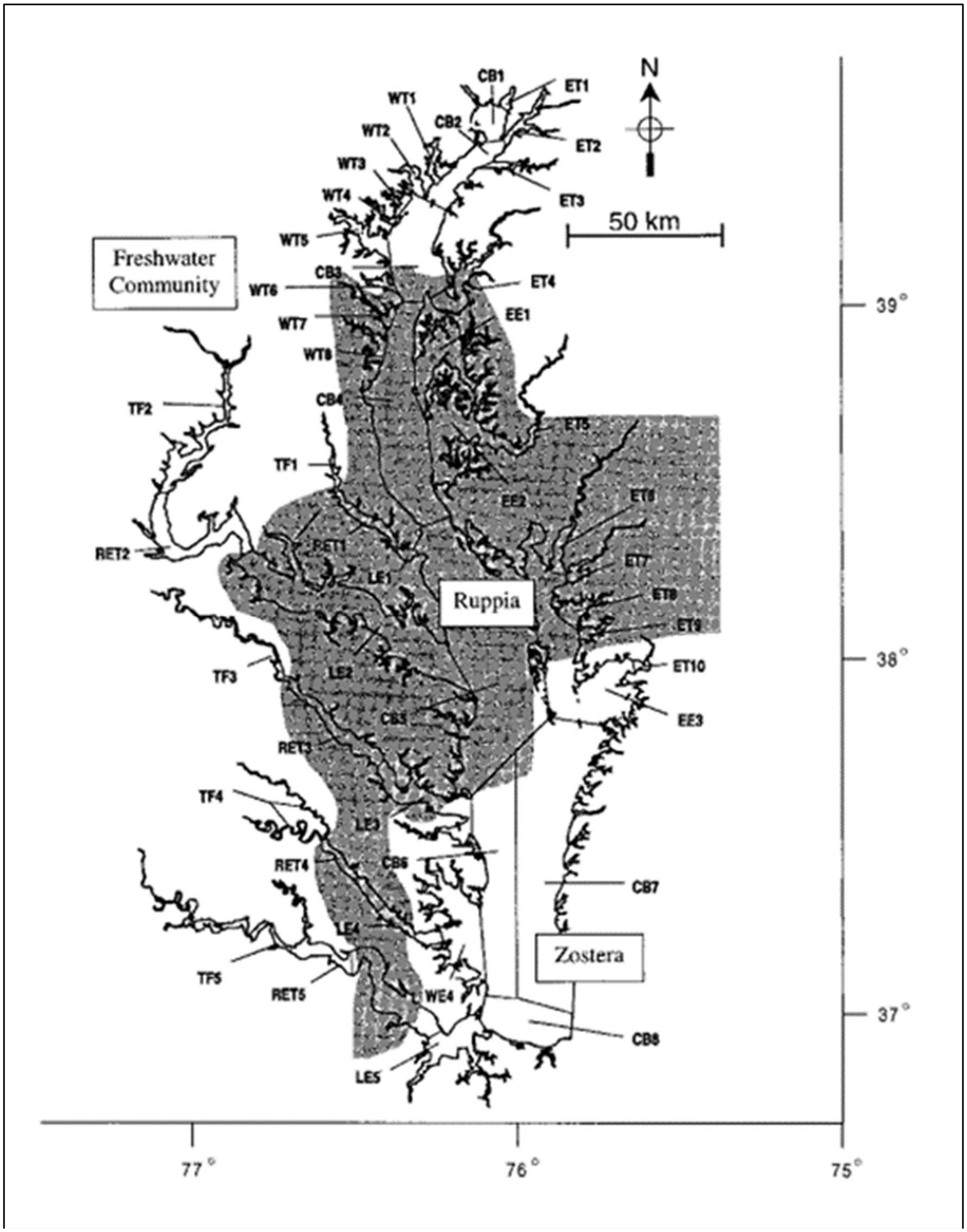


Figure 2. Spatial distribution of three model SAV communities (Cerco and Moore, 2001).

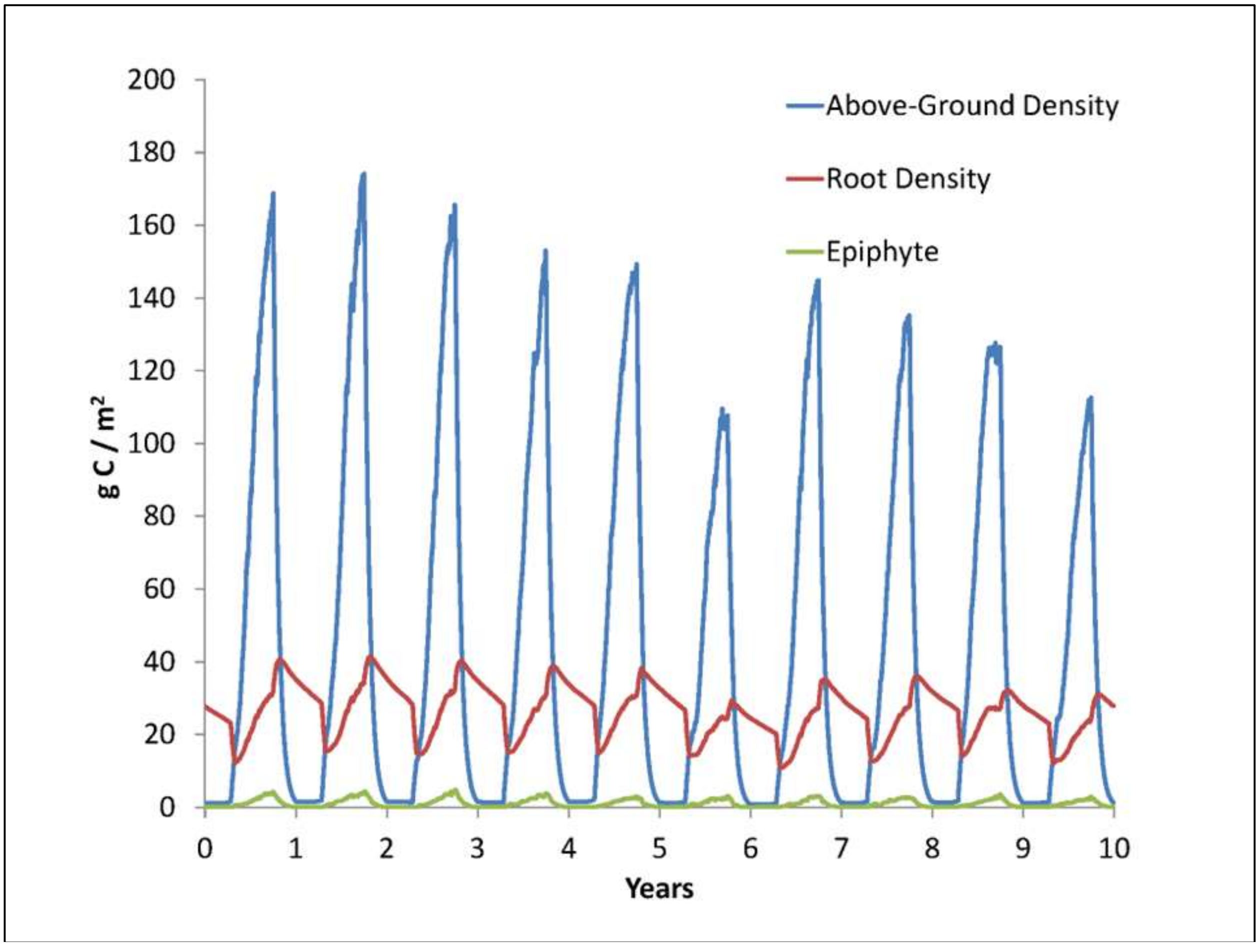


Figure 3. Computed density of SAV and epiphytes in the Valisneria community, 1991-2000.

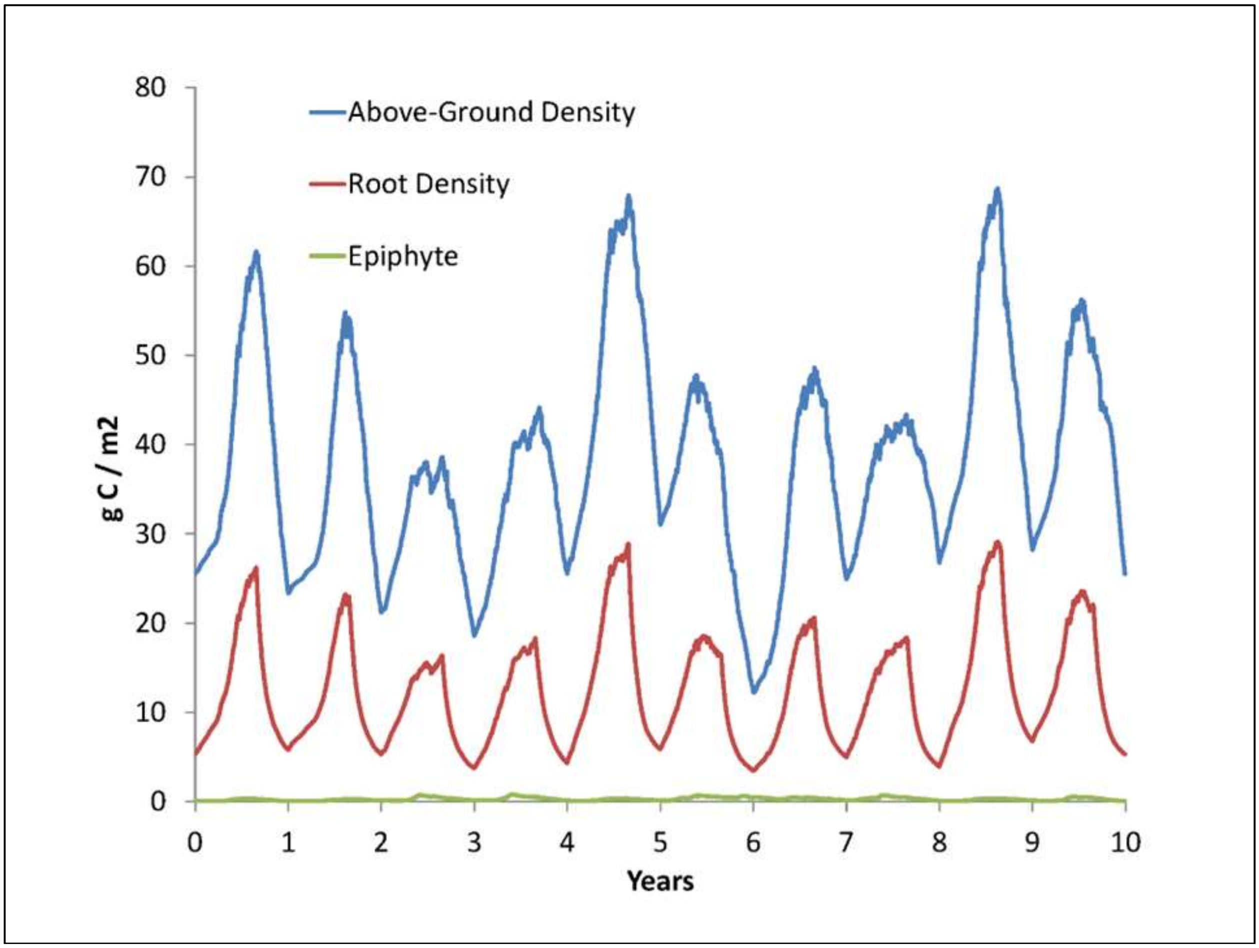


Figure 4. Computed density of SAV and epiphytes in the Ruppia community, 1991-2000.

