SNEP Watershed Grants

Evaluating Management Actions to Promote Salt Marsh Resilience

Executive Summary of Final Report

February 28, 2022


Grantee Organization:

Buzzards Bay Coalition
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Background

Salt marshes are productive coastal wetlands that provide important ecosystem services including habitat for fish and wildlife, nutrient removal, carbon sequestration, and storm protection for coastal properties. Across the northeast US, and especially in southern New England, marshes have lost significant area and the rate of loss is increasing in some places. The total loss and rate of loss are alarming, and communities urgently want solutions to help conserve remaining marsh, and restore marsh where possible. One technique gaining attention across the Northeast involves restoring tidal hydrology on marshes by creating small, shallow channels (“runnels”) that drain areas of expanding shallow water. If left untreated, these shallow water areas have the potential to expand outward rapidly, killing vegetation and converting interior marsh platform into open water.

Figure 1. Top: Map of the Buzzards Bay study area, marshes with study sites for runnel pilot test indicated with red dots. Bottom: Maps of Little Bay (left) and Ocean View Farm (right). Monitoring transects shown in green (reference sites) and purple (runnel sites). Runnels as-built shown in blue.

As of 2019, very little documentation was available on either the efficacy of runnels or best practices for implementation. Still, interest among resource managers in runnels was becoming widespread, including among non-profits and land-trusts in Buzzards Bay. As of 2020, there were 36 runnel projects planned, in-progress, or completed across 6 northeastern US states — the majority of these clustered in New England. In 2020, our team launched a project funded by the Southeast New England Watershed Grant Program to synthesize and communicate existing knowledge on runnels; test pilot runnels in Buzzards Bay; and identify where and when runnels are most effective in the context of marsh loss patterns and environmental conditions in Buzzards Bay salt marshes. Partners include scientists and resource managers from Buzzards Bay Coalition, Woodwell Climate Research Center, Buzzards Bay National Estuary Program, Save The Bay (Narragansett Bay), Bristol Country Mosquito Control Project, and the US Geological Survey.

Developing and Communicating Knowledge on Runnels

During this project, our team led efforts to gather and synthesize existing knowledge and best practices on runnels, and communicate that information through multiple mediums to diverse audiences. In March 2020, we held a workshop on runnels attended by more than 70 scientists, resource managers, regulators and other stakeholders. Team members Ferguson and Brennan presented background and case studies on runnels, and all team members helped to lead discussion groups and present on our project goals. We received uniformly positive feedback on the success of the workshop for covering background information, best practices, and remaining unknowns on runnels.

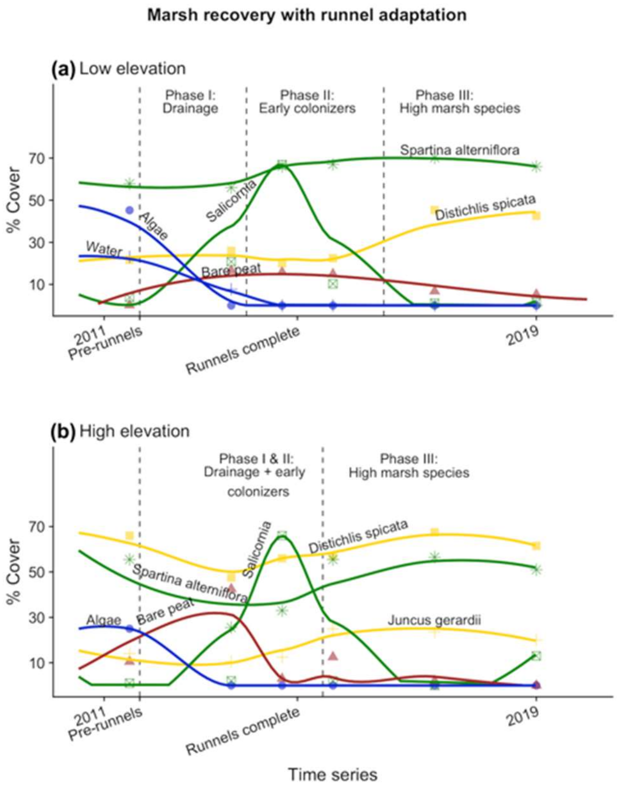


Figure 2. Recovery of Winnapaug marsh after runnelling shown for a) low elevation areas, and b) higher elevation areas. Ground and species percent cover shown relative to runnel construction timeline on x-axis. Adapted from Besterman et al. 2022.

We combined the information learned at our workshop with a case study from Winnapaug Marsh in Rhode Island (data from team member Ferguson), and literature review to produce a perspectives paper on runnels, now published in the scientific journal *Estuaries and Coasts*. This paper provides background on why marshes are experiencing loss, an overview of the history and use of runnels, case study data, and concludes by highlighting research questions that still need addressing. Using pieces of the story developed for the *Estuaries and Coasts* paper, Besterman has delivered 10 presentations to public, stakeholder, and scientific audiences. Partners have given another 6 presentations related to this project during the project period.


Figure 3. Creation of runnels at Ocean View Farm. Top and Bottom Left: Bristol County Mosquito Control operator creates a runnel with a low-ground pressure excavator. Bottom Center: Staff and volunteers hand-dig a runnel. Bottom Right: Wenley Ferguson hand digs a runnel. Photos: R. Jakuba, A. Besterman, W. Ferguson.

Pilot Study on Runnels in Buzzards Bay Estuary

Our team initiated an experiment in 2020 to test runnels using best practices identified from team-member experience. We used a Before-After-Control-Impact study design, meaning we monitored both experimental-runnel and reference sites without runnels before and after runnel creation. The study includes a total of 10 runnel-sites and 10 reference-sites, distributed across two marsh complexes in Buzzards Bay. Our objectives were 1) to experimentally test the efficacy of runnels, 2) to test runnel efficacy across a range of environmental characteristics identified as important to runnel success at our workshop and by partners, and 3) to test ecosystem-scale processes in response to runnels that provide insight into how marshes will respond long-term. We are monitoring a large suite of variables that quantify the vegetation, hydrology, soil characteristics, and structural properties of marshes. This effort has involved close partnership and significant time investment from all project partners, additional staff at partner institutions, undergraduate and graduate students, volunteers, landowners, and colleagues from other partnering organizations not directly involved with this project (e.g., Dartmouth Natural Resources Trust, Mass Audubon, US Fish and Wildlife Service, Round the Bend Farm, among others).

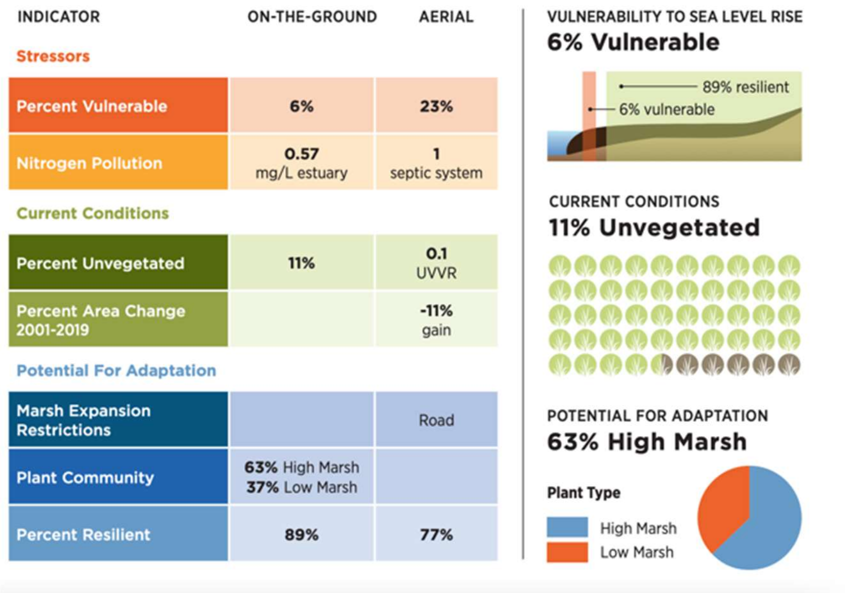

Figure 4. Buzzards Bay Coalition and Woodwell Climate Research Center Staff study vegetation, invertebrate fauna, and soils at a site with a runnel in 2021. Photo: R. Jakuba

The runnel and reference sites capture a wide range of characteristics likely to impact the efficacy of runnels (marsh elevation, depth of water in dieback areas, percent bare ground and condition of peat soil). As expected, the magnitude of changes in vegetation and water level varied along these environmental gradients. However, even after only one year there were indicators at both sites that runnels were effectively restoring tidal hydrology and revegetation was beginning in denuded areas. At Little Bay, a higher elevation marsh, water levels did not change dramatically. But vegetation cover appeared to increase significantly. At Ocean View Farm, a lower elevation marsh, water levels dropped significantly (to just below the soil surface), and some revegetation was beginning to occur.

Figure 5. Before (2020) and after (2021) photos of runnel sites at Ocean View Farm (left) and Little Bay (right). Photos: A. Besterman

Resilience, Vulnerability and Potential for Restoration Across Buzzards Bay Marshes

In order to extrapolate results of the runnel pilot study to other marshes in Buzzards Bay, we first needed to understand the state of marshes across the watershed. This information can be used by planners and resource managers to strategize which marshes might be good candidates for runnels. Initially we were interested in watershed-scale processes, but recognized these factors would have little bearing on the efficacy of runnels, which is determined by local, small-scale factors. For example, in the same sub-watershed, part of a marsh may border conservation land whereas another part of the marsh may be near several homes on septic systems. These two areas of the same marsh in the same sub-watershed clearly have different hyper-local nitrogen loading.



INDICATOR	ON-THE-GROUND	AERIAL
Stressors		
Percent Vulnerable	6%	23%
Nitrogen Pollution	0.57 mg/L estuary	1 septic system
Current Conditions		
Percent Unvegetated	11%	0.1 UVVR
Percent Area Change 2001-2019		-11% gain
Potential For Adaptation		
Marsh Expansion Restrictions		Road
Plant Community	63% High Marsh 37% Low Marsh	
Percent Resilient	89%	77%

Figure 6. Draft example of stressors, conditions, and adaptation potential for one of the 12 long-term monitoring marshes. Percent vulnerable and percent resilient are related to elevations, illustrated in the upper right image.

To account for this modification in thinking, we looked at stressors, current conditions, and the potential for adaptation at 12 marsh sites where Buzzards Bay Coalition is conducting long-term monitoring. We are developing a report that characterizes stressors, condition, and adaptation potential using both on-the-ground, and aerial measurements. Specifically, we are looking at the percent of the marsh that is vulnerable or resilient to loss with sea level rise (based on current elevation), nitrogen concentrations in the water near the marsh sites, the number of septic systems near the marsh sites, the presence of restrictions to tidal flow, how much of the marsh is covered with vegetation, what type of species dominate the site, whether there are barriers that would prevent marsh migration, and how much marsh loss has occurred over the last 20 years. Both Ocean View Farm and Little Bay are included in this analysis for simplified comparison of marsh characteristics in the context of runnels. We anticipate releasing this report in spring 2022.

Our next steps will be to model how marshes around Buzzards Bay with varying environmental characteristics respond to runnels using results of the runnel pilot study and baseline knowledge on marsh condition generated from the report described above. However, we are too early in our study to build those models at this time. To illustrate how conservation organizations strategize the application of various techniques, including runnels, we put together a case

Figure 7. Staff and interns from Buzzards Bay Coalition, Mass Audubon, Save The Bay, and Dartmouth Natural Resources Trust meet to discuss runnels and other conservation strategies at Ocean View Farm. Photo: R. Jakuba

study report on the collaborative restoration work underway at Allens Pond, a back-barrier salt pond in Dartmouth, Massachusetts, with high conservation significance. Ocean View Farm, one of our long-term monitoring and runnel marsh sites, is located within Allens Pond. We describe how non-profits, agencies, and research institutions are working collaboratively to address stressors on marshes at multiple spatial scales. Actions are being coordinated to address current stressors on the marsh platform (open water conversion), using in-marsh techniques (runnels), while also considering larger-scale stressors and conservation strategies (land protection, tidal restriction management, marsh migration facilitation). Buzzards Bay Coalition has led several stakeholder site-visits, and other meetings to share information and coordinate existing and planned conservation work.

Logistics of the Project – How We Got It Done

This project was supported by $223,533 in funding from the SNEP Watershed Grants Program and a match of over $135,000. The bulk of the project funds supported staff time by project partners Buzzards Bay Coalition, Woodwell Climate Research Center, and Save The Bay. SNEP funding also supported travel to project sites, supplies, participation in scientific conferences to share results, and publication of results in a scientific journal. All project partners dedicated significant time to the project through the various phases, including Buzzards Bay National Estuary Program, U.S. Geological Survey, and Bristol County Mosquito Control whose staff time was not supported by SNEP.

This SNEP Watershed Grant Program funding was matched by over $135,000. In-kind match was provided from volunteer support and institutional funding from the Buzzards Bay Coalition and the Woodwell Climate Research Center and through securing additional project funding from the Rose Family Foundation, the Fleetwing Foundation, and the Northeast Climate Adaptation Science Center. Additional match above $135,000 was provided by project partners Buzzards Bay National Estuary Program, U.S. Geological Survey, and Bristol County Mosquito Control who dedicated significant time and resources to this project.

Impact of the Project

Outreach and communication were major focuses during the past two years. Project partners spread awareness on marshes, how and why they are experiencing loss, and the potential for adaptation using runnels to diverse public, scientific, and environmental manager, and public health communities. We communicated these topics through a journal publication; technical reports; digital stories; webinars and virtual presentations; radio stories; and in-person meetings, workshops, and site visits. We also built awareness through working with undergraduate student interns, graduate students, and early-career professionals hired as seasonal staff.

In our outreach and communications, we widely shared existing best practices in runnel-use and application. We have helped to develop a baseline understanding of the technique among stakeholders. We also identified key remaining questions on runnels, outlined in our written and virtual media communications. Some of these questions should be addressed with future research projects, while we are currently studying others as a part of our pilot test on runnels.

We launched and completed the first two years of a pilot study on runnels in Buzzards Bay. Results will provide urgently needed data to help develop protocols, and generalize runnel effects to other marshes. We have analyzed data from our study, as well as data from a partner's runnel project in Rhode Island, and shared these results in written and virtual formats. Next steps will involve conducting more formal analyses that can model outcomes for marshes where runnels are used across a gradient of environmental conditions. Our synthesis on marsh condition, stressors, and potential for adaptation and early runnel results have "set the stage" for these more formal modelling analyses. We outlined decision-making processes, trade-offs, and potential synergies of different conservation strategies in a descriptive context through our Allens Pond case study.

Figure 8. Staff from Buzzards Bay Coalition; Save The Bay; and Bristol County, Plymouth County, and Cape Code Mosquito Controls meet to discuss runnels as a tool to combat mosquito breeding and conserve marshes at Little Bay. Photo: Brendan Annett

Significantly, the meetings and site-visits we have organized at Ocean View Farm, Little Bay and elsewhere have led to productive coalition-building among regional environmental non-profits and other agencies. While our groups have worked together before, working closely on the specific issues facing marshes in Buzzards Bay has bolstered partnerships and built capacity for more integrative future work. Partnerships between Buzzards Bay Coalition and three regional mosquito control agencies have highlighted runnels as a "win-win" for public health and environmental restoration. These strengthened partnerships have laid the groundwork for runnels to be used in more marshes around the watershed. In addition, the organizations partnering on this project are working more closely with Mass Audubon and Dartmouth Natural Resources Trust as a result of coordinating efforts at Allens Pond marshes. From our meetings and site-visits we have developed ideas for future monitoring, restoration, and grant proposals. Our collective reach to communities is also strengthened and broadened by our partnerships. Through this project, we have developed knowledge, partnerships, and capacity to further environmental initiatives in southern New England.

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Evaluating Management Actions to Promote Salt Marsh Resilience

Contract # SNEPWG-19-9-BBC-SM
September 1, 2019 – February 28, 2022

Project Final Report

Submitted February 28, 2022

Grantee Organization:

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Project Report Narrative

2.A. Project Results

PROJECT OVERVIEW:
This project brought together a unique team of experienced researchers and practitioners to address the loss of salt marsh habitat, which is happening at a dramatic and increasing rate in Southeast New England. Salt marshes are critical ecosystems that provide nutrient removal, storm and flood protection, and essential habitat. Multiple stressors are adversely affecting salt marshes including sea level rise, eutrophication, ditching, increased storm intensity, tidal restrictions, and low sediment supply. The goal of this project was to identify watershed/marsh characteristics and conservation strategies that will promote salt marsh resilience in Buzzards Bay. The project team included the Buzzards Bay Coalition (BBC), Woodwell Climate Research Center (Woodwell, formerly the Woods Hole Research Center), Buzzards Bay National Estuary Program (BBNEP), Save The Bay (STB), U.S. Geological Survey (USGS), and Bristol County Mosquito Control Project (BCMCP). This project took a two-prong approach – first, assessing the use of runnels, both by synthesizing information on completed projects and by performing field studies, and second, by mapping historical and current patterns of salt marsh loss, as well as vulnerability to future losses. The results provide a picture of salt marsh degradation and aid strategic planning for how best to promote salt marsh resilience in Buzzards Bay. The project drew on the long-term experience of project partners in: salt marsh field research/monitoring, geospatial analysis and mapping, implementation of runnels, water quality monitoring, and outreach to policy makers and the public. The project also leveraged recent aerial imagery of salt marshes collected in fall of 2018, a new salt marsh monitoring program in Buzzards Bay that began in summer 2019, and ongoing water quality monitoring performed by the BBC.

TASK 1: Evaluate current state of practice on runnels and potential application to Buzzards Bay

Task 1.1 – Workshop and white paper to synthesize knowledge on runnels –
To better understand the efficacy of runnels used for restoration, we organized a workshop of experts and stakeholders in coastal resource management that was held on March 2, 2020 at the Woodwell Climate Research Center. Workshop goals were to solicit expert opinion on the practice of runnelling and to try to build consensus around when and how to use runnels.

The workshop was attended by over 70 participants (Appendix I, list includes organizers/presenters and a few individuals who RSVP'ed but did not make it). There were representatives from a broad range of organizations including local land trusts; town conservation commissions; state regulatory, federal, and mosquito control agencies; and academic and research institutions. During the workshop, scientists and managers presented outcomes from recent runnel-projects, followed by panel and small group discussions to discuss situations where runnels could be used and to rank potential test sites for runnels.

Through the workshop we developed a collective understanding of how runnels might be used to slow or reverse open water conversion, and identified unresolved questions. This information was used to design our own experimental test of runnels (Task 1.2 below).

The feedback we received about the workshop was uniformly positive. The workshop demonstrated the significant interest in the potential of runnels for building marsh resiliency. Participants were surveyed post-workshop to quantify the number of runnel projects being considered in the Northeast. Between this survey, literature review, and subsequent discussions with partners we identified 36 runnel projects either completed, in-progress, being planned or considered around the Northeast (6 states). It is clear that developing rigorous information about the impacts of the technique is an acute need that this project has helped to fill.

Information from the workshop was summarized and combined with a literature review, and case study of runnels from Rhode Island to produce a journal publication (Besterman, A.F., Jakuba, R.W., Ferguson, W., Brennan, D., Costa, J.E., & Deegan, L.A. Buying Time with Runnels: A Climate Adaptation Tool for Salt Marshes. *Estuaries and Coasts* (2022) https://doi.org/10.1007/s12237-021-01028-8). This publication (open access and publicly available, attached as Appendix II) presents the current state of knowledge on the practice of runnelling as a climate adaptation technique, and also presents remaining questions and knowledge gaps that should be answered with empirical evidence before runnels are widely used in adaptation and restoration projects. SNEP funding not only supported the development of this publication but also allowed us to make the publication “Open Access” so anyone can download the article for free.

In addition to developing the manuscript as written documentation on the practice of runnels, we engaged stakeholders and practitioners through presentations and site visits. Project presentations were developed and delivered for both external (Restore America’s Estuaries 2020 Virtual Summit; University of Florida Water, Wetlands, and Watersheds Webinar; New England Estuarine Research Society Spring 2021 Meeting; Massachusetts Ecosystem Climate Adaptation Network Salt Marsh Working Group; Branford Rotary Club Speakers Bureau; East Caroline University Biology Research-In-Progress Seminar Series, Society of Wetland Scientists Webinar Series, Coastal and Estuarine Research Federation 2021 Biennial Conference) and internal (BBC Leadership Council, BBC Science Advisory Committee, Woodwell Climate Research Center Internal Seminar) audiences. We held a site visit at Ocean View Farm in October 2020 to discuss management of the Allens Pond tidal inlet, its impact on the marsh, and the runnel project with stakeholders. A site visit in May 2021 at the Little Bay site included staff from all three regional mosquito control agencies (Bristol County, Plymouth County, and Cape Cod) where we looked at the completed runnels and reviewed the process used for site selection, runnel digging, and permitting. A second site visit in May 2021 at the Ocean View Farm site brought together stakeholders from Allens Pond and non-profit staff (Dartmouth Natural Resources Trust, Mass Audubon, Buzzards Bay Coalition, Save The Bay) actively engaged in restoration techniques around the watershed. We also presented at a Dartmouth Natural Resources Trust Restoration Walk-And-Talk held for members and other members of the public at Ocean View Farm.

Task 1.2 – Design and install experimental runnels –
Prior to selecting locations for installing experimental runnels, the project team did an initial screening of potential locations using Google Earth satellite imagery. This was followed by site visits to ten locations to further assess the viability of the site. Of these, 10 were discussed and ranked with workshop participants. Taking into account the feedback from the workshop participants, additional field site visits by project team members and discussions with land owners, the project team selected two marsh complexes for creating experimental runnels. The experimental runnels were located at Ocean View Farm in Dartmouth and Little Bay in Fairhaven.

The property owners Dartmouth Natural Resources Trust and the Town of Fairhaven were both enthusiastic partners interested in the potential of runnels to increase the long-term resiliency of salt marsh habitat on their properties. Project partner BCMCP took the lead in applying for permits for the project work. Permits were secured from both the U.S. Army Corps of Engineers and Massachusetts Department of Environmental Protection. Ten experimental runnels were installed from October – November (five each at Ocean View Farm in Dartmouth, and Little Bay in Fairhaven). The bulk of the runnel installation was performed by project partner BCMCP with hand-digging assistance from project partners and their volunteers. Follow-up site visits between October 2020 and February 2021 were made to modify (widen, lengthen, extend where necessary to drain pooling water), and clean runnels (remove accumulated sediments or chunks of peat), and make measurements of runnel dimensions.

Task 1.3 – Assess the effect of runnels –
Monitoring for this project followed a project Quality Assurance Project Plan that was approved by EPA (Besterman and Jakuba 2020); we have included a table describing differences between our final sampling plan and the QAPP (Appendix III). The role of runnels in salt marsh ecosystems was assessed using a BACI (Before-After-Control-Impact) design. In our project proposal, we proposed the installation and monitoring of three experimental runnels. Through our numerous site visits around the watershed to look at potential locations and discussions with runnel workshop participants, we determined that three experimental runnels would not be sufficient replication to be able to conclusively assess the effect of runnels given natural variability. Thus, we decided to increase the number of experimental runnels from three to ten. Across the two marshes, we established twenty total monitoring transects, ten to monitor experimental areas where a runnel was dug and ten to monitor control areas where runnels were not dug. Transects were monitored in summer 2020 (prior to any runnel digging) and in summer 2021 (after runnels were dug at 10 of the sites).

To help support the increased instrumentation costs associated with expanding the number of monitoring transects, the BBC wrote a successful grant application to a private foundation for an additional $35,000 to support monitoring associated with this project and the BBC's long-term salt marsh monitoring (Rose Family Foundation). We also received support for additional instrumentation from the the Fleetwing Foundation. To support continuing the work into future years, we also wrote a successful grant application to the Northeast Climate Adaptation Science Center.

