Appendix 6-1: Interim Findings of the Decomp Physical Model

Colin Saunders, Susan Newman, Erik Tate-Boldt, Chris Hansen[1], Judson Harvey[1], Laurel Larsen[2], Brandan Buskirk[3], Jenny Lewis[1], Jesús Gomez-Velez[1], Allison Swartz[1], Rudolf Jaffé[2], Barry Rosen[1], Jay Choi[1], Eric Cline, Carlos Coronado-Molina, Christa Zweig and Fred Sklar

INTRODUCTION

The Comprehensive Everglades Restoration Plan (CERP) Water Conservation Area (WCA) 3 Decompartmentalization & Sheet Flow Enhancement – Part 1 (Decomp) Project is often called the heart of Everglades restoration. On October 21, 2004, the project delivery team for Decomp developed an issue paper proposing that demonstration tests be conducted "as a means to reduce uncertainties, narrow objectives of the project scope, build confidence in the predicted benefits and potentially reduce overall project costs." Subsequently, the Decomp project management plan (USACE and SFWMD 2002) was revised to include an adaptive approach, resulting in the discussion on how to incorporate a Decomp Adaptive Management Plan (DAMP) into the final project implementation report. The DAMP focuses on several key issues facing Decomp, including (1) What are the effects of hydrologic structures (canals, levees, weirs, and roads) on landscape structure and function? (2) What are the differential effects of partial versus complete backfilling of canals on landscape structure and function? (3) What are the effects of sheetflow and water table fluctuations on ridge and slough ecosystem processes? (4) What are the effects of sheetflow and water table fluctuations on tree island population dynamics? and (5) How can the variance and uncertainties of the hydraulic models, needed to develop restoration scenarios, be reduced?

As a relatively newer concept, the DAMP underscored that adaptive management is (1) a scientific, systematic approach for finding answers to ecosystem management questions; (2) a study that can be implemented at any point within the planning, design, construction, and operation of a restoration project; (3) a process of "learning by doing"—using the scientific method to evaluate natural resources and environmental impacts of large-scale restoration or management plans; (4) an organized and inclusive means for identifying and addressing key uncertainties (often an alternative to numerical models), allowing managers to move forward in the face of inadequate knowledge; and finally, (5) a directive of Section 601(h)(3) of the Water Resources Development Act of 2000.

After several years of planning and designing, the scope and cost of the DAMP was considered too great to implement, especially when the infrastructure proposed along the L-67A was no longer an element of the Modified Water Deliveries Project, an Everglades National Park and United States Army Corps of Engineers' (USACE) project to increase conveyance of water across Tamiami Trail. However, as the Decomp uncertainties remained, the Decomp Physical Model (DPM)—the first active adaptive management program in the South Florida Water Management

[1] Florida International University, Miami, FL
[2] University of California, Berkeley, CA
[3] United States Geological Survey, Reston, VA

District's and USACE's history—was launched in 2010 (http://141.232.10.32/pm/projects/docs_12_wca3_model.aspx). It is considered active because CERP planning funds have been used to build a small water control structure, remove 3,000 feet of levee, and fill part of a canal within the footprint of CERP restoration as a way to address scientific, hydrologic, and water management uncertainties (see uncertainties 1, 2, and 3 listed above) that require clarification prior to future planning and construction of Everglades restoration projects authorized in Water Resources Development Act of 2000. Installation of the DPM was completed in October 2013, followed by operational testing. This appendix presents the cutting edge science and technology needed to understand the complex movement and creation of Everglades organic matter. This document only presents interim findings and does not provide a synthesis or any water management or restoration recommendations because DPM requires a few more flow events before its role as an adaptive management guide can be fully realized.

BACKGROUND AND OBJECTIVES

DPM is a landscape-scale adaptive management study to evaluate the benefits of restoring sheetflow in the ridge-and-slough landscape. The project objectives include (1) evaluating the extent to which flow will move sediment from sloughs to ridges and build microtopography and patterning and (2) determining the ecological benefits of backfilling canals, completely or partially, to maintain natural sediment transport while reducing downstream eutrophication. Several of the findings from the first flow event [documented in the Volume I, Chapter 6, of the *2015 South Florida Environmental Report* (SFER) (Sklar and Dreschel 2015)] were again observed in the second flow event. In both flow events, dye injected at the S-152 structure spread radially across the pocket, moving preferentially eastward. High flow velocities [> 3 centimeters per second (cm/s)] were achieved primarily in sloughs, but limited to areas within 500 meters (m) of the structure. Velocities and shear stress measured at the sediment-water interface in sloughs were at or above the critical thresholds required to resuspend sediments. Several independent field measurements (e.g., traps, synthetic tracers, and water samples) demonstrated sediment transport increased, more so in sloughs than ridges. Finally, in both flow events, water velocities and sediment transport in the RS1 slough (nearest the S-152) increased substantially over the duration of flow despite relatively constant S-152 discharges.

This year's report focuses more narrowly in addressing the differences in the chemical and physical properties and the fate of transported sediments. Such differences have implications for how structures are operated in the interest of maximizing sediment redistribution. As an example, if nutrient content and total mass of sediment transport during initial flow pulses (from structure openings) are several-fold greater than during steady state flows, then optimal structure operations might include a combination of both pulse flows and steady state flows. Other data are presented to address the specific source of transported sediments (e.g., benthic sediments versus particles trapped in plant stems, and marsh versus canal sediments), and the extent to which sediment moved from sloughs into ridges. Finally, this report provides initial findings of a pilot study aimed at increasing flow and sediment transport using an active management approach (**Figure 1**, bottom panel). The latter was motivated by the limited spatial extent of high velocities observed in the first flow event.

METHODS

The study uses a before-after-control-impact (BACI) experimental design, with additional sites for synoptic surveys (**Figure 1**), to evaluate hydrological and ecological response variables to flow conditions and canal backfill treatments. Ten gated culverts are used to move water from the L-67A canal into an area known as "the pocket" between L-67A and L-67C canal/levee features. The

culverts were designed to generate velocities of at least 2 cm/s, the expected threshold velocity needed to resuspend sediments. The study is in its fifth year, including three baseline (before) years and two high flow (impact) events in fall 2013 and 2014. The third flow event is expected to begin November 2015.

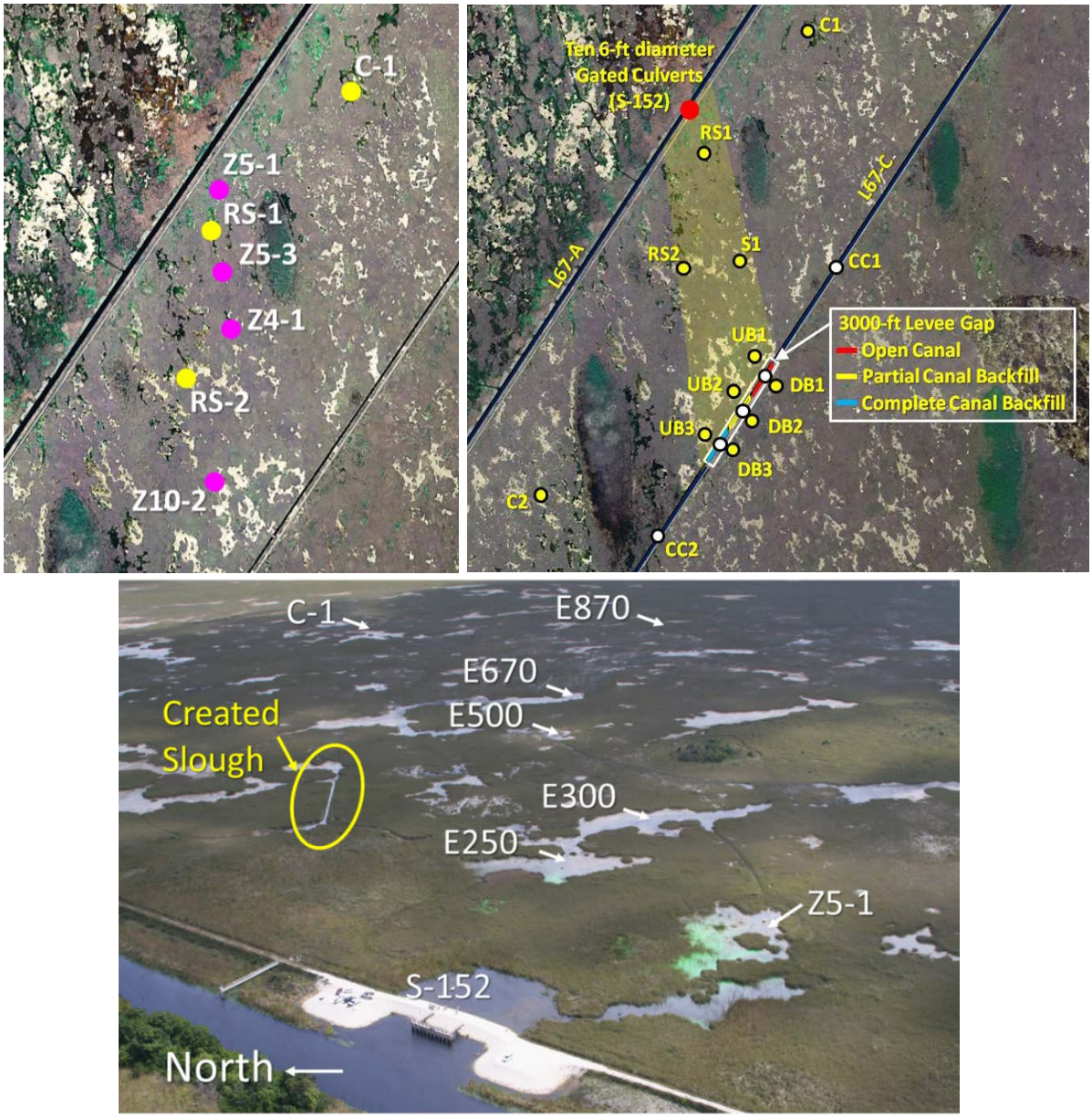

Figure 1. (Top left) DPM experimental site, located in "the pocket" between the L-67A and L-67C canal/levee structures. Hydrologic and biological response variables are measured at 11 marsh sites and 5 canal sites using a BACI experimental design. Site RS1 includes an upstream and downstream boardwalk, RS1U and RS1D, respectively. (Top right) Additional sites (pink) were added to analyze changes in spatial gradients along the north-to-south flow path in a subset of response variables. (Bottom) Location of east transect sites (E250, 300, 500, 670, and 870) for additional water quality and flow monitoring and a 3-m x 100-m created slough (circled, yellow), used to assess the benefits of active management in restoring flow and sediment redistribution.

WATER QUALITY

Water column samples along the BACI southern transect were collected monthly, July–March, during the 2013–2015 sampling periods. Samples were collected mid-water column, preserved and analyzed following standard South Florida Water Management District (SFWMD or District) protocols. The S-152 and S-151 samples were collected weekly. The dye study conducted in November 2013 demonstrated that the flow path was greater to the east than to the south (SFER 2015, Chapter 6), therefore additional grab samples were collected from sites east of the S-152 structure during the November 2014 flow event. Sites along this new easterly transect ranged ~250 to 870 m from the structure, similar distances to those measured routinely along the southern transect. Concurrent flow (Sontek Flowtracker®) and turbidity measurements were collected along with water samples.

To gain greater insight into the link between flow and surface water total phosphorus (TP), an autosampler was deployed at site Z5-1 for the second flow event. For the first two days of flow the autosampler collected water samples hourly and composited them every three hours. From November 6 to November 9, 2014, samples were collected every three hours, composited daily and analyzed for TP. The autosampler was redeployed prior to closing the structure and samples were collected every 6 hours. In addition to TP, continuous measurements of water level (Onset HOBO® water depth data logger), turbidity (Campbell Scientific OBS-500®), and flow (Sontek Argonaut-ADV®) were recorded at site Z5-1.

SEDIMENT CONCENTRATIONS AND SIZE DISTRIBUTIONS

Sediment concentrations and size distributions were characterized during high flow events to aid in testing the hypothesis that bed floc from sloughs is transported downstream and to ridges during these events. If this were the case, then the following would be expected: (1) elevated particle concentrations and particle sizes following a flow release, and (2) tapering concentrations and mean size of suspended particles with distance into the ridge.

To evaluate this hypothesis, the United States Geological Survey (USGS) deployed continuously recording laser diffraction particle size analyzers at the ridge and slough ends of the RS1D platform (Sequoia Scientific LISST-100x and LISST-Floc) and established a transect of suspended sediment pumping locations at six regularly spaced intervals across a ridge-slough transect from the RS1U platform (**Figure 2**). The suspended sediment pumping locations were paired with bed shear stress measurement locations, where a Vectrino profiler (Nortek, Inc.) was deployed to collect near-bed profiles of turbulence statistics before and during the flow release.