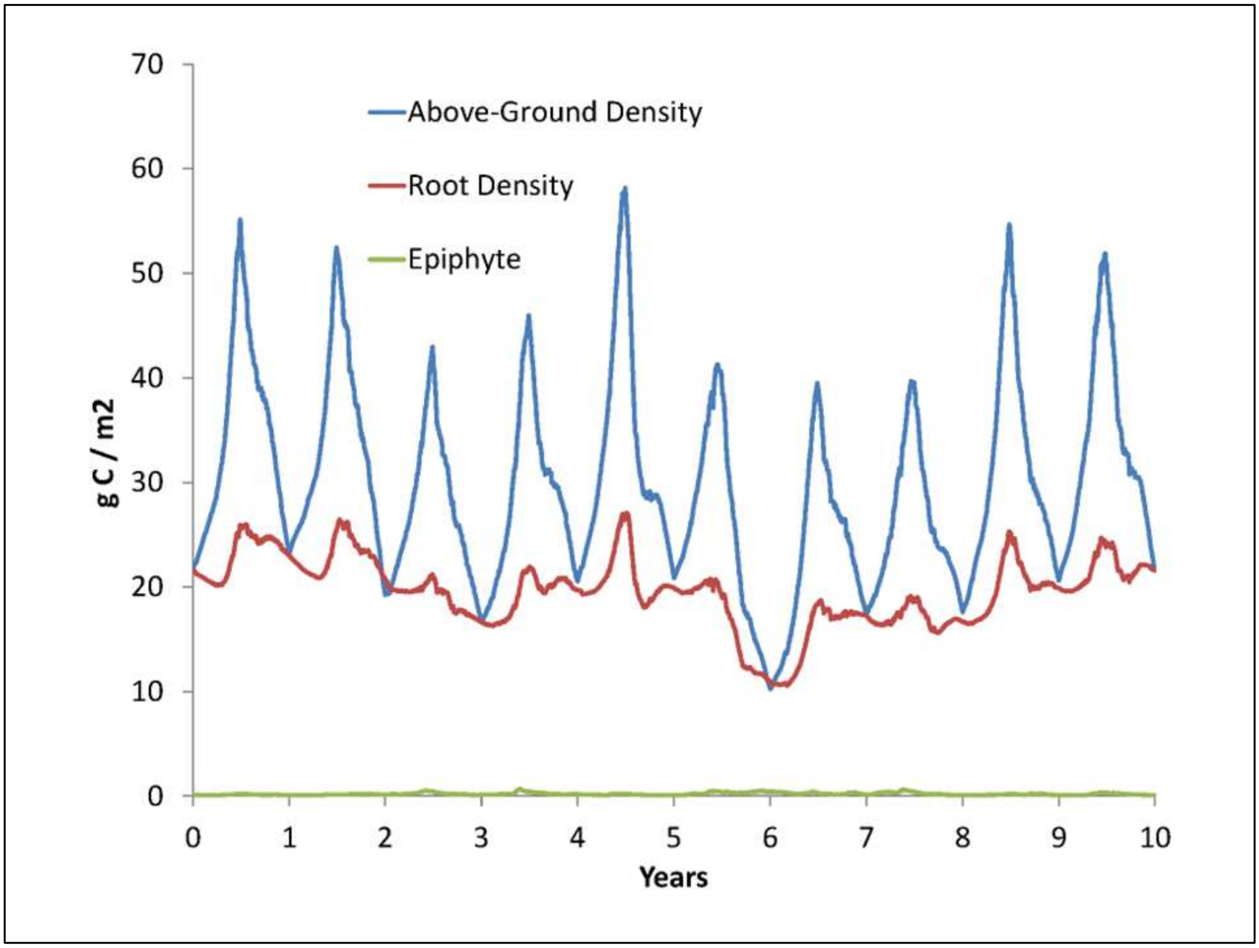


Figure 5. Computed density of SAV and epiphytes in the Zostera community, 1991-2000.

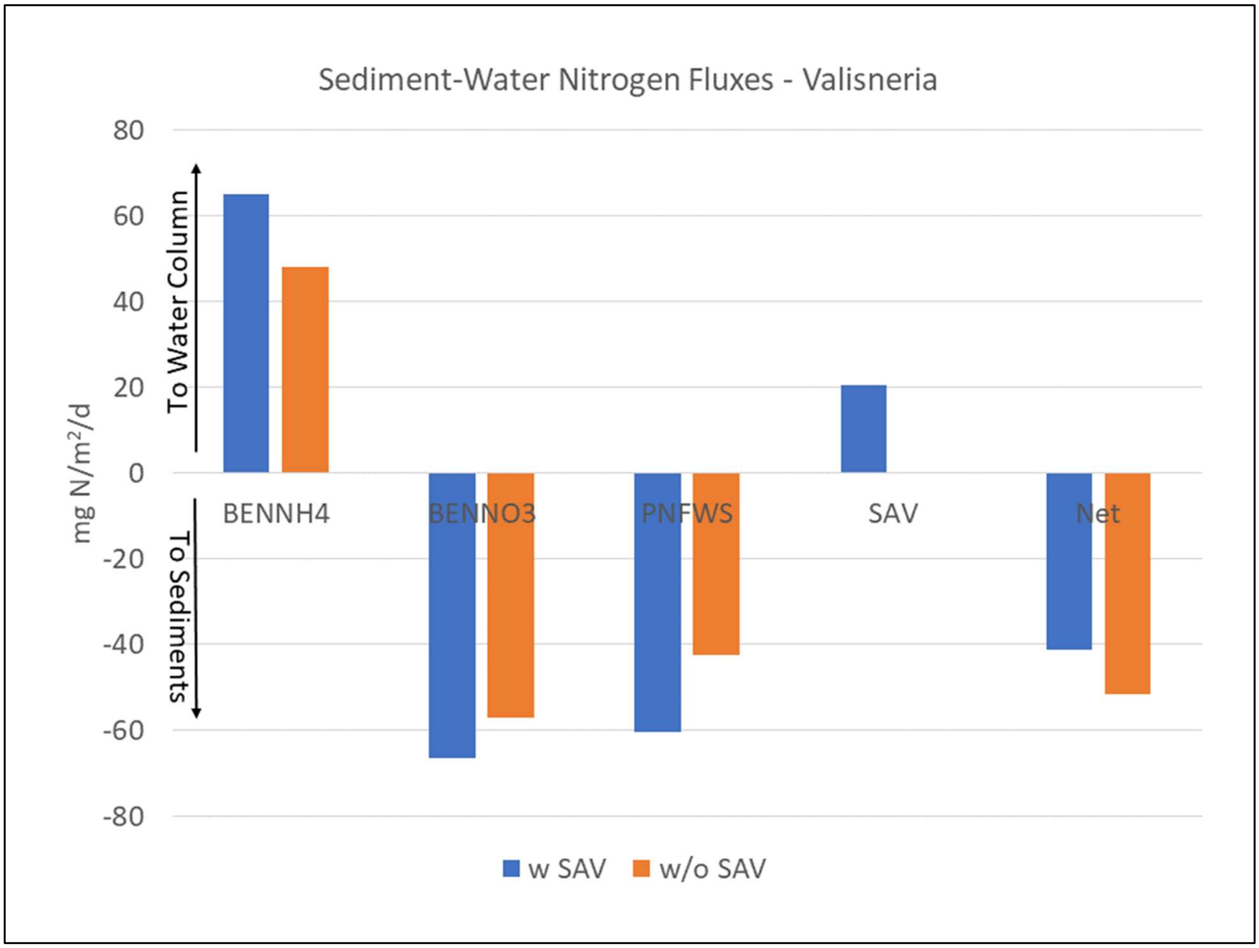


Figure 6. Effect of SAV on sediment-water nitrogen fluxes for a model cell in the Valisneria community. Fluxes are shown with and without SAV activated. The net flux is the sum of the preceding four fluxes.

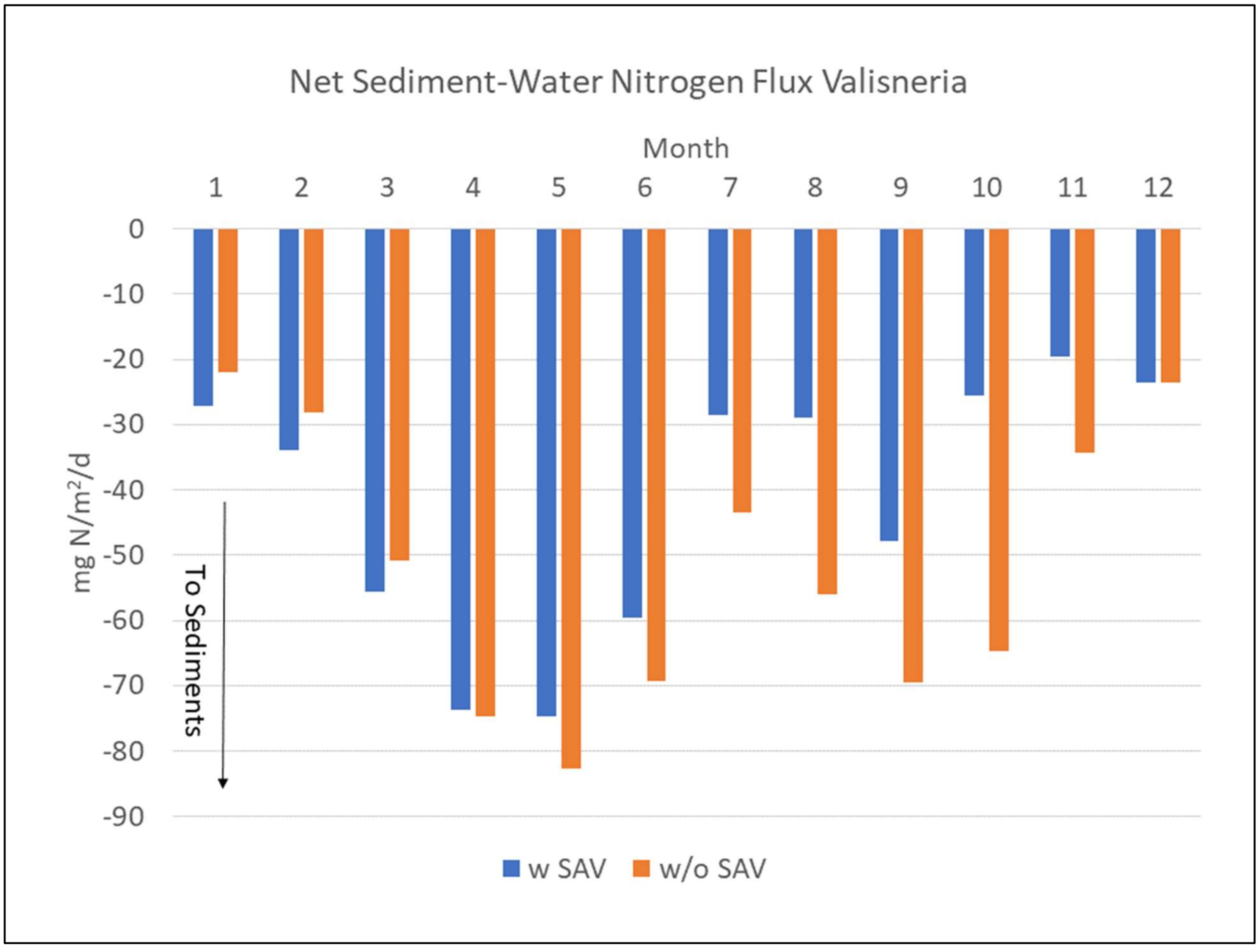


Figure 7. Monthly net sediment-water nitrogen fluxes for a model cell in the Valisneria community. Fluxes are shown with and without SAV activated.