There were some challenges as a result of the COVID pandemic that slowed down or complicated summer 2020 field season monitoring (e.g., extra time required to disinfect equipment, having a field team each use separate data sheets and travel separately); however, the vast majority of the work was accomplished as planned. Vegetation, photo, elevation, and water-level monitoring were carried out at 10 experimental and 10 reference transects. Additional measurements (more variables and higher replication) were made at a subset of 6 experimental and 6 reference transects including: deploying and retrieving sediment deposition plates, performing shear vane measurements, collecting sediment cores for analysis of soil properties (water content, bulk density, organic matter, and particle size distribution), deployment and retrieval of plaster erosion blocks, and measurements of dieback area water depth. Measurements were repeated in summer 2021, with the exception of two of the transects at Ocean View Farm (transects were located in a lower elevation, and more degraded area, and we wanted to minimize disturbance there). At these transects, we conducted limited monitoring (vegetation for a subset of key monitoring plots and photographs).

Initial monitoring results are described in detail in an attached report, "Early Responses to Runnels in Southern New England Salt Marshes", Appendix IV. In short, the results indicate runnels lowered the average water table height at Ocean View Farm, but not at Little Bay. Little Bay changes may not have been detected because a) water depths were less to begin with at Little Bay; b) there were very large differences in precipitation between 2020 (dry) and 2021 (wet); c) Little Bay reference sites were slightly drier than experimental-runnel sites, so statistical differences were not observed (further explanation and detail in Appendix IV). However, study of the high-frequency water level data still indicated that periods of prolonged inundation, or water levels very close to the soil surface, were less intense after runnels were installed at Little Bay. Vegetation showed a strong, positive response at Little Bay, even where water table changes were less clear. At Ocean View Farm there was also evidence of revegetation starting, but given initial conditions revegetation will take longer at Ocean View Farm than Little Bay. Other hydrologic and soil properties mostly did not change within the study period, or did not appear to change due to runnelling. Depending on the variable, this is either because of the precipitation differences between years, or because insufficient time has passed for ecosystem-scale responses to occur from runnelling.

TASK 2: Assess role of water quality and conservation strategies for marsh elevation and stability

Task 2.1 – Map salt marsh cover, loss, and geomorphology in nine sub-estuaries –

Project partners at the BBNEP developed a detailed salt marsh boundary layer of all the salt marshes around Buzzards Bay using aerial imagery from 2009, which provided the best coverage available for detailed mapping. By covering all the salt marshes around Buzzards Bay, this layer expands significantly from what was in our proposal, which was to perform the mapping in nine sub-estuaries. The 2009 layer was used as the basis to be able to move backwards and forwards through time to quantify marsh loss. To assess marsh loss, marsh area was quantified at an additional three time points (2001, 2014, 2019) at the 12 BBC long-term marsh monitoring sites. The marsh loss over the last 20 years at each of the 12 BBC long-term marsh monitoring sites will be included in the report "Buzzards Bay Salt Marshes: Vulnerability and Adaptation Potential" (the final version will be submitted in the next few months to be included as Appendix V). The expansion in the number of marshes mapped has slowed progress on this task, so map layers are not yet ready to be made publicly available. However, we still plan to upload the map layers to the Northeast Conservation Planning Atlas (NCPA) and BBNEP websites after project completion.

Task 2.2 – Map conservation regimes and stressors for nine sub-estuaries –
Our understanding of how to think about drivers of marsh loss evolved over the course of the project and influenced our approach. We found that looking at watershed-scale processes was not necessarily useful in the context of potential marsh restoration actions that would happen on a hyper-local scale (e.g., runnels). For example, in the same sub-watershed, part of a marsh may border conservation land whereas another part of the marsh may be near several homes on septic systems. These two areas of the same marsh in the same sub-watershed clearly have different hyper-local nitrogen loading. Similarly, within the same sub-watershed half of the marsh area may be bordered by conservation land, while the other half is bordered by residential properties or a golf course.

To account for this modification in thinking, we looked at stressors, current conditions, and the potential for adaptation at the 12 BBC long-term marsh sites on the marsh site scale rather than at the watershed scale. We developed a report that characterizes these things using both on-the-ground and aerial measurements. Specifically, we looked at the percent of the marsh that is vulnerable or resilient to loss with sea level rise (based on current elevation), nitrogen concentrations in the water near the marsh sites, the number of septic systems near the marsh sites, the presence of restrictions to tidal flow, how much of the marsh is covered with vegetation, what type of species dominate the site, whether there are barriers that would prevent marsh migration, and how much marsh loss has occurred over the last 20 years. We are making final changes to this document, and the final version will be submitted in the next few months to be included as Appendix V of this report.

Project partners at the U.S.G.S. completed a high-resolution wave thrust map and provided data to the project team for a subset of the Buzzards Bay sites. In reviewing the data, we decided not to include it in our analysis of marsh stressors because about half of the sites or focal areas are behind a barrier beach, and wave thrust models were not projected into back-barrier areas. Thus, the values available are not applicable to the marshes themselves.

Task 2.3 – Field Verification and Sampling – BBC and BBNEP staff worked together to validate aerial imagery interpretation through discussions and site visits. We also compared survey elevation data to LiDAR elevation data to validate elevation calculations from benchmarks and GPS data.

Task 2.4 – Compare watershed drivers with potential for restoration via runnels – Project partners' initial comparisons between marsh loss and elevation, along with extensive discussions on runnel design and implementation, suggest the most important factors determining runnel suitability are determined at the local-marsh scale, rather than watershed scale. To provide interested landowners and regulators with information on how to decide whether restoration via runnels is an appropriate tool for a given site, we developed two resources. The first resource is the journal publication described above in Task 1.1. The second resource, "Salt Marsh Conservation and Adaptation in Allens Pond: A Case Study in Buzzards Bay", is attached as Appendix VI. Using our Ocean View Farm site and the greater Allens Pond complex as a case study, this report describes different types of conservation and restoration activities for marshes, and how they address stressors at different spatial and temporal scales. We also described how environmental managers can use these strategies in-isolation, or as complementary tools depending on environmental conditions and resource availability. We will distribute this report to SNEP-area resource managers, regulatory agencies, collaborators and their networks, and attendees of our 2020 Runnel workshop.

2.B. Next Steps & Recommendations

With respect to the runnels implemented through this project, project partners secured additional funding to continue monitoring the effects of the runnels in summer 2022 and summer 2023 through the Northeastern Climate Adaptation Science Center. This continuation of the project will be extremely valuable for monitoring how ecosystems respond over time to runnels. We will continue to study the ability of vegetation to recover over multiple growing seasons. As a single year was insufficient to observe changes to structural properties of salt marshes (elevation, soil conditions), we will be able to assess how runnels will affect the long-term trajectories of salt marshes. And since precipitation can vary significantly between years, we will better understand how hydrology responds, and how we can best adapt runnels to be effective under multiple environmental conditions.

Runnels are a promising tool for salt marsh adaptation, but must be used in certain environments, under certain conditions. Project design is still highly context-specific, so we recommend future runnel projects include individuals with training and experience using the technique, or similar hydrologic management tools. The results of our continued monitoring will be useful for making the technique more generalizable, so that future practitioners can learn and apply the technique independently. We will share these results with practitioners, state and federal agencies, and researchers through presentations and journal publications.

Communicating current results remains a significant goal for this project. The attached reports (Appendices IV–VI) will be distributed to partners. The report on runnel responses from our experiment, and conservation strategies at Allens Pond (Appendices IV & VI) will be revised for format and length, and submitted for review to become journal publications later in 2022. Full data sets will be made publicly available by February 2024, at the completion of the Northeastern Climate Adaptation Science Center grant.

Six of the project team members are now participating in the Salt Marsh Working Group. The SMWG is one of five working groups of the Massachusetts Ecosystem Climate Adaptation Network (Mass ECAN). This group is working to coordinate efforts in New England and to foster collaborations and includes state, federal, nonprofit, and university researchers and coastal resource managers. The group has been developing a consensus document that defines priority research needs for resilient marshes. The current draft document includes three high level research priorities:

1. Improve understanding of ecological and physical process within salt marsh systems, establish baselines.
2. Identify vulnerable marshes; collect or develop data to track ecosystem changes and support predictive models.
3. Inform restoration and adaptation actions to sustain salt marshes and their associated functions and services.

This project, along with the BBC's long-term salt marsh monitoring, developed new information in each of these research priority areas.

2.C. Compliance

A Quality Assurance Project Plan (QAPP) was approved by EPA:

- Besterman, A., Jakuba, R. W. 2020. Quality Assurance Project Plan for Evaluating Management Actions to Promote Salt Marsh Resilience. 33 pp.

Permits for runnel installation were approved by U.S. Army Corps of Engineers and MassDEP:

- Approval via Pre-Construction Notification (PCN) under the US Army Corps of Engineers (ACOE) Massachusetts General Permit #15
- Approvals and Notifications required by the ACOE including:
  - Federal Consistency Concurrence from the Massachusetts Office of Coastal Zone Management
  - Historic Property Notification to the State Historic Preservation Office (SHPO), Board of Underwater Archeological Resources (BUAR), and Tribal Historic Preservation Officers (THPO)
- MassDEP 401 Water Quality Certification

2.D. Project Partners

This project was a truly collaborative endeavor and all project partners made meaningful contributions to strengthen the outcome of the project. The major activities of each project partner are summarized here.

BBC – Led the runnel workshop organization and planning; synthesized workshop results and led writing of *Estuaries and Coasts* publication; performed field visits to potential sites and liaised with property owners and town conservation commissions; led discussions about experimental runnel site selection; supported permit review by providing additional information; supported installation of permanent benchmark elevation benchmarks; coordinated and supported runnel installation; coordinated volunteer assistance for runnel implementation and data management; led monitoring (including drafting experimental plan and QAPP, supply and equipment procurement, preparation, and deployment, hiring/supervising summer field staff, implementing monitoring plan of vegetation, hydrology, sediment dynamics, soil characteristics, and elevation); performed lab analysis; performed data entry, data management, data quality assurance review, and statistical analyses; Baywatchers monitoring program collected nutrient samples that were analyzed at the Marine Biological Laboratory; led analysis of runnel experimental data; developed and delivered project presentations; conducted site visits with staff from other organizations that could also install runnels; led writing of the final report, including appendices; performed project management functions.

Woodwell – hosted runnel workshop and coordinated A/V requirements to allow for remote participants; assisted in workshop organization and planning and participated as a discussion group lead; participated in discussions about runnel site selection; assisted in the development of the experimental plan; provided oversight of research objectives; supported permit review by providing additional information; supported runnel installation; assisted in the review of initial data; performed field visits and supplied field monitoring assistance, and liaised with Woodwell and Northeastern University researchers to facilitate the collection of additional monitoring parameters by collaborators outside the SNEP project team; provided support for lab analyses; expanded monitoring of decomposition rates across sites in runnel experiment using multiple methods; measured soil redox, water content, and temperature using sensor probes; performed nutrient analysis of soil and surface water on marshes; contributed to preparation and revisions of *Estuaries and Coasts* publication.

BBNEP – assisted in workshop organization and planning and participated as a discussion group lead; participated in discussions about runnel site selection, runnel installation, and monitoring access; reviewed draft materials for permit submission; led installation of elevation benchmarks at runnel and long-term monitoring sites; collected GPS spatial and elevation data of benchmarks and markers; trained staff on the use of a digital laser level for salt marsh elevation measurements and assisted with elevation field work; converted digital level survey elevation data to NAVD88; developed salt marsh cover map layers for 12 marsh sites at four timepoints for the calculation of marsh loss; quality assurance review of salt marsh cover map layers; calculated septic density and other land use statistics near the 12 marsh sites; analyzed LiDAR elevation data and calculated elevation statistics for each marsh unit for all 12 marsh sites; helped validate aerial imagery interpretation of vegetation boundaries; performed analysis and quality assurance review of salt marsh elevation data; contributed to preparation and revisions of *Estuaries and Coasts* publication.

STB – assisted in workshop organization and planning and participated as a discussion group lead; participated in discussions about runnel site selection and installation access; provided key information on the design, permitting, and installation of runnels based past experience; led field visits to potential sites; supported permit review by providing additional information; co-led the runnel installation providing critical insight on exact placement of the runnels; made multiple return trips to runnel sites to maintain and check runnels; helped to coordinate and participated in field visits with stakeholders; shared data from and supported interpretation of Winnapaug runnel study that was included in the *Estuaries and Coasts* publication; contributed to preparation and revision of *Estuaries and Coasts* publication.

USGS – participated as a discussion group lead for runnel workshop; assisted in the development of the experimental plan; developing high resolution wind-wave thrust map covering the Buzzards Bay coastline; participated in project team meetings, analyzed samples for particle size analysis; deployed additional turbidity and water quality sensors at runnel sites, processed and provided sensor data; provided data on the unvegetated to vegetated ratio (UVVR) of all 12 marsh sites; provided support/review of analysis of marsh stressors, condition, and potential to adapt.

BCMCP– assisted in workshop organization and planning and participated as a discussion group lead; participated in discussions about runnel site selection; participated in field visits to potential runnel sites; led runnel permitting and coordination with regulatory agencies; co-led the runnel installation; provided the staff and excavator that performed the bulk of the runnel installation; coordinated with project partners and land owners on site access for staff and equipment; performed required maintenance checks at runnel sites; helped to coordinate and participated in field visits with stakeholders; participated in project team meetings; contributed to preparation and revision of *Estuaries and Coasts* publication.

2.E. Volunteer and Community Involvement

Volunteers supported this project in several ways. As part of the BBC Baywatchers Monitoring Program, volunteers collected nutrient samples from water bodies near the salt marsh monitoring sites. Volunteers assisted with data entry, organization, and management. Several students provided volunteer assistance with data entry, management, and analysis and used the experience to support their degrees. These included two Massachusetts Maritime Academy co-op students, a Union College student, and several high school students. Volunteers associated with the BBC and the Dartmouth Natural Resources Trust assisted with hand digging of runnels.

Project staff involved community members in parts of this project. One of the project runnel sites is located on the shores of Allens Pond. Allens Pond is a salt pond whose inlet migrates over time and periodically closes. Extended closures of the inlet harm the marsh vegetation and bird habitat so community members have historically worked with Mass Audubon to manage the inlet and have permits to re-open the inlet when it closes (detailed description of process and management in Appendix VI). Project staff communicated with and provided information to Allens Pond stakeholders once we realized that an inlet closure was likely. The inlet did close, so project staff kept in communication with Allens Pond stakeholders about inlet management and its re-opening.

Team members participated in the Massachusetts Ecosystem Climate Adaptation Network Salt Marsh Working Group, which is working to develop a state-wide strategy document on the most important research questions that need to be addressed (described above). This group also serves as a quarterly opportunity to communicate and learn about research, restoration projects, and new opportunities in applied salt marsh ecology and restoration from scientists and practitioners around the state of Massachusetts, and neighboring New England states.

BBC provided salt marsh data to consultants (Fuss & O’Neill) working with the Town of Mattapoisett on replacing a culvert near one of our long-term monitoring sites to help in their assessment of how the culvert may impact the adjacent marsh.

The BBC served as a host site for an Environmental Data Initiative (EDI) Fellow. EDI’s purpose is to promote and enable the curation and re-use of environmental data, and their fellowship program supports summer fellows by providing a stipend and training/support. Our EDI Fellow worked on performing the necessary data transformations, quality assurance review, and developing metadata for our vegetation data so that the data can be published and made freely available to the community. They anticipate completion and release of the data in 2022.

2.F. Outreach & Communications

As described in Task 1 results, the project team held a successful runnel workshop in March 2020, which was an opportunity to publicize the project with regional conservation organizations, academics, and local, state, and federal government officials. Information from the workshop was summarized and combined with a literature review and case study of runnels from Rhode Island to produce a journal publication (Besterman, A.F., Jakuba, R.W., Ferguson, W., Brennan, D., Costa, J.E., & Deegan, L.A. Buying Time with Runnels: A Climate Adaptation Tool for Salt Marshes. *Estuaries and Coasts* (2022) https://doi.org/10.1007/s12237-021-01028-8). This publication is attached as Appendix II.

At the outset of the project, BBC staff met with local municipal officials from six towns and with staff from the Plymouth and Barnstable Mosquito Control programs to describe the project, solicit feedback and ideas for runnel sites, and to publicize the runnel workshop. The project team coordinated two site visits in May 2021. One at the Little Bay runnel site included staff from all three regional mosquito control agencies. The second site visit was to the Ocean View Farm runnel site with stakeholders from Allens

Pond and non-profit staff (Dartmouth Natural Resources Trust, Mass Audubon, Buzzards Bay Coalition, Save The Bay) actively engaged in restoration techniques around the watershed. Both site visits were opportunities for the project team to show stakeholders the completed runnels; describe the process used for site selection, runnel digging, and permitting; and answer questions about the process.

The BBC developed digital outreach pieces related to the project that were shared with our members, which includes ~10,000 people:

- "Tackling saltmarsh decline with science at 11 sites around the Bay" June 29, 2020 (https://www.savebuzzardsbay.org/news/tackling-saltmarsh-decline-with-science-at-11-sites-around-the-bay/).
- "Protecting salt marsh" part of the "Coalition's 32nd Annual Meeting offers virtual trip around Buzzards Bay" August 21, 2020 (https://www.youtube.com/watch?v=CFz1tb-ebLI&t=1763s).
- "New technique to save Buzzards Bay salt marshes being piloted in Dartmouth and Fairhaven" November 6, 2020 (https://www.savebuzzardsbay.org/news/new-technique-to-save-buzzards-bay-salt-marshes-being-piloted-in-dartmouth-and-fairhaven/).
- "Studying a new technique to save threatened salt marshes" November 20, 2020 (https://www.youtube.com/watch?v=miswWA4MD24).
- "Coalition scientist elected to governing board of national research association" September 3, 2021 (https://www.savebuzzardsbay.org/news/coalition-scientist-governing-board/).
- "Buying time with runnels: A climate adaptation tool for salt marshes" February 2, 2022 (https://www.savebuzzardsbay.org/news/buying-time-with-runnels/).

The Woodwell Climate Research Center also published a version of one of the digital stories:

- "Assessing new salt marsh restoration technique in Buzzards Bay" November 17, 2020 (https://www.woodwellclimate.org/assessing-new-salt-marsh-restoration-technique-in-buzzards-bay/).

The Northeast Climate Adaptation Science Center published a digital story for their newsletter on the Estuaries and Coasts publication:

- "Buying Time With Runnels: A Climate Adaptation Tool For Salt Marshes" February 1, 2022 (https://necasc.umass.edu/news/buying-time-runnels-climate-adaptation-tool-salt-marshes)

The Dartmouth Natural Resources Trust included an article describing the project and related work "Salt Marsh Migration Work" in their summer 2021 "Milestones" newsletter. (https://dnrt.org/salt-marsh-migration-work/)

A November 2020 BBC press release was picked up by several news outlets including the Dartmouth Week (https://dartmouth.theweektoday.com/article/pilot-restoration-program-under-way-dartmouth-salt-marsh/50538), and the Cape and Islands NPR station (WCAI, https://www.capeandislands.org/science-environment/2020-11-17/new-method-to-save-salt-marshes-piloted-in-buzzards-bay). Versions of the WCAI story were also run on Boston (WGBH) and Connecticut Public Radio stations.

BBC project team members gave presentations on the project to public lay audiences including:

- Buzzards Bay Coalition Leadership Council Deeper Dive Series, April 9, 2021.
    - Besterman, Alice "Salt marsh adaptive management to sea level rise using runnels"
- Branford Rotary Club Speakers Bureau, May 12, 2021.
    - Besterman, Alice "Buying Time: Adapting Salt Marshes to 21st Century Sea Level Rise"
- Dartmouth Natural Resources Trust Events, September 29, 2021
    - Besterman, Alice "Salt Marsh Restoration Walk", Dartmouth, MA.

Project team staff gave presentations on the project to scientific audiences including:

- National Coastal and Estuarine 2020 Virtual Summit, September 29 – October 1, 2020.
    - Besterman, Alice "Developing Best Practices in Runnel Project Design and Planning."
- BBC's Scientific Advisory Committee consisting of local experts on marine science, land management, sediment, wetlands, and agriculture.
- University of Florida's Spring 2021 Water, Wetlands, and Watersheds Webinar series, March 31, 2021.
    - Besterman, Alice "Buying Time – Salt marsh adaptive management to sea level rise using runnels" Recording of the presentation available at: https://www.youtube.com/watch?v=a1Lyc2p5u6Q
- New England Estuarine Research Society Spring Meeting, April 27, 2021.
    - Herring, Melissa "Monitoring changes in *Spartina alterniflora* growth across a Southern New England Watershed"
    - Besterman, Alice "'Runnelling' toward climate adaptation: Assessing a hydrologic management strategy for salt marshes"
- Massachusetts Ecosystem Climate Adaptation Network Salt Marsh Working Group, April 7, 2021
    - Besterman, Alice "Evaluating salt marsh adaptive management to sea level rise using runnels"
- SNEP Coastal Resilience Webinar: Wetlands and Seagrasses: Nature's Superheroes in the Fight for Coastal Resilience in Southeast New England, July 15, 2021
    - Jakuba, Rachel "Building Coastal Resiliency in Buzzards Bay Salt Marshes"
- Coastal and Estuarine Research Federation 26th Biennial Conference, November 1 – 4, 8 – 11, 2021
    - Hoffart, Lillian "Establishing baseline conditions for rapidly degrading marshes across a southern New England watershed."
    - Sullivan, Hillary "The impact of runnelling as a hydrologic adaptation strategy on salt marsh carbon decomposition."

    - Besterman, Alice "'Runnelling' toward climate adaptation: Can interior drowning be reversed?"
- East Carolina University, Dept. of Biology, Research-In-Progress Seminar Series, Sep 27, 2021.
    - Besterman, Alice "Buying time – Salt marsh adaptive management to sea level rise using runnels."
- Society of Wetland Scientists Webinar Series, October 21, 2021.
    - Besterman, Alice "Buying time – Salt marsh adaptive management to sea level rise using runnels."
- 2021 Northeastern Mosquito Control Association (NMCA) Annual Meeting.
    - Brennan, Diana "Partnerships in the Salt Marsh: Mosquito Control meets Ecological Restoration."
- Woodwell Climate Research Center Internal Seminar, January 4, 2021
    - Besterman, Alice "Buying Time – Salt marsh adaptive management to sea level rise using runnels."

Project Budget Report

3.A. Summary Budget Tables

Table 1. Expenditures by federal cost category

Budget Category	Total Budgeted Funds	Total Budgeted Match	Grant Funds Expended This Period	Grant Funds Expended Cumulative	Match Funds Expended This Period	Match Funds Expended Cumulative	Match Source (note cash or in-kind)
Personnel	$120,278	$31,263	$14,679.46	$124,495	$2,754	$76,902	In-Kind
Fringe	$24,056	$1,167	$2,717.17	$24,176	$510	$11,541	In-Kind
Travel	$3,840	$0	$0.00	$4,157	$0	$0	
Equipment	$0	$0	$0.00	$0	$0	$0	
Supplies	$4,547	$0	$0.00	$559	$0	$13,728	Cash
Contractural	$36,650	$5,507	$6,778.08	$36,863	$0	$3,789	In-Kind
Other	$3,000	$27,789	$3,280.00	$3,280	$0	$15,218	In-Kind
Total Direct	$192,371	$65,726	$27,454.71	$193,530	$3,264	$121,177	
Indirect	$31,162	$7,002	$3,259.56	$30,003	$612	$14,276	
Total	$223,533	$72,728	$30,714.27	$223,533	$3,876	$135,453	

Table 2. Expenditures by task

Budget Category	Total Budgeted Funds	Expended Progress Period 1	Expended Progress Period 2	Expended Progress Period 3	Expended Progress Period 4	Expended Progress Period 5	Expended Progress Period 6	Expended Progress Period 7	Expended Progress Period 8	Expended Progress Period 9	Actual Expended to Date
Task 1 Evaluate Runnels	$113,657	$2,389.12	$25,526	$15,856	$26,018	$16,282	$15,159	$18,950	$22,400	$9,313	$151,892
Task 2 Assess drivers of marsh stabilit	$97,136	$489.00	$8,573	$4,106	$9,167	$4,584	$3,779	$6,159	$5,480	$17,088	$59,426
Outreach & Communications	$12,740	$123.00	$1,249.00	$1,027.00	$1,403.52	$775.87	$944.68	$1,008.79	$1,369.99	$4,312.81	$12,215
Total	$223,533	$3,001.12	$35,347.83	$20,989.27	$36,588.46	$21,641.96	$19,882.59	$26,117.58	$29,249.97	$30,714.27	$223,533

3.B. Budget Narrative

This project was supported by $223,533 in funding from the SNEP Watershed Grants Program and a match of over $135,000. The actual project expenditures followed very closely with the budgeted funds. There were savings in Supplies costs due to an external private foundation grant received part of the way through the project that covered Supplies. These savings were applied to Personnel to support additional staff time on the project. The bulk of the project funds supported staff time by project partners BBC, Woodwell, and STB. All project partners (also including BBNEP, USGS, and BCMCP) dedicated significant time to the project through the various phases including coordinating and hosting the Runnel Workshop; design/permitting/installation of experimental runnels; planning and implementation of experimental monitoring plan; site visits before and after runnel installation; outreach through presentations and meetings with stakeholders; outreach to the community through digital stories and newsletter pieces; and development of documents to share results analysis and lessons learned (i.e., journal publication, case study, public report, etc). SNEP funding allowed the BBC to hire a full-time postdoctoral researcher who was dedicated to this project. The scope of work proposed was significant and what was accomplished would not have been possible without a single person focused on the project in addition to the large investment in time by all project partners. In addition to staff time, SNEP funding supported travel to/from project sites and participation in multiple scientific conferences to share results. SNEP funding supported the fees associated with publishing the runnel paper in *Estuaries and Coasts* and making it freely available to the public. A small amount of SNEP funding supported purchase of supplies to perform monitoring activities.