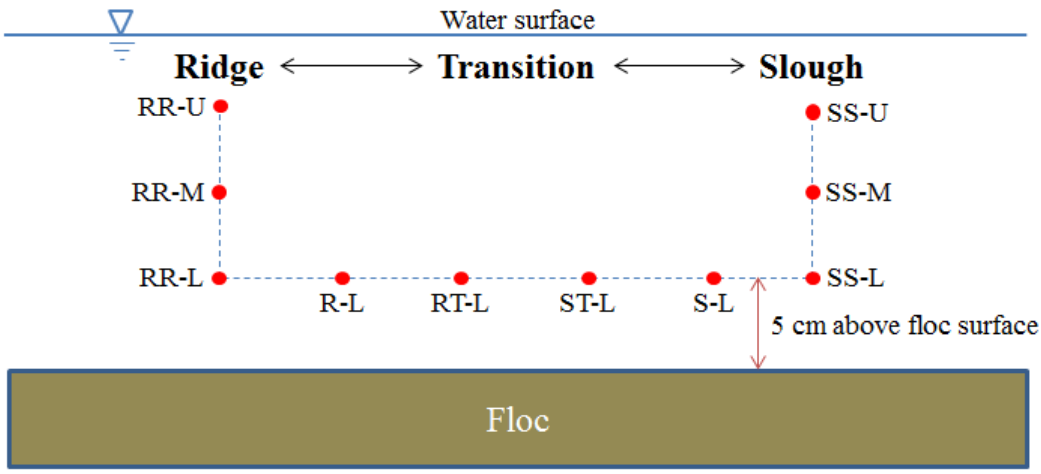

Figure 2. Water sampling transect at RS1U. At the ends of the transect, samples were collected from upper (U), middle (M), and lower (L) water depths. For the interior sampling stations, water samples were pumped from lower locations, approximately 5 centimeters (cm) above the floc surface.

Measurement of Particle Size Distribution and Suspended Sediment Concentration

The LISST instruments provide volume concentrations of particles in 32 size categories, from 1.25 to 250 microns (µm). Volumetric concentrations may then be converted to mass concentrations by multiplying binned volumetric concentrations by density for that size class, obtained through previous settling column experiments.

Suspended sediment was collected from the locations identified in **Figure 2** with a peristaltic pump. Samples were stored on ice and kept in the dark until subsequent laboratory analysis. In preparation for lab analysis of the suspended sediment a 0.7 µm-filter (Whatman GF/F) was prepared for each sample by vacuum filtering 100 milliliters (mL) of deionized water and oven drying each filter at 60 degrees Celsius (° C). The initial dry mass of the filter was measured on an analytical balance. The volume of each suspended sediment sample was measured prior to filtration with a graduated cylinder. Each sample was then processed by vacuum filtration through a prepared 0.7-µm filter (Noe et al. 2010). The sediment laden filters were dried in an oven at 60° C and the mass of each filter was measured using an analytical balance. With this information, suspended sediment concentration can be calculated for each sampling time at each site:

$$SSC\left(\frac{\mu g}{l}\right) = \frac{M_{Sediment\ and\ Filter} - M_{Filter}}{V_{water\ sample}}$$

$$(M = mass\ (\mu g),\ V = volume\ (l))$$

Vectrino Profiler Measurements and Computation of Bed Shear Stress

To compute bed shear stress, a Vectrino Profiler was mounted on a vertically sliding rod and deployed to sample flow immediately above the bed. Each instrument reading consisted of instantaneous velocity collected over 18 points within a 2.5-centimeter (cm) vertical profile, at a spacing of 2.0 millimeters (mm). The instrument was operated at high power to achieve the

maximum signal-to-noise ratio, with pinging set to "max interval." Each reading was acquired over a period of 5 minutes. At the end of 5 minutes, the profiler was moved to its next location along the sliding rod (which overlapped with the first by about 0.5 cm) and again deployed. In this manner, four stacked 2.5-cm profiles were obtained near the bed. A fifth 2.5-cm profile was acquired in the middle of the water column at each site.

Raw velocity records were filtered to remove data points that did not meet standards for signal-to-noise ratio (at least 5 decibels), correlation (at least 40 percent), or consistency in redundant measurements of the z-direction velocity component. Instrument noise spikes were removed using the Goring and Nikora Threshold Despiking algorithm (Goring and Nikora 2002). Following Biron et al. (2004), bed shear stress was calculated from profiles of turbulent kinetic energy.

BIOMARKERS

Vegetation-specific molecular markers, or biomarkers, have been developed and applied as a useful approach to identify the sources, transport and ultimately the fate of organic matter in the Everglades (Jaffé et al. 2001, Gao et al. 2007, Saunders et al. 2015). The n-alkane-derived proxy, Paq, effectively distinguishes sawgrass from deeper water slough sources such as *Eleocharis* spp., *Nymphaea odorata*, and submerged aquatic vegetation (SAV; such as *Chara* spp.; Mead et al. 2005, Saunders et al. 2014). Other proxies include Kaurenes, diterpenoids that are highly enriched in (although not exclusive to) sawgrass tissues (particularly enriched in belowground biomass). Other biomarkers have been identified as being indicative of green algae (Botryococcenes) and cyanobacteria (highly branched isoprenoids; C20 HBIs) (Gao et al. 2007, Gao 2007). As such, the combination of Paq, C20 HBIs, the Kaurenes, and the Botryococcenes were used to determine changes in the source of organic matter composition of floc and water column particulates. Biomarker analyses were performed on ridge and slough floc collected at BACI and spatial survey sites within the DPM during the pre-, during, and post-flow periods around the first flow event. It was expected that redistribution of sediment from sloughs into ridges would be evidenced by more slough-like biomarker values in ridge floc. To some degree, it was also expected that biomarkers would support findings of increased sediment transport (e.g., from traps) by showing a "moving front" of sediment biomarker values along the north-to-south flow path during high flow conditions.

ALGAL TAXONOMY

Changes in the algal component of advected sediments were characterized from samples collected in horizontal sediment traps (2015 SFER – Volume I, Chapter 6). Sample collected from each trap was split into subsamples for mass determination (~40 percent of the total), nutrient chemistry (40 percent), and algal taxonomy (20 percent). Taxonomy subsamples were collected in Whirl-Pak® Sample Collection Bags and kept refrigerated until examined. The sample was gently homogenized and one subsample (approximately 0.1 mL) mounted on a glass slide and 22-(square millimeter) mm^2 glass coverslip before microscopic examination at 400x. The presence and relative abundance of algal species was counted in each subsample. Samples examined included three pre-flow deployments (February 6, 2013, March 7, 2013, and October 30, 2013) and deployments two and five weeks after flow was initiated (November 20, 2013, and December 11, 2013). The total number of species of algae and cyanobacteria was determined in 77 samples from RS1, C1, and RS2 and four sites downstream of the backfill (DB1-3 and the control site DCC2S).

HYDROLOGY AND SEDIMENT DYNAMICS OF THE L-67C CANAL AND LEVEE GAP

ADV and Dye Studies

The hydrodynamics of surface water flow near the L-67C canal before and during flow releases has been assessed by quantifying surface flow velocities at UB and DB sites (see **Figure 1**) using acoustic Doppler velocimeter (ADVs) or Vectrinos and in the L-67C open canal treatment (MB1) and partial backfill (MB2) using Argonaut XRs. The surface water flow velocity was measured continuously from August 2014 to March 2015 at UB2 and DB2, and the discrete velocity profiles were also obtained at all UB and DB sites before and after the flow release experiment started. Due to instrument failure, the velocity profile at UB3 during the flow release experiment did not pass the quality assurance/quality control test. Using the depth averaged velocity estimated from the collected velocity profiles and associated water depth measurements at UB and DB sites, the water fluxes per unit width [square centimeters per second (cm^2/s)] at each site were calculated and are displayed as vectors. At MB1 and MB2, it was not possible to calculate the flux due to lack of continuous measurements of water depth; therefore, velocity vectors of canal flow are provided at MB sites instead of the flux.

During the second flow event, two additional dye studies were completed, focused on observing water flow through the L-67C backfill treatments and levee gap. On January 26, 2015, 9:00 AM, 40 pounds of fluorescein dye solution (4:1 site water to dye mixture) were injected into the L-67C canal at a location approximately 100 meters upstream (northeast) of the open canal backfill treatment. Dye was deployed utilizing an airboat equipped with a trailing hose. The dye was injected in the center of the canal parallel to the canal orientation over approximately a 50-m linear swath then further mixed in-situ with the boat wake. At 9:40 AM, 25 pounds of Rhodamine-WT dye solution (4:1 mixture) was injected along a 95 meter linear swath mid-way between the UB1 and UB2 sites. This shallow water linear injection was conducted via airboat and trailing hose and covered both a slough and sawgrass ridge habitat.

Canal Sediments

The canal sediment biomarkers component has three basic questions: (1) Will canals act as sediment traps, reducing overland transport of sediment under increased sheetflow? (2) Will high flows entrain high nutrient canal sediments and carry them into downstream areas? and (3) To what extent are these responses altered by different canal backfilling options, including partial and full backfills? To answer these questions, a total of 40 sediment trap samples were analyzed from pre-, during, and post-flow periods. Vertical sediment traps were used to collect sediment and have been described previously (see 2015 SFER – Volume I, Chapter 6). Canal sediments were analyzed using the same biomarkers as described above. Average values regardless of the collection time as well as some time series are presented.

ACTIVE MANAGEMENT PILOT STUDY

In September 2014, an experimental slough was created in a sawgrass-dominated area by clipping and removing aboveground live and dead sawgrass biomass. The created slough, located approximately 300 m east of the S-152 (**Figure 1**), spans 3 m x 100 m, oriented parallel to the predominant flow direction (east-west). Prior to and during the flow event, velocities were measured mid-water column at a number of sites within the created slough and in the adjacent sawgrass. Measurements were made using a Sontek Flowtracker, a handheld ADV. Sediment movement was tracked using a dual signature tracer (DST), paramagnetic (due to embedded magnetite inclusions) and hydraulically matched to Everglades floc particle size and settling velocity. Two weeks after flow was initiated in November 2014, approximately 25 kilograms (kg)

of DST was deployed at both upstream and mid-point locations in the slough. Prior to these deployments, 11 gauss magnets were placed along 5-m transects oriented perpendicular to flow. In January, near the end of the flow event, the DST was collected from magnets, dried, and weighed.

RESULTS

CHANGES IN THE SOURCE AND NUTRIENT CHEMISTRY OF TRANSPORTED PARTICLES UNDER HIGH FLOW

Water Column Phosphorus and Sediment Dynamics

To focus on the effects of flow, this report presents data associated with the November 2013 and 2014 flow events; pre-, during and post-flow, and our discussion emphasizes those sites closest to inflow. In general, water entering the DPM footprint through the S-152 structure was 1-2 microgram per liter (µg/L) lower in TP concentration than that measured at the upstream S-151 structure (**Figure 3**).

As observed in previous years, there was a distinct seasonality in TP concentrations within the canal system and, to a lesser extent, in the marsh (**Figures 3** and **4**). Highest concentrations were observed during the transition from dry to wet season, typically May to June. Phosphorus (P) concentrations at RS1, the BACI site closest to inflow, appeared closely tied with those of the adjacent canal, L67A. One possibility is there is a direct relationship between canal water chemistry and the marsh; however it is also possible this is due to a greater contribution of TP from suspended sediments.

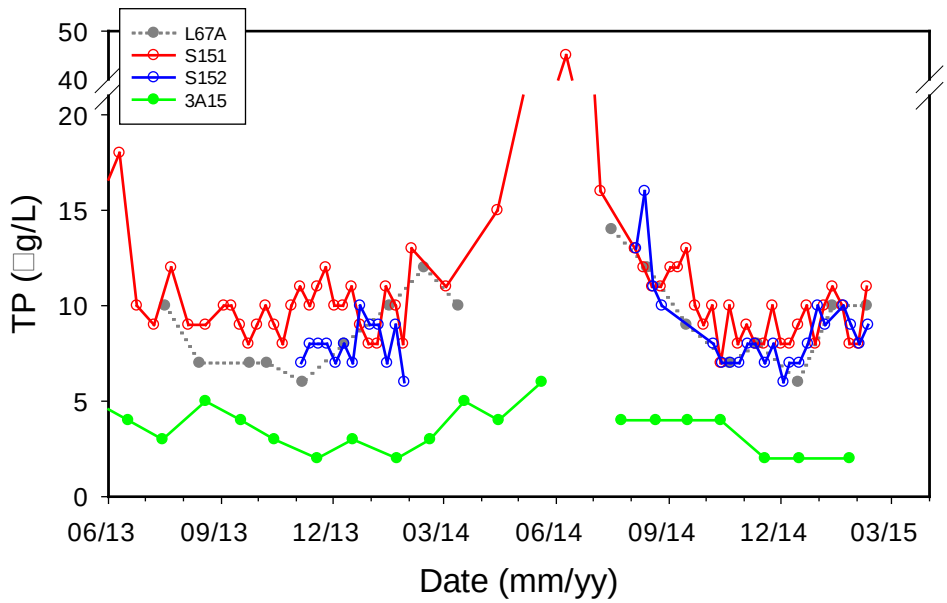

Figure 3. TP concentrations measured at inflow (S-152, L-67A), upstream (S-151), and reference wetland site (3A-15, in WCA-3A) during 2013 and 2014 sampling periods. Shaded areas depict durations the S-152 structure was open.

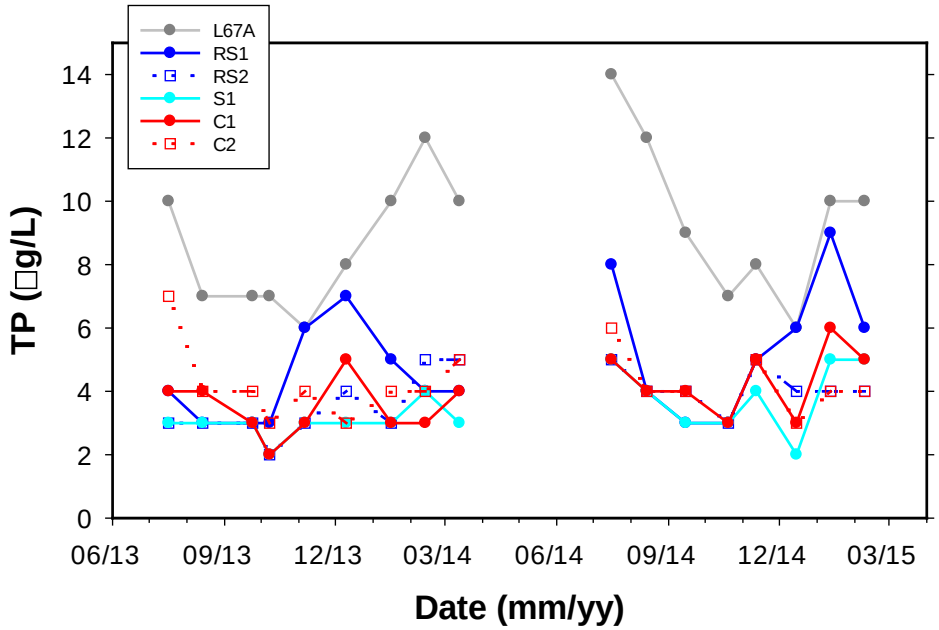

Figure 4. Changes in surface water TP concentrations observed pre-, during and post-flow at BACI sites throughout the DPM flow-way. Shaded areas depict durations the S-152 structure was open.