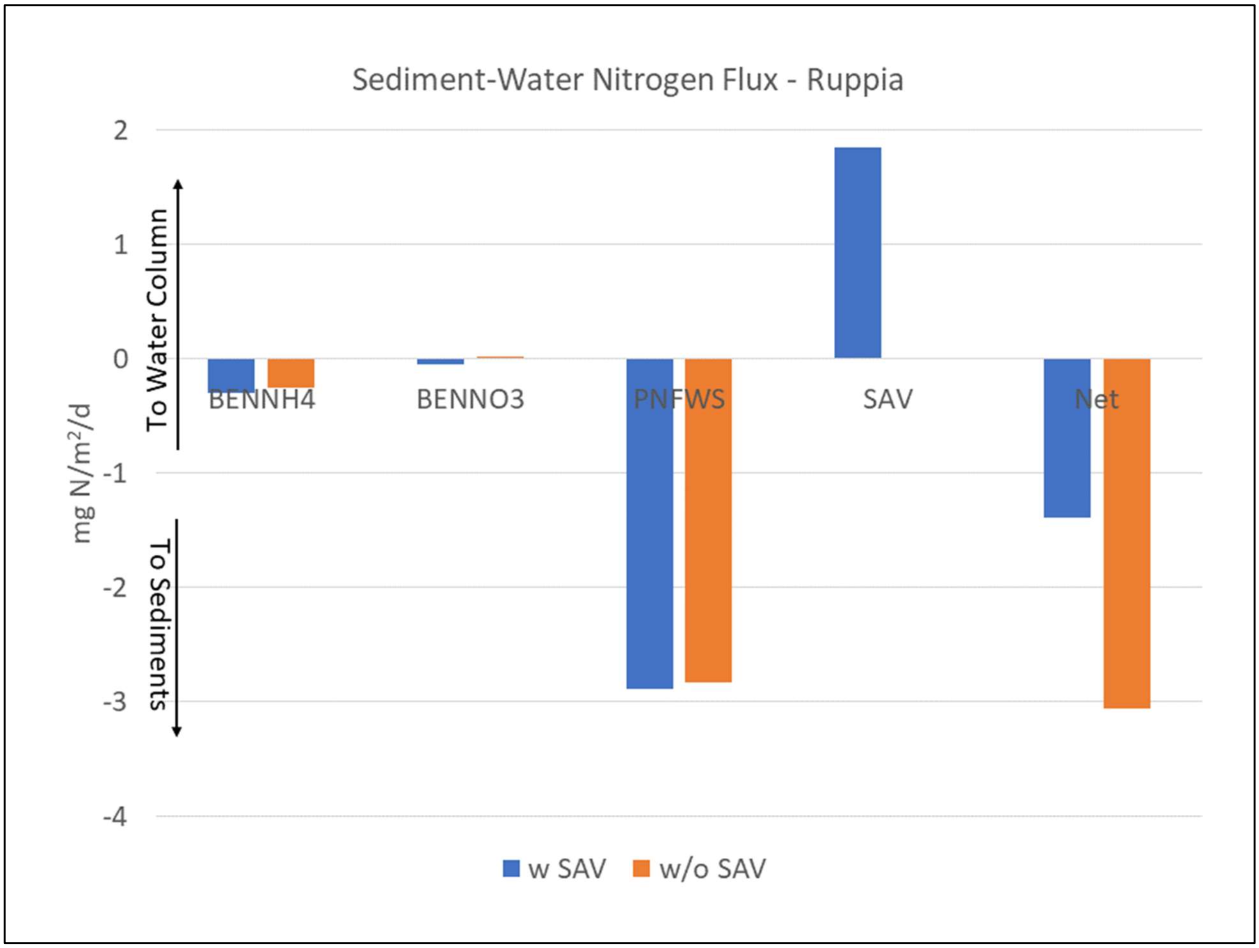


Figure 8. Effect of SAV on sediment-water nitrogen fluxes for a model cell in the Ruppia community. Fluxes are shown with and without SAV activated. The net flux is the sum of the preceding four fluxes.

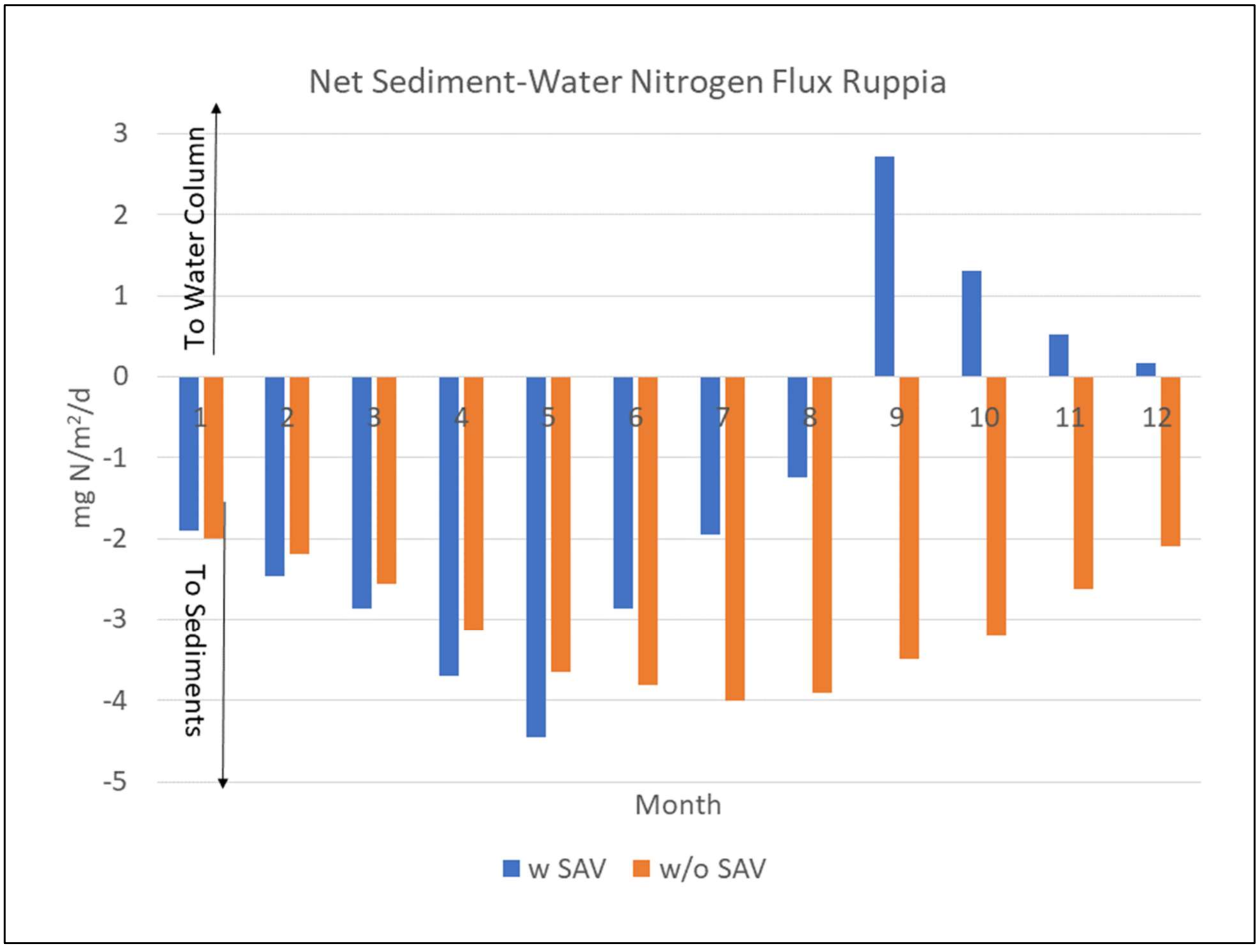


Figure 9. Monthly net sediment-water nitrogen fluxes for a model cell in the Ruppia community. Fluxes are shown with and without SAV activated.

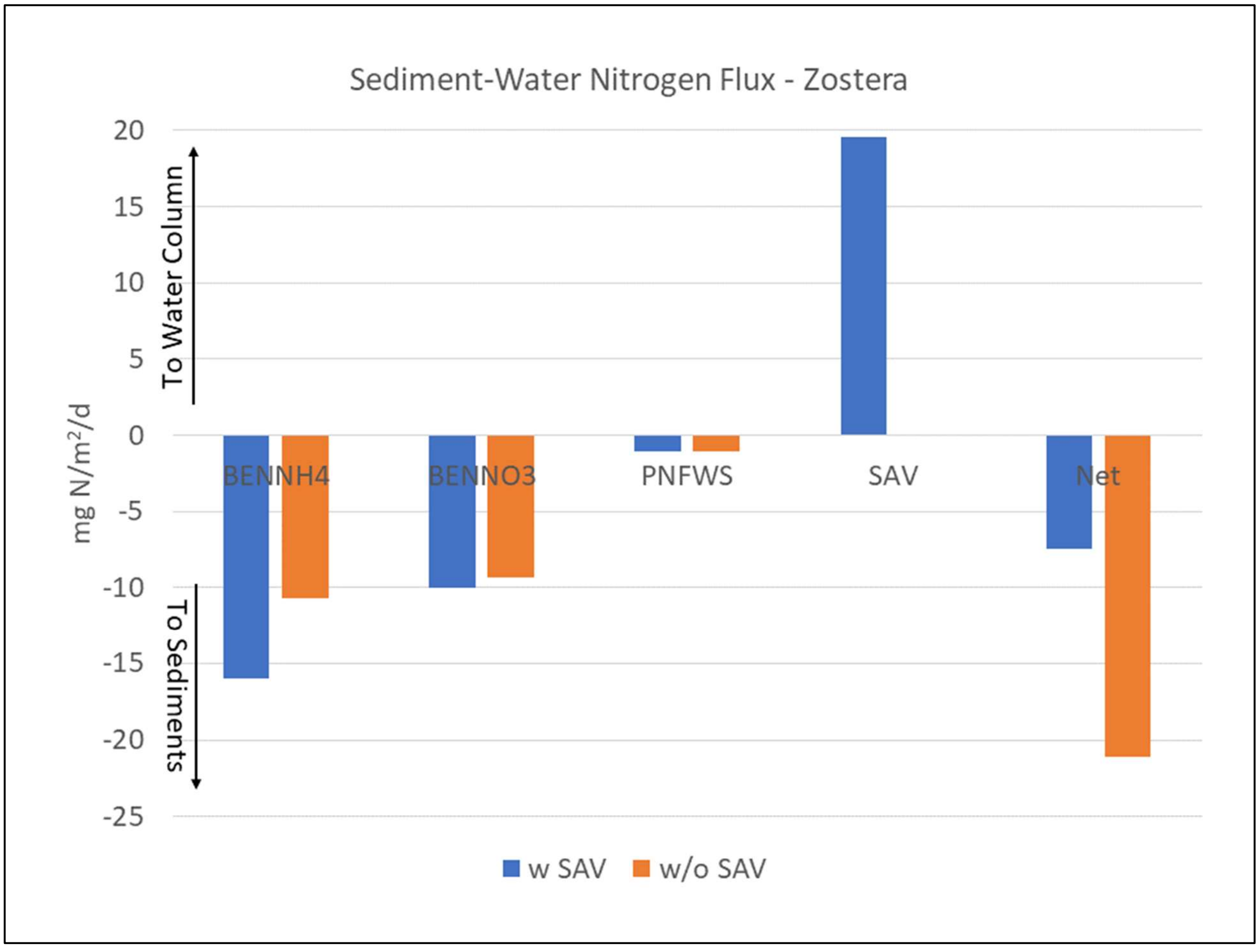


Figure 10. Effect of SAV on sediment-water nitrogen fluxes for a model cell in the Zostera community. Fluxes are shown with and without SAV activated. The net flux is the sum of the preceding four fluxes.

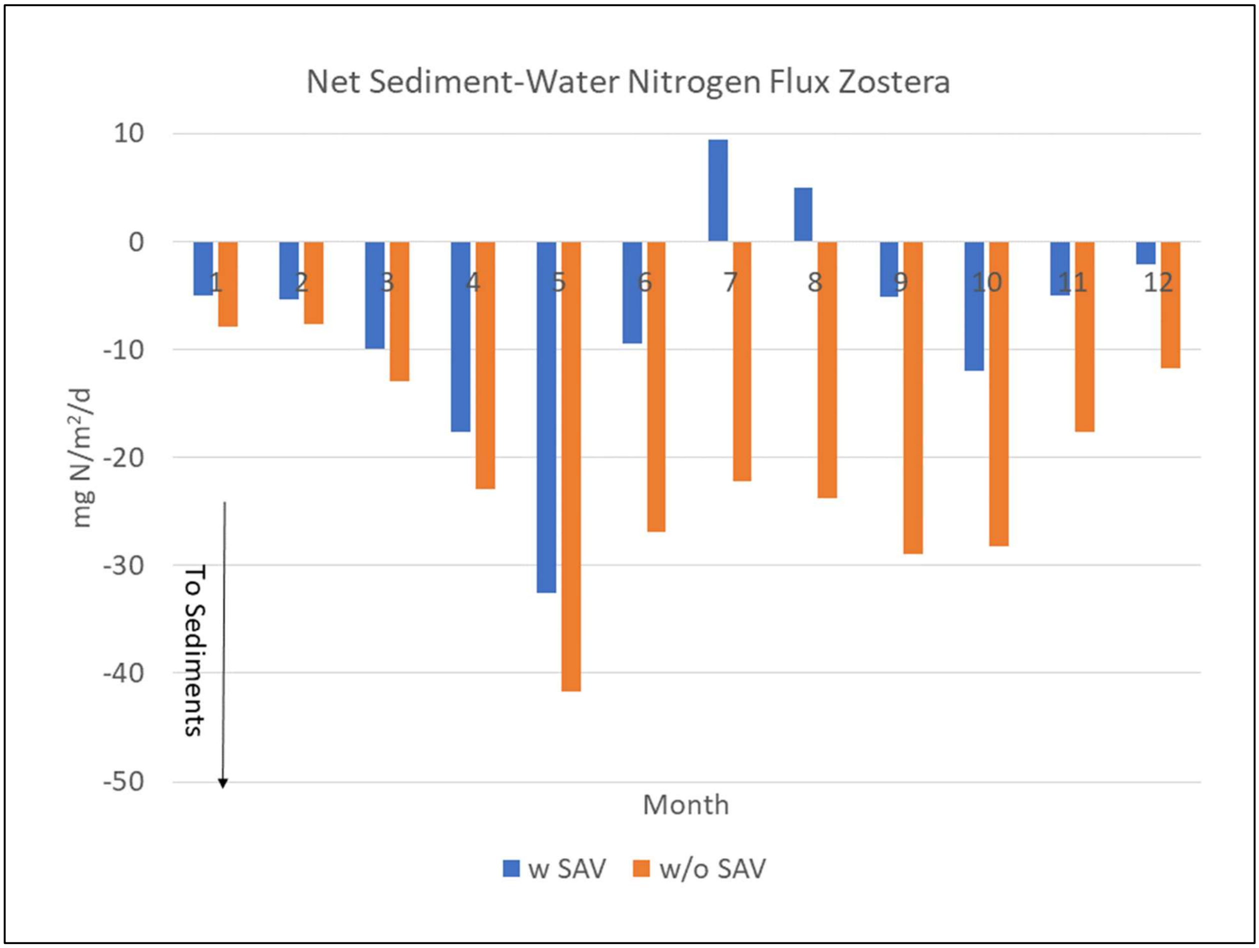


Figure 11. Monthly net sediment-water nitrogen fluxes for a model cell in the Zostera community. Fluxes are shown with and without SAV activated.