The project match documented here was significantly higher than initially budgeted and represents a 60% match of the SNEP funds. Match funds came from many sources. In-kind match was provided by the BBC through its Baywatchers Water Quality Monitoring Program, where volunteers collected samples that were analyzed for nitrogen concentrations by the Marine Biological Laboratory and through institutional funding to support additional staff time. The BBC also secured external grants from the Rose Family Foundation and the Fleetwing Foundation, which supported the purchase of supplies. The Woodwell provided partial support for indirect costs as in-kind match. The Woodwell also secured a grant from the Northeast Climate Adaptation Science Center, which provided additional time for staff support of this project and which will allow the continuation of the monitoring associated with this project for an additional two field seasons.

Additional match not captured in this budget table is support by project partners BBNEP, USGS, and BCMCP. Each of these project partners dedicated time and resources to this project as detailed in the Project Partners section above. Critical parts of this project were performed by these partners at no cost to this project. While a dollar value of the match is not presented, we cannot understate how important the support of these partners was to the projects' success.

4. Supporting Materials

A number of supporting materials are provided as appendices, digital links, and attachments to this report.

Appendices:

- Appendix I: Attendees, presenters and organizers of the 2020 "Evaluating Runnels for Salt Marsh Adaptation" workshop.
- Appendix II: Journal publication on runnels: "Besterman, A.F., Jakuba, R.W., Ferguson, W., Brennan, D., Costa, J.E., & Deegan, L.A. Buying Time with Runnels: A Climate Adaptation Tool for Salt Marshes. Estuaries and Coasts (2022) https://doi.org/10.1007/s12237-021-01028-8"
- Appendix III: Updated Methodology Summary
- Appendix IV: Technical report on initial monitoring results: "Besterman, A.F., R.W. Jakuba, H.A. Sullivan, J.E. Costa, W. Ferguson, D. Brennan, L.A. Deegan. 2022. Early Responses to Runnels in Southern New England Salt Marshes. 68 pages."
- Appendix VI: Case study on approaches and considerations for salt marsh conservation and adaptation: "Besterman, A.F., W. Ferguson, R. W. Jakuba.

2022. Salt Marsh Conservation and Adaptation in Allens Pond: A Case Study in Buzzards Bay. 13 pages."

Digital Resources:

- "Tackling saltmarsh decline with science at 11 sites around the Bay"
    - https://www.savebuzzardsbay.org/news/tackling-saltmarsh-decline-with-science-at-11-sites-around-the-bay/
- "Protecting salt marsh" part of the "Coalition's 32nd Annual Meeting offers virtual trip around Buzzards Bay"
    - https://www.youtube.com/watch?v=CFz1tb-ebLI&t=1763s
- "New technique to save Buzzards Bay salt marshes being piloted in Dartmouth and Fairhaven"
    - https://www.savebuzzardsbay.org/news/new-technique-to-save-buzzards-bay-salt-marshes-being-piloted-in-dartmouth-and-fairhaven/
- "Studying a new technique to save threatened salt marshes"
    - https://www.youtube.com/watch?v=miswWA4MD24
- "Coalition scientist elected to governing board of national research association"
    - https://www.savebuzzardsbay.org/news/coalition-scientist-governing-board/
- "Buying time with runnels: A climate adaptation tool for salt marshes"
    - https://www.savebuzzardsbay.org/news/buying-time-with-runnels/
- "Assessing new salt marsh restoration technique in Buzzards Bay"
    - https://www.woodwellclimate.org/assessing-new-salt-marsh-restoration-technique-in-buzzards-bay/
- "Buying Time With Runnels: A Climate Adaptation Tool For Salt Marshes"
    - https://necasc.umass.edu/news/buying-time-runnels-climate-adaptation-tool-salt-marshes
- "Salt Marsh Migration Work"
    - https://dnrt.org/salt-marsh-migration-work/
- "Pilot restoration program under way in Dartmouth salt marsh"
    - https://dartmouth.theweektoday.com/article/pilot-restoration-program-under-way-dartmouth-salt-marsh/50538
- "New Method to Save Salt Marshes Piloted in Buzzards Bay"
    - https://www.capeandislands.org/science-environment/2020-11-17/new-method-to-save-salt-marshes-piloted-in-buzzards-bay
- "Buying Time – Salt marsh adaptive management to sea level rise using runnels"
    - https://www.youtube.com/watch?v=a1Lyc2p5u6Q

Attachments:

- Project Poster: "Evaluating Management Actions to Promote Salt Marsh Resilience."
- Press release: "New technique to save Buzzards Bay salt marshes being piloted in Dartmouth and Fairhaven."

5. Certification

The undersigned verifies that the descriptions of activities and expenditures in this final report are accurate to the best of my knowledge; and that the activities were conducted in agreement with the grant contract. I certify that the matching fund levels established in the grant contract and reported here have been met.

Grantee Signature:

Rachel W Jakuba

Name: Rachel Jakuba
Job Title: Vice President for Bay Science
Date: 2/28/2022
Organization: Buzzards Bay Coalition

Appendix I: Attendees, presenters and organizers of the 2020 “Evaluating Runnels for Salt Marsh Adaptation” workshop. This list includes all attendees that indicated they would attend, a few (less than 5) were ultimately unable to make the workshop. Institutions and job titles were gathered at the time of the workshop, while we have updated some affiliations, some may be out-of-date (e.g., seasonal staff and students). Some are also unknown, as attendees did not provide this information during registration.

Last	First	Institution	Title
Adamowicz	Susan	US Fish and Wildlife Service	Biologist
Annett	Brendan	Buzzards Bay Coalition	Vice President, Watershed Protection
Ardito	Thomas	Restore America’s Estuaries	Director, Southeast New England Watershed Grants Program
Ayvazian	Suzanne	Environmental Protection Agency-Atlantic Ecology Division	Research Ecologist
Barteau	Louise	Fairhaven Acushnet Land Preservation Trust	
Besterman	Alice	Buzzards Bay Coalition	Postdoctoral Researcher/Fellow
Bidlack	Ellen	Plymouth County Mosquito Control Project	Entomologist
Boeri	Bob	Coastal Zone Management	Project Review Coordinator
Boonisar	Nate	Norfolk County Mosquito Control	Surveillance Technician
Brennan	Diana	Bristol County Mosquito Control Project	Wetlands Ecologist
Bride	Jim	Sippican Lands Trust	Executive Director
Burdick	Dave	University of New Hampshire	Research Professor
Bushee	Drew	Bristol County Mosquito Control Project	Foreman
Callow	Cynthia	Marion Conservation Commission	Member
Carullo	Marc	Coastal Zone Management	GIS/Habitat Analyst
Chaffee	Caitlin	Coastal Resources Management Council	Coastal Policy Analyst
Costa	Joe	Buzzards Bay National Estuary Program	Executive Director
Deegan	Linda	Woodwell Climate Research Center	Senior Scientist
Duprey	Alexandra	Tufts University	Graduate Student
Ferguson	Wenley	Save The Bay	Director of Habitat Restoration
Frapaise	Laurent	Tufts University	Graduate student
Ganju	Neil	US Geologic Survey	Research Oceanographer
Gettman	Alan	Rhode Island Mosquito Abatement	Coordinator
Giblin	Anne	Marine Biological Laboratory - The Ecosystems Center	Senior Scientist

Gillett	Brandon	Plymouth County Mosquito Control Project	Equipment Operator
Glenn	Kathryn	Coastal Zone Management	North Shore Regional Coordinator
Grady	Sara	MassBays and North and South Rivers Watershed Association	South Shore Regional Coordinator and Watershed Ecologist
Hanlon	Heidi	US Fish and Wildlife Service	Wildlife Biologist
Hartley	Mitch	Atlantic Coast Joint Venture	Assistant Coordinator
Hopping	Russell	The Trustees of Reservations	Ecology Program Director
Huguenin	Mike	Mattapoissett Land Trust	President
Iwanejko	Tom	Suffolk County Vector Control	Director
Jacek	Christine	Army Corps of Engineers	Permit Project Manager
Jakuba	Rachel	Buzzards Bay Coalition	Vice President, Bay Science
Jameson	Danielle	Tufts University	Graduate student
Janik	David	Coastal Zone Management	South Coast Regional Coodinator
Keer	Georgeann	Department of Ecological Restoration	Ecological Restoration Specialist
Keimel	Annaliese	Tufts University	Graduate student
Kennedy	Cristina	MA Division of Ecological Restoration	Coastal Wetlands Restoration Specialist
King	Katelynn	Northeast Massachusetts Mosquito Control and Wetlands Management District	Wetlands Coordinator
Laskaris	John	US Fish and Wildlife Service	Biologist
Lawson	David	Norfolk County Mosquito Control	Director
Leidhold	Elizabeth	Conservation Commission- Town of Mattapoisett	Conservation Agent
Maher	Nicole	The Nature Conservancy- Long Island	Senior Coastal Scientist
McClees	Whitney	Conservation Commission- Town of Fairhaven	Conservation Agent
McPhee	Matthew	Plymouth County Mosquito Control Project	General Foreman
Michaud	Conor	Wildlands Land Trust	Community Stewardship Program Coordinator
Montesano	Joseph	Suffolk County Vector Control	Biologist
Moran	Ross	Westport Land Trust	Executive Director
Morris	Bart	Cape Cod Mosquito Control Project	Assistant Superintendent
Nickerson	Josh	Bristol County Mosquito Control Project	Operator
Noone	Barry	Northeast Massachusetts Mosquito Control and Wetlands Management District	District Director
O'Reilly	Mike	Conservation Commission- Town of Dartmouth	Conservation Agent
Pappal	Adrienne	Coastal Zone Management	Habitat and Water Quality Program Manager

Paton	Suzanne	US Fish and Wildlife Service - Southern New England Coastal Program	Senior Biologist
Pau	Nancy	US Fish and Wildlife Service - Parker River NWR	Wildlife Biologist
Perrin	Mike	Wareham Land Trust	
Perry	Danielle	Mass Audubon	Coastal Resilience Program Director
Phippen	Peter	MassBays	Upper North Shore Regional Coordinator
Pichette	David	Conservation Commission- Town of Wareham	Conservation Agent
Purtell	Gina	Massachusetts Audubon- Allens Pond Wildlife Sanctuary	Sanctuary Director
Quintal	Sara	Buzzards Bay Coalition	Restoration Ecologist
Raposa	Ken	National Estuary Research Reserve- Narragansett Bay	Research Coordinator
Rasmussen	Mark	Buzzards Bay Coalition	President
Rickley	Elizabeth	Tufts University	Graduate student
Rossetti	Ross	Plymouth County Mosquito Control Project	Assistant Superintendent/Pilot
Rozsa	Ron	Retired CT DEP	
Sakolsky	Gabrielle	Cape Cod Mosquito Control Project	Superintendent and Entomologist
Sheremet	Vitalii	University of Rhode Island	Marine Research Scientist
Smith	Joseph	US Fish and Wildlife Service	Wildlife Biologist
Stearns	Rachel	US Fish and Wildlife Service	Salt Marsh Technician
Turek	James	NOAA Fisheries- Greater Atlantic Regional Fisheries Office	Restoration Ecologist
Tyrell	Megan	National Estuary Research Reserve- Waquoit Bay	Research Coordinator
Vanderveer	Linda	Dartmouth Natural Resources Trust	Land Manager
Vincent	Rob	MIT, Sea Grant College Program	Assistant Direction for Advisory Services
Weldon	Aimee	Atlantic Coast Joint Venture	Coordinator
Wigand	Cathy	Environmental Protection Agency- Atlantic Ecology Division	Research Ecologist
Wilson	Geoff	Northeast Wetland Restoration	Principal
Wolfe	Roger	Department of Energy and Environmental Protection	Wetland Restoration/Mosquito Management Coordinator

Appendix II: Attached as PDF

Besterman, A.F., Jakuba, R.W., Ferguson, W., Brennan, D., Costa, J.E., & Deegan, L.A. Buying Time with Runnels: A Climate Adaptation Tool for Salt Marshes. *Estuaries and Coasts* (2022) https://doi.org/10.1007/s12237-021-01028-8

Appendix III: Updated Methodology Summary

Through this project, we sought to carefully document the effect of runnels on a number of parameters in the field and to characterize marshes based on a range of watershed characteristics. Over the course of performing this project, we adapted our approach to incorporate learnings as we went. The following table compares our planned approach as described in the project QAPP with the approach applied.

Method Type	**Planned Approach**	**Approach Used**
Task 2		
Study sites:	5 runnel/5 reference sites in Town of Dartmouth marsh, 4 runnel/4 reference sites at Town of Fairhaven marsh. All variables measured at all sites.	5 runnel/5 reference sites at both marshes; established 3 runnel/3 reference sites at each marsh to be “Intensives” where monitored all variables at full replication; 2 runnel/ 2 reference established as “Non-intensives” where we monitored subset of variables at fewer replicate locations.
Vegetation percent cover: Point-intercept	Intensive transects (n = 6 transects x 6 sample plots x 1 times) = 72 samples per year	Intensive transects (n = 12 transects x 11 – 13 sample plots x 1 times) + Non-intensive transects (n = 8 transects x 5 sample plots x 1 times) = 191 samples per year
Vegetation percent cover: Braun Blanquet	All transects (n = 18 transects x 6 samples x 2 times = 216)	Did not complete – instead conducted more spatially extensive point-intercept monitoring
Stem height	All transects (n = 18 transects x 6 samples x 2 times = 216)	Intensive transects (n = 12 transects x 11 – 13 sample plots x 1 times) + Non-intensive transects (n = 8 transects x 5 sample plots x 1 times) = 191 samples per year
Stem density	Intensive transects (n = 6 transects x 6 samples x 2 times) = 72 samples per year	Intensive transects (n = 12 transects x 11 – 13 sample plots x 1 times) +

		Non-intensive transects (n = 8 transects x 5 sample plots x 1 times) = 191 samples per year
Belowground biomass	Intensive transects (n = 6 transects x 6 x 1 time = 36)	Determined ~ triple this sampling intensity would be needed to detect an effect of runnels. Did not want to create that much disturbance, so did not perform these measurements.
Sediment organic matter/ water content/ bulk density	All transects (n = 18 transects x 6 sample x 1 time) = 108 samples per year	Intensive transects (n = 12 transects x 11 – 13 sample plots x 1 times) = 151 samples per year 5-cm deep cores
Shear vane	All transects (n = 18 transects x 6 sample x 1 time) = 108 vertical profile samples per year 90-cm depth vertical profiles	Intensive transects (n = 12 transects x 12 sample locations x 1 – 3 measurement depths x 1 time) = 144 vertical profile samples per year 30-cm depth vertical profiles (limited sampling to zone where changes likely to be observed)
Redox Potential: IRIS Tubes	All transects (n = 18 transects x 2 samples x 1 time = 36 samples)	Piloted 5/site in 2020. Method not effective in saline marshes, at length of deployment we required. Did not repeat in 2021.
Elevation surveys	All transects (n = 18 transects x 6 samples x 1 time = 36 samples)	> 1000 measurements across all transects per year (measured at all plots + every 2 m + any unusual topographic features)
Water level loggers	3 loggers per transect	1 logger per site, used elevation data to relate locations to across impoundments/transects
Water level: Tide stakes	NA	Used bamboo skewers with color-dyed glue coating to measure water depths at 36 locations, 12 intensive transects, 1 time per year
Sediment accretion:	Ceramic tiles, deployed for 6–10 weeks	Acrylic plates with glass microfiber filters. In 2020 deployed for 2 weeks (too long,

		filters degraded). Improved method in 2021 to deploy for only 2–4 days. Repeated deployments at both marshes 2 times per year.
Plaster dissolution blocks	NA	Deployed plaster blocks for controlled length of time to determine mass transport (or cumulative wave + current energy from water and sediment surface). 10 blocks x 12 intensive sites x 1 time (2020 only)
Conductivity logger	1 per site	1 per site, subset of sites
Sediment grain size	NA	1 50-mL sample per site, collected from surface sediments (2-cm depth). Analyzed by USGS using established protocols.
Task 3		
Approach to analysis:	Statistical analysis of 20 marshes (2 marshes in 10 embayments)	More marsh units per embayment were ultimately mapped (> 300), at 4 time points to assess change over time. The expansion in the number of marshes mapped slowed progress on this task. Data have not been thoroughly QA/QC'ed yet, so we did not perform statistical analyses. Instead: Produced a descriptive report on marsh condition and vulnerability of 12 marshes (~ 20 marsh units) for a public audience (BBC/BBNEP long-term monitoring sites). Accomplishes same task using a semi-quantitative, comparative method.
Characteristics to be analyzed:	Marsh cover, marsh loss, elevation, land cover and conservation lands (watershed), tidal restrictions, nutrient	Marsh area, vegetated and bare coverage, marsh loss, elevation statistics (% vulnerable, % resilient), tidal restrictions, nutrient loading, UVVR.

	loading, wind-wave exposure	

Appendix IV: Attached as PDF

Besterman, A.F., R.W. Jakuba, H.A. Sullivan, J.E. Costa, W. Ferguson, D. Brennan, L.A. Deegan. 2022. Early Responses to Runnels in Southern New England Salt Marshes. 68 pages.

Appendix V: To be attached as PDF upon completion in spring 2022.

Jakuba, R.W., Hoffart, L., Besterman, A., Costa, J.E., Ganju, N., Deegan, L. (2022). Buzzards Bay Salt Marshes: Vulnerability and Adaptation Potential. XXpp.

Appendix VI: Attached as PDF

Besterman, A.F., W. Ferguson, R.W. Jakuba. 2022. Salt Marsh Conservation and Adaptation in Allens Pond: A Case Study in the Buzzards Bay Estuary. 13 pages.

Estuaries and Coasts
https://doi.org/10.1007/s12237-021-01028-8

PERSPECTIVES

Buying Time with Runnels: a Climate Adaptation Tool for Salt Marshes

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Abstract

A prominent form of salt marsh loss is interior conversion to open water, driven by sea level rise in interaction with human activity and other stressors. Persistent inundation drowns vegetation and contributes to open water conversion in salt marsh interiors. Runnels are shallow channels originally developed in Australia to control mosquitoes by draining standing water, but recently used to restore marsh vegetation in the USA. Documentation on runnel efficacy is not widely available; yet over the past 10 years dozens of coastal adaptation projects in the northeastern USA have incorporated runnels. To better understand the efficacy of runnels used for restoration, we organized a workshop of 70 experts and stakeholders in coastal resource management. Through the workshop we developed a collective understanding of how runnels might be used to slow or reverse open water conversion, and identified unresolved questions. In this paper we present a synthesis of workshop discussions and results from a promising case study in which vegetation was restored at a degraded marsh within a few years of runnel construction. Despite case study outcomes, key questions remain on long-term runnel efficacy in marshes differing in elevation, tidal range, and management history. Runnel construction is unlikely to improve long-term marsh resilience alone, as it cannot address underlying causes of open water conversion. As a part of holistic climate planning that includes other management interventions, runnels may "buy time" for salt marshes to respond to management action, or adapt to sea level rise.

Keywords Runnel · Salt marsh · Sea level rise · Shallow water · Climate adaptation · Coastal restoration

Introduction

While for centuries salt marsh loss was driven by direct human alterations (Gedan et al. 2009), sea level rise (SLR) now poses one of the chief threats to salt marshes globally (FitzGerald and Hughes 2019; Bindoff et al. in press). Direct alterations (e.g., draining, filling) led to prolific reductions in the global inventory of salt marshes (Gedan et al. 2009; Mcowen et al. 2017). Regulations have mitigated direct loss of wetlands along many temperate coastlines (Gedan et al. 2009; Bindoff et al. in press); however, legacy impacts from agriculture (Adamowicz et al. 2020) and mosquito ditching (Vincent et al. 2014; Burdick et al. 2020), in interaction with SLR (Raposa et al. 2017; Watson et al. 2017), continue to alter hydrology and stress vegetation. A primary manifestation of these stressors in Northwest Atlantic and Mississippi Delta marshes has been the expansion of unvegetated, shallow water features in marsh interiors, i.e., open water conversion (Barras et al. 2003; La Peyre et al. 2009; Vincent et al. 2014; Kearney and Turner 2016; Watson et al. 2017; Adamowicz et al. 2020) (Fig. 1c–e). Globally, salt marsh coverage is most extensive in low-lying temperate zones of the North Atlantic (Mcowen et al. 2017). Thus, marsh losses to open water conversion in this region are globally significant.

A surge in restoration of Northwest Atlantic salt marshes (specifically, northeastern USA) occurred over the past decade, funded by the US government in the

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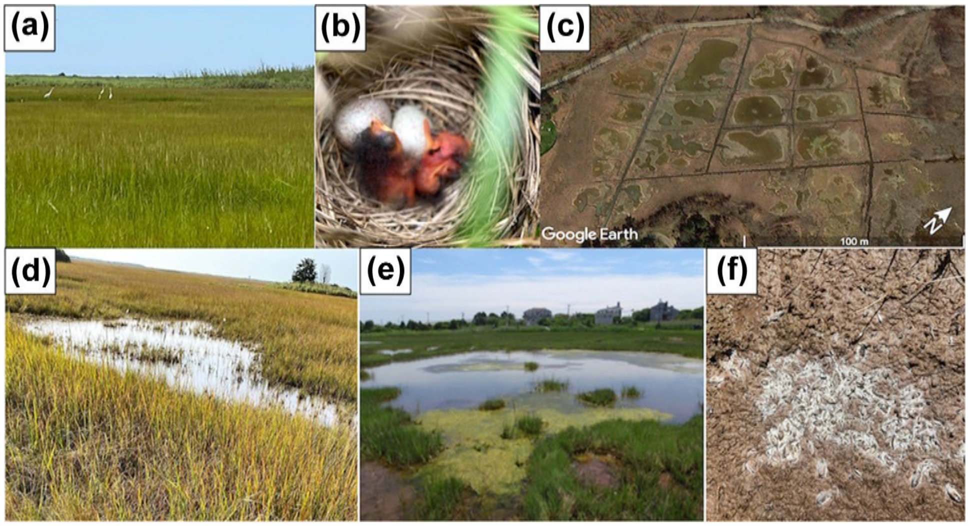

Fig. 1 **a** Salt marsh ecosystems support wildlife, e.g., great egrets (*Casmerodius albus*) and **b** saltmarsh sparrows (*Ammospiza caudacuta*). **c** Salt marsh interiors increasingly impacted by sea level rise, in interaction with legacy effects from human activity, are experiencing plant death and drowning. **d** Plant death is recent; with short, stressed vegetation and intact peat present with impounded water and **e** and algal mats. **f** Dead killifish (*Fundulus heteroclitus*) stranded when a shallow water area is drained

aftermath of Superstorm Sandy in 2012 (Babson et al. 2020). One technique involved digging "runnels"—small channels meant to drain standing water and promote revegetation (Wigand et al. 2017; Raposa et al. 2019; Babson et al. 2020; Perry et al. 2021; Wolfe et al. 2021). As of 2019, knowledge on runnel efficacy as a tool to build marsh resilience to SLR (defined here as the ability of a marsh to resist a state-change to open water) had not been widely shared. Recognizing the need to critically evaluate runnels as a climate adaptation tool, we organized a workshop on the runnel technique in early 2020. Workshop goals were to solicit expert opinion on the practice of runnelling and to build consensus around when and how to use runnels. This information was used to design our own experimental test of runnels, which is now underway. Seventy people including scientists, regulators, landowners, and resource managers from government, academia, and non-profits participated. During the workshop, scientists and managers presented outcomes from recent runnel-projects, followed by panel and small group discussions.