During the 2014 flow, a series of surface water samples were split and analyzed for particle size using a LISST-Portable particle size analyzer (Sequoia Scientific), and TP content (Buskirk et al. 2015). TP content increased immediately following flow implementation and was associated with a decrease in particle size (results are presented in greater detail in the following sections). However, unless sufficiently concentrated, fine particles may not be reflected in changes in turbidity, which relies on optical backscatter for detection. This likely explains the lag in turbidity response, following the dramatic TP increase, from 5 to 26 µg/L, observed at E250 immediately upon opening the gate (**Figure 5**). The decrease in particle size observed by Buskirk et al. (2015) was short lived, lasting only a few hours, thus likely explaining the increase in turbidity at sites E250 and E300, two to three hours after flow initiation. Flow also increased TP and turbidity at site E500, which was the furthest east site that exhibited a distinct response to flow restoration to the DPM flow-way. However, the lag between increased TP and turbidity was not apparent at eastern transect sites more than 250 m from inflow.

Point measurements allow us to assess the broad-scale effects of flow at multiple locations; however, given the observed short-term nature of surface water TP and particles, assessment at a greater temporal resolution was essential, resulting in the intensive monitoring initiated at site Z5-1 during the 2014 flow event. The initial opening of the S-152 caused a higher tailwater stage, from 7.26 to 8.10 m. Downstream the opening of the structure resulted in a flow pulse, from < 1 to > 5 cm/s (**Figure 6**). The high head differential between the marsh and canal likely caused the flow to pulse along with the spike in turbidity, because flow continued to increase after the initial pulse, while turbidity decreased. Opening the structure also resulted in an increase in surface water TP from 5 to 8 µg/L although the lag between TP and turbidity was not as evident as observed at E250; however, nor was the TP increase as dramatic, a 3 versus 21 µg/L change. There are several hypotheses that might explain the differences observed at the two sites including (1) Site E250 was in the preferential flow path from the structure, experiencing greater flows and potentially greater sediment transport or local disturbance exemplified by the rapid break-up of periphyton in the E250 slough (**Figure 5**, right panel); (2) aerial imagery using the box-on-aircraft (BOA) suggest that the location of the autosampler was not within the preferred flow path in the Z5-1 slough area,

further damping any potential signal because of the inability to capture higher flow pulses and lower likelihood of capturing fine sediments; and (3) differences in local sediments impact their suspension and effect on TP concentrations. While fluctuating, surface water TP concentrations remained elevated for several hours before returning to background concentrations.

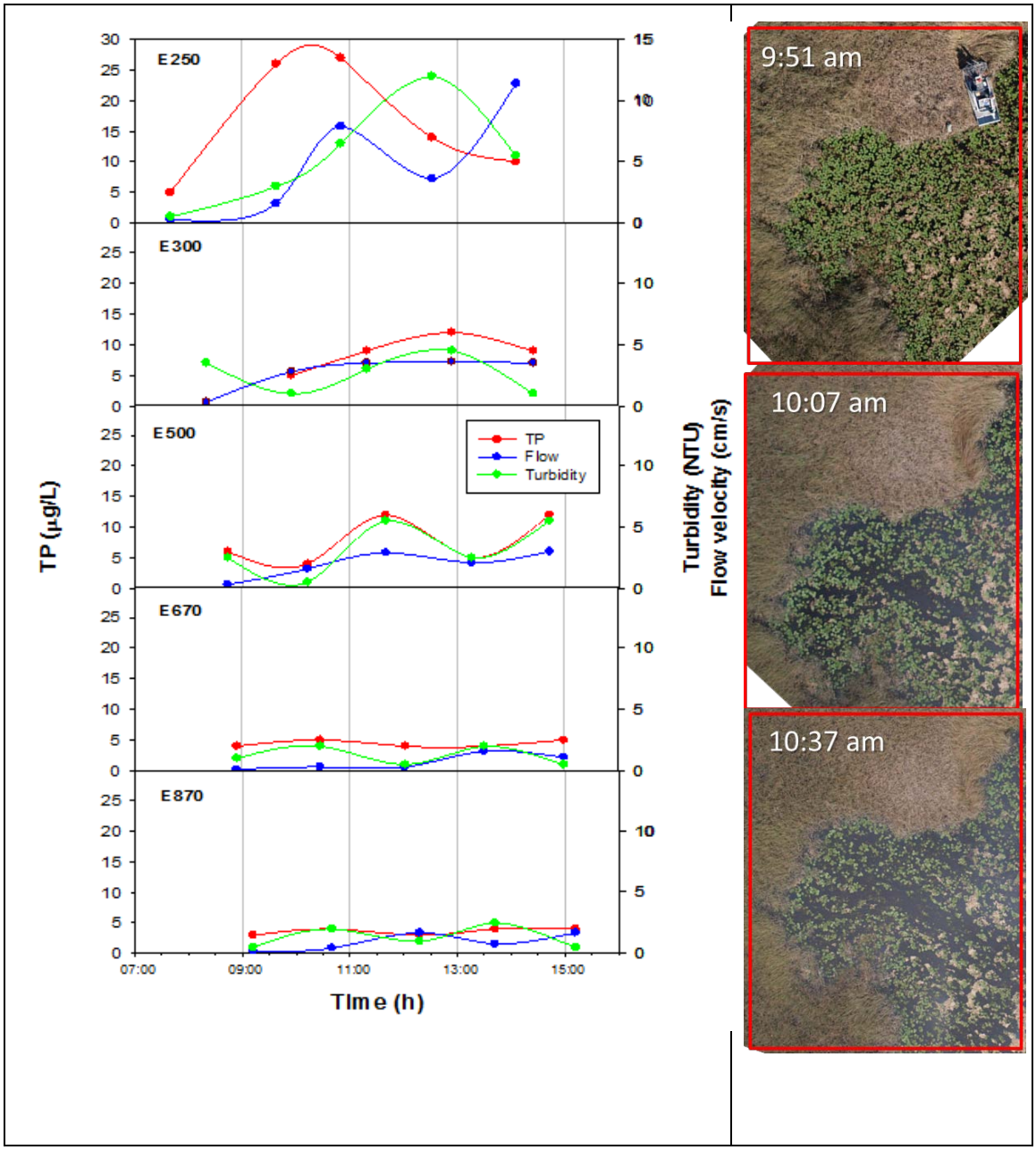

Figure 5. Changes in surface water TP concentrations, flow velocity, and turbidity observed along the eastern flow path during flow day November 4, 2014 (left). Note structure opening began at approximately 9:30 am. Rapid changes in slough metaphyton at site E250 approximately one hour after flow was initiated High-resolution images taken by Matt Burgess (UF) using the BOA system (right) (see 2015 SFER – Volume I, Chapter 6). [Note: NTU – nephelometric turbidity units.]

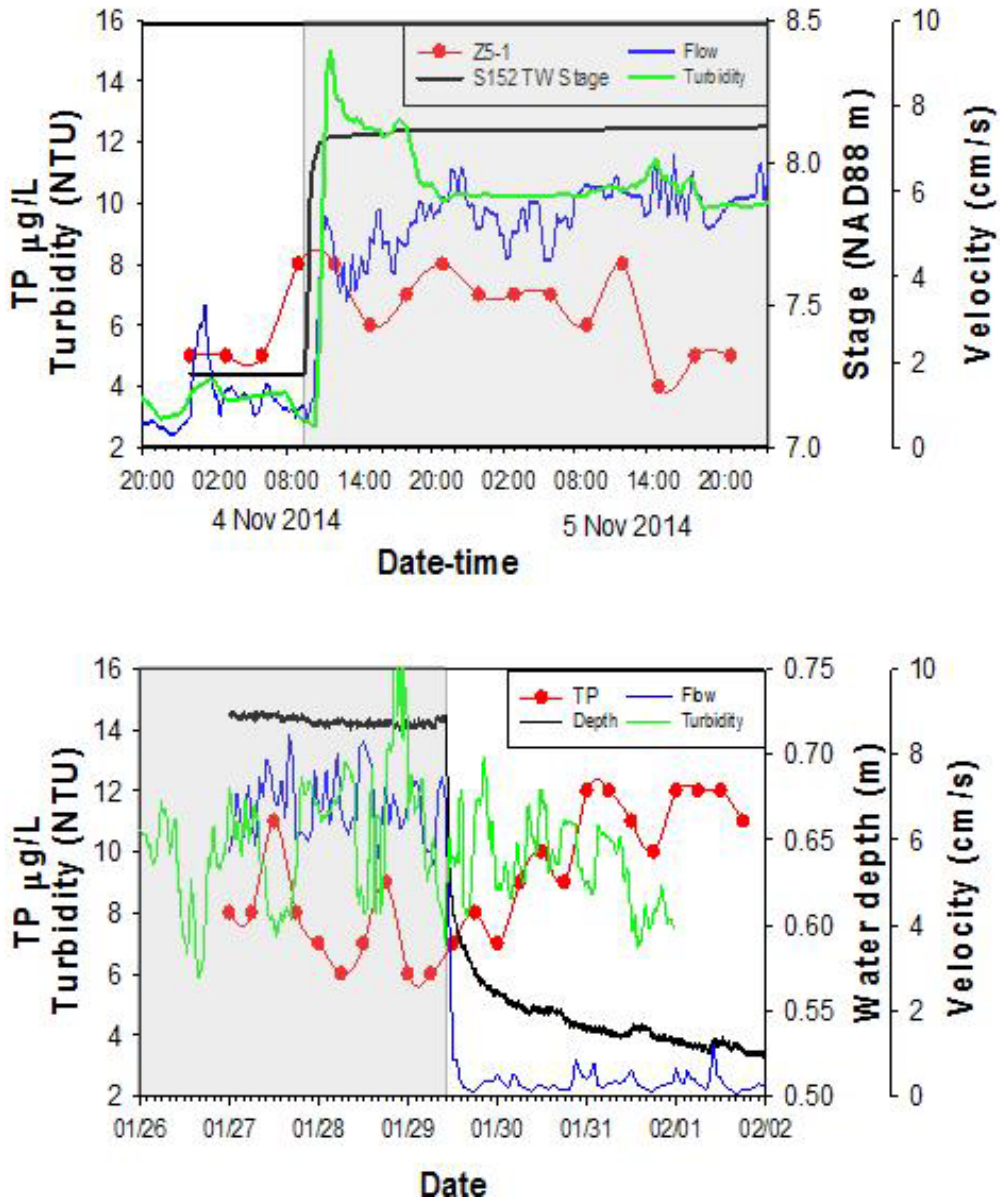

Figure 6. Intensive monitoring at site Z5-1 in response to opening (top image) and closing (bottom image) of the S-152 structure. Shaded area depicts when structure was open. [Note: NAD88 – North American Vertical Datum of 1988 and NTU – nephelometric turbidity units.]

Similarly, the response to closing the structure was also an increase in surface water TP. It is not clear what caused the increase, it could be attributed to local disturbance following rapid decline in water levels (e.g., increased sediment suspension and displacement of particulate material from plants) and lack of flow to transport those suspended materials, which in turn may explain the highly variable turbidity even after flow cessation. However, at this point this is speculation, further data analysis looking at periodicity may shed some light on these observations.

SEDIMENT CONCENTRATIONS AND SIZE DISTRIBUTIONS IN THE RIDGE AND SLOUGH

Bed Shear Stress Relative to the Floc Entrainment Threshold

Prior to the flow release in both 2013 and 2014, bed shear stress remained below the 0.01 Pascals entrainment threshold for Everglades bed floc, determined experimentally in laboratory flumes by Larsen et al. (2009) and in a field flume by Harvey et al. (2011) (**Figure 7**). Following the 2013 flow release, that threshold was exceeded twofold in the slough. Bed shear stresses were within the error of the entrainment threshold in the transition zone sites and ridge site, with the exception of ridge site two, which was in exceedance of the threshold. Relative to the other ridge sites, RS2 was relatively devoid of vegetation, possibly causing it to develop preferential flow pathways. It was also near one of the magnets used for collecting the synthetic floc tracer, which may have interfered with the Vectrino measurements. Post-flow release mid-water column velocities reflected the spatial patterns in bed shear stress, with high velocities in the slough (up to 6 cm/s) and low velocities in the ridge and the transition zone (approximately 2 cm/s). All post-flow velocities exceeded pre-flow velocities by an order of magnitude.