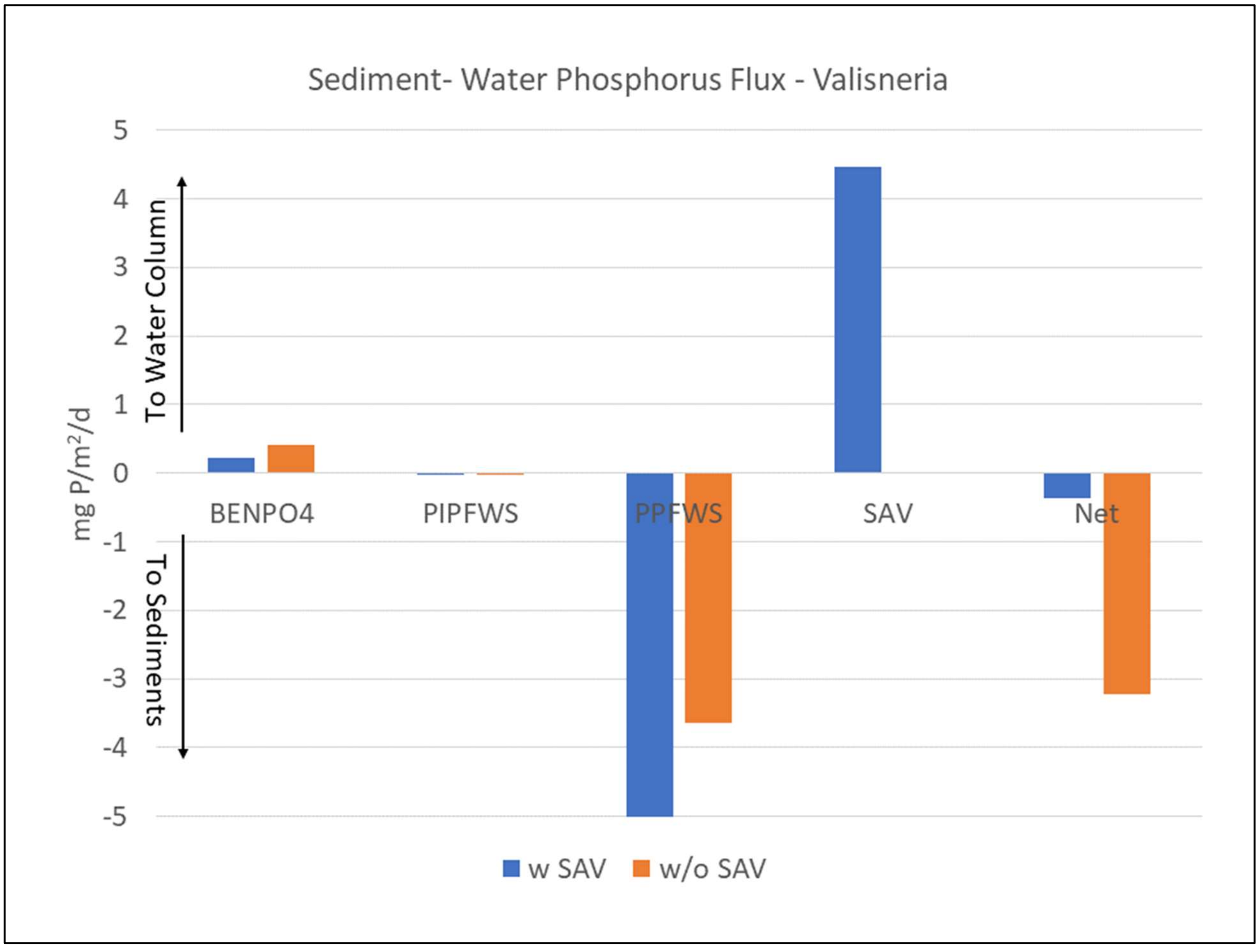


Figure 12. Effect of SAV on sediment-water phosphorus fluxes for a model cell in the Valisneria community. Fluxes are shown with and without SAV activated. The net flux is the sum of the preceding four fluxes.

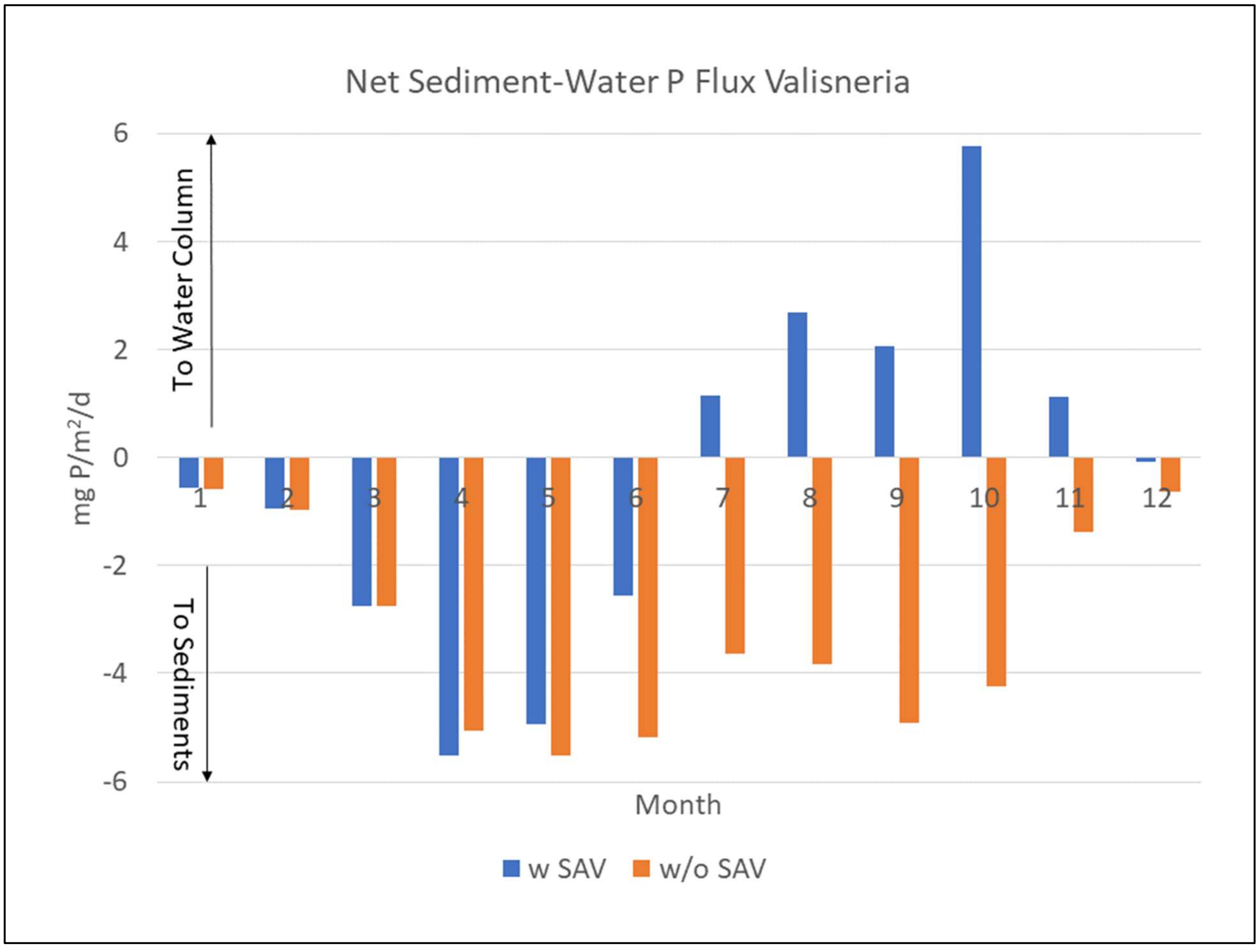


Figure 13. Monthly net sediment-water phosphorus fluxes for a model cell in the Valisneria community. Fluxes are shown with and without SAV activated.

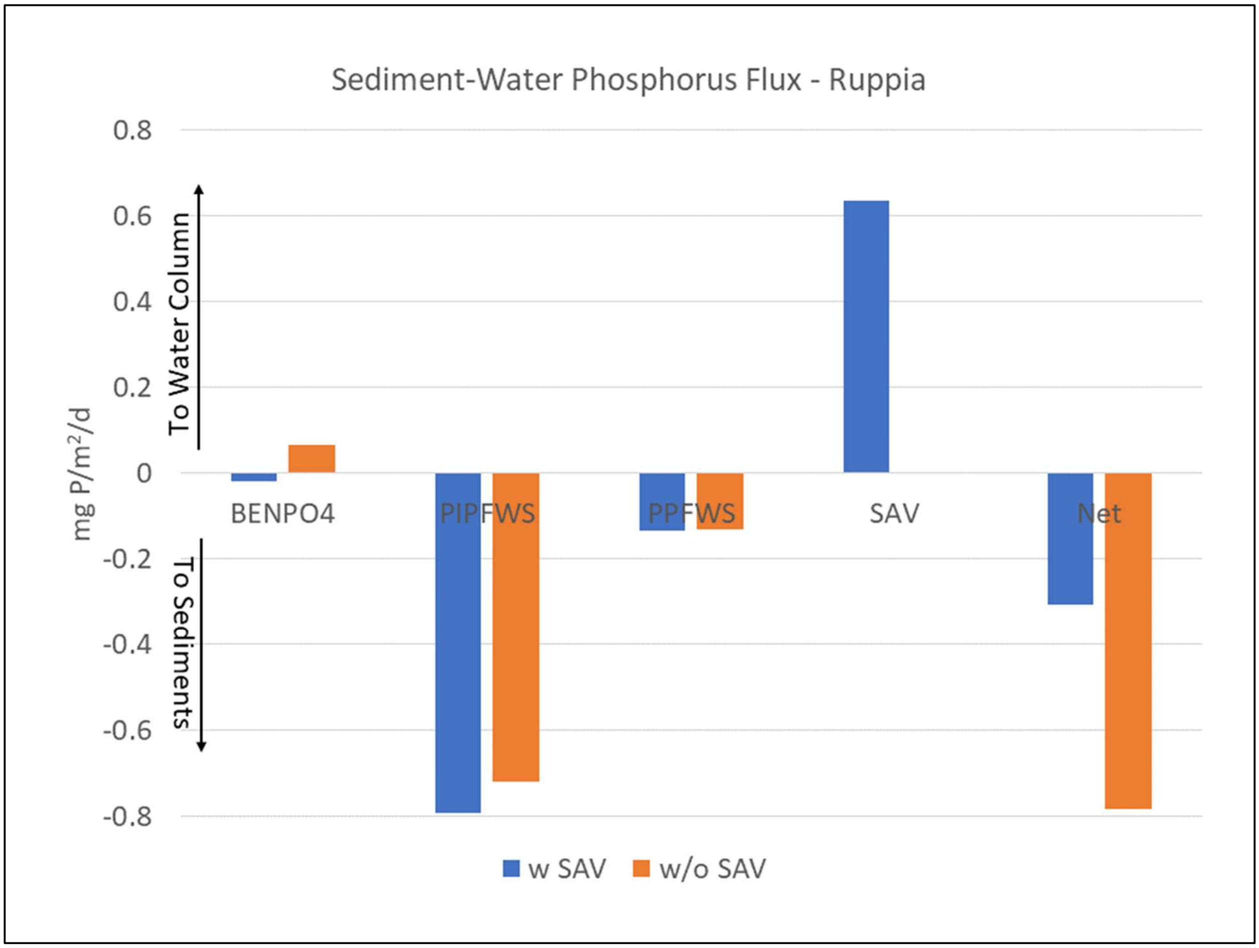


Figure 14. Effect of SAV on sediment-water phosphorus fluxes for a model cell in the Ruppia community. Fluxes are shown with and without SAV activated. The net flux is the sum of the preceding four fluxes.