This paper is a product of the workshop, subsequent engagement among participants, and literature review. Three focal questions will be discussed here: (Q1) What problem do managers use runnels to address? (Q2) What is a runnel and how does it work? and (Q3) How effective are runnels? We focus on runnel use to mitigate marsh loss caused by interior shallow water expansion, describe runnel mechanics and present a case study, and discuss lessons learned on efficacy and remaining knowledge gaps. To address remaining gaps, we present specific research topics needing attention. We synthesized information from workshop presentations and subsequent engagement, and literature review to address all three questions. We used the case study to supplement our discussion of Q2 and Q3.

The Problem: Changing Hydrologic Dynamics

Pre-colonial salt marsh hydrology in the Northwest Atlantic featured networks of channels, as well as isolated pannes and pools (Redfield 1972). "Single-channel" hydrology included a primary channel intersected by dendritic tributaries draining the platform (Redfield 1972). Pannes and pools dot marsh platforms and create habitat for unique plants, fish, and waterbirds (Fig. 1a). These features were classically considered in dynamic equilibrium with the vegetated platform (Ewanchuk and Bertness 2004; Adamowicz and Roman 2005; Wilson et al. 2014; Adamowicz et al. 2020). Pannes are shallow depressions with waterlogged soils covered with sparse forbs and bare sediment that form and revegetate within a few years (Ewanchuk and Bertness 2004). Pools are deeper depressions that remain flooded and enlarge, and may drain and revegetate slowly over decades to centuries (Adamowicz and Roman 2005; Wilson et al. 2014).

A natural cycle of "pool recovery," also applicable to shallow pannes, has been documented in some marshes (Wilson et al. 2014; Mariotti 2016). Pools form and expand until they connect to a headward eroding creek that drains the pool. After pool drainage, the remaining bare peat area revegetates. Theoretical models suggest that a large tidal range (> 1 m), large sediment supply (> 70 mg/L), and accretion rates equal to or greater than relative SLR (RSLR) favor pool recovery (Mariotti 2016). Empirical work has shown that pool recovery can occur without satisfying all criteria (Smith and Pellew 2021). The idealized conditions promote pool recovery by maintaining marsh elevation such that unvegetated basins of pools and pannes are suitable for vegetative growth relative to local sea level. If these unvegetated pool and panne basins become too low in relative elevation to revegetate, then pool recovery cannot occur. Without dynamic recovery, pool and panne expansion may lead to the conversion of marsh interiors to open water (Kearney and Turner 2016; Mariotti 2016; Himmelstein et al. 2021).

Recent studies report the expansion of bare and shallow water areas on marsh surfaces across the Northwestern Atlantic (Table 1). In Mississippi Delta marshes, the formation and expansion of interior pools has been contributing to marsh loss for decades (DeLaune et al. 1994; Barras et al. 2003). While pannes and pools were not classically considered to contribute to net marsh loss (Ewanchuk and Bertness 2004; Adamowicz and Roman 2005), observed increases in the number and size of unvegetated features suggest that marsh hydrology is not in equilibrium—and a trend toward net conversion of vegetated marsh to bare and shallow water areas (Table 1, and references therein). In North America, pre-colonial salt marsh hydrology was altered by colonial farmers, and later for mosquito control (Vincent et al. 2014; Adamowicz et al. 2020). Historic modifications to marshes including ditches, side-cast ditch spoils that form artificial levees, ditch-plugs, and embankments altered topography and hydrology, lowering resilience to current stress from SLR. Ditching lowered marsh platform elevations (Burdick et al. 2020), while artificial levees, embankments, and ditch-plugs created microtopographic impoundments that block natural water flow pathways (Vincent et al. 2014; Adamowicz et al. 2020; Wolfe et al. 2021). Increased inundation from SLR, in interaction with lowered platform elevations and impaired drainage, have lengthened hydroperiods and likely contributed to the recently observed increases in bare and shallow water areas within marshes (Fig. 2a–c) (Adamowicz et al. 2020; Himmelstein et al. 2021; Wolfe et al. 2021). Ecosystem managers have observed that vegetation communities in recently developed bare and shallow water areas do not resemble the diversity of "forb pannes" expected for northern New England (Ewanchuk and Bertness 2004, personal communication). Water depths in these recently developed areas appear intermediate between pannes and pools, creating conditions inhospitable to vegetation (Fig. 1d, e), but too shallow or hypersaline to support fish (Fig. 1f). Understanding whether marsh ecosystem function and resilience are being permanently altered depends on the trajectory of these shallow water areas.

Mariotti (2016) proposed a framework of shallow water expansion that described three scenarios: "pool recovery" (described above), "drowning," and "pool collapse." Drowning occurs when water becomes impounded on the marsh platform and stresses vegetation (Mariotti 2016). Plant death and peat subsidence follow, initiating a positive feedback cycle of water expansion (DeLaune et al. 1994; Chambers et al. 2019). Marsh drowning is predicted for marshes where

Table 1 Selected studies quantifying interior shallow water expansion in tidal marshes Table summarizes the findings on shallow water expansion, and any information provided by the study on background environmental characteristics is summarized

Location and study	Study findings	Environmental background
Buzzards Bay, MA (Costa and Weiner 2017, Costa, unpub. data)	Historical aerials of marshes between 1938 and 2009 show pannes generally expand and deepen (occasional drainage and revegetation in high marsh), while deeper pools only appear to expand	Elevations of 6 unditched marsh islands ranged from −0.15 to 0.37 m above local sea level. Buzzards Bay in general has low turbidity; tidal ranges ~ 1 m or less, and majority of mainland marshes have been ditched
Narragansett Bay, RI (Watson et al. 2017)	Between 1972 and 2011, 20 out of 36 marshes lost marsh to interior ponding	Marsh median elevations 0.34–0.59 m NAVD88; tidal ranges < 1 m; low turbidity < 5 mg/L; SLR > 3.5 mm/yr. Majority of marshes have been ditched
Blackwater River, MD (Schepers et al. 2017)	Up to 21% of marsh area converted to pools between 1981 and 2010	Microtidal, spring tidal ranges ~ 0.2–1.0 m across system. Local RSLR 3.72 mm/yr; historical marsh accretion 1.7–3.6 mm/yr
Fire Island National Seashore, NY (Campbell and Wang 2019)	Doubling of pannes and pools between 1994 and 2015	Microtidal, mean tidal range 0.455 m; surface elevation tables indicate marshes not accreting sufficiently to keep pace with SLR
Chesapeake Bay and Delaware Bay (Taylor et al. 2020)	Increase of 14,000 ha of interior surface water in marshes between 1984 and 2014	Regional study including sites with different conditions, ranges not reported

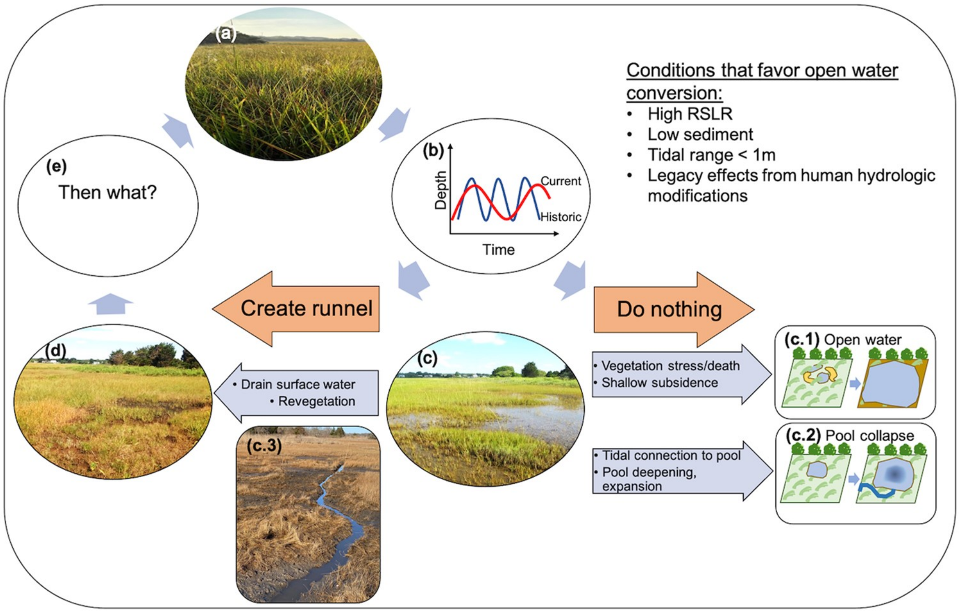

Fig. 2 (**a**) Marshes with environmental conditions that favor conversion to open water are experiencing (**b**) longer periods of inundation on marsh interiors and (**c**) standing shallow water on marsh platforms (Winnapaug marsh, RI). If no action is taken, expanding shallow water leads to (**c1**) open water or (**c2**) pool collapse. If a (**c3**) runnel is created, (**d**) surface water should drain allowing revegetation (Winnapaug marsh, RI). But without changing the conditions that led to shallow water formation, (**e**) what is the long-term trajectory of runnel-adapted marshes?

RSLR is high (> 10 mm yr^{-1}), and the entire platform is accreting at less than RSLR. Pool collapse involves a pool becoming tidally connected by a creek, similar to pool recovery, except the pool expands and deepens (Mariotti 2016; Schepers et al. 2020). This may occur when the pool basin elevation is too low relative to sea level for vegetation to recover. Instead of drainage, tidal water conveyed by the creek can erode unconsolidated material underlying pools (Schepers et al. 2020). Pool collapse happens when the marsh platform keeps pace with RSLR, but the basin of the pool does not, and can occur at lower rates of RSLR than drowning (5–8 mm yr^{-1}). Rates of RSLR capable of inducing pool collapse are higher than current SLR (3–4 mm yr^{-1}) experienced by the majority of marshes globally (Oppenheimer et al. in press). Other factors in addition to RSLR are important in determining whether a shallow water area proceeds along a collapse or recovery trajectory. The likelihood of pool collapse may increase with a smaller tide range, lower sediment supply, and when a larger volume of water is conveyed through the connecting creek (Mariotti 2016; Schepers et al. 2020). As a result, drowning and pool collapse are two mechanisms by which interior vegetated marsh areas convert to shallow water and contribute to marsh loss.

Researchers and resource managers have recently pointed to the widespread increase of interior shallow water as an indicator of marsh loss (Watson et al. 2017; Campbell and Wang 2019; Adamowicz et al. 2020; Schepers et al. 2020; Taylor et al. 2020; Duran Vinent et al. 2021; Himmelstein et al. 2021), and have responded with management actions to stop or slow open water conversion (Wigand et al. 2017; Raposa et al. 2019; Adamowicz et al. 2020; Babson et al. 2020; Perry et al. 2021; Wolfe et al. 2021). However, in some marshes an increase in standing surface water could represent a recovery of "natural" hydrology after marshes were historically over-drained by ditches, and some marshes show potential for pool recovery (Wilson et al. 2014; Smith and Pellew 2021). While these recovery scenarios may occur in some places, coasts with low sediment supply or small tidal ranges, and where legacy effects of agriculture and ditching have altered hydrology are unlikely to follow these trajectories (Mariotti 2016; Adamowicz et al. 2020; Wolfe et al. 2021). Rather, increasing periods of inundation will likely lead to drowning, pool collapse, or another mechanism of open water conversion (Fig. 2). In these marshes with low recovery potential, managers are using runnels as a low-cost tool to address increasing surface water and restore vegetation (Table 2 and Supplemental File 1).

Introducing Runnels: History and Progress

Runnels as a Climate Adaptation Tool

Runnels used for climate adaptation to SLR are a new application of an existing mosquito control technique used in the USA and Australia (Hulsman et al. 1989; Wolfe 1996). Historic mosquito ditches were excavated > 60 cm deep, causing peat oxidation and subsidence of the inter-ditch marsh platform (Burdick et al. 2020). More recently, mosquito control programs began constructing runnels that resembled natural channels to drain standing water (mosquito larvae habitat) and allow fish passage (mosquito larvae predators), with minimal impact to marshes (Hulsman et al. 1989).

A runnel is a small channel (generally ≤ 30 cm wide and deep) that drains standing water on the marsh surface. Runnels are constructed using hand-digging and low-ground

Table 2 Selected runnel adaptation projects from the northeastern USA The table includes the year each project was initiated, project name and location, the closest NOAA tide station and tidal range and SLR reported for that station, primary motivations for the project, the number of runnels used in the project (if known), and general vegetation response to runnels

Year	Project name	NOAA station	Tidal range (m)	Sea level rise (mm/yr)	Motivations	No. of runnels	Vegetation response
2004	**Mile Creek Marsh A** 41.28, – 72.29	Bridgeport, CT	2.05	3.08	Revegetate dieback, mosquito control	2	After 2–5 years
2014	**Round Marsh** 41.51, – 71.37	Newport, RI	1.05	2.83	Phragmites control, mosquito control	8	After 1 year
2014	**Mile Creek Marsh B** 41.28, – 72.29	Bridgeport, CT	2.05	3.08	Revegetate dieback, wildlife habitat	4	After 1 year
2015	**Parker River NWR, Ditch Plug Removal** 42.78, – 70.81	Boston, MA	2.89	2.87	Revegetate dieback, low-marsh to high-marsh species	22	After 1 year
2017	**Reeds Beach at Cape May National Wildlife Refuge** 39.12, – 74.88	Cape May, NJ	1.48	4.88	Low-marsh to high-marsh species, wildlife habitat	40	After 1 year
2018	**Potters Pond** 41.38, – 71.53	Newport, RI	1.05	2.83	Revegetate dieback, mosquito control	7	After 2–5 years
2019	**Furbish Marsh Restoration** 43.28, – 70.58	Seavey Island, ME	2.47	2.05	Revegetate dieback, low-marsh to high-marsh species	2	No results yet
2019	**NFWF Gardiners** 40.69, – 73.27	Sandy Hook, NJ	1.43	4.15	Revegetate dieback, low-marsh to high-marsh species	40	After 1 year
2020	**Little Bay Conservation Area** 41.63, – 70.87	Newport, RI	1.05	2.83	Research and assessment, revegetate dieback	5	No results yet
2020	**Ocean View Farm** 41.52, – 71.00	Newport, RI	1.05	2.83	Research and assessment, revegetate dieback	7	No results yet
2020	**Smith Point** 40.74, – 72.88	Sandy Hook, NJ	1.43	4.15	Mosquito control, revegetate dieback	56	No results yet

pressure excavators or ditchers (Supplemental File 1) to follow topographical low areas, and only drain water within the rooting zone (Hulsman et al. 1989; Wigand et al. 2017). Runnels are similar in principle to tidal creek extension projects that connect an area of inundation to the tidal creek network, though tidal creek extensions are larger in scale than runnels (Raposa et al. 2019; Taylor et al. 2020; Wetland restoration at Farm Creek Marsh 2021). After observing rapid expansion of shallow water within northeastern US marshes, restoration ecologists began working with mosquito control agencies to use runnels for the dual purpose of mosquito abatement and marsh adaptation to SLR. Practitioners used the technique to target shallow water features that were expanding, had formed within the last few decades, and where an anthropogenic topographic feature was impairing water flow (ditch spoils, plugged ditches, embankments) (Wigand et al. 2017; Adamowicz et al. 2020; Perry et al. 2021; Wolfe et al. 2021). True ponds that remained flooded throughout the tide cycle, with unconsolidated sediments in the basin, and that appeared stable in dimension on decadal timescales, were not targeted with this technique (workshop communications). Save the Bay (STB), an environmental non-profit, launched a series of projects using runnels in Rhode Island (RI), USA beginning in 2010. In our 2020 workshop, resource managers reported projects on dozens of marshes across six northeastern US states, and another half dozen northeastern and mid-Atlantic marshes were under consideration for runnel-adaptation by land trusts, NGOs, and government agencies (Supplemental File 1). The majority of projects from the workshop, and one recently published study on runnels (Perry et al. 2021), have reported some vegetation recovery within 1–5 years (Table 2 and Supplemental File 1).

Runnel Case Study: Winnapaug Marsh, RI

An STB restoration project provides a case study on patterns of vegetation recovery. We selected this project because it has the longest monitoring record (8 years) of the STB projects, including pre-treatment data. Habitat restoration using runnels can be summarized by three phases. Phase I: "Drainage" is characterized by a loss of standing surface water. Phase II: "Early colonizers" is characterized by bare sediment which is colonized by *Salicornia* spp. and *Spartina alterniflora*. Phase III: "High-marsh species" is characterized by *Distichlis spicata*, *Spartina patens*, and *Juncus gerardii* succeeding early colonizers.

Winnapaug back barrier salt marsh in RI (41.3306°N, −71.7684°W) is a grid-ditched marsh with significant surface water cover and platform degradation (Fig. 3). Tidal range at the nearest tide station in Newport, RI is 1.05 m; however, tidal amplitudes are restricted in back-barrier environments such as Winnapaug. Ditches were created during the 1930s, and peat spoils were placed along ditch edges, creating linear impoundments. Altered topography in combination with RSLR in RI (5.26 mm yr^{-1} between 1999 and 2015) (Raposa et al. 2017) led to the "waffle-maple-syrup" pattern (Adamowicz et al. 2020) seen in aerial imagery (Fig. 3). As of 2011, large mats of filamentous algae were growing in shallow water areas (Fig. 1e), and mosquito larvae were observed. Initial depths of shallow water areas ranged from a few centimeters up to about 25 cm and were generally less than 15 cm deep.

STB and Town of Westerly, RI, secured funds and permits to create runnels targeting shallow water areas. Environmental and vegetation monitoring was conducted prior to runnel creation in 2011, and post-implementation monitoring was repeated in 2013–2015, 2017, and 2019. Initial hand excavation of a few small runnels began in summer 2012. In May 2013, STB and RI Department of Environmental Management's Mosquito Abatement Program used a low-ground pressure excavator to expand the runnel network, and volunteers hand dug smaller runnels. Clogged mosquito ditches were cleared, and the material was used to fill selected ditches and degraded areas. Hand digging continued in 2013–2014 to facilitate additional drainage. In total, around 33 runnels were created ranging from 2 to 8 m in length. Runnel widths ranged from 10 to 24 cm, and depths ranged from 10 to 18 cm.

Surveys of vegetation and surface water were conducted using quadrat sampling along transects (Roman et al. 2001). Vegetation and ground cover was estimated as percent cover of each transect (Fig. 3). In the text below, transect data was aggregated to present coverages by species or cover type for the entire marsh. Initially (2011), algal mats covered 44%, open water 14%, and bare peat 4.5% of the marsh platform. The marsh was dominated (57% cover) by *Spartina alterniflora*, a species which tolerates frequent inundation (Fig. 3). Less-flood tolerant, "high-marsh" species included *Distichlis spicata* (26%), *Spartina patens* (18%), and *Juncus gerardii* (2.7%).

Ecosystem responses to runnels proceeded as across the marsh (Fig. 4). During Phase I open water decreased to 5% by 2013, and was absent in 2014 across the entire marsh. Algal mats disappeared by 2013. During Phase II,

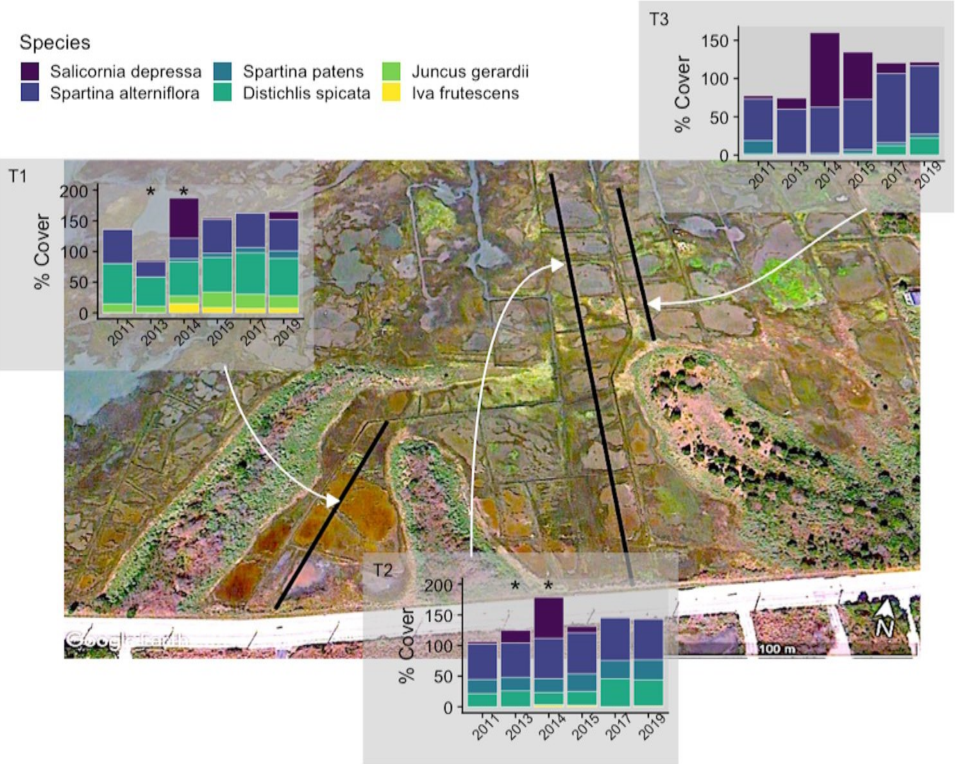

Fig. 3 Vegetation change shown as percent cover for Winnapaug transects (T1, T2, T3 bar plots) with runnelling (*excavation years) displayed over aerial imagery from 2011. Species in legend are ordered from most tolerant of inundation (purple — *Salicornia*) to least tolerant (yellow — *Iva*), and transects shown as black lines. White arrows indicate respective vegetation cover data. T2 and T3 had significantly greater surface water than T1 to begin with, and T1 had greater recolonization of high-marsh species than T2 or T3

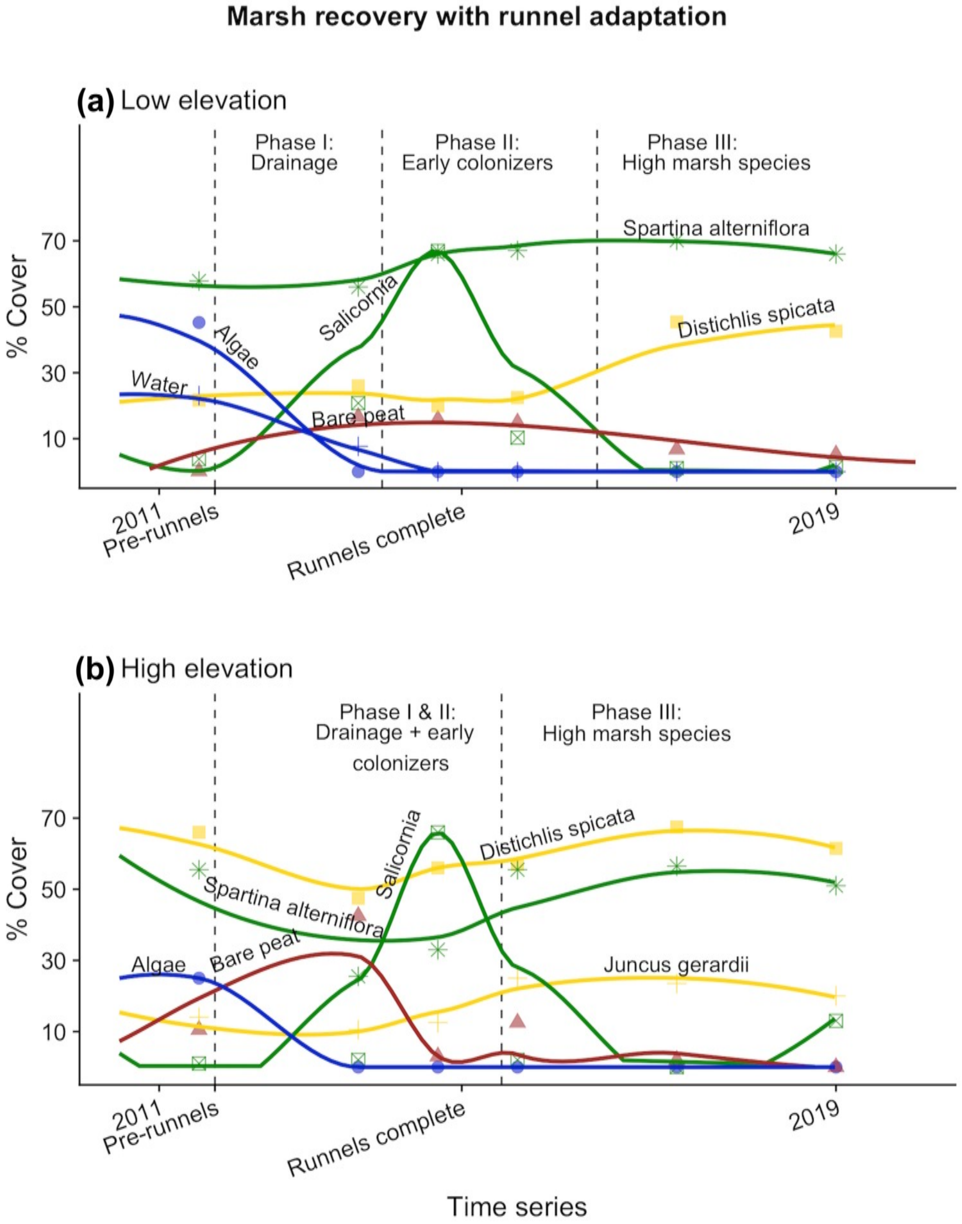

Fig. 4 Recovery of Winnapaug marsh after runnelling shown for **a** low elevation, T2 in Fig. 3, and **b** high elevation, T1 in Fig. 3, areas. Elevation was inferred from water table monitoring. Ground and species percent cover shown relative to runnel construction timeline on *x* axis. First dashed line (2012) indicates when digging began; excavation continued through 2014 ("Runnels complete"). Monitoring dates listed in text. Note that Phases I and II occurred simultaneously, and Phase III occurred sooner along the high-elevation transect

bare peat initially increased as water drained from the site (maximum of 26% by 2013), but then declined (3.2% by 2019) as areas were recolonized. *Salicornia depressa*, a flood-tolerant, early-colonizing species, increased rapidly from 3.3% prior to runnels to 73% in 2 years (2014). *Salicornia* then declined to 4.3% by 2019 as less flood-tolerant, high-marsh species increased. After 3 years (2015), Phase III-high marsh species began to increase. After 7 years (2019), *Distichlis* had increased to 42% cover, *Spartina patens* to 24% cover, and *Juncus* to 3.8%. *Spartina alterniflora* remained the dominant cover, increasing to 65% cover after 3 years, and 68% after 7 years (2019). The increase in vegetation, especially high-marsh species, suggests that runnels have potential for short-term restoration of marsh plants.