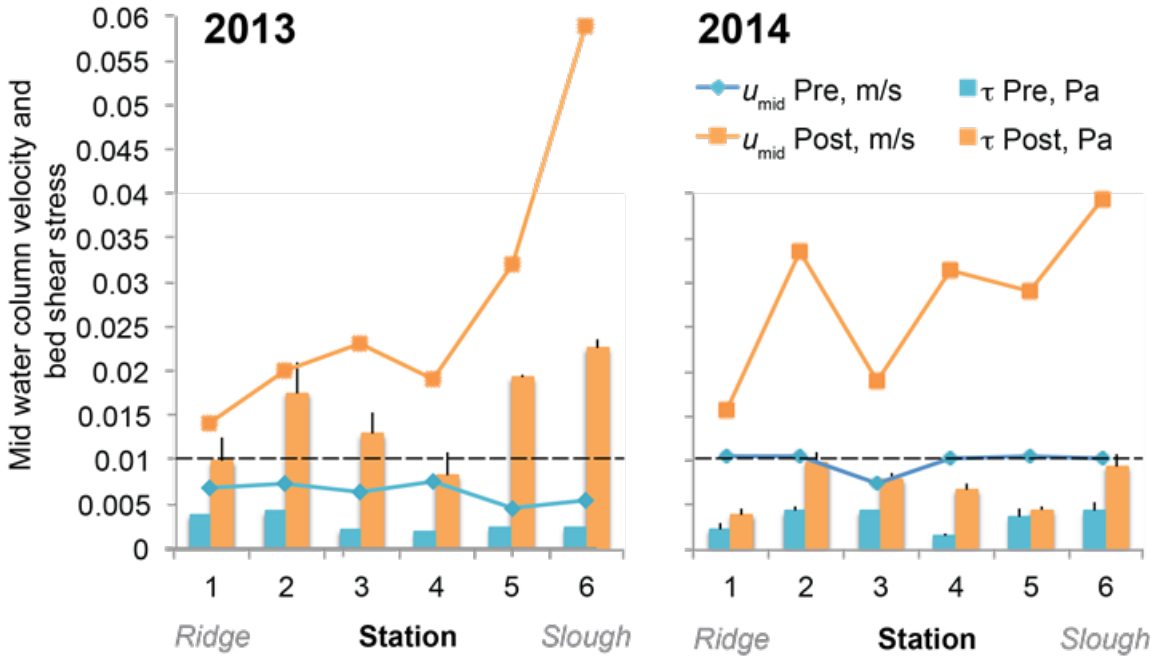

Figure 7. Bed shear stress before and after the 2013 and 2014 flow release (bars) relative to the 0.01 Pa entrainment threshold (dashed line) from the flume experiments of Larsen et al. (2009). Mid-water column velocities are depicted as data points connected by line segments. Error bars are standard errors computed across different profiles from the Vectrino instrument.

Patterns in bed shear stress and mid-water column velocities resulting from the 2014 flow release differed from the 2013 data. Bed shear stress at the most central slough station was within error of the entrainment threshold but did not exceed it, as was the case for the anomalous RS2. Mid-water column velocities were also lower than those recorded in 2013, approaching just 4 cm/s within the slough. The lower bed shear stress and velocities are consistent with the slightly lower S-152 discharge on the first day of flow. S-152 discharge on November 4, 2013, ranged from 230 to 280 cubic feet per second (cfs), whereas discharge ranged from 200 to 240 cfs on November 3, 2014.

Suspended Sediment Analysis

In 2013, immediately prior to the flow release, suspended sediment concentrations (SSC) were less than 1,500 µg/L for ridge and slough, with higher concentrations low in the water column, consistent with settling-dominated Rouse SSC profiles. At the start of the flow release, SSC increased by an order of magnitude to approximately 10,000 µg/L suspended sediment and were well mixed vertically, with concentrations indistinguishable between upper and lower water column locations (**Figure 8**). Within 10 hours of this initial spike, SSC dropped to values lower than the initial value within the slough but remained well mixed vertically in the slough. At this point, the bed shear stress remained above-threshold, so the decline in SSC may have reflected depletion of the particle source, a phenomenon that was also observed in the field flume experiments by Harvey et al. (2011). It is hypothesized that, as in Harvey et al. (2011), this source of particles was metaphyton, located within the vegetation canopy and high in the water column. At 70 hours post flow release, ridge and slough concentrations began to diverge, with higher concentrations in the slough than in the ridge. The SSC were highest low in the water column, possibly reflecting a combination of a settling-dominated profile and a primary source of particles low in the water column.

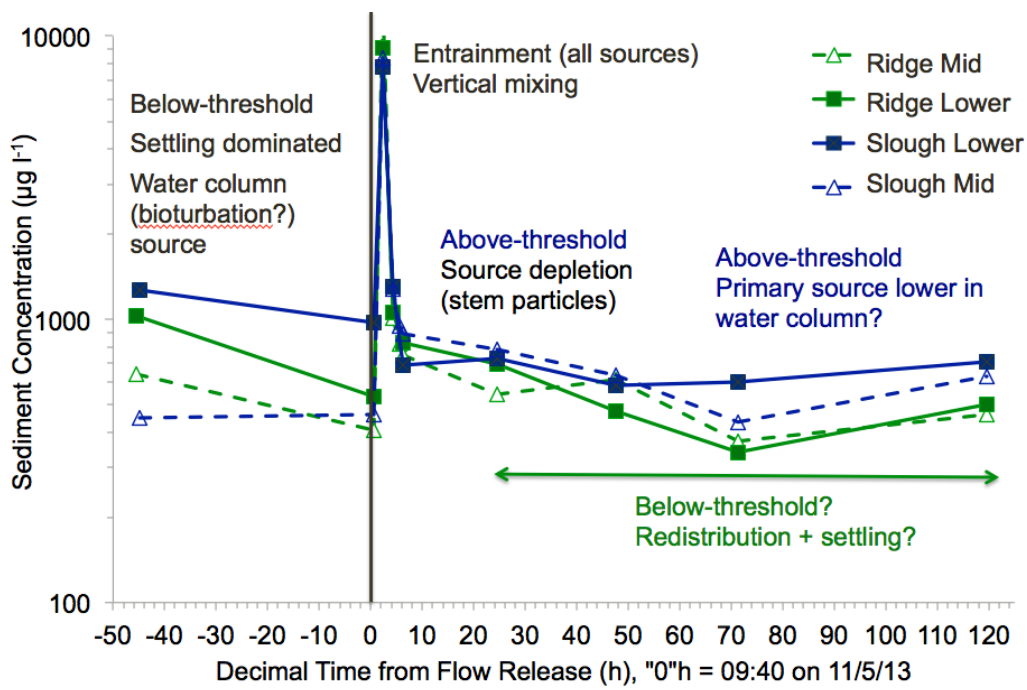

Figure 8. Time series of SSC before and after the 2013 flow release (denoted with the vertical black line). The depicted data comes from the ridge site located farthest into the ridge and the slough site farthest into the slough.
[Note: µg l^{-1} – micrograms per liter.]

In 2014, the baseline (pre-flow release) SSC featured higher values in the mid-water column locations compared to the lower water column locations, which may reflect a high supply of water column sources of particles (e.g., metaphyton) (**Figure 9**). Immediately following the flow release, only the slough mid-water column location experienced a spike in SSC, followed by depletion in all sampling locations. At 75 hours after the flow release, SSC again increased at all sampling locations, with the highest value in the ridge mid-water column location. This pulse of high SSC from the ridge is consistent with the hypothesis of metaphyton particle source depletion within the slough from the initial entrainment pulse, which left a reservoir of mid-water column particles

relatively intact within the ridge. In all cases, lower water column sampling locations had a lower SSC than the mid-water column locations, suggesting poor vertical mixing and/or a dominant source higher in the water column. As noted from the 2014 high resolution aerial images, loss of metaphyton at some sites within hours after flow initiation (**Figure 5**) would be consistent in providing both the mid-water column source of particles and the rapid increase (as metaphyton breaks up and moves) and decrease as particles are transported, captured, or settled.

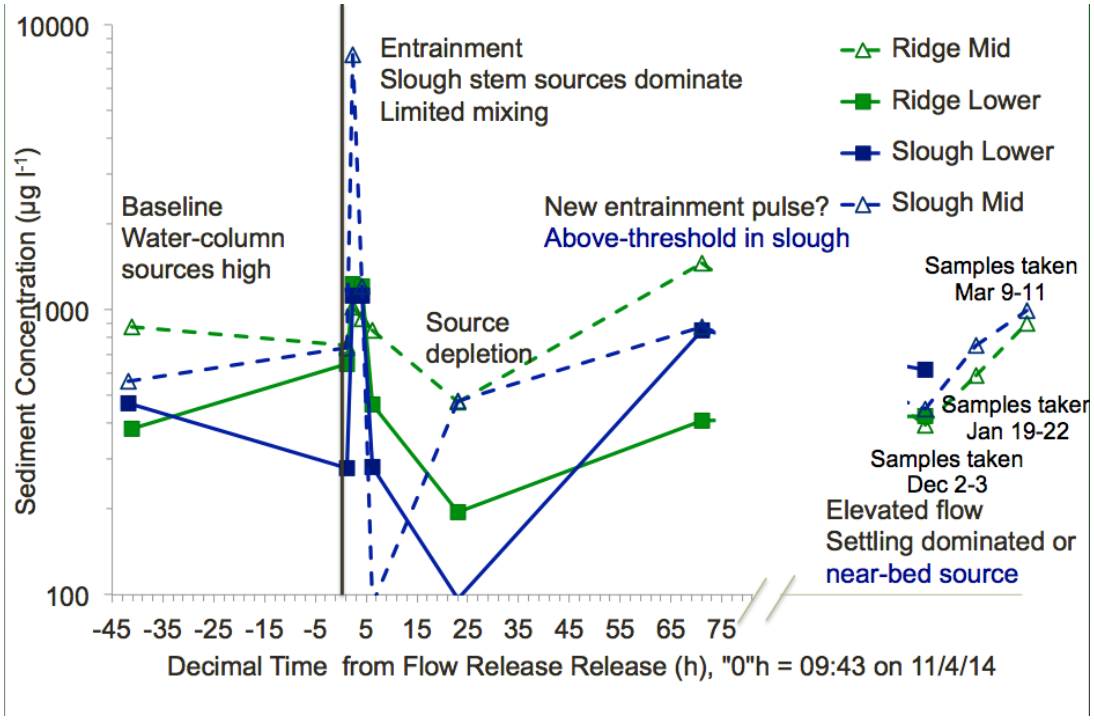

Figure 9. Time series of SSC before and after the 2014 flow release (denoted with the vertical black line). The depicted data comes from the ridge site located farthest into the ridge and the slough site farthest into the slough.
[Note: µg l^{-1} – micrograms per liter.]

These results make it clear that future experiments need to distinguish between bed floc particle sources and mid-water column (i.e., metaphyton) particle sources. If our interpretation of the data is correct, it appears likely that bed floc was entrained from sloughs but not ridges during the 2013 flow release, consistent with the governing hypothesis. However, in 2014 it appears that only mid-water column particles were entrained, and that flows were not sufficient to entrain bed floc at the RS1U sampling location. Velocity results, however, suggest that higher velocities were experienced elsewhere, so it is cautioned against extrapolating these SSC and bed shear stress results to other locations within the DPM footprint.

Grain Size Analysis

In order to examine how P transport could be affected by restoration, temporal changes were measured for SSC, suspended particle size distributions, and TP concentrations during experimental flow releases in November 2013 and 2014, when TP concentrations in the water column are generally lowest. Comparison of pre-flow release and high flow data indicated an increase in SSC during high flow for which the median diameter of suspended particles in the water column decreased from approximately 400 to 40 µm. TP concentration relatively doubled, from approximately 4 µg/L during the pre-flow period to 9 µg/L at high flow, reflecting a greater

concentration of TP in finer particles. When combined with higher flow speeds and greater depths of water during high flows, the transported TP load was elevated for the duration of the high flow period.

These changes were most evident at sites such as RS1 that were proximate to the S-152 culvert and were less evident downstream. Particle size measured continuously in the ridge and slough showed a short-lived decrease in particle size as the the flow pulse passed, but quickly recovered to pre-flow conditions within hours of flow initiation (**Figures 10** and **11**). Ridges and sloughs experienced similar changes in average particle size. Once the new flow regime had steadied at a new water depth and velocity (days after flow initiation), the average particle size of SSC samples returned to pre-flow release values. Together, the data suggest that the initial increase in entrained particles with higher P concentrations may be short lived and related to temporary transport of fine particles with high P concentration from an easily mobilized, but limited source. Another TP source could be from increased high flow contributions of TP from the L-67A canal.

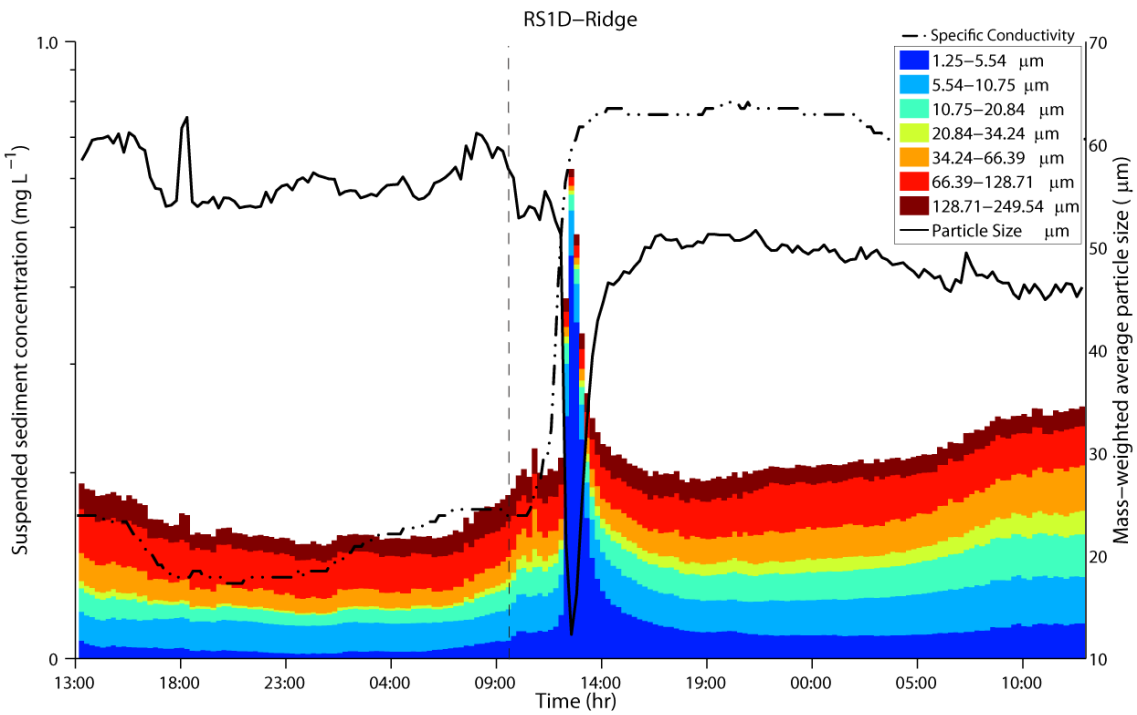

Figure 10. Time series of particle size distribution and average mass-weighted particle size at ridge Site RS1D. Deployment period: November 4–6, 2013. The dashed line indicates the initiation of the flow release. [Note: hr – hour and mg L^{-1} – milligrams per liter.]