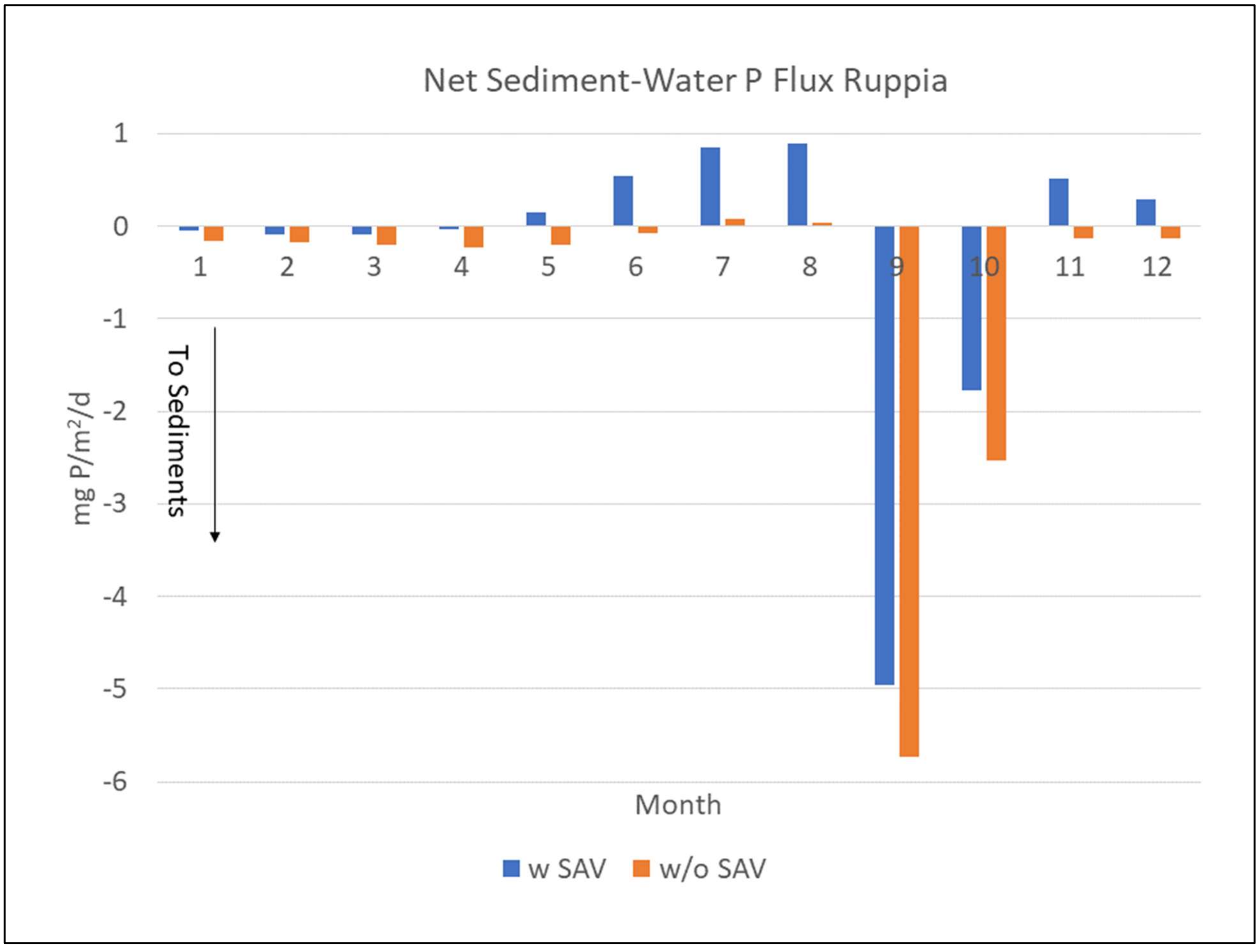


Figure 15. Monthly net sediment-water phosphorus fluxes for a model cell in the Ruppia community. Fluxes are shown with and without SAV activated.

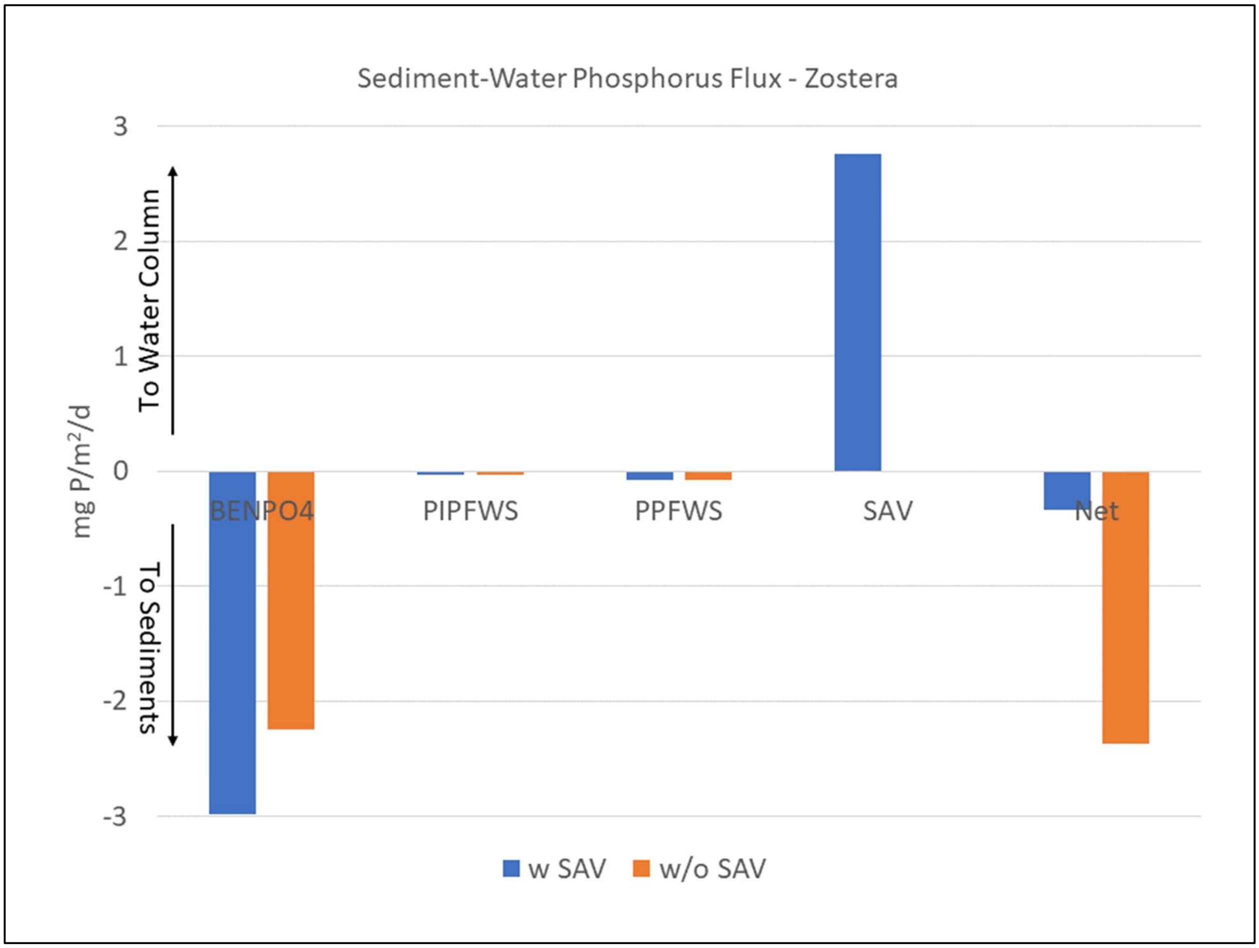


Figure 16. Effect of SAV on sediment-water phosphorus fluxes for a model cell in the Zostera community. Fluxes are shown with and without SAV activated. The net flux is the sum of the preceding four fluxes.

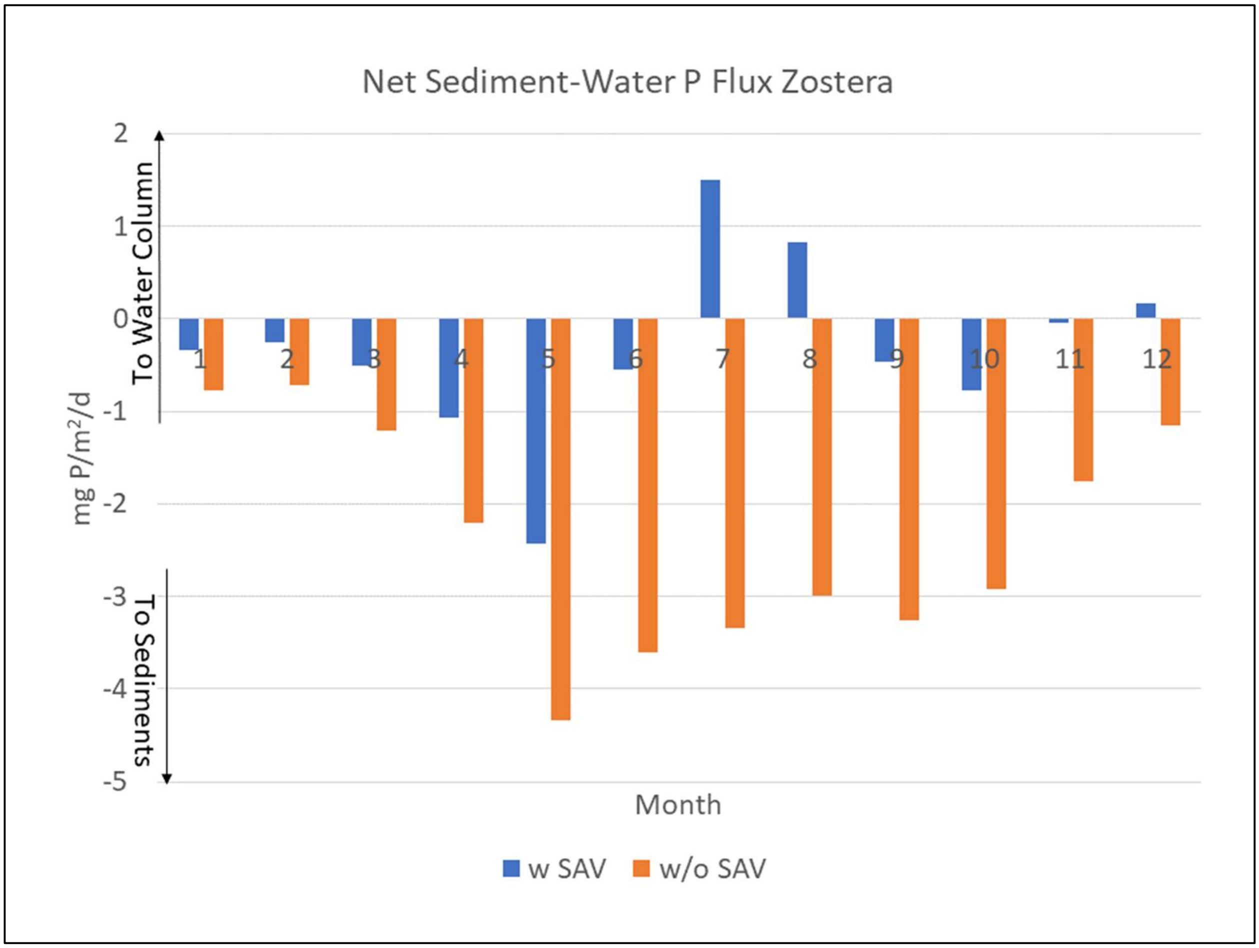
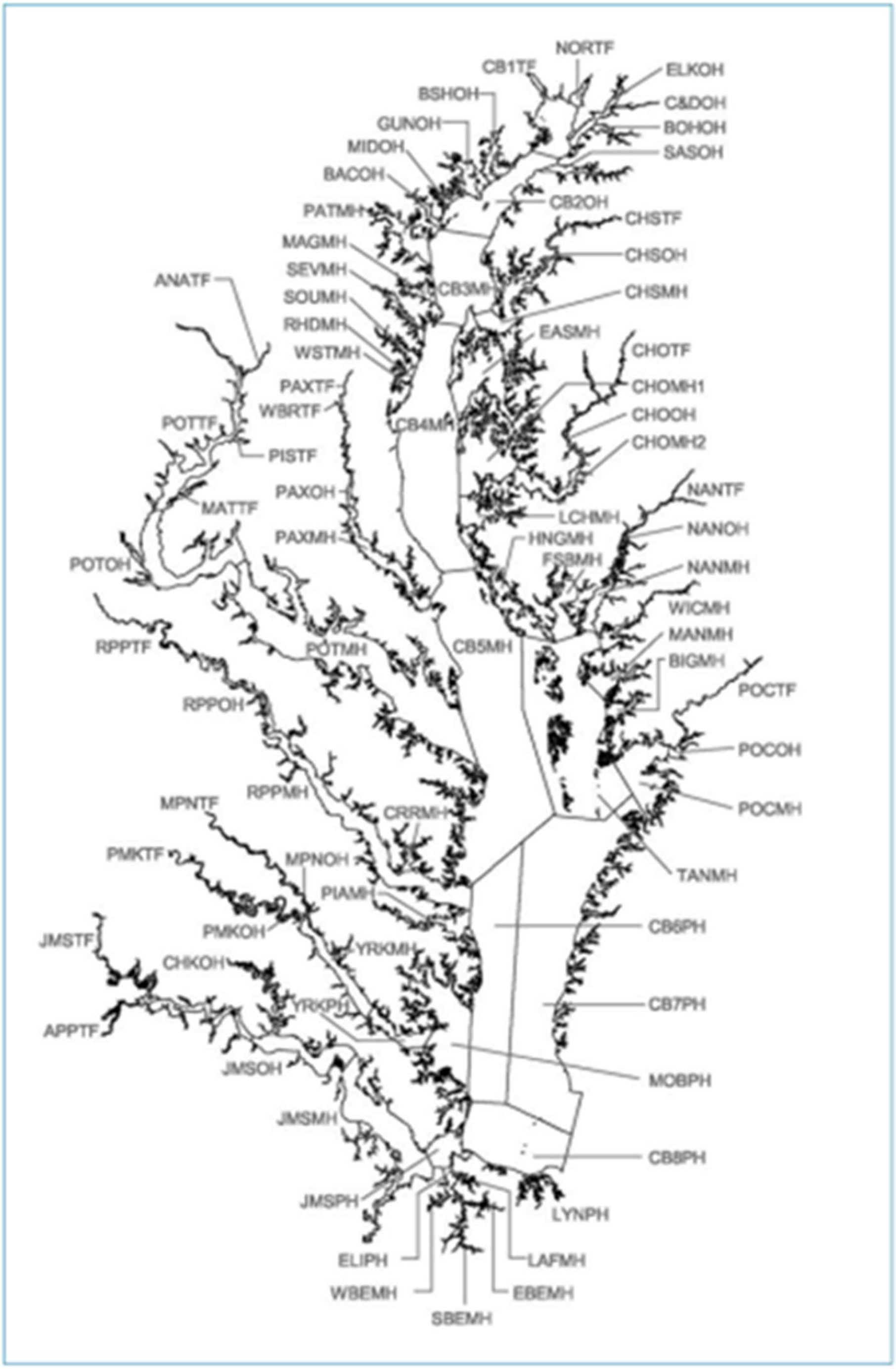