While vegetation recovered across the marsh on the whole, responses differed across the marsh. Platform elevations along transect T1 were conducive to high-marsh species growth prior to runnel creation; as a result, draining the shallow water areas allowed bare peat to recolonize with high-marsh species quickly (Fig. 3). In contrast, the shallow water areas at the northern ends of transects T2 and T3 (Fig. 3) showed minimal response to runnels. Water levels decreased, but the features never fully drained and vegetation did not recover. As a result, T2 and T3 vegetation responses differed from T1 (Fig. 3). Based on water table monitoring

(Supplemental File 2), STB believes that basin elevations in some of the northern shallow water areas were too low in elevation for vegetation to recover. Long-term monitoring at this and other runnel project sites is important for assessing which marshes are good candidates for runnels, and how much time we can "buy" using this technique (a few years, decades, or more).

Efficacy of Runnels: Can We Buy Time for Salt Marshes?

Runnels have promise as a climate adaptation technique. Practitioner experiences shared at our 2020 workshop suggest that runnels will be most effective in higher elevation areas, and where peat is less degraded with root mats still intact and still firm within shallow water areas. Since only a few of the resource management projects that have used runnels included experimental designs or extensive data collection, work is still needed to statistically test runnel efficacy (Table 2 and Supplemental File 1). As a result, first-order questions remain on how responses in vegetation and the spatial footprint of a single runnel vary across a range of elevations, degradation levels (extent of elevation loss and peat decomposition within shallow water areas), tidal ranges, and suspended sediment concentrations. Key second-order questions remain as well, including when runnels risk triggering pool collapse, which ecosystem services are improved, if peat oxidation ever occurs, and, most critically, whether runnels can rebuild long-term resilience of salt marshes.

In 2020, our team launched an experiment to test runnels and address a set of these first- and second-order questions. We established 20 study sites (10 treatment, 10 control) at a range of elevations and degradation levels across two marsh complexes (Little Bay Conservation Area and Ocean View Farm; Table 2) using a replicated-BACI design. We are monitoring responses in vegetation, hydrology, soil properties, elevation, and decomposition, as well as a suite of baseline environmental characteristics. With this study, we will measure the rate of vegetation recovery and the spatial footprint of runnels and determine how hydrologic and vegetation responses differ along gradients of elevation and degradation. However, tidal range (~ 1 m) and suspended sediment concentrations (low) are similar at all our sites, so future studies will be needed to assess runnel efficacy along those gradients. Below, we discuss second-order questions on runnels, how our study is helping to answer them, and where future research is needed.

Avoiding Pool Collapse

Pool collapse could result from creating a runnel if the basin of a shallow water area is too low in elevation for revegetation, if RSLR is faster than the accretion rate in the basin, or if too little suspended sediment is available for drained shallow water areas to accrete. While creating a runnel into a basin that is too low in elevation should be avoided, cases may exist where a resource manager does not have access to elevation data, or where the threshold elevation for revegetation is unknown. To avoid undesirable outcomes, practitioners manage water volumes flowing out of and into the shallow water area with sills, and by creating runnels in phases. Sills are shallow runnel segments that function as "speed bumps" to slow water velocity, and trap any unconsolidated material that could erode out of shallow water areas after runnel installation. Sills are created by shallower excavation or leaving unexcavated platform, while retaining positive drainage. Sills between runnel terminus and the connecting creek are important when larger tidal channels or high winds could expose bare soil to erosive energy. Runnel construction has been used as an adaptive management approach (Williams 2011), using phased construction to avoid erosion. After initial construction, managers evaluate drainage, and redistribute any sediment trapped in the runnel across the marsh platform. Removing unconsolidated sediment from the runnel avoids plugs forming, and conserves sediment which is a limited resource in many northeastern US marsh systems. Continued excavation is usually required to fully drain standing water. These approaches are encouraged by practitioners even when risks of pool collapse are not obvious, as they also help to avoid over-draining marshes with too much excavation at once. Long-term monitoring is still needed to determine whether pool collapse can be prevented in microtidal, low-sediment marshes with runnels.

Ecosystem Services

Observations suggest functional improvement of marshes after runnel construction. After 2016 excavated peat has been used to create small "islands" of elevated habitat for nesting saltmarsh sparrows (*Ammospiza caudacuta*; Fig. 1b), and other birds. Formerly these spoils were required under federal permits to be disposed in upland areas. Authors have observed sparrows nesting in areas drained by runnels shortly after creation. Small killifish (*Fundulus heteroclitus*) use runnels to access new foraging habitat, sometimes within hours of excavation. Invasive *Phragmites australis*, which outcompetes resident vegetation (but has a low salt tolerance), can be reduced in height and density by draining freshwater with runnels. Surveys of vegetation and wildlife before and after runnel creation are needed to understand the extent and longevity of habitat improvements. Research on other ecosystem services potentially affected by runnels including nutrient cycling and organic matter storage is still needed.

Risk of Peat Oxidation

Over-draining marshes (e.g., with deep ditches) can lead to peat oxidation and platform subsidence (Burdick et al. 2020). Elevation losses worsen flooding stress from RSLR, and contribute to open-water conversion (Ganju et al. 2020). Runnels are designed to emulate naturally formed channels and avoid over-draining soils by only lowering water in the root zone. Water measurements from Winnapaug runnel sites show that the water table remained within a few centimeters of the soil surface (Supplemental File 2), suggesting minimal risk of over-draining from the shallow runnels used at this site. Further, one study found no increase in CO_2 emissions after installing runnels, suggesting that peat oxidation rates did not change (Perry et al. 2021). Over-draining soils could limit recovery of target vegetation species as well. A review of tidally restored marshes in Connecticut, USA found improved vegetation recovery when mean water tables were 24 cm below the marsh surface over cases with deeper water tables (29 cm below) (Warren et al. 2002). With a maximum runnel depth of 30 cm used in runnel projects (20 cm in some cases), we suggest that there is generally little risk of peat oxidation or creating inhospitable conditions for target vegetation species with runnels. Further research investigating how runnels impact soil saturation, decomposition, and resultant elevation is needed. In our current experimental work, we are measuring decomposition rates and monitoring hydroperiod, water table, elevation, and redox of marshes before and after runnel creation to address some of these questions.

Runnels and Long-Term Resilience of Marshes

Short-term responses to runnel construction are encouraging, but long-term ecosystem responses are uncertain. Runnels are proposed to imitate pool recovery in marshes where it may not otherwise occur by draining standing water and facilitating revegetation. They “buy time” for marshes to naturally adapt to SLR by vertical accretion or upland migration, or for additional intervention by managers to occur. However, empirical knowledge of critical thresholds past which marshes cannot recover from an open water conversion trajectory is sparse. As pool recovery occurs with large tidal ranges and high sediment loads, it remains unclear if runnels will be effective without these characteristics over the long term. The volume of tidal water flowing through a runnel and whether water drains fully from a shallow water area are critical variables that will define effectiveness — whether an area revegetates or deepens to a become a permanent pool (Mariotti 2016; Schepers et al. 2020). Evident in this discussion is the need for a clear understanding of runnels from both theoretical and mechanistic perspectives.

Conditions that reduce marsh resilience to RSLR, specifically, low tidal range, low sediment supply, and low elevation capital, are not changed by runnel creation. Microtidal marshes are particularly vulnerable, where low tidal range corresponds with low sedimentation rates and reduced elevation capital as compared to mesotidal and macrotidal systems (Kearney and Turner 2016). These marshes are still vulnerable to drowning without an external sediment source (Kearney and Turner 2016; Ganju et al. 2020), or compensatory upland space to migrate (FitzGerald and Hughes 2019). Thus, runnels are unlikely to improve long-term marsh resilience to RSLR without additional adaptation strategies, e.g., marsh migration facilitation and sediment placement (La Peyre et al. 2009; FitzGerald and Hughes 2019). Facilitating marsh migration has been attempted by conserving marsh-adjacent habitats and removing human-made barriers. Other techniques include digging runnels into bordering freshwater wetlands, and “terracing” techniques have been proposed (Salt marsh bird conservation plan for the Atlantic Coast 2019). Sediment placement can compensate for low sediment supply by increasing elevation capital (La Peyre et al. 2009; Salt marsh bird conservation plan for the Atlantic Coast 2019). While additional adaptive action is likely required for marshes to persist, neither sediment placement nor marsh migration will be successful if marsh hydrology is severely compromised. Sediment additions into shallow water areas without facilitating drainage are unlikely to revegetate because waterlogged soil conditions will not support plant growth. Marsh migration into adjacent habitats occurs within a narrow range of elevation. If marsh just below this is stressed by flooding or has converted to open water, then migration is restricted. Runnels will not save salt marshes alone, but by helping salt marsh vegetation recover they complement other approaches.

Conclusions: Runnels and Resilience

The rate of marsh loss during the past few decades has raised alarm among managers, landowners, and communities who began urgently seeking solutions. In response to interior drowning of northeastern US marshes, ecosystem managers are using runnels to drain water and restore vegetation. Runnel projects proceeded without systematic examination of the conditions in which runnels are most effective or appropriate. Practitioners, regulators, and scientists alike have called for an evaluation of runnel projects to better inform management and funding decisions. Our workshop connected stakeholders and scientists to stimulate knowledge sharing on the runnel technique. In this paper, we synthesized those discussions to document current consensus on runnel practice and known efficacy. While initial projects have shown runnels can facilitate revegetation of degraded marshes under some conditions, interactions with elevation and tide range are just a few of the factors needing assessment to include runnels in holistic adaptive planning to restore marsh habitat, and improve salt marsh resilience.

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Early Responses to Runnels in Southern New England Salt Marshes

A technical report on results from a collaborative experiment testing the efficacy of runnels, an emerging climate adaptation tool, in Buzzards Bay.

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Contributions: Besterman led project design and coordination, sample collection, analyses and report writing. Jakuba and Deegan contributed to project design and conception, field sampling, and data analysis. Ferguson and Brennan contributed to site selection, runnel design and implementation, adaptive management and other guidance. Sullivan led the sample collection, processing, and analysis for data on soil water content, porewater salinity, redox potential, and decomposition. Costa provided training, equipment, and analytical support on elevation surveys. Neil Ganju and Noa Randall (USGS) provided and analyzed turbidity data. Anastasia Pulak (Woodwell Climate Research Center) provided significant field and lab support for multiple analyses.

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Summary

- This project tested runnels, an emerging climate adaptation technique used to restore tidal hydrology and revegetate marshes experiencing interior open-water conversion.

- Runnels were tested at two salt marshes in Buzzards Bay. The study includes 10 sites with experimental runnels and 10 reference sites, split between both marshes. Sites were monitored before (2020) and after (2021) runnels were installed. This report presents data from before and after runnel creation, collected at 12 of the 20 sites where we completed intensive sampling (6 sites each marsh).

- Little Bay in Town of Fairhaven is a fringing marsh exposed to an open embayment. Ocean View Farm in Town of Dartmouth is a sheltered marsh within a back-barrier salt pond, separated from Buzzards Bay by barrier spit and connected by a narrow tidal inlet. Marshes and sites within marshes differed in platform elevations, level of peat degradation, depth shallow water in areas of vegetation dieback, landscape position (proximity to upland and/or creek), and degree of vegetation loss. Tidal range differed between the two marshes as well.

- Early responses showed evidence of a runnel-effect at both marshes. At Little Bay, visual evidence of vegetation change from photographs illustrated revegetation occurring. At Ocean View Farm, water table heights decreased significantly, from chronically above the soil surface to below the soil surface.

- Responses differed between marshes. At Little Bay, water table heights and soil properties related to soil moisture indicated conditions were either the same, or wetter in 2021 (after runnels) than in 2020 (before runnels). This is likely due to less severe initial conditions at Little Bay (shallower water features, higher platform elevation), in combination with precipitation differences. In addition, large differences in precipitation between the years probably masked some runnel effects (2020 dry, 2021 very wet).

- At Ocean View Farm some revegetation was beginning to occur at runnel-sites (based on visual inspection of photographs), but changes appear lower in magnitude than at Little Bay. This is probably because conditions were more degraded at Ocean View Farm than Little Bay initially, as described above (lower platform elevation and deeper water features, as well as greater vegetation dieback and bare ground cover).

- We did not observe evidence that runnels would over-drain marshes, lead to altered decomposition patterns, or platform subsidence.

- We did not observe evidence that runnel installation altered hydroperiods, or decreased sediment deposition on marshes.

- Additional years of sampling will be needed to quantitatively assess vegetation changes, and understand how hydrology, soil processes, sediment dynamics, and geomorphology will change with runnels.

1. Introduction

1.1. Background

Salt marshes are productive coastal wetlands that provide important ecosystem services such as nutrient removal, carbon sequestration, and storm protection for coastal properties. Direct (dredging, draining, filling, tidal flow restriction) (Gedan et al. 2009, Burdick et al. 2020) and indirect (sea level rise) (Kearney and Turner 2016, Mariotti 2016, FitzGerald and Hughes 2019) human activities have contributed to salt marsh loss. A prominent form of salt marsh loss is interior conversion to open water, which occurs when water becomes impounded on the surface of a marsh, stresses vegetation, and leads to plant death. Communities and resource managers are urgently in need of tools to address this problem of expanding shallow water in marshes. Over the past ten years, creating "runnels" has emerged as a tool in New England salt marshes to address marsh loss to interior shallow water (Besterman et al. 2022).

Runnels are shallow channels that were originally developed in Australia to control mosquitoes by draining standing water (Hulsman et al. 1989). Studies have demonstrated runnels are an effective mosquito-management technique with low-environmental impacts in Australia (Knight et al. 2021, and references therein). However, less data is available on runnels as a conservation strategy. In the context of marsh conservation, runnels work by draining shallow water from the marsh surface and restoring tidal hydrology, allowing revegetation to occur (Wigand et al. 2017, Babson et al. 2020, Perry et al. 2021, Besterman et al. 2022). When used in coordination with other management strategies, they may help marshes adapt to rising sea level over longer time horizons (Wigand et al. 2017, Besterman et al. 2022).

Runnels appear to be a promising conservation strategy based on several projects conducted over the past 10 years in the northeast U.S. (Perry et al. 2021, Besterman et al. 2022), especially when used for restoring vegetation and decreasing surface water depths. However, few projects have experimental designs that included monitoring before and after implementation, and of treatment as well as reference sites (a Before-After-Control-Impact, or BACI design). Projects have not typically included experimental replicates, or testing along environmental gradients. Further, ecosystem-scale responses to runnels including soil dynamics, sediment transport, elevation change, and hydrodynamics have only been measured in a few projects (e.g., Perry et al. 2021). Data from most of these projects is not yet available publicly or through publications. As a result, knowledge of runnel efficacy across a range of environmental conditions and marsh types is generally qualitative, and difficult to generalize beyond practitioner experience. With growing interest in using runnels from natural resource managers, quantitative data are needed to support both regulatory approval processes and effective application of the technique.

1.2. Objectives and Approach

Our team initiated an experiment in 2020 to test runnels using best practices identified from team-member experience. Our objectives were 1) to experimentally test the efficacy of runnels using a replicated BACI-design, 2) to test runnel efficacy across a range of characteristics (platform elevation, depth of shallow water area, level of peat degradation, tidal range, wind exposure), and 3) test ecosystem-scale processes in response to runnels that provide insight into how marshes will respond long-term. In this report we present our study design and methods, background site characteristics, and some early responses to runnels (one-year post-implementation). While we are measuring a large suite of variables in this project, we have limited this report to those variables which are likely to have responded within a single year. For a few variables, we tested to see if any change had occurred in one year, and after determining there were no differences, proceeded to present background-only data. These variables are specified below.

2. Methods

2.1. Site Selection

We selected two marsh complexes within Buzzards Bay, Massachusetts. We initially identified marshes where we observed shallow water and bare areas in aerial imagery, and then conducted site visits, field assessments, and meetings with local partners and municipalities. We assessed the characteristics in Table 1 and selected marshes that met the "good candidate" criteria in as many categories as possible. These characteristics were identified as important to runnel project success by experienced project partners, as well as through a workshop on runnels held in 2020 (Besterman et al. 2022). There are other factors groups could consider during site selection (Besterman et al. 2022), but these were the priorities for our project team based on our goals and available resources, and the environment of Buzzards Bay.

Little Bay Marsh in Town of Fairhaven and Ocean View Farm in Town of Dartmouth were selected as study marshes (Figure 1). These two marshes are both protected lands with protected upland space to migrate, have supportive landowners with whom we partnered, and are located in towns where we had municipal, public, partner, and county mosquito control support to initiate and maintain the project. These marshes have both been historically ditched, and have many shallow water areas present that appear to have formed recently.

Little Bay (LB) is a fringing marsh exposed to an open embayment, with high exposure to wind-waves and a tidal range of 1.15 m. Adjacent upland at LB is covered by low-lying forest, including red maple swamp habitat, and we have observed fresh surface water inputs where the high marsh borders the upland. Ocean View Farm (OVF) is a sheltered marsh with adjacent uplands covered by hay fields. OVF sits within a back-barrier salt pond and is connected to Buzzards Bay through a narrow tidal inlet. The tidal range estimated from a tide station outside of the salt pond is smaller than at LB (0.96 m), and the tidal inlet further restricts the tides within the pond. Approximately every five years the inlet migrates, narrows, and closes. Prior to a full closure, the tidal range becomes further restricted, with tidal connectivity eventually cut off completely. A local non-profit and homeowner's group manage the re-opening by dredging a new inlet within weeks of a full closure. A full closure occurred between December 2020 and January 2021, and the inlet was reopened in February 2021. Based on partial tidal data obtained from a water level data logger in the pond (Onset HOBO U20L-04), it appears the tidal range in 2020 was around 0.35 m in the pond. After dredging, the tidal range increased appreciably, but tidal elevations were still slightly dampened relative to tide station data, so the tidal range at OVF was still less than then 0.96 m estimated from outside the pond.

In addition to the tidal range and landscape differences between LB and OVF, these marshes also differ in platform elevation and degree of degradation within shallow water areas. Both marshes exhibited a within-marsh gradient of elevation and condition. Within each marsh we selected sites (shallow water areas) for our study that spanned a range of horizontal size, platform elevation, depth, vegetation cover, and peat degradation. These characteristics ranged from meeting "good candidate" characteristics, to nearly "poor candidate" characteristics (Table 1). We did not select sites that would qualify as poor candidates across all environmental categories, as we wanted to test sites that resource managers could realistically expect a response from runnel adaptation.

Table 1. Marsh characteristics used to select study sites. Based on authors' experience using runnels over the past ten years, and knowledge synthesized from a 2020 workshop on runnels. Marsh characteristics are divided into Environmental Characteristics and Logistics and Community Considerations (practical factors affecting the implementation and sustainability of a runnel project). Characteristics were sorted into "good" and "poor" categories. Many sites exhibited features in-between these end-points.

Marsh Characteristic	Good Candidate	Poor Candidate
Environmental Characteristics		
Shallow water areas	• Features present • Bed of shallow water area is firm, with intact peat • Evidence of recent formation • Evidence of horizontal spread/expansion	• Features not present • Bed of shallow water area is soft and covered with layer (>10 cm) of unconsolidated material • Evidence of older formation (40+ years) • Stable border, no signs of horizontal spread/expansion
Microtopography and water flow	• Embankments, levees, ditch spoils, and/or clogged ditches that create barriers to flow	• No evidence of topographic barriers to flow • Barriers that cannot be fixed with a runnel (e.g., undersized culvert)
Elevation	• Platform around shallow water feature is at or above mean high water • Bed of shallow water area sits 20 cm or less below the platform	• Platform around shallow water feature is close to mean sea level • Bed of shallow water area sits greater than 20 cm below the platform
Adaptation potential	• Adjacent upland has a low topographic slope, no hardened barriers to migration • Marsh complex is large with significant amount of marsh area found at or above mean high water	• Topographic slope or hardened barrier prevent migration • Marsh complex is small, fringing, narrow, and/or mostly sits below mean high water
Logistics and Community Considerations		
Public and municipal interest	• Public health issues due to standing water (mosquito breeding) • Expansion of invasive *Phragmites australis*	• Unsupportive municipality and community

	associated with shallow water areas • Municipality concerned about marsh loss; supportive of restoration/adaptation activities • Marsh provides coastal defense to local community/property	
Landowner interest	• Landowner concern about marsh loss; supportive of restoration/adaptation	• Unsupportive landowner
Adaptation potential	• Marsh and adjacent upland protected from development	• Existing and extensive infrastructure directly adjacent to marsh (e.g., dense housing)
Stewardship potential	• Established partnerships with volunteer-community, municipality, mosquito control agency, landowners • Interest among partners to maintain runnels	• No local partners
Access	• Marsh is easy to access by road and foot • Accessible to partners • Machinery (if needed) for runnel creation or monitoring can access marsh	• Only accessible by boat • Highly restrictive access (difficulty gaining permission for future monitoring/maintenance) • No access for machinery (if machinery needed)

2.2. Experimental Design

We used a replicated-BACI (Before-After-Control-Impact) design to test the effect of runnels on salt marsh hydrology, vegetation, sediment and soil dynamics, and other ecosystem processes. We selected 10 distinct areas of shallow, standing water at both LB and OVF as study sites (20 sites total). As described above, the degree of vegetation loss, elevation loss, and peat degradation within each of these shallow water areas varied. Of the 20 sites, twelve were intensively monitored with greater replication and more variables monitored. This report presents methods and data from the intensive sites only.