Biomarkers of Floc and Advected Sediment

Molecular biomarkers were analyzed in benthic floc of paired ridge and slough samples, in the pre-, during, and post-flow periods for the 2013 flow, spanning October 2012 to May 2014 (**Figure 12**). For the n-alkane proxy Paq, a statistically different average value was observed for both the ridge and slough floc in the post-flow period, in which greater Paq values reflected increased slough-derived organic matter. Although Kaurenes were not statistically different during the 2014 sampling dates compared to 2013 (not shown), a much higher range of values for Kaurenes was observed during high flow conditions compared to pre-flow conditions (**Figure 12**). Comparative analyses of the C20 HBI and Botryococcenes are shown in **Figure 12**, panels b and d. Using all available data from all sites, no significant differences were observed among the pre-, during, and post-flow conditions in ridge and slough samples for the C20 HBI. Although Botryococcenes showed a high degree of variability. the slough values were significantly different (higher) in the post-flow period. It is stressed that these data are preliminary, as they encompass only the first flow event and as a result unbalanced (far fewer samples in the flow and post-flow periods). Nevertheless, changes do appear consistent with the hypothesis that flow increased the presence of slough-derived organic matter settling in ridges. That slough Paq values also increased suggests some changes occurred in the content of the slough floc itself. A change in algal composition, indicated by the Botryococcenes at site RS1, was also observed.

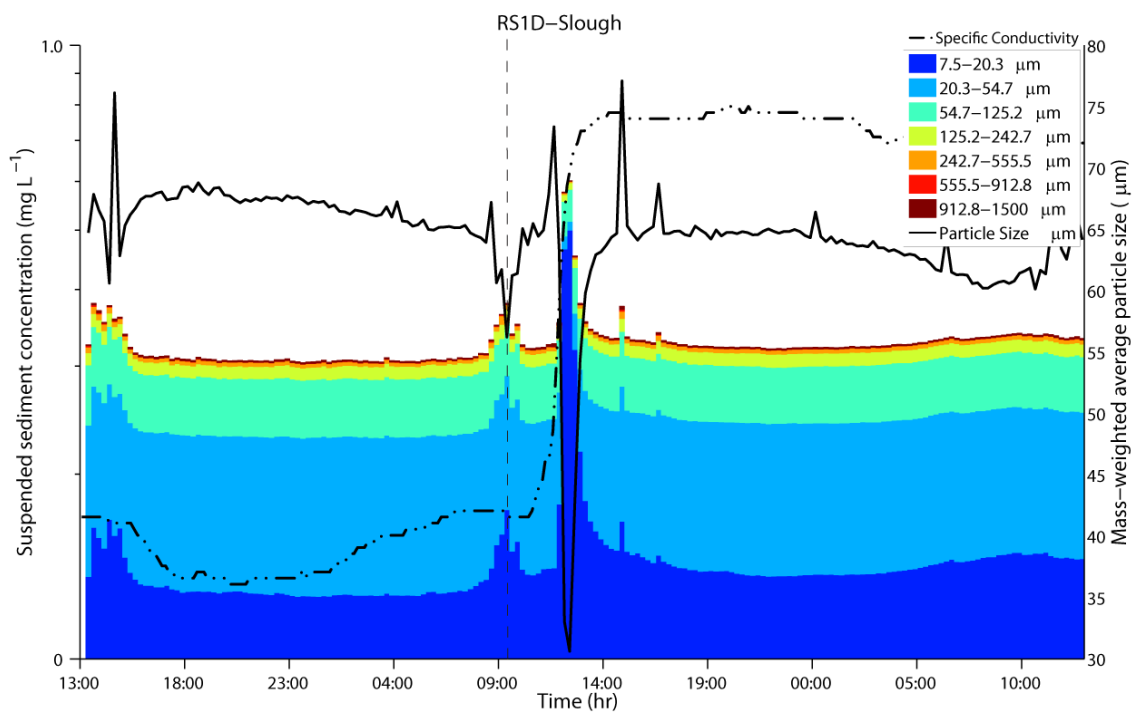

Figure 11. Time series of particle size distribution and average mass-weighted particle size at slough Site RS1D. Deployment period: November 4–6, 2013. The dashed line indicates the initiation of the flow release. [Note: hr – hour and mg L^{-1} – milligrams per liter.]

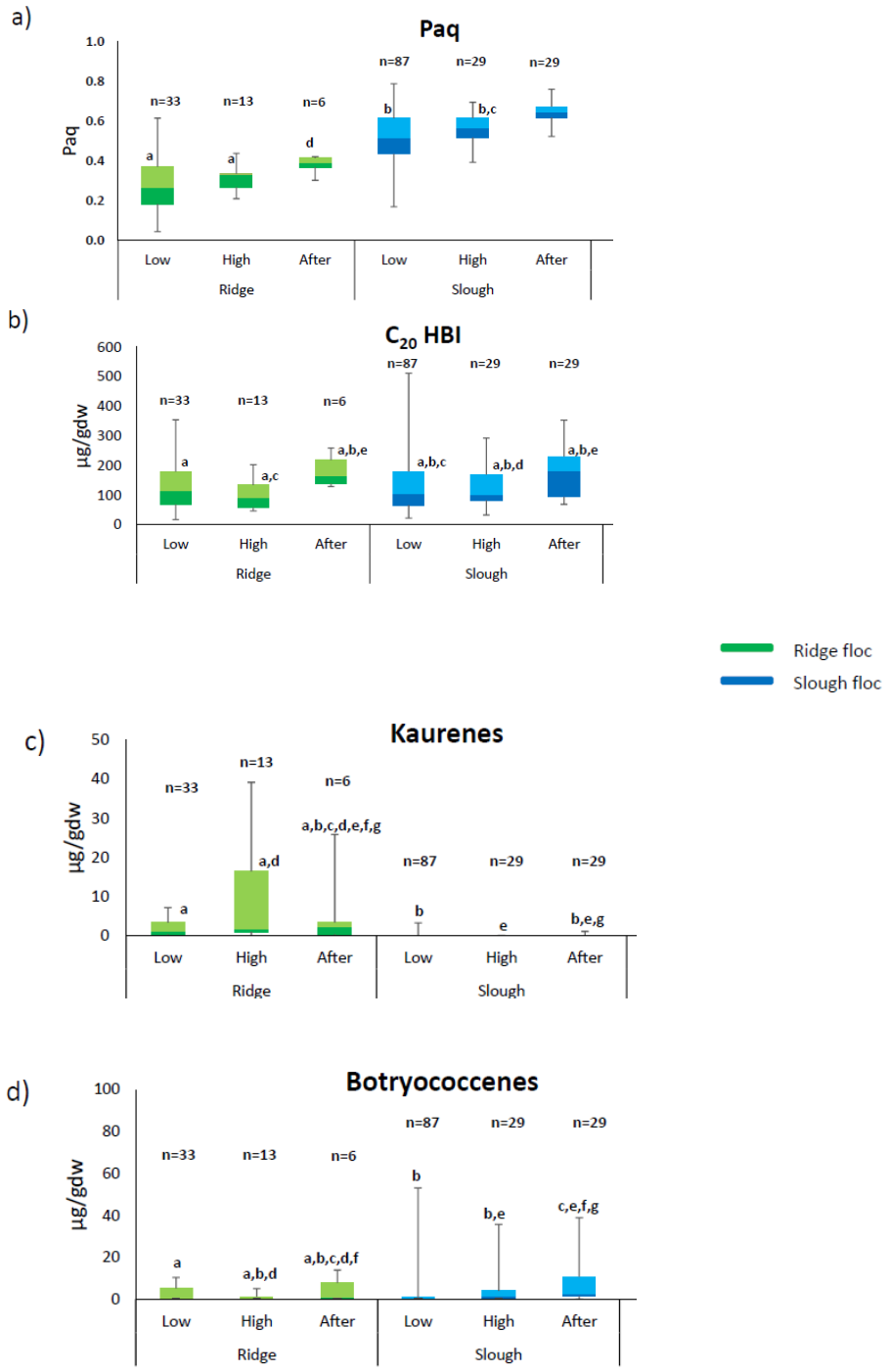

Figure 12. Comparison of biomarkers Paq, C20 HBI, Kaurenes, and Botryococcenes in ridge and slough floc collected from BACI and spatial survey sites, in the pre-, during, and post-flow sampling periods (Low, High, and After, respectively). Different letters indicate statistically different data sets; unmarked plots are statistically different from all other groups. Sample size (n) = 197. [Note: µg/gdw – micrograms per grams dry weight.]

Some uncertainty remains about the mechanism of sediment redistribution, since biomarker changes occurred primarily in the post-flow period rather than the actual flow event. Substantial capture of sediments by vegetation in the water column was observed, qualitatively, during flow, especially at RS1. Therefore, it is hypothesized that the biomarker changes in floc post-flow reflects the slower process of vegetation litter fall (which would include settling of captured sediments) over several months. An alternative hypothesis is that biomarker changes reflect shifts in local algal communities that ultimately produce a lot of the floc material. However, the taxonomy of advected sediment showed flow-driven changes in the algal community were fast (within weeks, see the *Algal Taxonomy of High versus Low Flow Sediment and Floc* section below) and therefore less likely to underlie the slower, monthly changes in benthic floc biomarkers.

While the algal biomarkers C20 HBI and Botryococcenes are highly variable, closer inspection of the spatio-temporal distribution of all biomarkers suggests changes were widespread but mostly near the S-152 structure (**Figure 13**). In the pre-flow samples, the Paq showed some hotspots but generally decreased south along the flow path and decreased in the drier months (January–April). However, after high flows ended starting January 2014, and water levels dropped, the Paq increased throughout the south flow path (**Figure 14**). No specific spatio-temporal features were observed for Kaurenes (**Figure 14**, which are usually very low in abundance or absent in slough floc. Periphyton-derived biomarker C20 HBI showed the highest temporal variability in the northern-most sections of the study site, possibly as a result of canal seepage, and a concentration gradient decreasing along the north-south flow path (**Figure 13**). Botryococcenes were almost undetectable throughout the pre-flow period, but showed a significant increase after the 2013–2014 flow started (**Figure 13**). The southward moving boundary of the Botryococcenes over the flow and especially in the post-flow period is suggestive of a change mediated by the enhanced flow. Biomarker analyses were conducted on advected sediment collected in horizontal traps at the northernmost site Z5-1. These samples exhibited very high Botryococcene concentrations [31–44 micrograms per gram (µg/g)], suggesting some of the increases in Botryococcenes in areas downstream of Z5-1 (i.e., RS-1) could have been caused by sediment transport (suspended or as benthic floc), as well as local changes in algal communities (in response to water quality changes) in the north portions of the flow path.