Figure 17. Monthly net sediment-water phosphorus fluxes for a model cell in the Zostera community. Fluxes are shown with and without SAV activated.



2003 Chesapeake Bay Segmentation Scheme

Figure 18. Chesapeake Bay Program Segments (Chesapeake Bay Program Office, 2004).

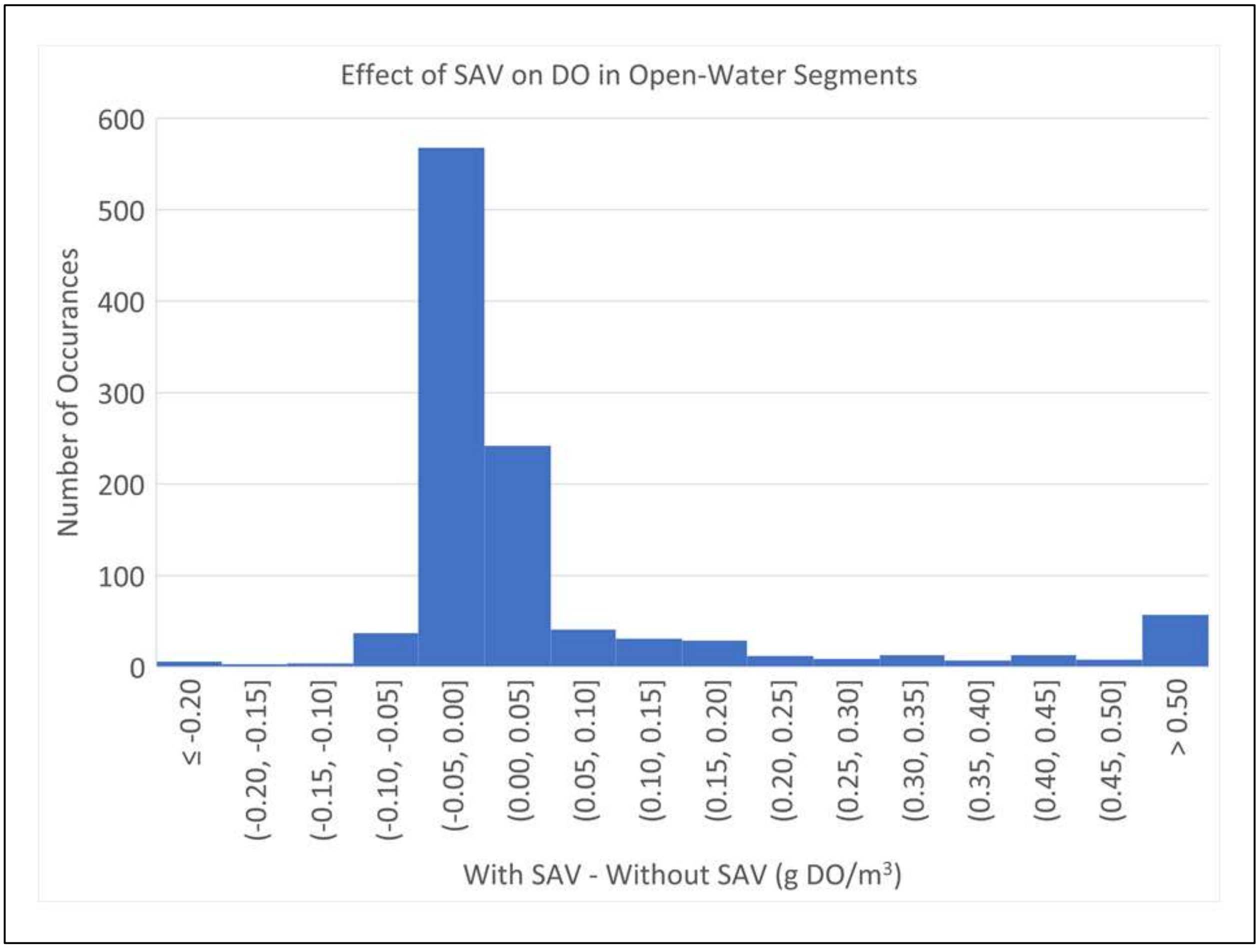


Figure 19. Effect of SAV on DO in open-water habitats under existing conditions. Each occurrence represents a monthly average over a CBSEG. Differences are shown between model runs with and without SAV activated.

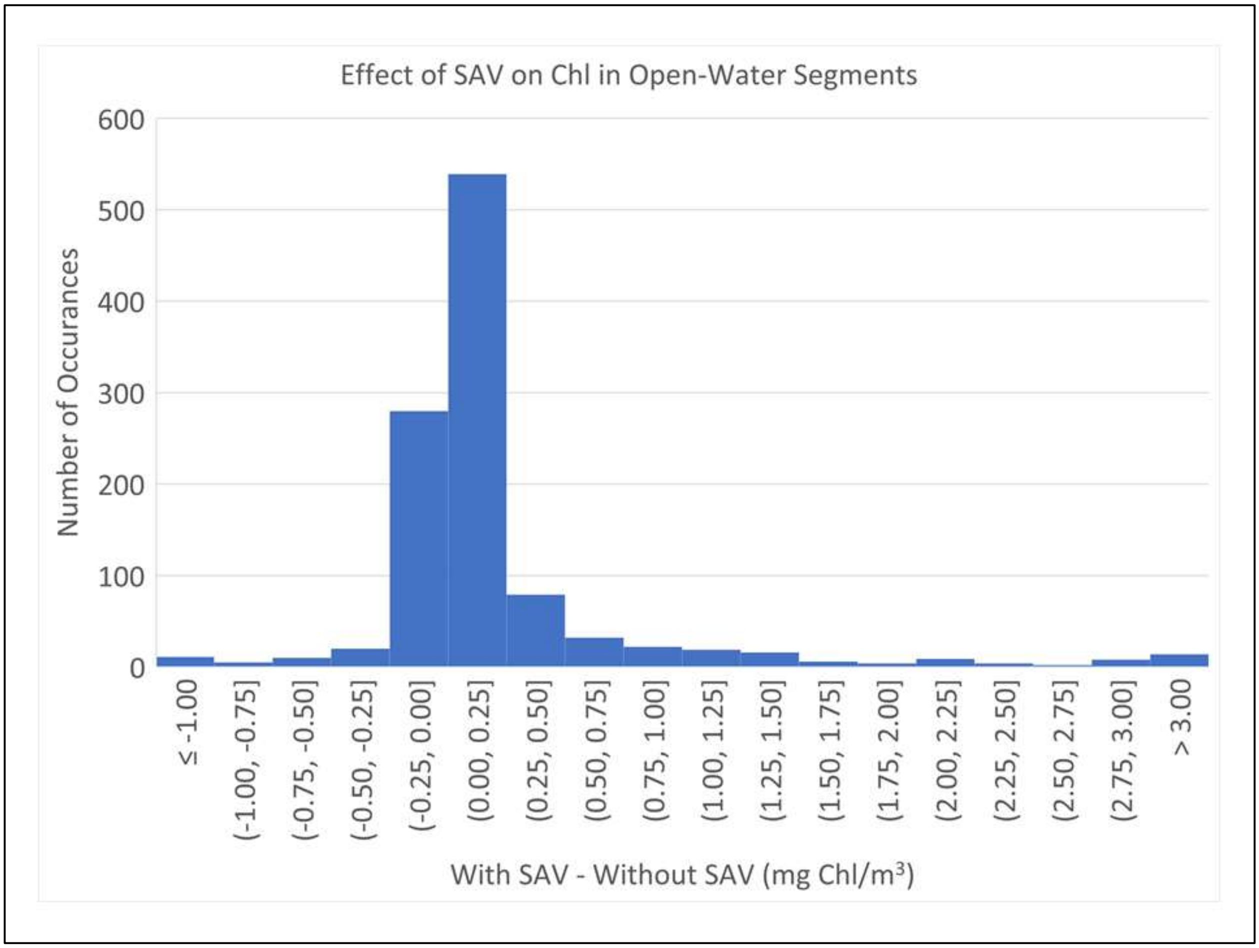


Figure 20. Effect of SAV on Chl in open-water habitats under existing conditions. Each occurrence represents a monthly average over a CBSEG. Differences are shown between model runs with and without SAV activated.