Sites within each marsh complex were hydrologically independent, separated by a microtopographic barrier such as a levee, ditch, or creek. At each site we identified an approximate mid-point within the shallow water area (centroid), and then established a monitoring transect that bisected the shallow water area and extended from the high marsh toward the low marsh. Three zones were established for sampling: Zone 1 (0–5m upland and seaward of the centroid), Zone 2 (5–15m upland and seaward of the centroid), and Zone 3 (15–30m upland and seaward of the centroid). We established 1-m^2 monitoring plots along the transect, assigning five plots to Zone 1, four plots to Zone 2, and four plots to Zone 3. In some cases, shallow water areas were located too close to the upland or seaward edge of the platform to fit all of the Zone 2 or Zone 3 plots; fewer monitoring plots were used on those transects. One side of each transect was designated for walking and disturbance (e.g., collection of soil cores), and the other was dedicated to vegetation monitoring and left undisturbed. Monitoring took place in the summer and fall of 2020 before runnels were created at all sites, and during the winter, spring and summer of 2021 after runnels were created. Monitoring frequency differed across variables; details on each variable monitored are presented below.

2.3. Background Variables

2.3.3. Turbidity

Sediment suspended in the water column floods marshes with each high tide, deposits onto the marsh platform and contributes marsh vertical accretion. Degraded marshes undergoing erosion may lose sediment, contributing to suspended sediment concentrations in adjacent waters. Water turbidity provides a measurement of suspended sediment concentration, and can be measured using sensors to understand the marsh sediment balance, i.e., whether a marsh is gaining or losing sediment (Nowacki and Ganju 2019). We deployed water quality sondes (YSI

EXO2) to measure turbidity at LB and OVF. One sonde was deployed on the bed of the open embayment adjacent to each marsh. Sondes were mounted on platforms 15 cm off the bed, and protected with anti-fouling copper tape and wiper blades. We deployed these instruments for four weeks in August 2021 to measure available sediment to Buzzards Bay marshes, and determine the average sediment balance at each marsh.

Sondes measured turbidity in Nephelometric Turbidity Units, or NTUs. Sondes were calibrated using NTU standards prior to deployment in accordance with USGS protocols. We calculated standard summary statistics and percentiles for turbidity throughout the deployment. We also calculated the difference between turbidity during flood and ebb tide, which has been shown to correlate well with whether a marsh is losing or gaining sediment on average. Finally, we examined how patterns of turbidity corresponded with wind events at LB and OVF to assess how sensitive the sediment dynamics at these marshes are to wind. Wind speeds were gathered from a NOAA Buoy at the mouth of Buzzards Bay, buoy number BUZM3.

2.3.1. Elevation

At each site, elevations were measured along transects against benchmarks using a digital laser level (Leica Sprinter 250m) and barcode staff. Along each transect the barcode staff was placed on the vegetation-side of the transect. Measurements were collected at every monitoring plot, as well as every 2 m along the transect and at any visible microtopographic transitions (e.g., depressions or hummocks on marsh platform). The benchmarks were NGS rod style benchmarks installed for this study in 2019 and 2020. The elevations of benchmarks were documented using a GPS system (Juniper Systems Geode) and software (EZSurv) using post-processed kinematic (PPK) survey technology. Vertical elevations were corrected to the North American Vertical

Datum of 1988 (NAVD88). At least two elevation observations were made for each benchmark, and observations were generally repeatable to 3 cm.

Elevation surveys were undertaken during the growing season in 2020 and 2021. Reference transects at LB were established and surveyed prior to initiating this experiment (2019), providing an additional time point of elevation measurements. A few transects were surveyed twice in a season to confirm measurements. After inspecting the data, we determined variation between surveys was within the expected error range of the method, so all data were included in analyses. We did not expect to see a difference in marsh platform elevations from runnels after one year, and visually inspected the data to confirm this expectation. Measurements were within the expected error range, thus we averaged across all surveys to estimate elevations.

Elevation measurements were used to calculate two metrics: platform elevation and depth of shallow water areas. Measurements were collected at slightly different horizontal positions between surveys, although some positions were consistent (e.g., established monitoring plots). To process the data, we first averaged measurements collected at the same horizontal locations across surveys. To create a smoothed profile across measurements collected at different horizontal positions in different surveys, we calculated a rolling average across three or four values for each transect (determined for each transect separately to avoid over-smoothing or over-interpreting unique elevations). We restricted the rolling-average analysis to elevations measured within Zone 1 and Zone 2, as those were most relevant for the geomorphology of the shallow water area.

The platform elevation was interpreted as the median value (Watson et al. 2017) of the smoothed profile. To determine the depth of the shallow water area we needed to compare the elevations within the shallow water area to the surrounding platform, while accounting for a negative slope between the upland and seaward end of the transect. The negative slope was removed from the data by detrending the smoothed profile. The minimum detrended elevation within the shallow water area was compared with the detrended platform elevation (median) to estimate the depth of the shallow water area. This approach provided a reproducible method that avoided over-interpreting any individual elevation measurement (e.g., small holes or hummocks can bias estimates).

2.3.4. Soil Shear Strength

Soil shear strength, or the amount of shear stress a soil can withstand without moving, provides information on the stability of a soil. In these marshes, greater shear strength corresponds with higher root density, more intact and drier peat, while lower shear strength measurements would be found in more saturated, less consolidated soils with lower root density. Shear strength may also increase if platform subsidence occurs within areas of dieback, vegetative and elevation context is important to interpreting shear strength measurements. We used a field inspection vane (Humboldt Field Vane Shear Set) to measure soil shear strength in shallow water areas. Measurements were collected in a well-vegetated high marsh area along each monitoring transect for comparison, as well as in the shallow water area. In the shallow water area shear strength was measured on the walking-side of the transect (but away from walking paths) in a location corresponding with the centroid, and the nearest upland and seaward monitoring plots. While measurements were not taken in monitoring plots, we selected ground patches with similar cover to each plot (similar water depth, cover of vegetation and bare peat). In each of the four monitoring locations, three replicate vertical profiles were tested within a 1-m^2 area. In the high marsh, measurements were taken at 10 cm depth. In the shallow water areas measurements were taken at 5-cm, 15-cm, and 30-cm depths. In total, nine measurements were made at each depth at each site within the shallow water area, and three measurements in the high marsh (fewer in a couple cases due to rocks). These measurements were averaged for analysis. Shear strength was measured in 2020 before runnels were created, and again in 2021 after runnels were created. As no differences between the before and after periods were detected, we present only pre-runnel data from 2020 as background information about the sites.

2.3.2. Sediment Grain Size

Sediment grain size distributions were used in this report to interpret exposure of shallow water areas to flooding tides, and vulnerability to erosion. Across the marsh platform coarser sediments are deposited closer to the platform-water interface, while little coarse material is transported to the interior of the marsh. Thus, we would expect to see coarser sediments near to creeks and the marsh bank. Surface sediments (depth of 2-cm) were collected within the shallow water area to quantify the distribution of sediment grain sizes in 2020 before runnels were created. We calculated the percent of fine sediments (grains < 0.05 mm) in the shallow water areas as an indicator for water and sediment dynamics, and vulnerability to erosion. Sediment samples were processed to remove organic material. Samples were then processed using laser diffraction to estimate the distribution of sizes.

2.4. Response Variables

2.4.1. Water Level

Water levels were monitored using Onset HOBO Water Level Loggers (U20L-04) deployed in PVC wells at each site. Wells were installed on the “walking side” of each transect, at least a meter away from the transect line but within the deepest part of the shallow water area. Perforated PVC pipes were inserted into the marsh platform and loggers were suspended by nylon-coated steel wire from a locking well cap. In 2020, 0.40-m pipes were inserted to a depth of approximately 0.30 m in the marsh. We modified the design in summer 2021 to use 1.20-m pipes installed to approximately 1.0 m-depth. The deeper wells improved vertical stability. In both designs loggers were deployed so that the tip of the logger rested at the base of the well (~0.30 m and ~1.0 m below the soil surface in 2020 and 2021, respectively). All water level measurements were adjusted relative to the soil height at each well to account for small differences in deployment depth, so that a depth of 0.0 m is equal to the soil height.

Loggers recorded pressure every 15-minutes, which was converted into a water depth using a standard conversion procedure. Loggers were deployed from July – October 2020, January or February 2021 – June 4, 2021, and June 8, 2021 – August 2021. At a few sites a deployment was missed due to equipment malfunctions. Across the twelve sites and three deployments we collected 289,000 water level measurements. To understand fluctuations of the water table over time we calculated the daily minimum water level, and used that as a proxy for the water table height.

To analyze changes in water level over time we statistically tested the effect of the runnels using a three-way interaction linear model including: treatment (runnel or reference), time (before or after runnels), and marsh (LB or OVF). This model tested if a change in water level between before and after runnels were created varied between reference and runnel-treatment sites, while also allowing LB and OVF to follow different patterns.

2.4.2 Hydroperiod

Hydroperiod is a measure of the length of time a wetland is inundated with water. For this study, we were interested in the tidal hydroperiod specifically (i.e., discounting the impounded, permanent inundation at some sites). Tidal hydroperiod can influence the amount of marine-sourced sediment deposited on the marsh, with longer hydroperiods providing greater potential for sediment deposition. Most of the shallow water sites we studied were inundated with water either permanently or intermittently and did not drain as the tide receded. We needed a method to differentiate the tidal flooding from the longer-term inundation to understand tidal hydroperiod. To accomplish this, we used a software package developed in the R programming language for detecting high and low tides in water level time series, and human interpretation to adjust parameters and ensure we were not capturing spurious water level fluctuations. After identifying high and low tide moments in the time series, we calculated the length of time between each high and subsequent low, then multiplied that value by two to estimate the hydroperiod for each flooding tide. Because differentiating tidal flooding from background water levels required a detailed and iterative process, we focused on a subset of sites to determine whether hydroperiod changed with runnelling. We selected one reference and one runnel site at both LB and OVF. We tested a model comparing hydroperiod length from before and after runnels were installed, from both reference and runnel sites.

2.4.3. Water Table Dynamics

The water table is impacted by factors other than runnelling, and these variables may modify the efficacy of the runnel. These factors include precipitation, the tidal phase (spring vs. neap tide), location on the platform relative to the upland and creek, and depth of the depression within the shallow water area. For this analysis we focused on daily precipitation measured at local weather stations, and the tidal phase. Tidal phase was interpreted by calculating the maximum daily water level at each site, presumed to be the height of the highest tide occurring each day. We compared precipitation and tidal phase in 2021 with water table heights across sites and treatment groups at both OVF and LB. We compared the relative effects of tidal phase and precipitation on water table heights between sites, and treatment groups.

2.4.4. Visual Ecosystem Changes

At each site we installed photo posts to collect standardized, long-term photographs of sites over time. Photographs were taken before runnels were created, and after runnels were created at multiple time points. In this report we present photos taken during the autumn between late-September and early-November in both years. Photos were always taken at the same angle using the camera in a mobile "smart" phone. As one year is insufficient to quantitatively analyze changes in vegetative cover and community composition, these photographs provide an early indicator of how the sites overall responded to runnels.

2.4.5. Sediment Deposition

Sediment deposition on the marsh platform occurs with incoming tides, and helps marshes to vertically accrete. We measured sediment deposition within shallow water areas to understand the importance of suspended sediment in Buzzards Bay marshes in general, and whether runnels affected the magnitude of sediment deposition in shallow water areas. Deposition was measured using sediment traps constructed with acrylic plates (~100-cm^2) and glass microfiber filters (9-cm diameter). We fixed filters to plates using UV-resistant rubber bands. Plates were then secured to the soil surface using aluminum gutter spikes (20.34 cm length). These sediment traps were deployed on the vegetation-side of the transect, at least 1-m away from our vegetation plots. This location was chosen to avoid any disturbance from walking or sampling. A trap was placed at distances corresponding with each vegetation plot in Zone 1 (n = 5), in an area with similar ground cover to the vegetation plot.

Traps were deployed for ~2 weeks in 2020. However, some filters were lost or damaged when deployed for this long. Filters with significant damage were not included in analyses. Traps were deployed for 2-3 days in 2021 during spring tide cycles to ensure tides would reach the traps, but limit exposure to water and waves to reduce damage. This revised method was a significant improvement, and only a couple of traps were excluded due to damage or erroneous measurements. Traps at OVF suffered more damage, and we also faced some logistical issues with deployments. As a result, our sample size was insufficient for statistical comparisons at OVF, and we proceeded with analyses at LB only. One reference site at LB was also problematic because sediments within the dieback were mineral and loosely packed due to intensive crab burrowing (LBSB, Table 2). A massive quantity of sediment washed onto traps at this site from the surrounding soil, and we had no good way to differentiate this sediment from the surrounding sediments. Thus, we excluded this site from analysis. In total we analyzed data from two deployments in 2020 for 5 sites ($n_{site} = 3 – 10$, fewer than 10 due to losses and trap damage), and two deployments in 2021 for 5 sites ($n_{site} = 10$), yielding a total of 88 observations at LB.

After traps were collected in the field, they were stored frozen until analysis. Traps were dried at 60° C until constant weight, then dry weights were compared with initial filter weights to calculate total accumulated sediment. Filters were then ashed in a muffle furnace for 4 hours at 450° C to calculate the quantity of inorganic sediment accumulated on the trap. Inorganic sediment is a more useful measure of sediment deposition because organic deposits typically decompose rapidly, and do not contribute as significantly to vertical accretion. Since the deployment length changed between years, we normalized accumulated sediment mass to the number of tides that flooded shallow water areas by at least 10 cm. Tides were identified and counted using the same approach as the hydroperiod analysis. We tested for an effect of runnels using a linear model with an interaction effect between time period (before and after runnels) and treatment (runnel and reference sites), while accounting for between-site differences.

2.4.6. Soil Moisture Content and Porewater Salinity

Soil moisture refers to the quantity of water contained within a soil matrix. Too much soil water can stress and kill plants, while too little can lead to decomposition of the organic matter in soils, resulting in elevation loss. We measured soil water content to understand the effect of runnels on soil moisture. Porewater salinity can vary in salt marshes depending on the salinity of flooding waters, distance from creeks, inundation frequency, and effects of upland freshwater from both surface runoff and groundwater sources. We measured soil moisture content and porewater salinity using a modified 60-mL syringe to collect soil cores to a depth of 5 cm. Duplicate cores were collected at 6 – 7 locations distributed along the walking-side of the sampling transect in May and October 2020, and in May, August and October in 2021. Duplicate cores were combined in a single centrifuge tube, and frozen until analysis.

To measure porewater salinity, tubes were thawed, centrifuged, and supernatant was extracted from the soil core. Salinity was measured on the supernatant of each core using a laboratory probe. To measure soil moisture content, a 5-g subsample was taken from each soil core, weighed, dried for 24 hours at 60° C, then reweighed. The difference between the wet weight and dry weight was interpreted as the mass of water in the soil. For analyses, core-locations were categorized into three groups: Up (Zone 2 and 3, landward of the shallow water area), Center (Zone 1), and Down (Zone 2 and 3, seaward of the shallow water area). These three groups each contained 2–3 sampling locations.

2.4.7. Redox Potential

The redox potential of a soil is an electrochemical indicator for how easily organic matter can be decomposed. Values are measured in millivolts (mV); positive and higher values indicate a greater potential for organic matter decomposition, while negative and lower values indicate lower potential for decomposition. Soils of wetlands become saturated, which lowers oxygen and other electron acceptor availability in the soil (gases diffuse more slowly into liquid than air). Reduced electron acceptor availability lowers the redox potential, and the rate of decomposition. For this study, we were interested in redox potential as indicator for how microbial decomposition might change in response to runnels. We measured redox potential using a probe (Extech RE300 ExStik ORP Meter) inserted 5 cm into the soil. Measurements were collected adjacent to the 6 – 7 locations where cores were collected (above), once per month between May and October in both 2020 and 2021. Measurements were grouped into the Up, Center, and Down categories as described above.

2.4.8. Decomposition

Decomposition of organic material in soils is an ecosystem process affected by the quantity of organic matter and the redox potential of a soil. We were interested in comparing decomposition rates from before and after runnels were created to determine whether draining surface water would alter decomposition rates (specifically, if rates would increase). We measured decomposition with an established protocol using green and herbal (red) tea bags. This "tea-bag experiment" involves drying and weighing bags, burying them for 80 days, then collecting, drying, and reweighing. The difference in mass lost between the green and red tea bags is used to calculate a decomposition constant (K). Higher K-values indicate faster decomposition, while lower K-values indicate slower decomposition rates. We buried bags at three locations corresponding with the Up, Center, and Down zones along the walking-side of the transect at a depth of 5 cm. In 2020, 5 green and 5 red tea bags were buried in each location.

In 2021, 10 green and 10 red tea bags were buried in each location. Bags were buried during the growing season in both years.

3. Results and Discussion

3.1. Soil Structure and Geomorphology

Platform elevations varied within and between marshes. OVF sites were lower in elevation (0.272 – 0.472 m NAVD88) than LB (0.543 – 0.833 m NAVD88) (Table 2). Similarly, depression-depths within shallow water areas varied within marshes (Table 2, Fig. 2), with OVF sites ranging between 0.056 m and 0.181 m, and LB sites ranging between 0.011 m and 0.148 m. LBSB differed from other sites in that the unvegetated area did not coincide with a depression in elevation, so we excluded this site from depth calculations. Soil shear strength also varied between and within marshes, indicating a range of peat degradation. Lower soil shear strength within the dieback areas indicates peat has undergone greater decomposition and soil is less consolidated. OVF had generally lower soil shear strength in the surface 5 cm of soil than LB, indicating greater peat degradation (Fig. 3). Across both marshes, sites with deeper depressions generally also exhibited lower soil shear strength throughout the profile (Figs. 2 & 3), indicating these sites were likely more degraded to begin with than sites with shallower depths and greater soil shear strength.

Table 2. Background variables on site soil structure and geomorphology. Sites are organized by treatment and marsh, and averages with standard deviation (SD) presented. Platform elevation as meters above NAVD88, the depth of the depression within the shallow water area as meters below the platform, and percent of fine sediments within surface 2-cm of shallow water areas are displayed.

Site	**Platform Elevation (m NAVD88)**	**Depth of Dieback (m)**	**Percent fines**
Ocean View Farm Reference Sites			
OVFD/Reference 1	0.399 m	0.058 m	71.4%
OVFF/Reference 2	0.382 m	0.067 m	72.2%
OVFG/Reference 3	0.272 m	0.181 m	79.6%
Average (SD)	**0.351 (0.07) m**	**0.102 (0.07) m**	**74.4 (4.5) %**
Ocean View Farm Runnel Sites			
OVFA/Runnel 1	0.472 m	0.056 m	37.9%
OVFE/Runnel 2	0.393 m	0.098 m	95.5%
OVFH/Runnel 3	0.290 m	0.142 m	75.1%
Average (SD)	**0.385 (0.09) m**	**0.099 (0.04) m**	**69.5 (29.2) %**
Little Bay Reference Sites			
LBNA/Reference 4	0.734 m	0.148 m	60.7%
LBSC/Reference 5	0.543 m	0.021 m	60.7%
LBSB/Reference 6	0.833 m	NA	39.7%
Average (SD)	**0.703 (0.15) m**	**0.085 m**	**53.7 (12.1) %**
Little Bay Runnel Sites			
LBND/Runnel 4	0.706 m	0.025 m	39.8%
LBNF/Runnel 5	0.682 m	0.011 m	56.2%
LBSM/Runnel 6	0.644 m	0.071 m	74.2%
Average (SD)	**0.677 (0.03) m**	**0.036 (0.03) m**	**56.7 (17.2)%**

3.2. Visual Changes in Vegetation

Initially OVF had greater bare ground cover than LB within shallow water areas (Figs. 4–26, even numbers). Areas were larger, with less total vegetation and more contiguous loss as opposed to the patchier vegetation-loss at LB. At both LB and OVF, 1-year after photographs show some positive revegetation at runnel sites (Figs. 4 – 8, 16 – 20 even numbers). The amount of change varied across sites, but consistent positive responses were observed. LB generally appears to have greater revegetation at runnels sites than OVF. Reference sites showed little or no change in vegetative cover (Figs. 10 – 14, 22 – 26 even numbers).

3.3. Water Levels

Water table heights and tidal amplitudes experienced at each site differed within and between marshes (Figs. 5–27, odd numbers). As discussed above, tidal ranges are known to differ between LB and OVF due to different geomorphic settings, and between years at OVF due to the tidal inlet dredging. Tidal amplitudes increased in 2021 relative to 2020 across OVF sites as a result of re-opening the inlet; however, differences were still apparent between runnel and reference sites. With deeper shallow water areas and lower platform elevation, we observed higher water table heights at OVF than LB in both years, and longer periods of continuous inundation above the soil surface (Figs. 5–27, odd numbers).

3.3.1. Effects of Tides and Precipitation on Water Levels

To understand how differences in tidal phase and precipitation affected water table heights we tested various linear models. There were no interactions between treatment (runnel vs. reference sites) and either tidal phase or precipitation at marshes. At OVF, both precipitation and tidal phase significantly affected water levels, and effects differed across sites ($p_{model} < 0.0001$, $p_{precipXsite} = 0.02$, $p_{tidalXsite} < 0.0001$). Precipitation had the largest impact at OVFA/Runnel 1, where 10mm of rainfall led to an increase of 0.9mm in the shallow water area (9% increase). This effect was similar in magnitude at OVFD/Reference 1, and OVFE/Runnel 2, and larger than effects at OVFF/Reference 2, OVFG/Reference 3, and OVFH/Reference 3. Tidal phase predictably had a much larger effect on water levels at OVF than precipitation. The effect was largest at OVFA, with a 10mm increase in tidal height leading to a 1.8mm increase in water table heights (18% increase). Patterns were similar as with precipitation, with OVFD and OVFE appearing similar, and OVFF, OVFG, and OVFH showing dampened effects of tidal phase on water levels. Water levels at OVFF, OVFG and OVFH were more consistent through time than

OVFA, OVFD, and OVFE, regardless of tides or precipitation. This suggests water table heights at these three locations are controlled by landscape position, platform elevation, depression depth, and microtopographic features that can block hydrologic flow. Note that we used 2021 data for this analysis, after runnels were created. Since OVFE and OVFF are similar in platform elevation, landscape position, and depression depth, the difference between these two sites likely indicates the runnel successfully breached a microtopographic barrier, allowing flooding to resemble tidal patterns more closely. Meanwhile, water levels at OVFF remain constant, indicating continued impoundment.

At LB we also observed effects of precipitation and tidal phase, but precipitation effects did not differ across sites ($p_{model} < 0.0001$, $p_{precip} = 0.03$, $p_{tidalXsite} < 0.0001$). Across the marsh precipitation had a lesser effect than at OVF, with a 10mm rainfall event corresponding with a 0.6mm rise in water table heights (6% increase). Tidal phase also affected water table heights, with a larger effect of tidal flooding at LB than at OVF on water levels, and differing effects across sites. The largest effect of tidal height was seen at LBSB/Reference 5, where an increase in tidal height of 10mm led to a 3.4mm increase in the water table (34% increase). Tidal effects were mostly similar across sites, except for LBSM/Runnel 6 where tidal effects were dampened to a 1.1mm increase in water table height per 10mm higher tide (11% increase in water level).

3.3.2. Water Table Heights and Soil Water

We use a linear mixed-effects model to test for an effect of runnels on water table heights. We included a three-way interaction between time (before or after runnels installed), treatment (runnel or reference site), and marsh (LB vs. OVF), while accounting for differences between individual sites. We found that runnels significantly reduced water levels at OVF ($p_{treatXtimeXOVF} < 0.0001$) relative to reference sites, but not at LB ($p_{treatXtimeXLB} = 0.68$) (Fig. 28).