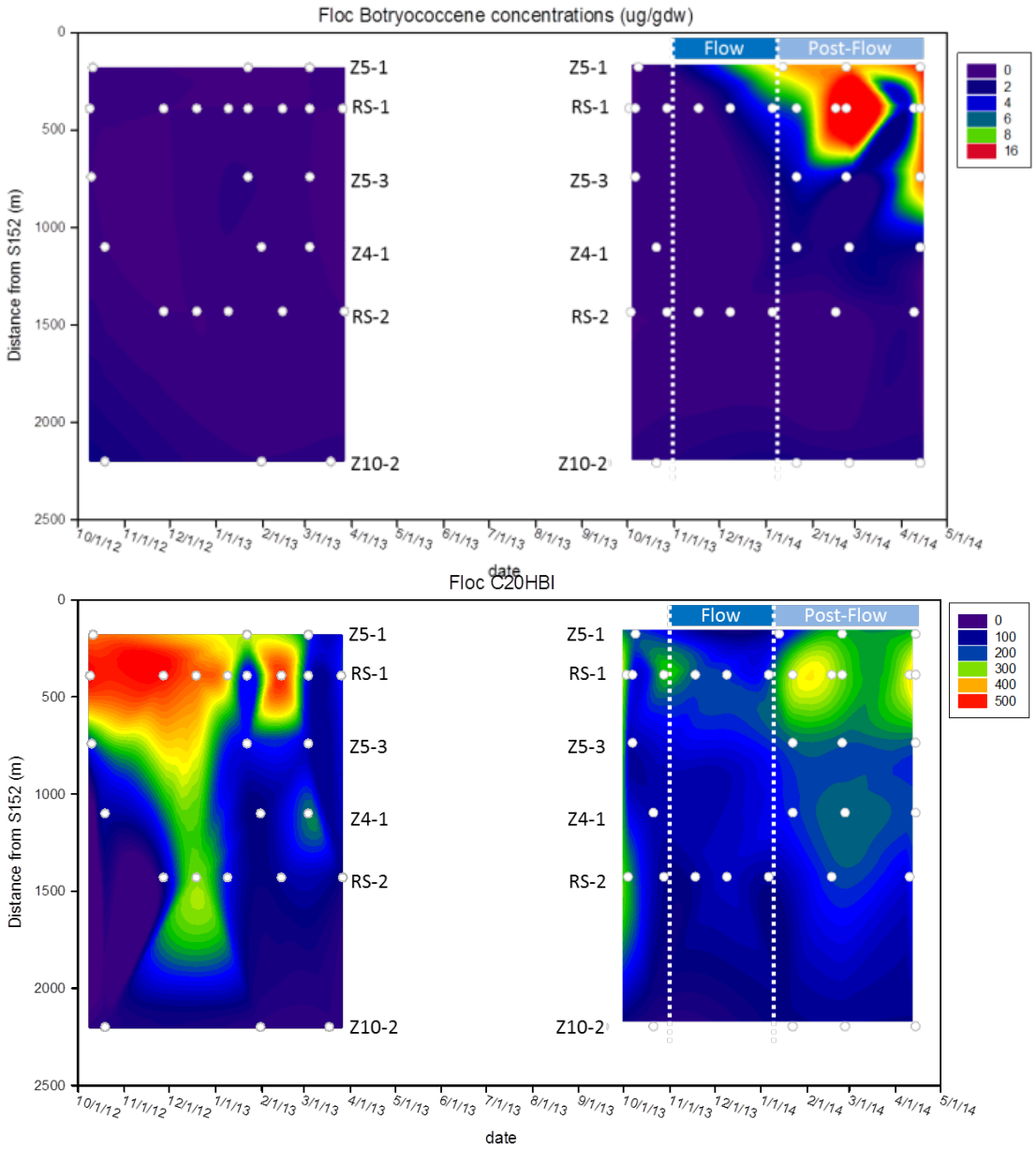

Figure 13. Spatio-temporal changes in C20 HBI (µg/g) and Botryococcenes (µg/g) in slough floc collected at sites along the north-south flow path in the pre- (October 2012–October 2013), during (November 2013–December 2013) and post-flow (January 2014–May 2015) sampling periods.

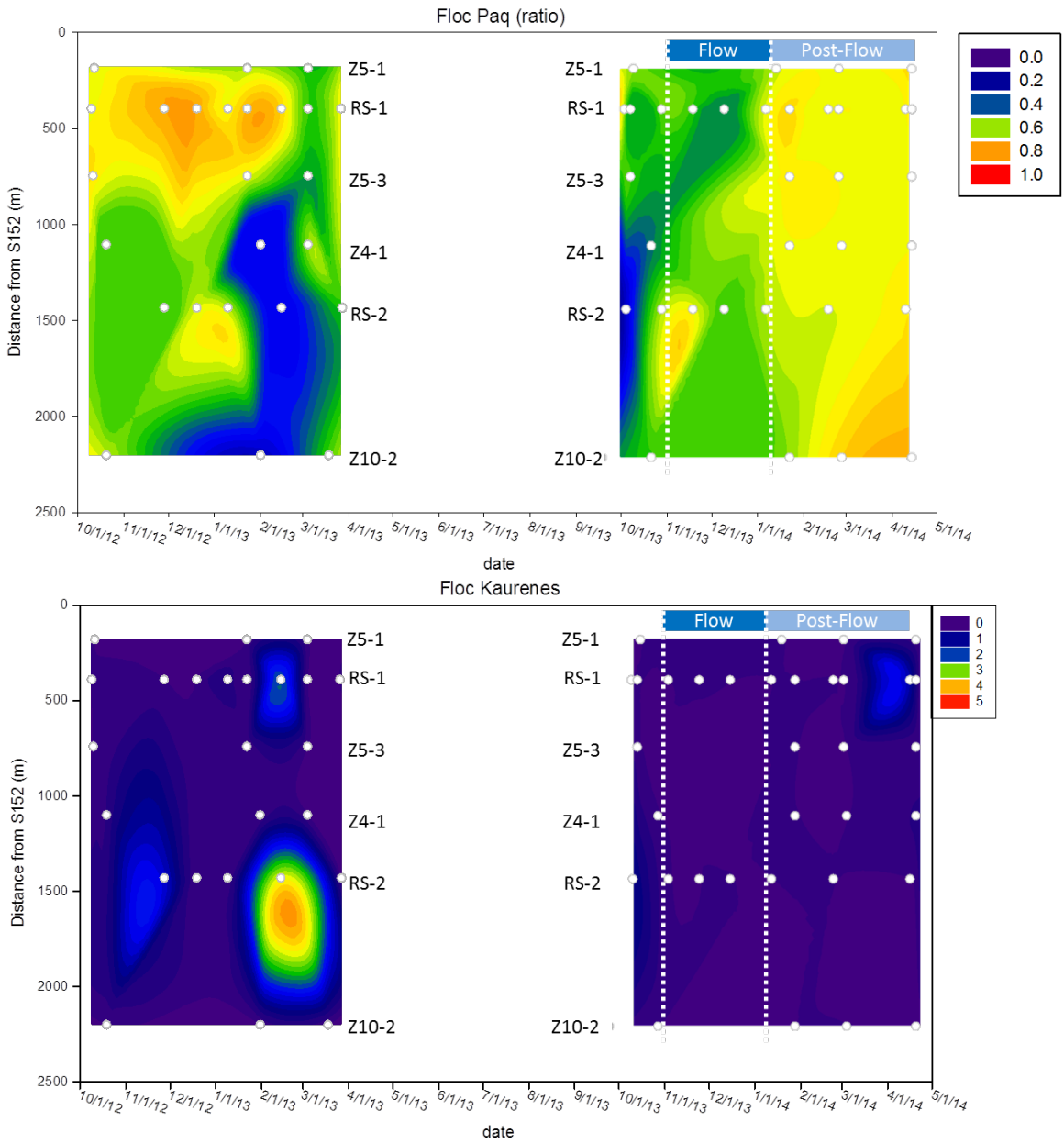

Figure 14. Spatio-temporal changes in Paq (ratio) and Kaurenes (µg/g) in slough floc collected at sites along the north-south flow path in the pre- (October 2012–October 2013), during (November 2013–December 2013) and post-flow (January 2014–May 2015) sampling periods.

Algal Taxonomy of High versus Low Flow Sediment and Floc

Changes in algal composition of advected sediments were notable after flow began in November 2013 (**Figure 15**). Prior to flow, the RS1 site (ridge and slough) had the lowest species richness of all 77 samples, with only diatoms present. The few species present are known to thrive in calcium-rich habitats. At RS1-slough, species richness increased substantially two weeks after the flow event and increased further five weeks after flow, with green algae and cyanobacteria accounting for over 55 percent of new species counted. Diatom species richness also increased during the first two-week period in the slough and even greater by the fifth week, while the ridge at RS1 did not show the increase in richness until the fifth week. The additional diatoms species responsible for this increase in richness were not from calcium-rich habitats, which may reflect the loss of metaphyton at RS1 and other sites nearby (**Figure 5**). C1 ridge had low species richness (dominated by diatoms) and no changes between before and the two weeks after flow. After five weeks of flow, however, the C1 ridge showed a marked increase in species richness, with a significant increase in the number of cyanobacteria and the appearance of green algae. C1 slough was slightly greater in species richness compared to the C1 ridge, dominated by diatoms, and no perceptible change as a result of flow. RS2 did not show a response to flow. The green alga, Botryococcus, a known source of the Botryococcene biomarkers, was found in 6 percent of the samples of the 77 sediment trap samples.

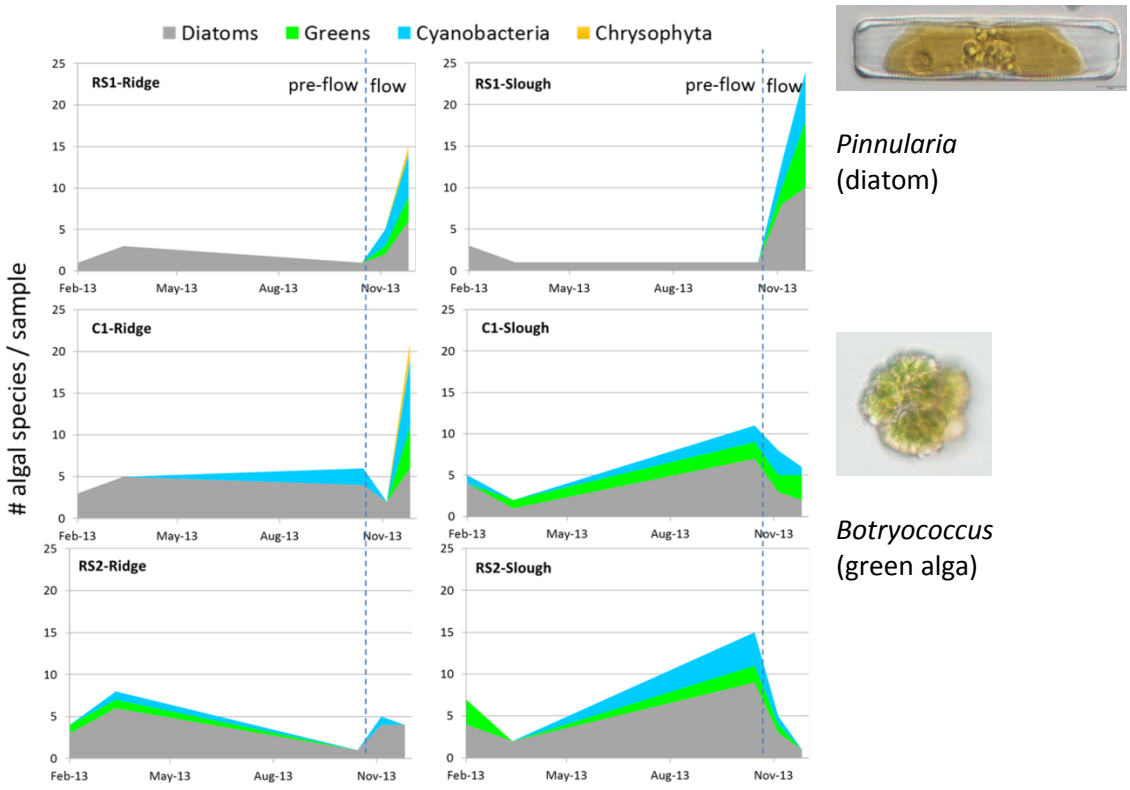

Figure 15. Species richness of algae counted in advected sediment collected from horizontal sediment traps deployed in paired ridges and sloughs at RS1 (top row), C1 (middle), and RS2 (bottom). Initiation of first flow event denoted by dashed vertical line.

The three backfill treatments had the greatest species richness, with approximately equal numbers of green and diatom species and slightly fewer cyanobacteria. None of these treatments showed changes in species richness in response to flow. DCC2, the control site, did not show a response to flow.

FLOW IMPACTS ON HYDROLOGY AND SEDIMENT DYNAMICS IN THE L-67C CANAL AND LEVEE GAP

Velocities and Water Budgets: UB, Canal, and DB sites

The flow speed at UB and DB sites increased from the flow release at S-152 by approximately 200 percent at both UB and DB sites. The flow directions at UB sites were oriented between 110 and 170 degrees (rotating clockwise from north) prior to the flow release, but the flow directions during the flow release experiment changed a little bit more to southward, which could be influenced by the preferred downstream flow path through the main opening into WCA-3B. In addition, the flow directions at DB sites prior to the flow release showed a wide variation (70 to 150 degrees from the north) between the three DB sites, but more consistent south-eastward flow, that is more perpendicular to the L-67C canal was observed during the flow release experiment. The canal flow at both MB sites during the flow release was faster by more than twice that of the pre-flow period. The flow directions at MB1 and MB2 are controlled by the relative locations of the two main openings connecting the canal to WCA-3B along the levee (**Figure 16**). The channelized flow through these openings into WCA-3B probably controls the hydrologic conditions at DB sites in WCA-3B.