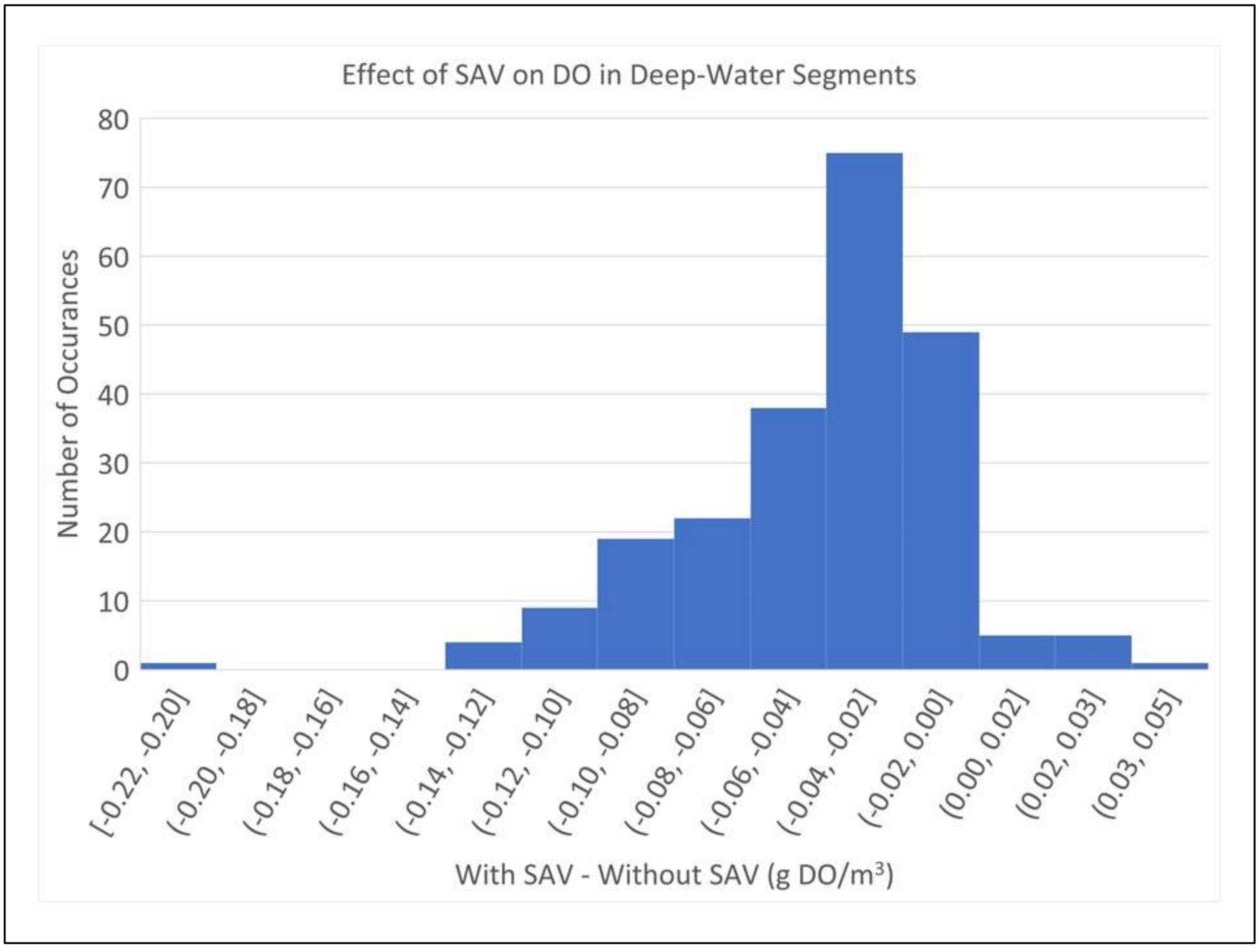


Figure 21. Effect of SAV on DO in deep-water habitats under existing conditions. Each occurrence represents a monthly average over a CBSEG. Differences are shown between model runs with and without SAV activated.

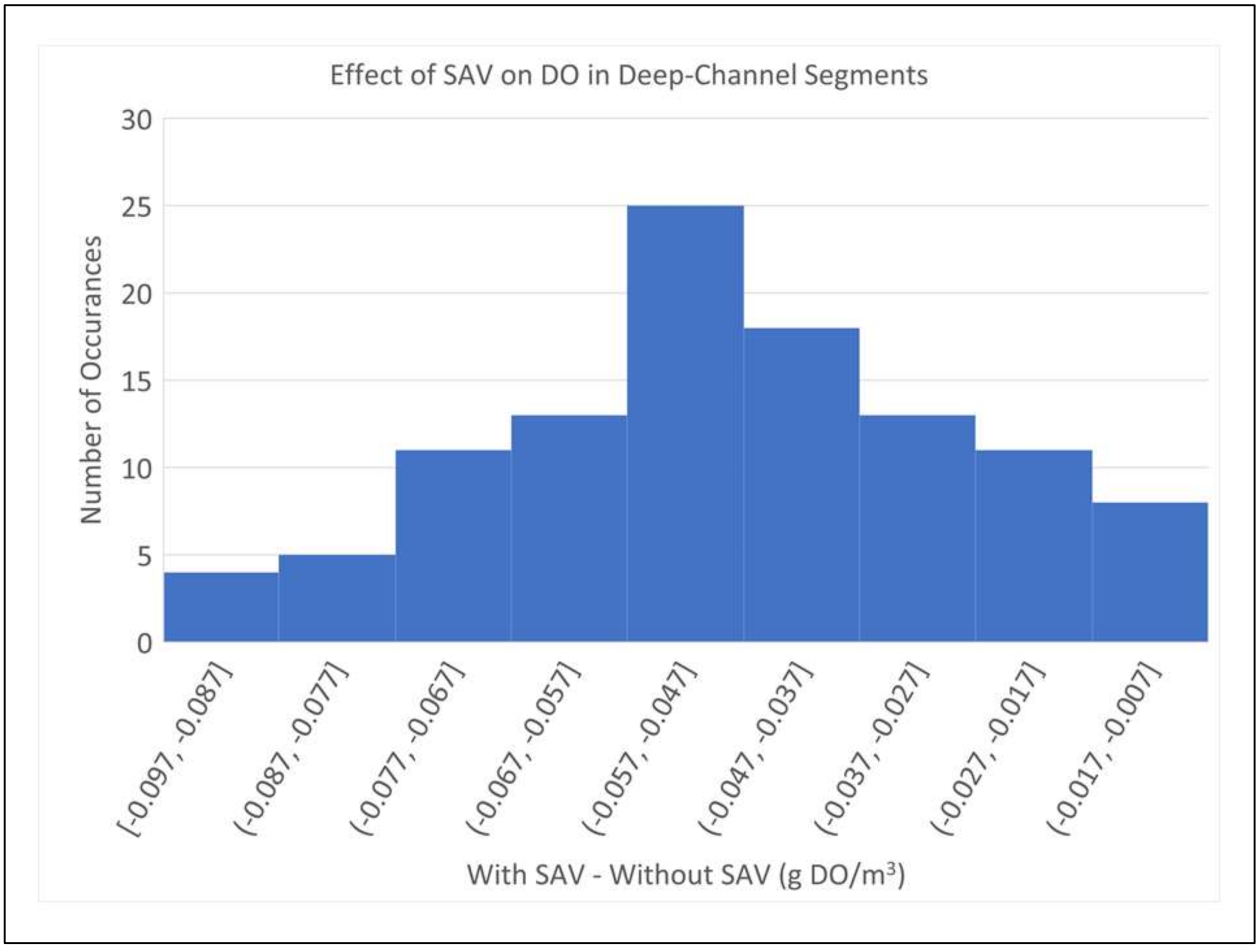


Figure 22. Effect of SAV on DO in deep-channel habitats under existing conditions. Each occurrence represents a monthly average over a CBSEG. Differences are shown between model runs with and without SAV activated.

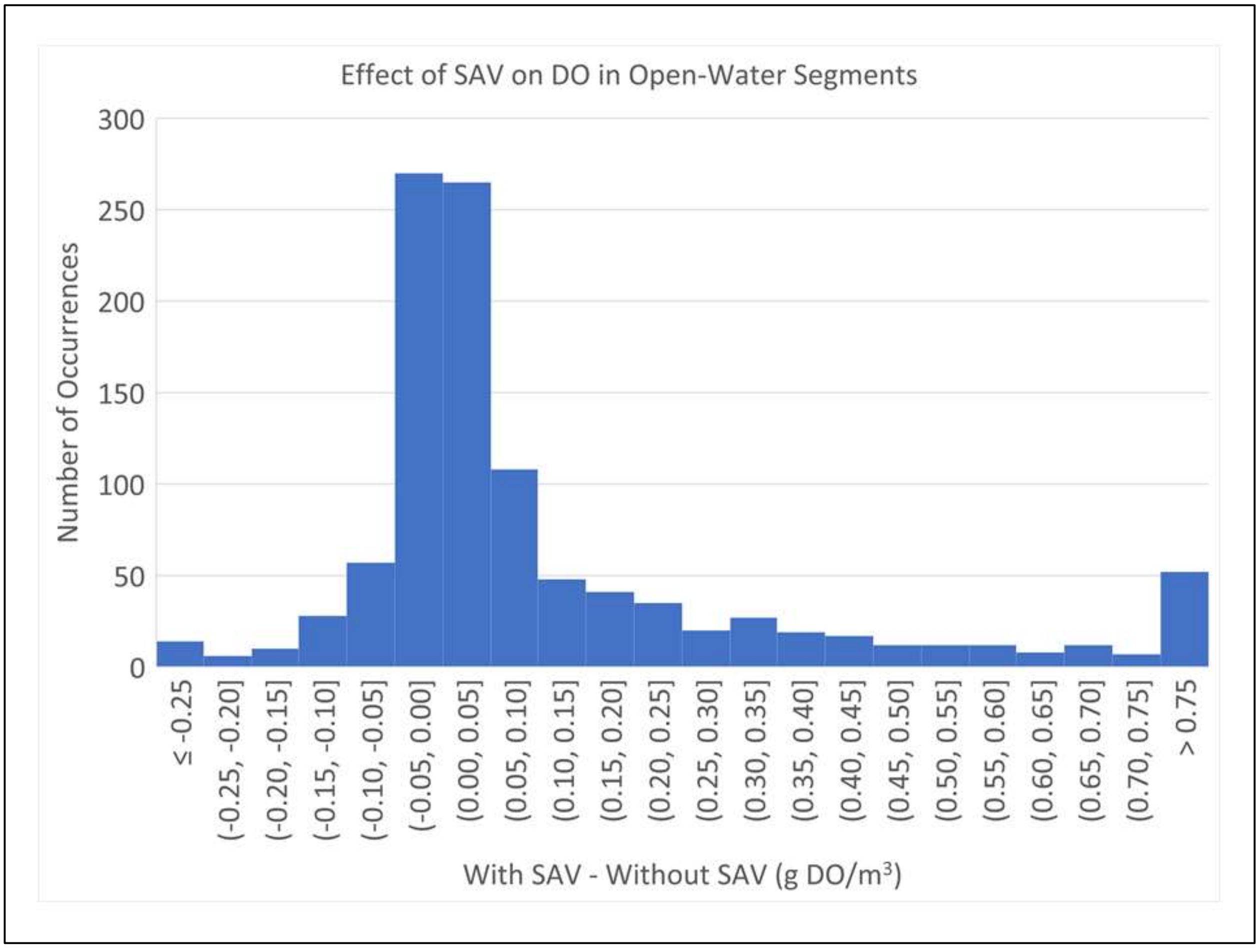


Figure 23. Effect of SAV on DO in open-water habitats under WIP3 conditions. Each occurrence represents a monthly average over a CBSEG. Differences are shown between model runs with and without SAV activated.

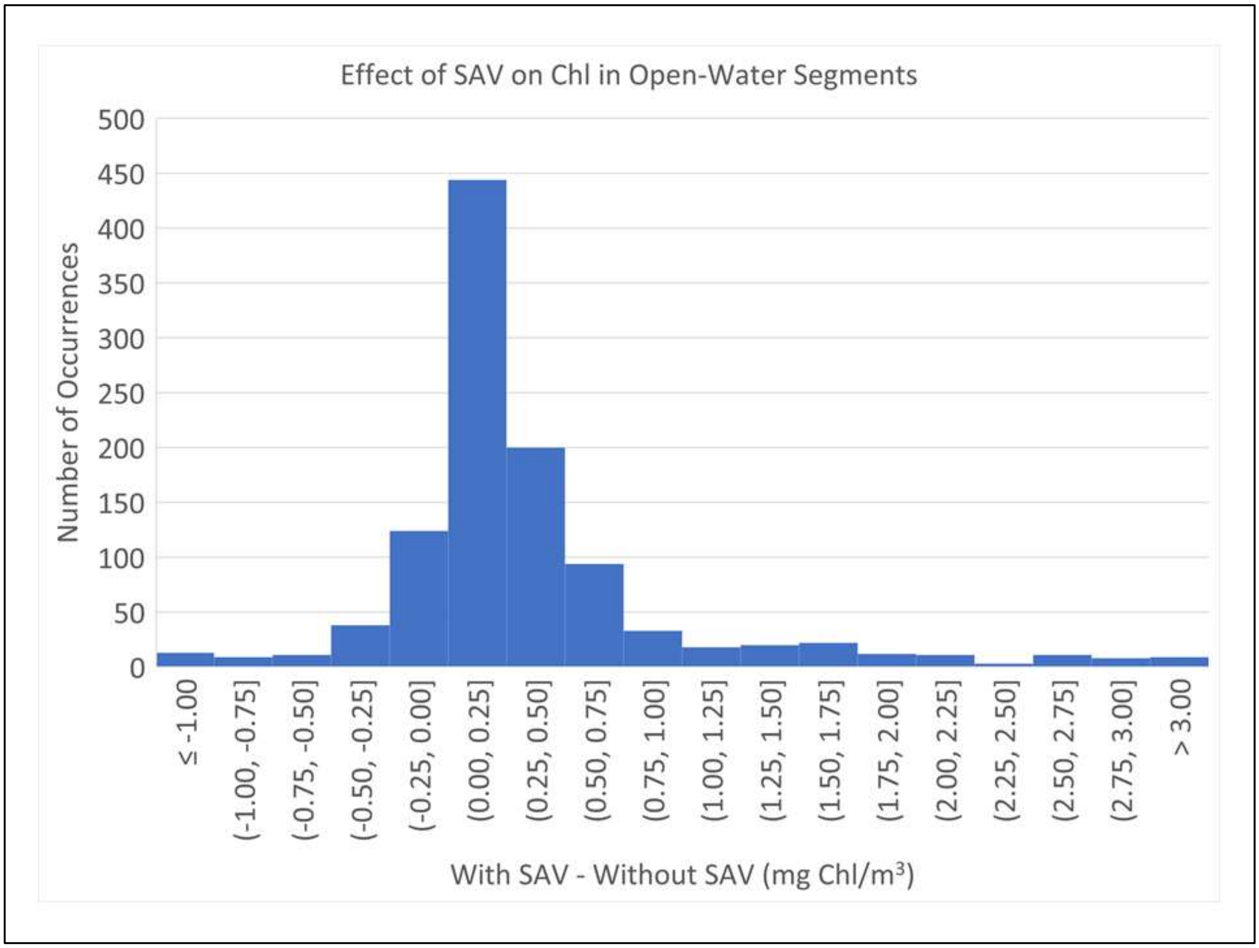


Figure 24. Effect of SAV on Chl in open-water habitats under WIP3 conditions. Each occurrence represents a monthly average over a CBSEG. Differences are shown between model runs with and without SAV activated.