There were, however, visible differences in the length and frequency of inundation events at LB runnel sites (Figs. 4–27, LB sites). A few factors may have contributed to the absence of a statistical effect. First, water levels were lower across LB, and especially at reference sites, prior to runnel installation. Thus, any runnel effect on water table heights would have been smaller in magnitude and more difficult to detect. Second, precipitation was much lower in 2020 than in 2021, so a small effect of lowered water table heights from runnels may have been countered by overall wetter conditions. Precipitation may not have mediated an overall runnel effect at OVF because precipitation had little significance on water levels for 3 of the 6 sites.

The hypothesis that precipitation reduced runnel effects on water table heights at LB is supported by soil moisture content and porewater salinity data (Figs. 29 & 30). Though we did not perform statistical tests on these data, soil moisture content appeared higher in 2021 than 2020 across all experimental zones and at all sites (Fig. 29). Porewater salinity also appeared lower across all sites and experimental zones (Fig. 30). Differences in soil moisture and porewater salinity between the two years were present at both OVF and LB, though appeared larger at LB. Thus, it seems likely that higher precipitation at LB increased soil moisture, decreased soil salinity, and masked any effects of the runnel on the water table.

Porewater salinity, independent from precipitation effects, could either increase or decrease with runnelling. Porewater may freshen with runnels if runnels prevent tidal water from becoming impounded on the marsh where it becomes hypersaline over time with evaporation. High marsh areas are particularly vulnerable to forming hypersaline conditions since they are flushed less frequently than more seaward locations. Porewater may become more saline after runnels if high freshwater inputs from upland sources were contributing initially to water impoundment, and runnels restore tidal connections to shallow water areas. At both LB and OVF in 2020, average porewater salinities were slightly higher (around 35–45 ppt) than those of flooding waters (~33 ppt). Porewater salinity decreases occurred everywhere in 2021, though effects were especially pronounced in the 'Up' zone adjacent to upland areas. That effects appeared more pronounced in the Up zone further supports an effect of precipitation and freshwater input on differences in marsh hydrology between 2020 and 2021, and the hypothesis precipitation differences masked a runnel effect, if any occurred. Determining how runnels will ultimately affect porewater salinity and overall marsh hydrology at these marshes will require further years of sampling since the 2020 – 2021 period was strongly affected by precipitation patterns.

3.3.3. Hydroperiod

We analyzed hydroperiods at two reference and two runnel sites at OVF and LB (OVFE/Runnel 2, OVFF/Reference 2, LBNF/Runnel 4 LBNA/Reference 4) to determine whether runnels impacted hydroperiod. The runnel at LBNF did not impact hydroperiod relative to LBNA ($p_{treatXtimeXLB} = 0.9$). OVF did show a decrease in hydroperiod at both OVFE and OVFF, with a greater decrease at the reference (OVFF). The decrease in hydroperiod is most likely driven by the dredging of a new tidal inlet at OVF. The inlet had already narrowed substantially by summer 2020, before closing fully over the winter. Thus, the dredging should have increased the tidal flushing in the summer of 2021 relative to 2020. Given the lack of an effect at LB, and the decrease in hydroperiod at both runnel and reference sites at OVF, we conclude that runnels at the scale constructed for this project do not alter hydroperiods.

3.4. Soil Chemistry and Processes

Redox potential and decomposition (Figs. 32 & 33) followed patterns that would be expected based on the soil moisture data and pattern of increased precipitation. We did not perform statistical tests on these data, but observed an apparent decrease in redox levels between 2020 and 2021 in all three experimental zones at runnel and references sites at both marshes (Fig. 32). Wetter conditions correspond with lower redox potential. Rainfall likely explains the difference between these two years. Similarly, wetter conditions and lower redox potential can result in decreased rates of decomposition, which we observed in 2021 relative to 2020 at all sites (Fig. 33). Long-term measurements over a few years will be needed to determine whether runnels have a net impact on soil chemistry and processes.

3.5. Sediment Dynamics

3.5.1. Turbidity

Turbidity, an indicator for suspended sediment, was generally low at both LB and OVF (Fig. 34). We used a formula developed elsewhere to convert NTUs to suspended sediment concentration for comparisons with other systems (Nowacki and Ganju 2019). While a system-specific conversion is needed, these values provide a first-order approximation of suspended sediment in the system. At LB, sondes measured an average of 6.9 mg L^{-1} of sediment, (SD = 7.9 mg L^{-1}). Values were similar, but slightly lower at OVF, with an average of 6.3 mg L^{-1} (SD = 3.4 mg L^{-1}) measured. These values are near the minimum suspended sediment concentrations (4 mg L^{-1}) measured across 13 different marsh complexes in North America. This follows expectation, as Buzzards Bay is a low sediment system. The implication is very little inorganic sediment is available to subsidize elevation in marshes. During significant wind events, sediments were resuspended at LB and temporarily led to higher turbidity in the water column (Fig. 34). Resuspension events have the potential to transport sediment onto marsh platforms. With OVF protected behind a barrier island and narrow inlet, winds were unable to generate enough wave energy to resuspend sediments, and no spike in suspended sediment was observed (Fig. 34).

The flood-ebb turbidity differential appeared to be near neutral at both OVF and LB. OVF slightly favored sediment import, with a positive differential of 0.4. LB very slightly favored sediment export, which can indicate erosion occurring (-0.1). However, this value is near enough to zero to consider the sediment balance neutral between import and export. For comparison, the highest import observed across marsh sites measured in Nowacki and Ganju was +5, while the largest sediment export differential measured was -17 (Nowacki and Ganju 2019). While very little sediment is available to LB and OVF in general, neither marsh is losing sediment, and wind-driven resuspension can lead to sediment import events at LB.

3.5.2. Sediment Deposition

Across all sites and both years the average sediment deposition was 31.8 mg per tide of 10 cm or more (mg T^{-1} hereafter), with SD of 26.3 mg T^{-1} (excluding LBSB/Reference 5). Due to changes in methodology between 2020 and 2021, a reduced sample size we suggest sediment deposition results be interpreted as tentative until more sampling can be conducted. Statistical tests indicated that inorganic sediment deposition increased within shallow water areas at LB runnel sites relative to reference sites after runnels were installed ($p_{treatXtime} = 0.01$, $F = 6.47$, $df = 83$) (Fig. 35). Increases in sediment deposition were apparent from 2020 to 2021 at both reference and runnel sites (due to either methodological or environmental differences). However, runnel site deposition increased by 31.2 mg T^{-1} from 2020 to 2021, while reference sites increased by 3.5 mg T^{-1} (difference of 27.7 mg T^{-1}).

To ensure these increases were not simply caused by disturbance to soils from runnel creation, and subsequent sediment mobility, we compared the percent organic content of deposited sediments. If the higher deposition was only caused by mobilized surface sediments within the dieback areas, we would expect the percent organic to increase from 2020 to 2021, and the percent organic sediment to resemble the percent organic content of the surrounding soils. First, average organic content of sediment deposited on filters (18% in 2021) was lower than organic content of soil cores collected from sites (> 40% for most samples, data not presented here). Second, the percent organic decreased at runnel sites relative to reference sites between 2020 and 2021 ($p = 0.07$), although high variability suggests this result requires greater scrutiny. Whether or not the relative increase in inorganic material deposited is supported with subsequent sampling, it does not appear that the increased deposition could be driven by eroding or mobilized marsh surface sediments.

Tentative evidence suggests inorganic sediment deposition may increase within shallow water areas as a result of runnels. If further data collection supports this finding, it may be caused by runnels increasing connectivity between the interior marsh platform and open embayment. With microtides and low sediment in Buzzards Bay, very little sediment would make it into the interior platform areas where the shallow water dieback areas occur. The runnels may provide a more direct conduit for sediment to be transported into the marsh interior. However, more robust sampling and testing at both OVF and LB is needed to confirm these results.

4. Conclusions

Early responses of two salt marsh complexes in the Buzzard Bay Estuary show promising results for runnels as a climate adaptation technique. Visual evidence of vegetation changes, and water table dynamics show that tidal hydrology and marsh vegetation are beginning to show signs of restoration, with variation across sites and marshes. Variation is likely caused by large differences in background conditions at the two marshes, and among sites, including platform elevation, depth of dieback area, landscape position, peat degradation and tidal range. In addition, temporal factors such as precipitation significantly affected water dynamics at the two marshes, and resulting soil chemistry and processes. The higher rainfall occurring in 2021 over 2020 confounded our ability to detect an effect of runnels on multiple marsh properties and to determine the “footprint” of a runnel across the marsh platform (between experimental zones). We found very tentative evidence of increased inorganic sediment deposition within dieback areas after runnels were created; however, this result needs further study to confirm. Additional years of data collection are needed to fully understand the responses of these marshes to runnels, and how a number of spatial and temporal factors interact with the runnelling approach to affect marsh hydrology, geomorphology, and vegetation.

Figure 1. Site maps of LB and OVF. Green lines represent sampling transects at reference sites, and purple lines indicate sampling transects at runnel sites. Light blue lines illustrate the runnels created in October and November 2020. The stars indicate the intensive sites. All reporting in this document focuses on the intensive sites only.

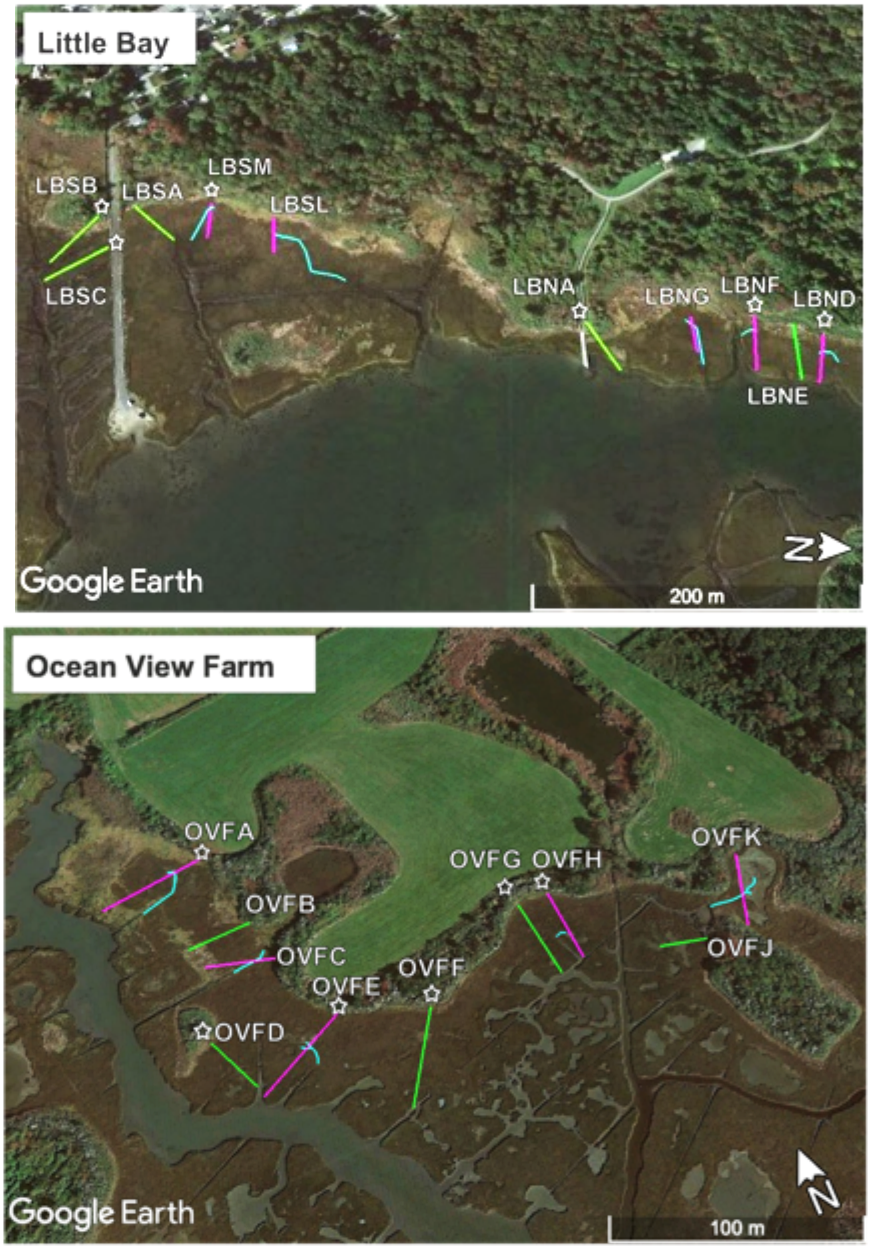
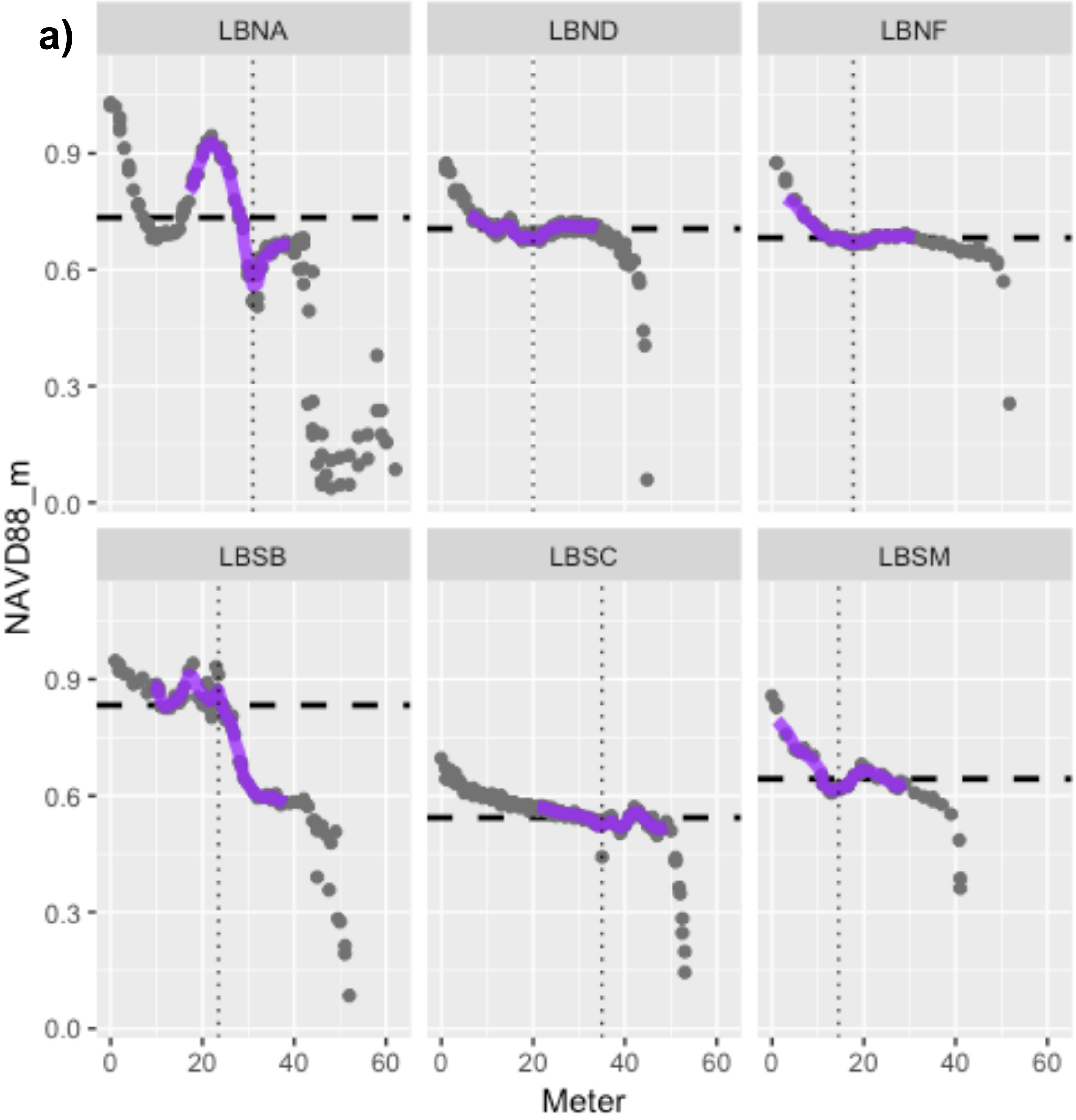


Figure 2. Elevation profiles at **a)** LB, and **b)** OVF. See Table 2 for experimental treatment units of each site (4-letter codes). Profiles extend from the high marsh-upland border (0 on x-axis) seaward toward open water. Gray dots are averaged elevation measurements collected along sampling transects, and the smoothed depth profile of the shallow water area is illustrated with the purple line. Long-dashed horizontal line shows the median elevation for each transect, interpreted as the platform elevation. The dotted vertical line illustrates the centroid of the shallow water area along transect.



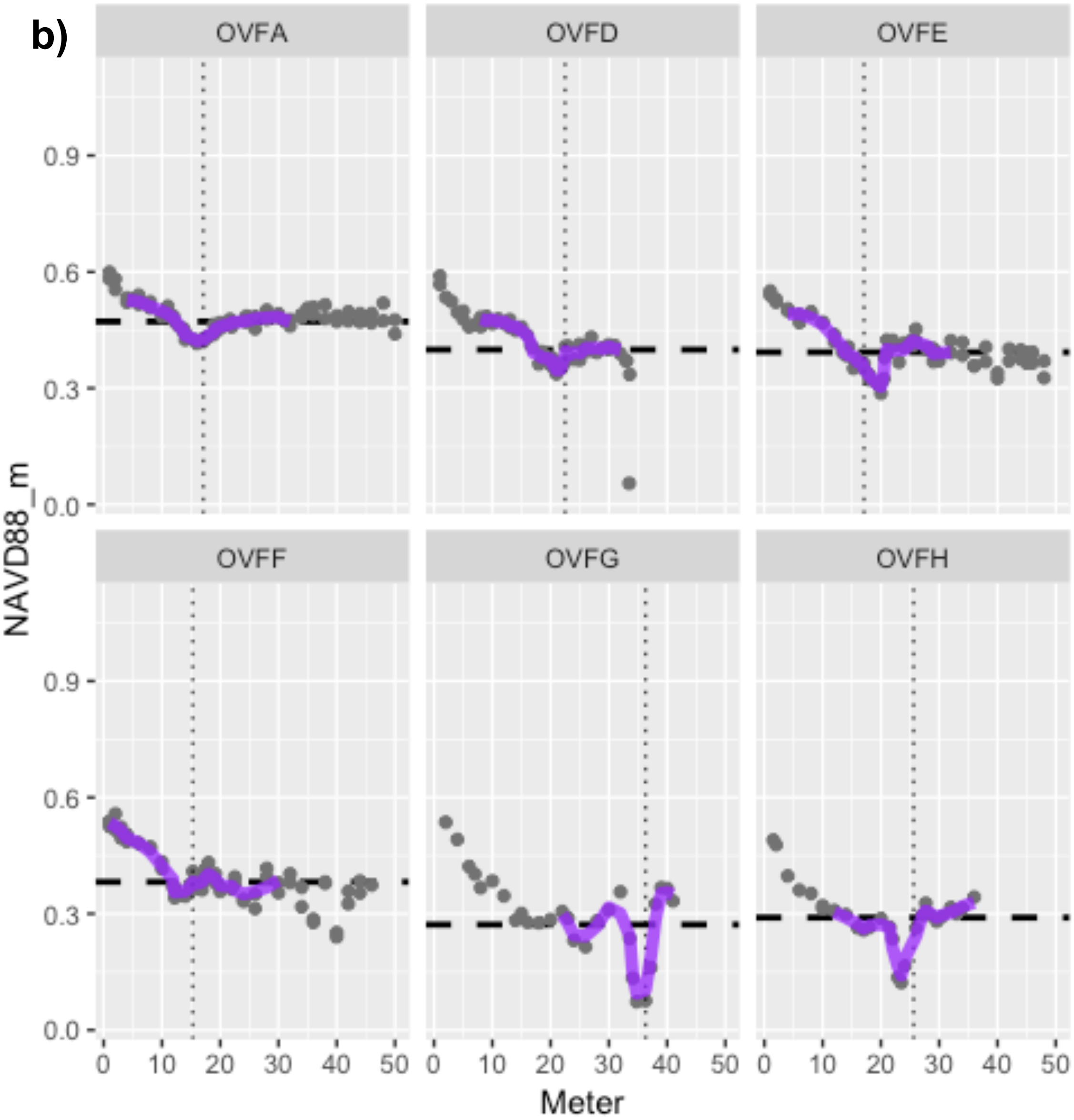

b)
OVFA
OVFD
OVFE
OVFF
OVFG
OVFH
NAVD88_m
0.0
0.3
0.6
0.9
0
10
20
30
40
50
Meter

Figure 3. Soil shear strength vertical profiles (mean +/- SE) collected at **a)** LB and **b)** OVF. See Table 2 for experimental treatment units of each site (4-letter codes). Black line illustrates the shear strength profile at 5, 15, and 30 cm depths within the shallow water area (or "dieback"), and the green point shows the shear strength in a well vegetated patch of marsh from the upland edge of the transect (usually high marsh vegetation) collected at 10 cm depth.

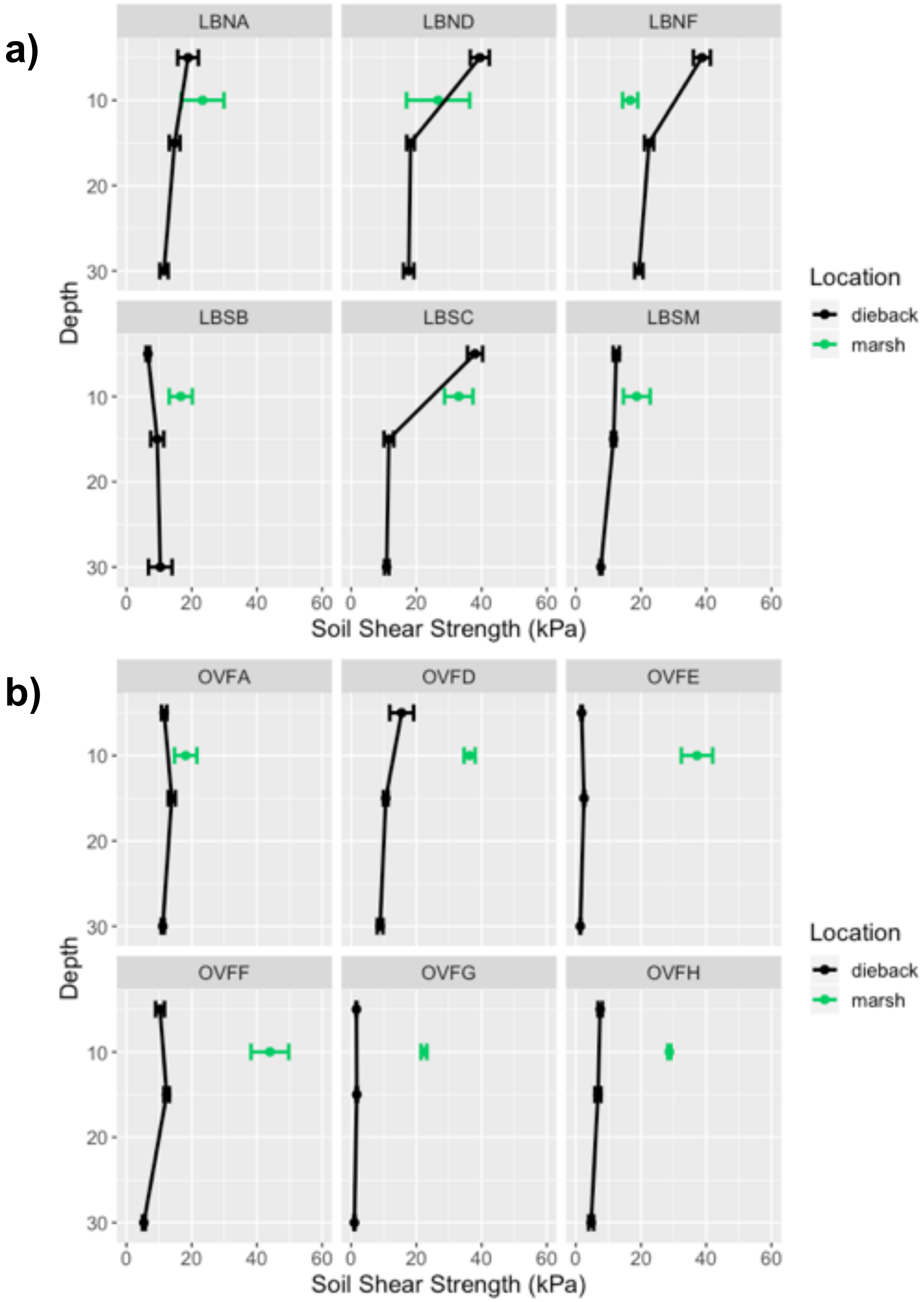


Figure 4. Before and after photograph at OVFA, Runnel Site 1.