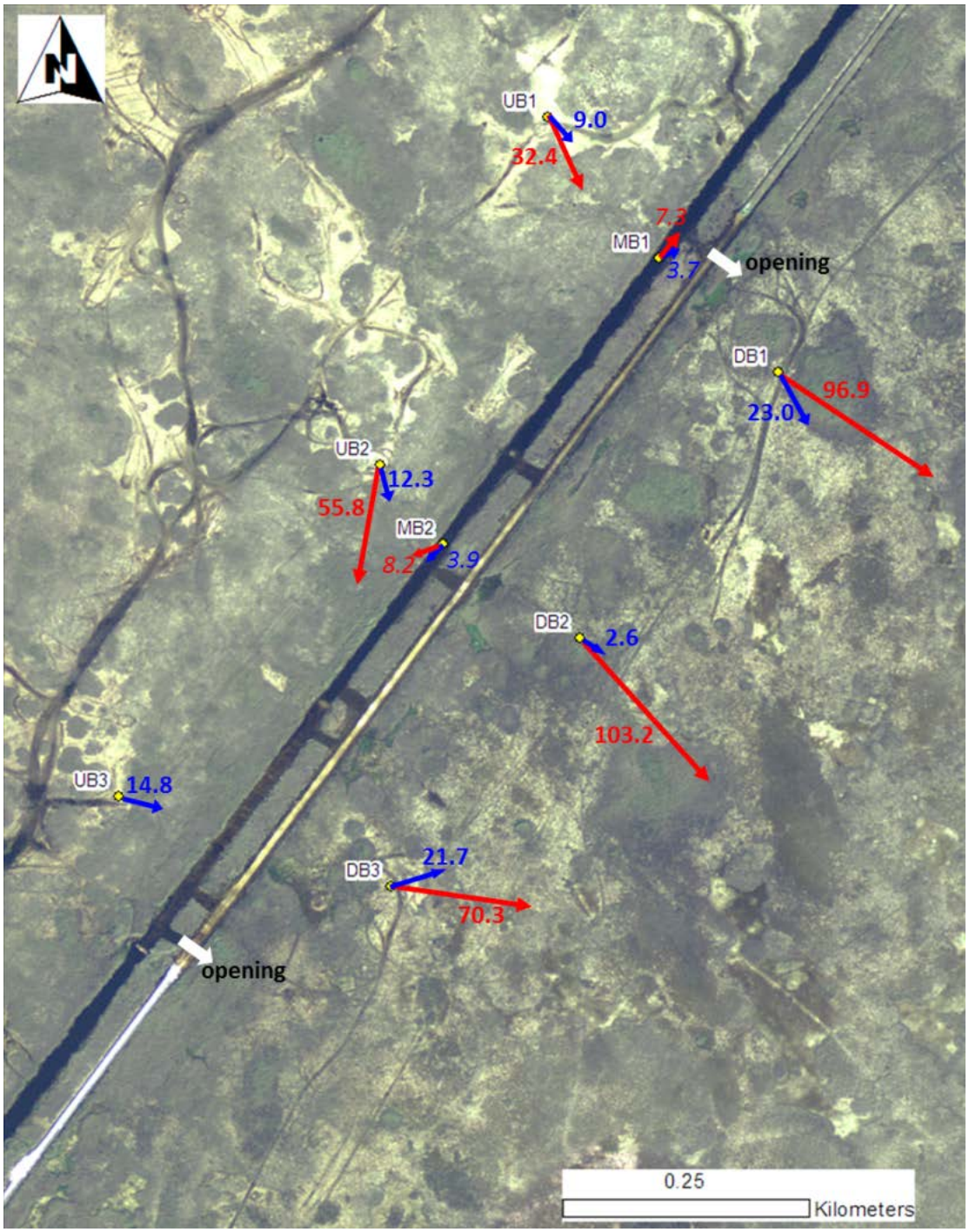

Figure 16. The vectors at UB1, UB2, UB3, DB1, DB2, and DB3 show direction and magnitude (labeled) of water flux per unit width (cm^2/s). At open canal (MB1) and partial backfill (MB2) sites, the vectors are water velocity in cm/s. Blue arrows indicate values pre-2014 flow release and red indicate during the 2014 flow release.

Two dye studies, conducted in January 2015, were useful in showing differences between water moving from the marsh into canal backfill treatments versus water entering from the canal itself (i.e., immediately north of the backfill the treatments). The Fluorescein dye plume, released in the L-67C canal approximately 100 m upstream (northeast) of the open canal treatment, quickly moved down the canal and into WCA-3B across the degraded levee (**Figure 17**). At 10:36 AM the dye had traveled approximately 114 m down the canal, approximating a flow velocity of 1.9 cm/s. Over the next 24 hours the dye plume traveled into WCA-3B flowing generally in a north-east direction at a rate of 0.7 cm/s, but also continued to flow in a southwesterly direction down the L-67C canal. The dye that traveled from the canal into WCA-3B initially did so along the northernmost edge of the degraded levee, then moving into the marsh, as shown in **Figure 17** (top panel). Compared to the Fluorescein dye, the Rhodamine dye plume, deployed near UB-2 (**Figure 17**, middle panel), moved very slowly southward toward the canal backfill treatments. Twenty-eight hours after deployment, the majority of the dye plume had moved from the marsh into the canal (**Figure 17**, bottom panel), traveling that distance at a rate of 0.1 cm/s. The leading edge of the dye was visually detected from an airboat and had traveled through an opening in the backfill/degraded levee treatment and into WCA-3B traveling in a more southerly direction along the length of the L-67C at a rate of 0.2 cm/s. This result was of interest as it showed that source water moving across the backfilled treatment contains some mixture of canal water as well as from the marsh. Based on the approximate frontal area (1000-m width x 0.5-m depth) and velocities of water moving south from the UB sites (0.1 cm/s) into the canal backfill area, the water inflow from the marsh is approximately 0.5 cubic meters per second (m^3/s). Given the frontal area water moving down-canal (12-m width x 4-m depth) and the velocity (1.9 cm/s), the water inflow from the canal itself is roughly 0.9 m^3/s. The dye study suggests that the canal conveys twice the volume of water flowing into the canal backfill area as compared to water flowing in from the UB marsh sites.

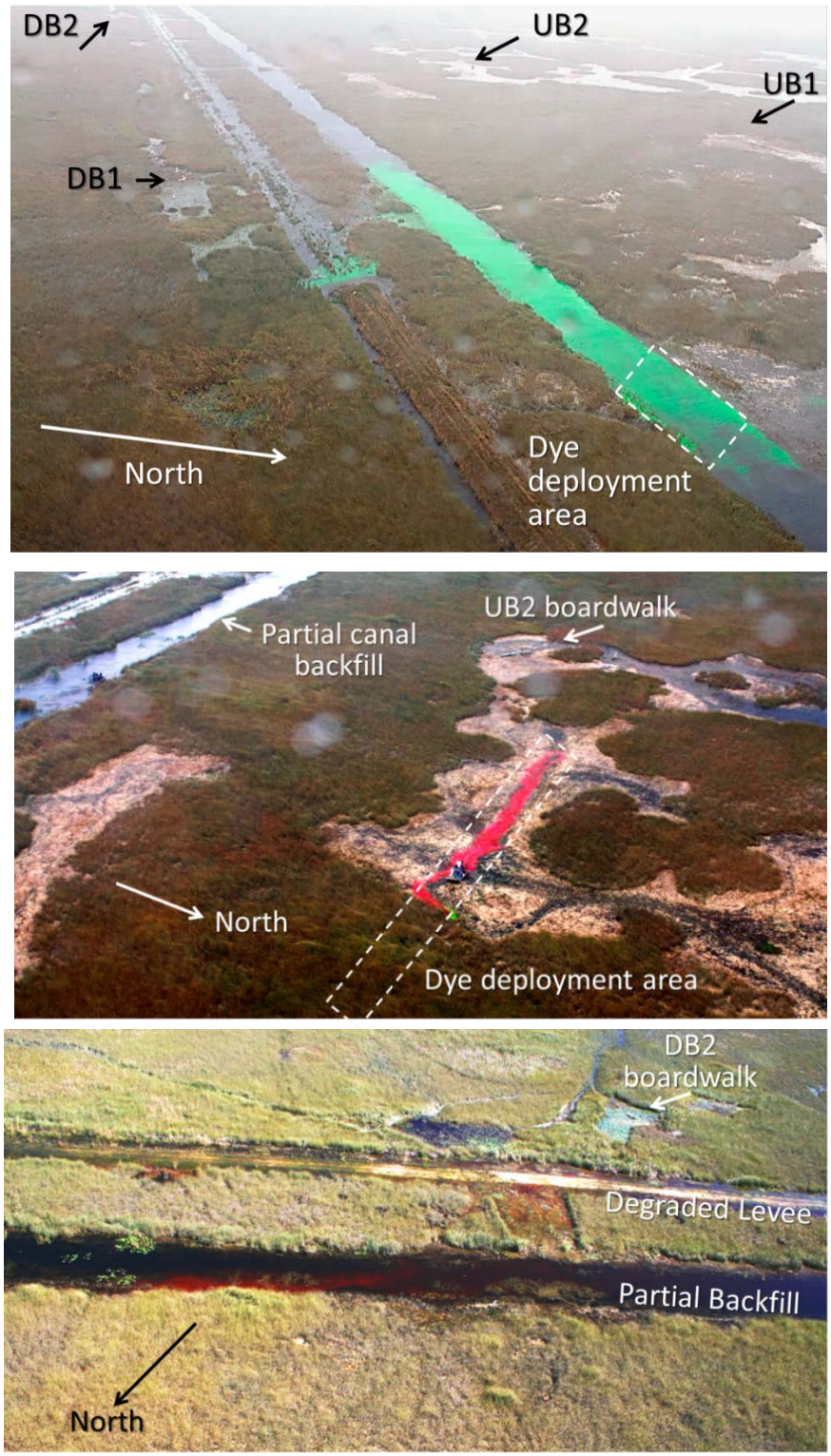

Figure 17. (Top) Fluorescein dye moving into the open canal treatment (L-67C canal) and across the degraded levee. (Middle) Rhodamine dye deployed upstream of partial backfill. (Bottom) Rhodamine dye moving across L-67C partial backfill and levee gap and into WCA-3B.

Flow Impacts on Sediment Biomarkers in the L-67C Backfill Treatments

The Paq values in trapped canal sediments showed a remarkable consistency with notable lower variability than the seasonally monitored floc samples. Paq values were consistently high and in the expected range for slough-derived organic matter. No significant differences were observed between the CB1-3 and the corresponding reference sites CC1-2. However, lower Paq values were observed for the high flow season, a quite unexpected result (**Figure 18**). This observation suggests that unlike the floc, high flow conditions resulted in fine particulate organic matter being mobilized with a somewhat less 'slough-like' character. In contrast, the variability of the periphyton markers, C20 HBI and Botryococcenes, was significantly higher, but more similar to each other than for the floc sample time series or other samples throughout the data set. The previously observed maximum for the floc C20 HBI for the end of wet season sampling period (baseline period) was not observed when considering the combined data set. However, a lower C20 HBI abundance was observed during the high flow conditions; but low flow conditions were significantly lower in abundance than after high flow. In contrast to the slough floc samples, Kaurenes were present in all sediment trap samples, but no significant difference was observed for the high flow period (**Figure 18**).The Botryococcene distribution was similar to that of the Kaurenes, in that it showed no significant differences among the time series or flow conditions.

The biomarker data, in particular the Paq-based assessment, suggests that consistently the sediment trap materials are primarily derived from the slough environment. Other expected results were the apparent increase in 'slough-like' characteristics of the floc materials during high flow conditions. However, while two end-member mixing estimates for baseline period suggested that the great majority of the particulate organic matter in sediment traps was derived from the slough environment, the data from the combined baseline and high flow samples indicate that significant contributions from the ridge environment may also be accumulating in the sediment traps. However, high variability of the data on both spatial and temporal scales, particularly for 2014 samples, may skew this assessment.

The data also suggests that conditions before and after high flow are not necessarily equal, and that when high flow conditions are terminated, there may be lag time to return to pre-flow conditions. Thus high flow conditions may have caused a significant 'disturbance' in the present day particulate organic carbon dynamics of the DPM site. This is not necessarily a particularly unexpected result. However, the simultaneous decrease in slough-like conditions (i.e., significantly lower Paq value) in the sediment trap materials during high flow is somewhat puzzling, as it potentially suggests erosion of ridges. An alternative explanation such as a change in canal inputs controlled seasonally is unlikely based on control site data comparisons. Vegetation at the immediate marsh-canal edge is largely dominated by sawgrass (*Cladium jamaicense*) or cattail (*Typha* spp.), so it is also possible erosion of the canal edge can explain the data. Paq and C20 HBI changes may also suggest internal canal sediments, and additional samples of canal benthic sediments will be collected in the coming year to help address that question. The relatively faster movement of water in the canal, confirmed by the dye studies (**Figure 17**), and velocities of 7 and 8 cm/s measured in the canal under high flows (**Figure 16**) suggest it is reasonable to hypothesize entrainment of sediments within the canal could be occurring.