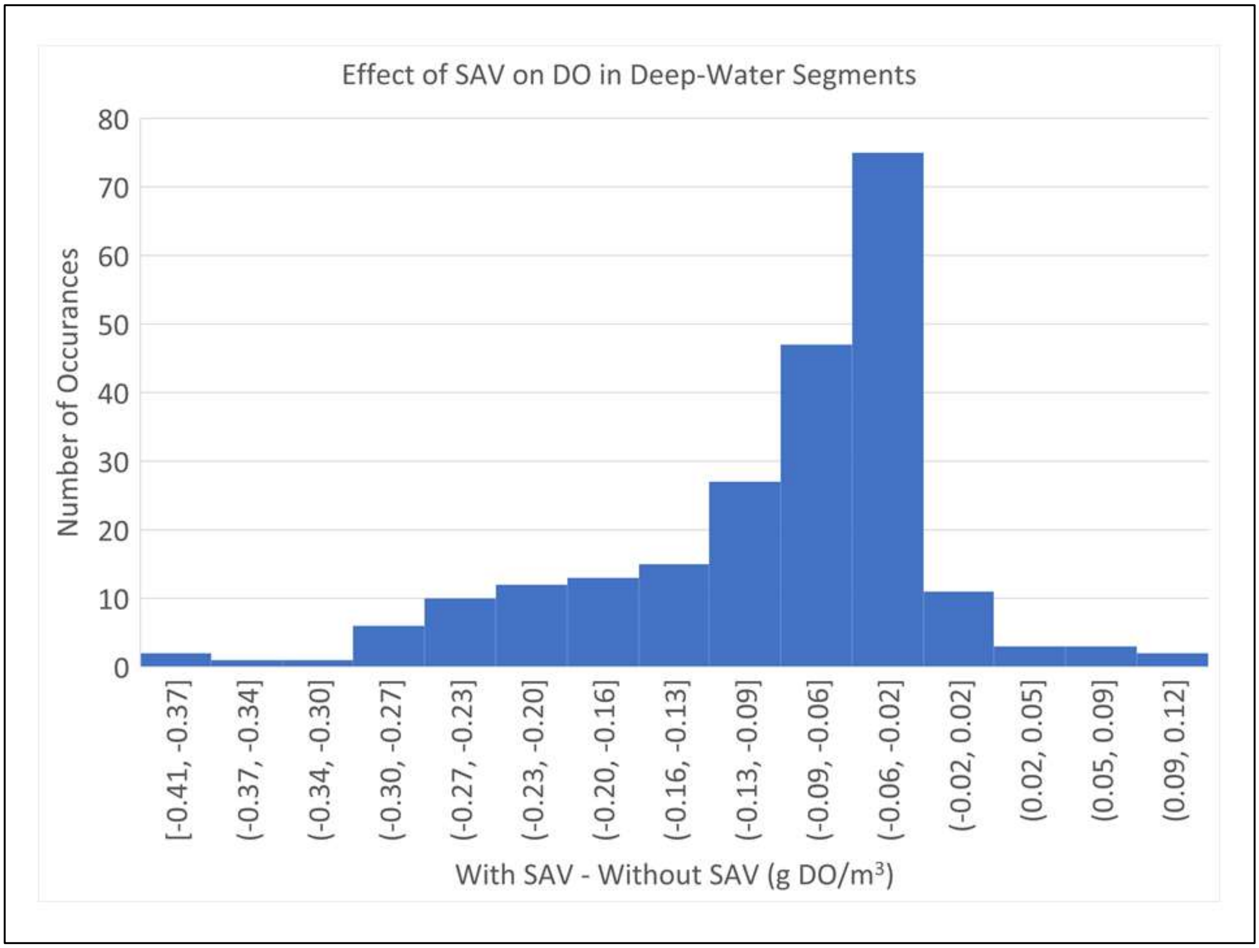


Figure 25. Effect of SAV on DO in deep-water habitats under WIP3 conditions. Each occurrence represents a monthly average over a CBSEG. Differences are shown between model runs with and without SAV activated.

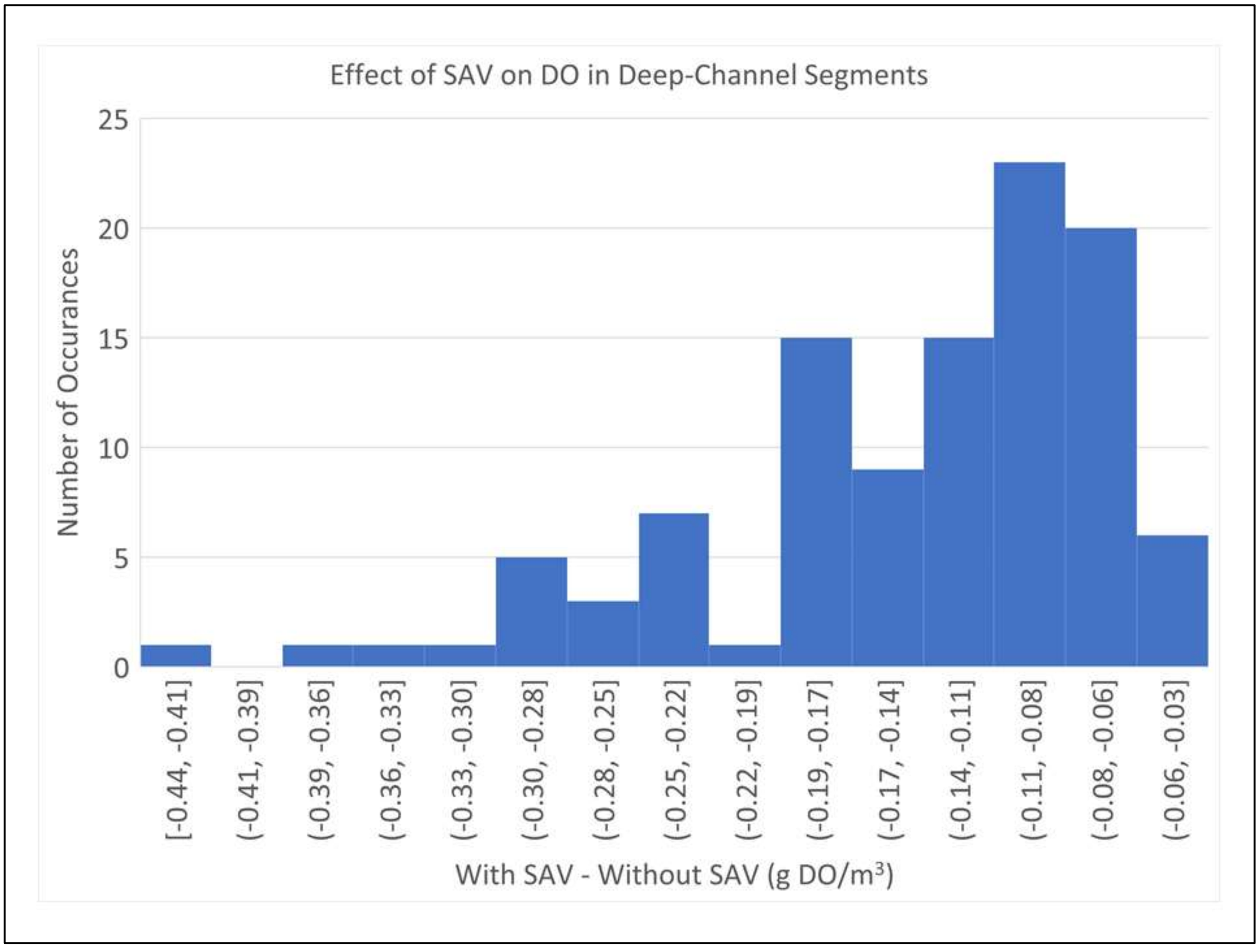


Figure 26. Effect of SAV on DO in deep-channel habitats under WIP3 conditions. Each occurrence represents a monthly average over a CBSEG. Differences are shown between model runs with and without SAV activated.

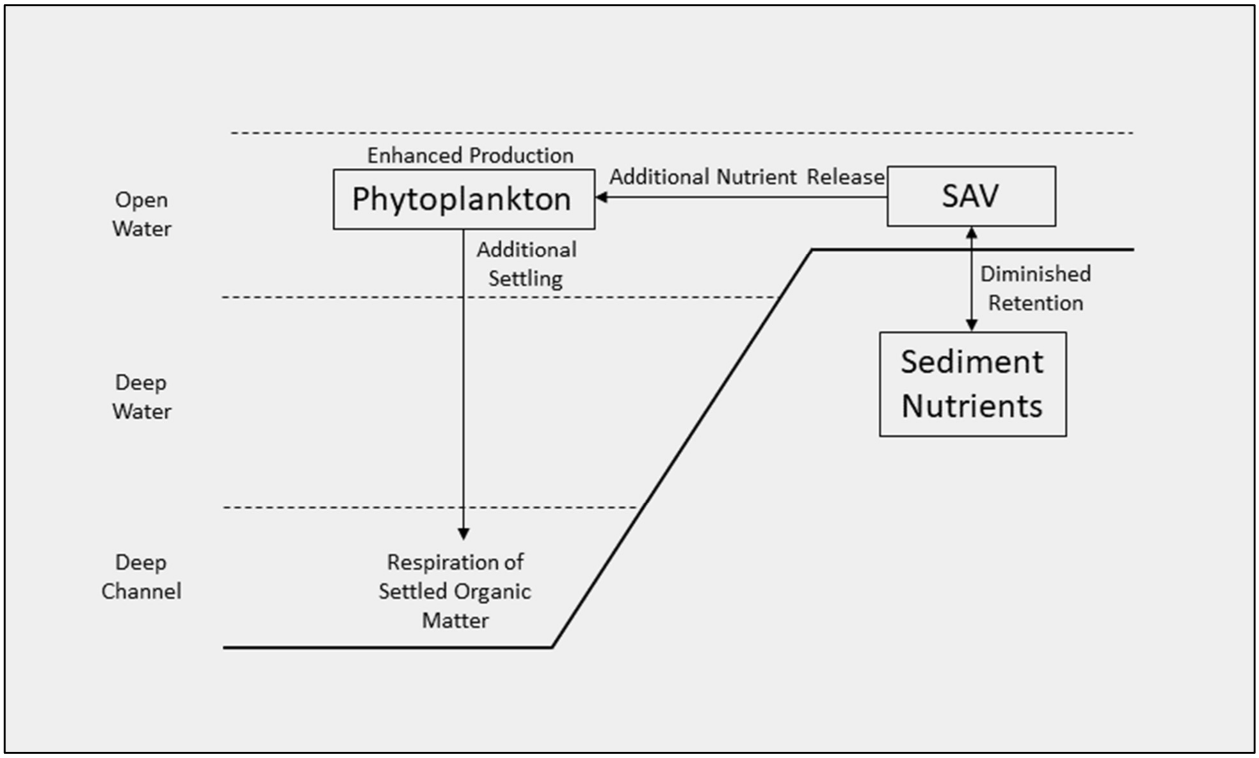


Figure 27. Conceptual model of the influence of SAV on DO and surface chlorophyll.