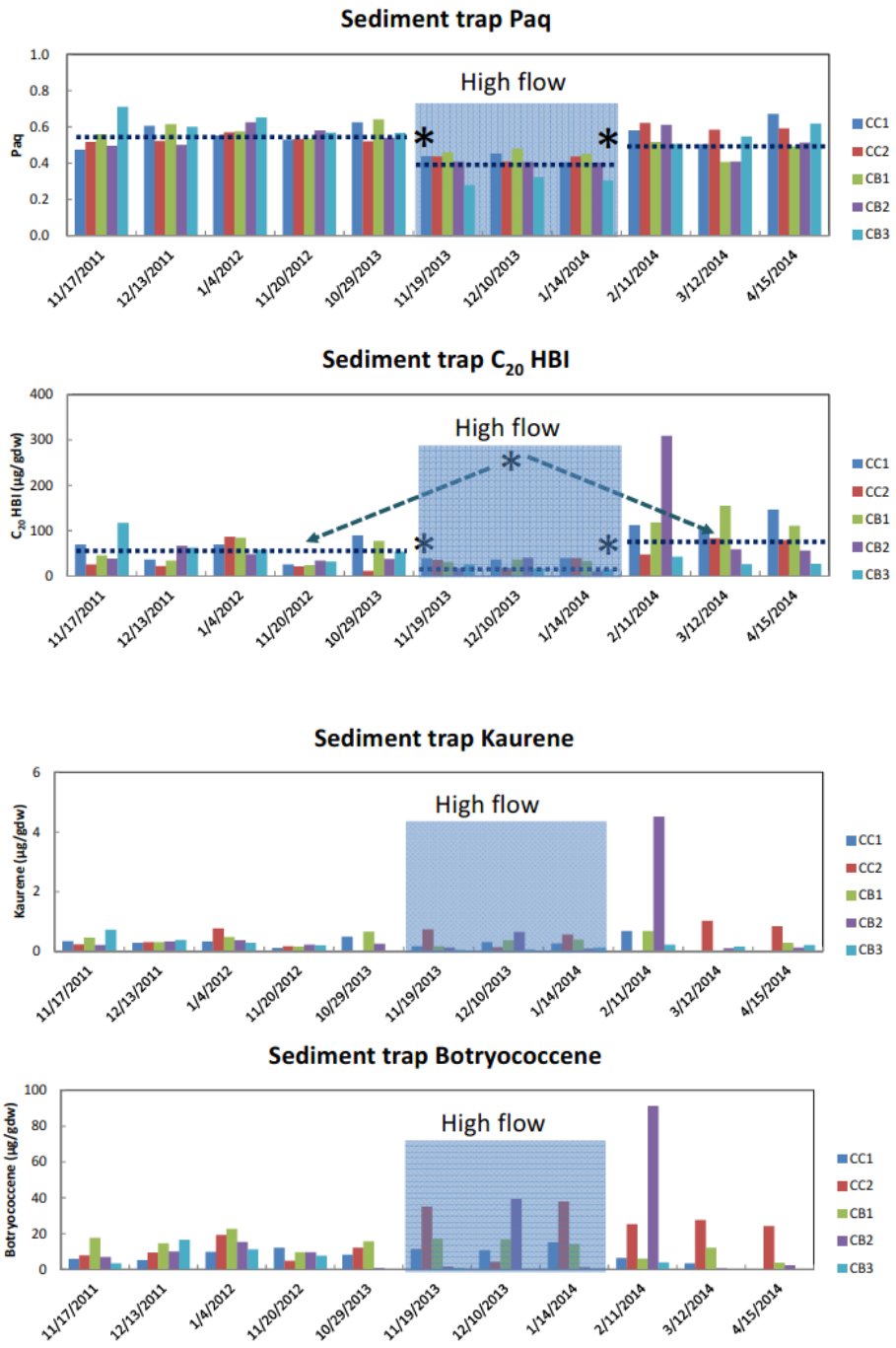

Figure 18. Timeseries for Paq, C20 HBI (C_{20} HBI), Kaurenes, and Botryococcenes for sediment traps during the baseline period (November 2011–October 2012), high flow period (November–December 2013), and post-flow period (February–April 2014). [Note: µg/gdw – micrograms per grams dry weight.]

ACTIVE MANAGEMENT PILOT STUDY

Sawgrass encroachment and loss of sloughs is evident throughout WCA-3B, including the DPM study. The Active Management Pilot Study was conducted to determine the extent to which velocities could be increased by actively creating sloughs in sawgrass-dominated areas. During the second flow event (November 2014 to January 2015), velocities measured in sawgrass communities, surrounding the created slough, ranged from 1 to 3 cm/s (**Figure 19**). In contrast, velocities in the upstream, middle and downstream portions of the created slough were several-fold higher, averaging 16 cm/s. This result strongly suggests that active management can be an effective tool to increase localized flows in sloughs, while maintaining lower velocities in sawgrass.

The degree to which these conditions increased transport and net movement of sediment into ridges was quantified by capturing the dual-use synthetic tracer (DST) released in the slough interior. DST captured along slough-to-ridge transects (normal to flow) showed sediment was transported down the entire 100-m extent of the slough. Importantly, the DST was also found to move out of the slough and into the ridge. Capture of DST in the ridge was greatest toward the downstream portion of the slough, where the adjacent sawgrass vegetation was less dense. While sediment movement into the ridge does occur, it was limited to areas near the ridge-slough ecotone. Analysis of benthic sediments collected at locations 10, 20, and 30 m into the ridge are ongoing, but preliminary evidence suggests DST settles within 10 m of the ecotone (C. Zweig, SFWMD, personal communication), as would be expected where lower velocities allow for more particle settling.

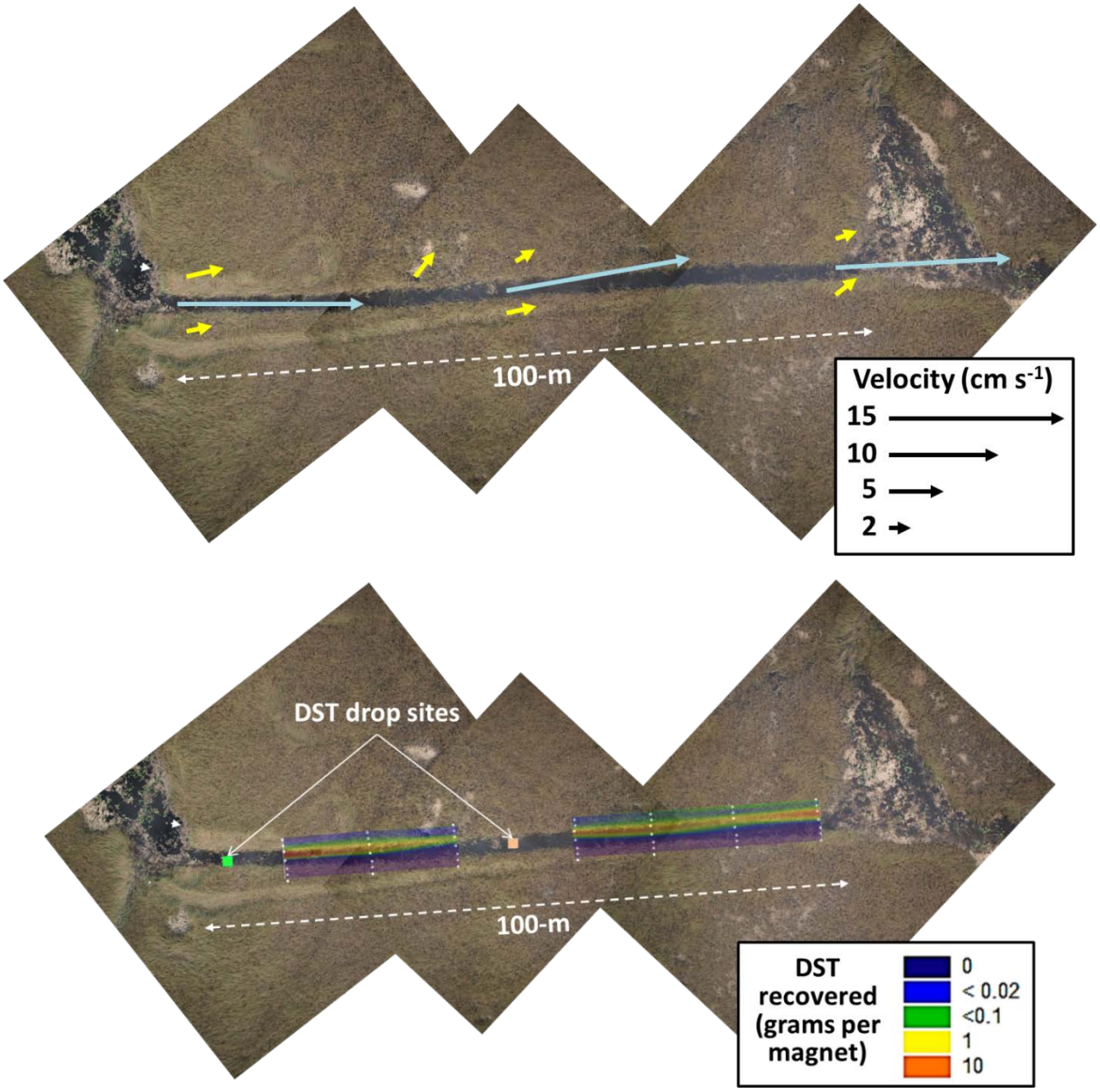

Figure 19. (Top) Mid-water column flow velocities measured in the created slough and in adjacent sawgrass. Velocities were measured using a Sontek Flowtracker during the second high flow event on December 30, 2014. Base of arrow represents location of measurement. (Bottom) DST captured on magnets along 5-m transects spanning the slough and adjacent ridges. Magnet locations are indicated by white dots. Location of DST drops at upstream and mid-slough location indicated by squares. High resolution imagery was taken from helicopter on November 4, 2014. [Note: cm s^{-1} – centimeters per second.]

RELEVANCE FOR WATER MANAGEMENT

Operational Strategies to Maximize Sediment Redistribution – Importance of Pulse Flows, Steady State Flows, and Sediment Types

Structured flows aimed at maximizing sediment and P redistribution among ridges and sloughs may benefit by utilizing either short-term flow pulses (e.g., opening S-152 for 1–2 days only) or steady state flows (i.e., continuously open several weeks to months). The extent to which each, or some combination, maximizes total sediment redistribution will be provided in subsequent data analysis and DPM reporting. However, findings so far indicate substantial variation in the amount and type of sediments moved during the initial and steady state flows. The discussion below summarizes the extent of that variation at multiple spatial and temporal scales. Operational decisions to take advantage of that variation (i.e., to maximize pattern and topography restoration) are also discussed, including remaining uncertainties.

During the initial pulse flow itself, substantial variation was observed in the type of sediment transported. As evidenced at sites nearest the structure (e.g., E250), initial changes included increased water TP. This change occurred before the arrival of S-152 water [based on dye velocities, ADV velocities and specific conductivity data (not shown)], indicating the P was produced within the slough itself. Other evidence at RS1 showed initial sediment spikes consisted of small diameter particles, which are characteristic of periphyton. Particle diameter and high resolution imagery (showing the break-up of slough SAV-periphyton) suggest the P source is perhaps metaphyton-derived. The limited supply of this sediment type is also reflected in the short-term nature of the TP spike. Additional imagery showed the fragmented metaphyton accumulating downstream along ridge edges, and observations on the ground indicated some settled within the slough. Though additional data are needed to support the robustness of this finding, it follows that generating pulses sufficient in magnitude to break up and redistribute metaphyton within sloughs could be used as an operational strategy. Active management approaches to increase sheetflow over larger areas could also accelerate this process. Within a couple weeks after the S-152 was closed, regrowth of slough SAV was observed (C. Saunders, SFWMD, and E. Tate-Boldt, SFWMD, personal observation), indicating that regenerating this source of particles is also feasible. This regrowth is consistent with the turnover time of P in periphyton (10 days) observed by Noe et al. (2002). To address this dynamic, the third flow event will included a “pulse” test at the beginning of flow (i.e., opening, closing, and reopening the S-152) to help pinpoint the extent to which disintegration of metaphyton or sloughing of metaphyton particles contributes to water column sediments and redistribution of P.

A second type of pulse-driven sediment was observed (again exemplified at E250), mainly characterized by increased turbidity. At E250, for instance, this peak in turbidity occurred about 2 hours after the peak in TP and fragmentation of the metaphyton mat. Changes in turbidity may reflect larger diameter particles than those creating the TP spike. However, maximizing this source of particles may be less beneficial for management strategies. As shown by turbidity and SSC monitoring (this report and the 2015 SFER – Volume I, Chapter 6), this source of particles is rapidly depleted (peak dissipates within a few hours). The timing of the high turbidity pulse mirrored that of the Fluorescein dye, indicating this source of sediments included sediments directly discharged from or nearby the S-152 culvert, potentially including remnant construction sediments. If these particles are derived from the S-152 and not a result of local entrainment, pulse flows are unlikely to affect ridge and slough sediment dynamics vary far from the S-152, regardless of the extent to which sheetflow could be restored across the greater landscape.

Steady state flows also confer advantages to maximizing sediment redistribution. During both flow events, sediment transport gradually increased over the span of 6 to 8 weeks after the flow began. Over this time slough velocities also increased, while, in contrast, S-152 discharges

remained relatively constant. Imagery and visual observations of expanding "open" areas in sloughs (and mounding of floc, SAV, and litter elsewhere) suggested the formation and development of preferential flow paths, which is hypothesized to explain increased velocities and transport. Benthic sediments were clearly observable in these open areas and it is presumed more easily erodible in preferential flow paths. As shown in the 2015 SFER – Volume I, Chapter 6 (Sklar and Dreschel 2015), the critical entrainment threshold velocity needed to resuspend benthic slough sediments became greatly reduced after flow, in part a seasonal phenomenon. The advantage therefore of maintaining continuous sheetflow (as opposed to pulses) is that benthic sediments are more likely to play a role in sediment redistribution. Whereas pulse flows may simply move slough particles into ridges, building ridge elevation, steady state flows also have the potential to actively erode the slough, decreasing slough elevations. To adequately assess this benefit, erosion of benthic sediments during steady state flows must be monitored in greater detail in forthcoming flow events.

Biomarker analyses were critical in showing that ridge floc became more slough-like, an important finding that underscores the effectiveness of sheetflow in building ridge topography (and removing sediments from sloughs). The lagged-change in biomarkers suggest sediment capture by vegetation may play a role in this process. Additional analysis of sediment biomarkers and taxonomy from the second flow event are in progress. These data and those from the third flow event will help elucidate this link between flow conditions, sediment transport, and settling.

Results from the created slough indicated that active management of vegetation, combined with high flow conditions can be successful in generating high slough velocities. An important next step in this substudy will be to increase the areal expanse of individual sloughs that are currently dominated by sawgrass. Given evidence showing the importance of vegetation in shaping the direction and speed of flows, it is anticipated that larger-scale active management of sloughs could be used to redirect more flow toward the natural (south) orientation of the landscape, and to increase the areal extent of sheetflow and sediment redistribution (i.e., to kilometers rather than a few hundred meters).

Ecological Responses in the Canal Backfill Treatments and Levee Gap

ADVs indicated canal velocities roughly doubled under high flow, reaching 7 to 8 cm/s. Therefore, backfill sediment dynamics may be strongly influenced by velocity changes within the canal and sediment transport within the upstream portions of the canal. Given the high TP of canal sediments, this process could potentially alter P cycling in the canal. Additional sampling and biomarker analyses of canal benthic sediments may elucidate if the canal sediment entrainment could explain the contrasting changes in biomarkers of canal sediments versus those of ridge and slough floc.

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