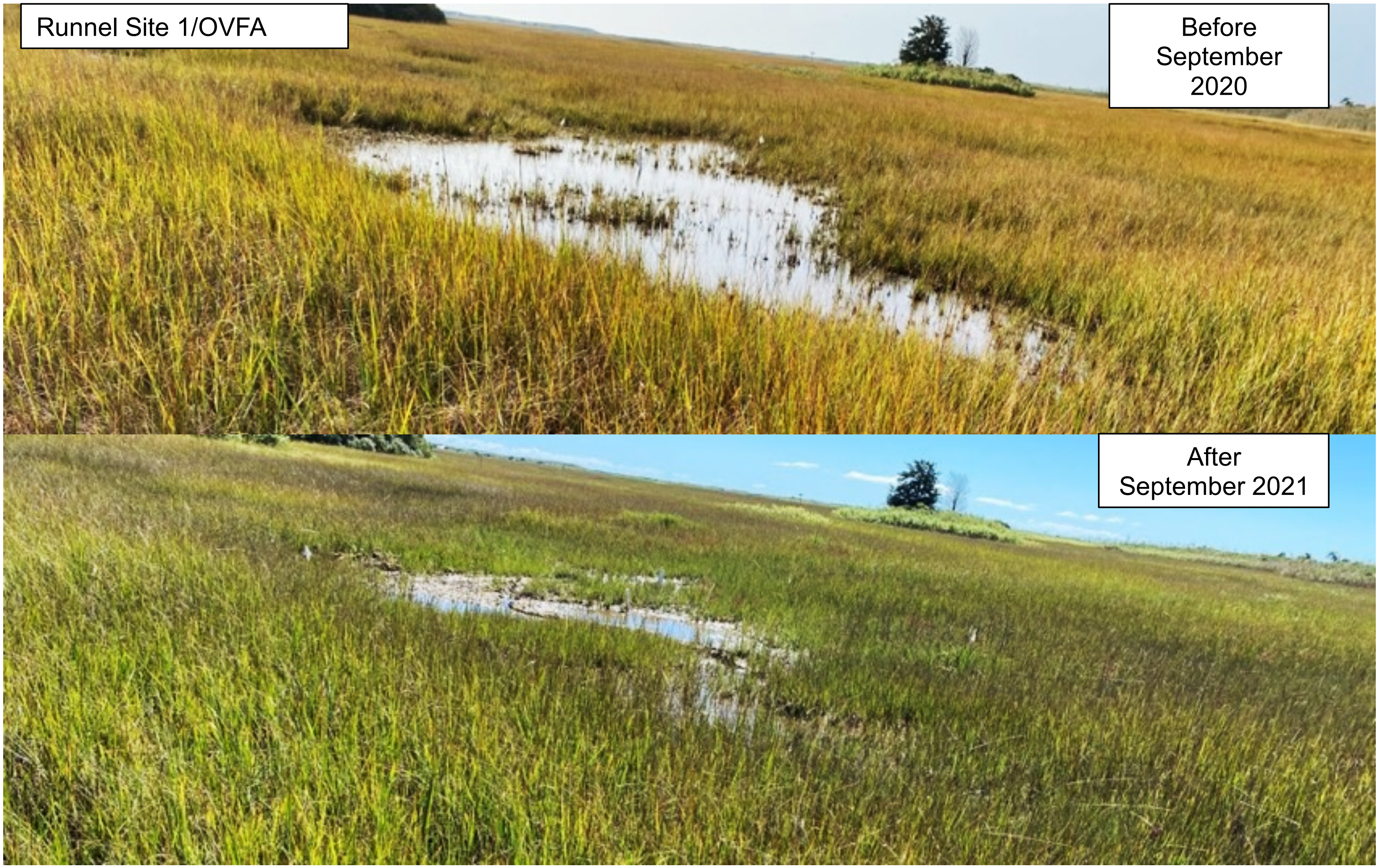


Figure 5. Local precipitation, and water levels from before runnels were installed (2020) and after (2021) at OVFA, Runnel Site. 1. Light blue line shows 15-minute data, and the dark blue line shows the water table height.

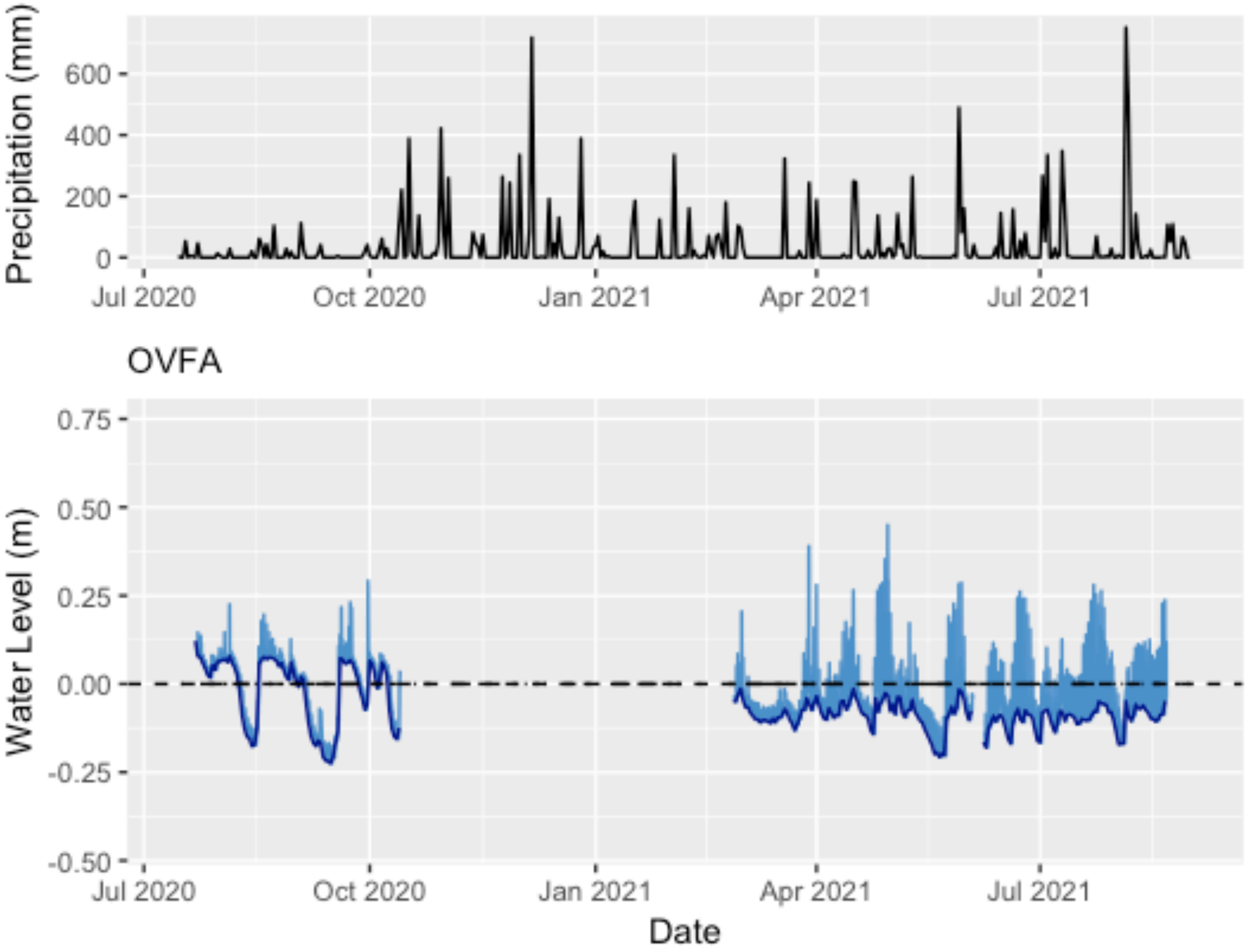


Figure 6. Before and after photograph at OVFE, Runnel Site 2.

Figure 7. Local precipitation, and water levels from before runnels were installed (2020) and after (2021) at OVFE, Runnel Site. 1. Light blue line shows 15-minute data, and the dark blue line shows the water table height.

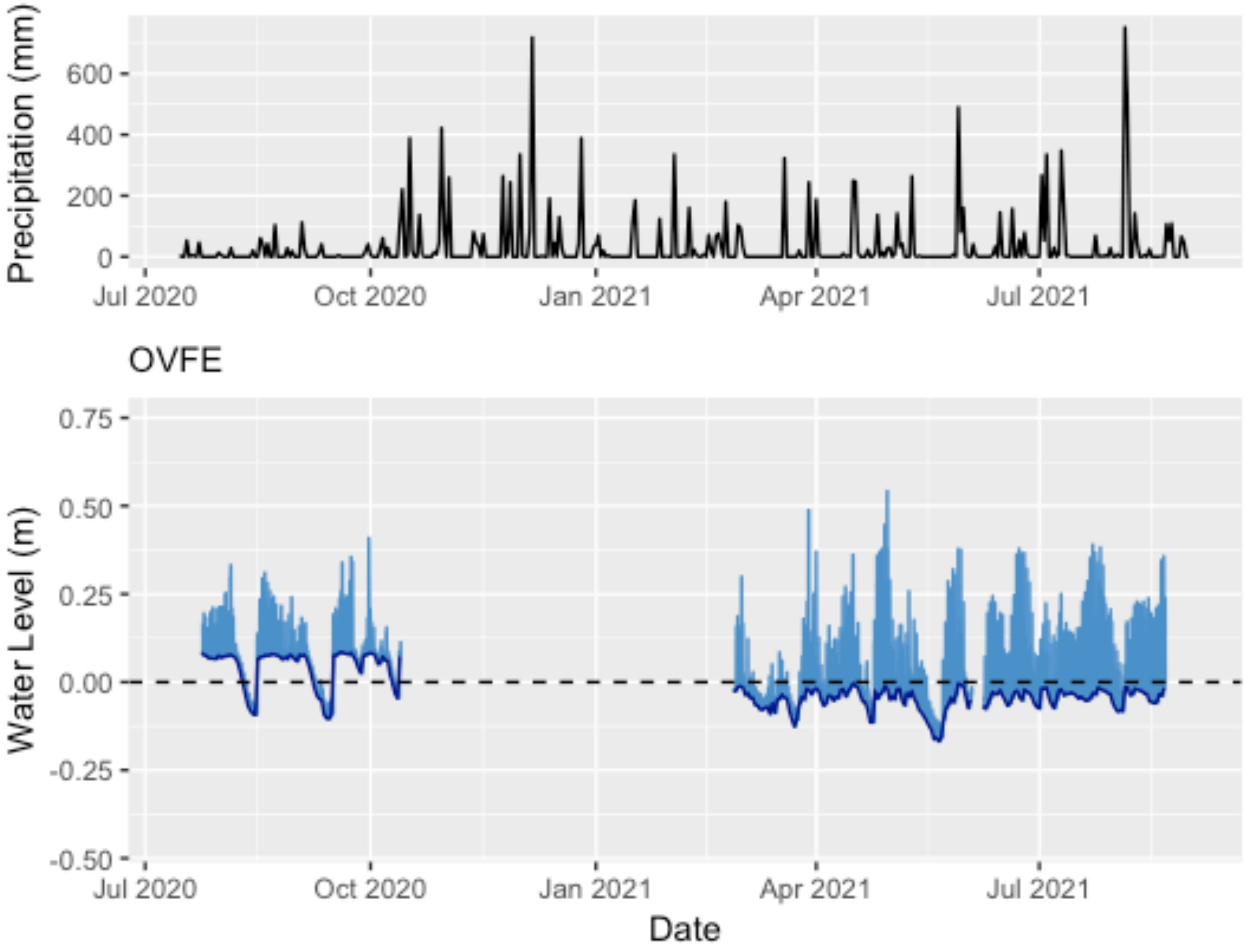


Figure 8. Before and after photograph at OVFH, Runnel Site 3.

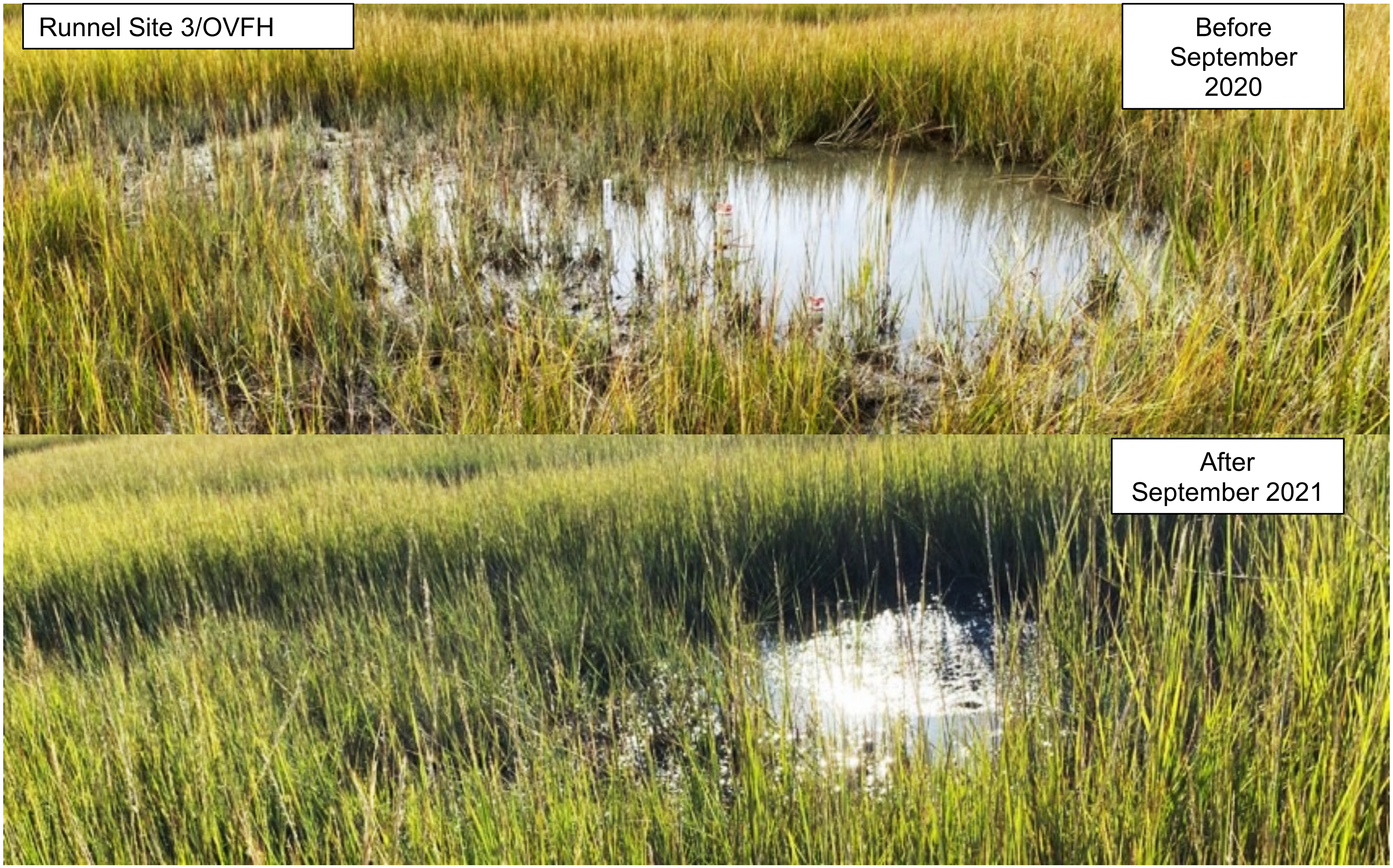


Figure 9. Local precipitation, and water levels from before runnels were installed (2020) and after (2021) at OVFH, Runnel Site. 3. Light blue line shows 15-minute data, and the dark blue line shows the water table height.

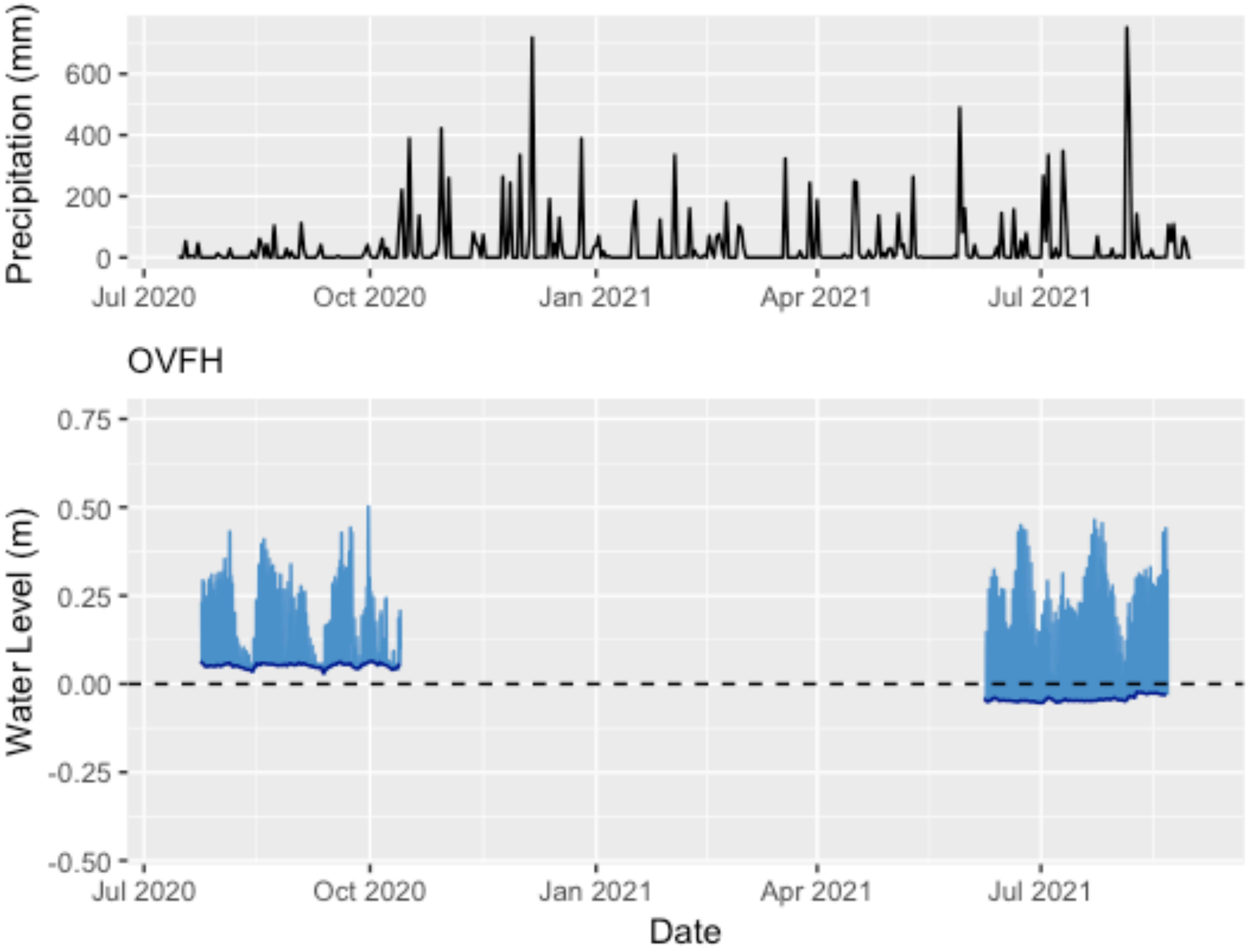


Figure 10. Before and after photograph at OVFD, Reference Site 1.

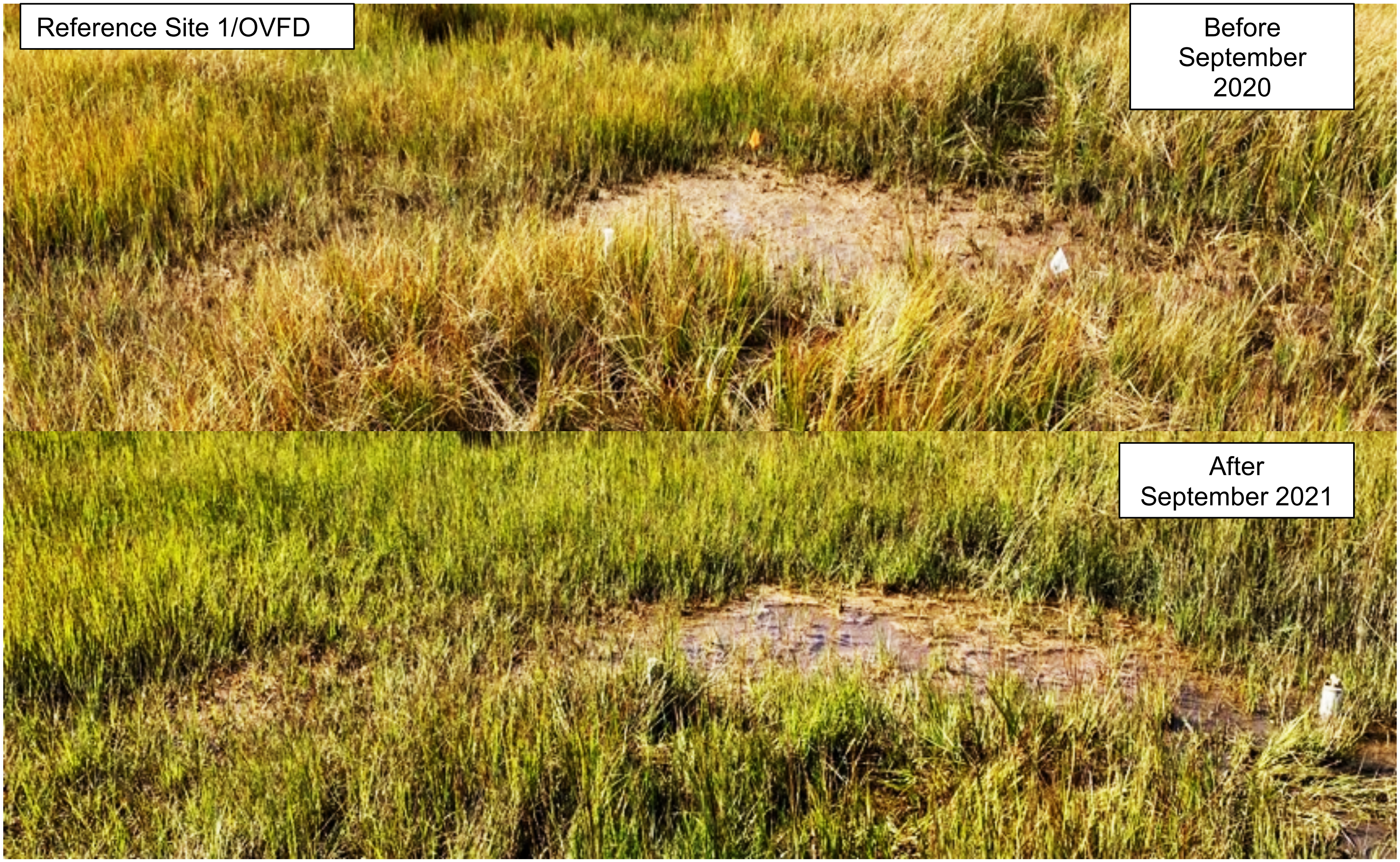


Figure 11. Local precipitation, and water levels from before runnels were installed (2020) and after (2021) at OVFD, Reference Site 1. Light blue line shows 15-minute data, and the dark blue line shows the water table height.

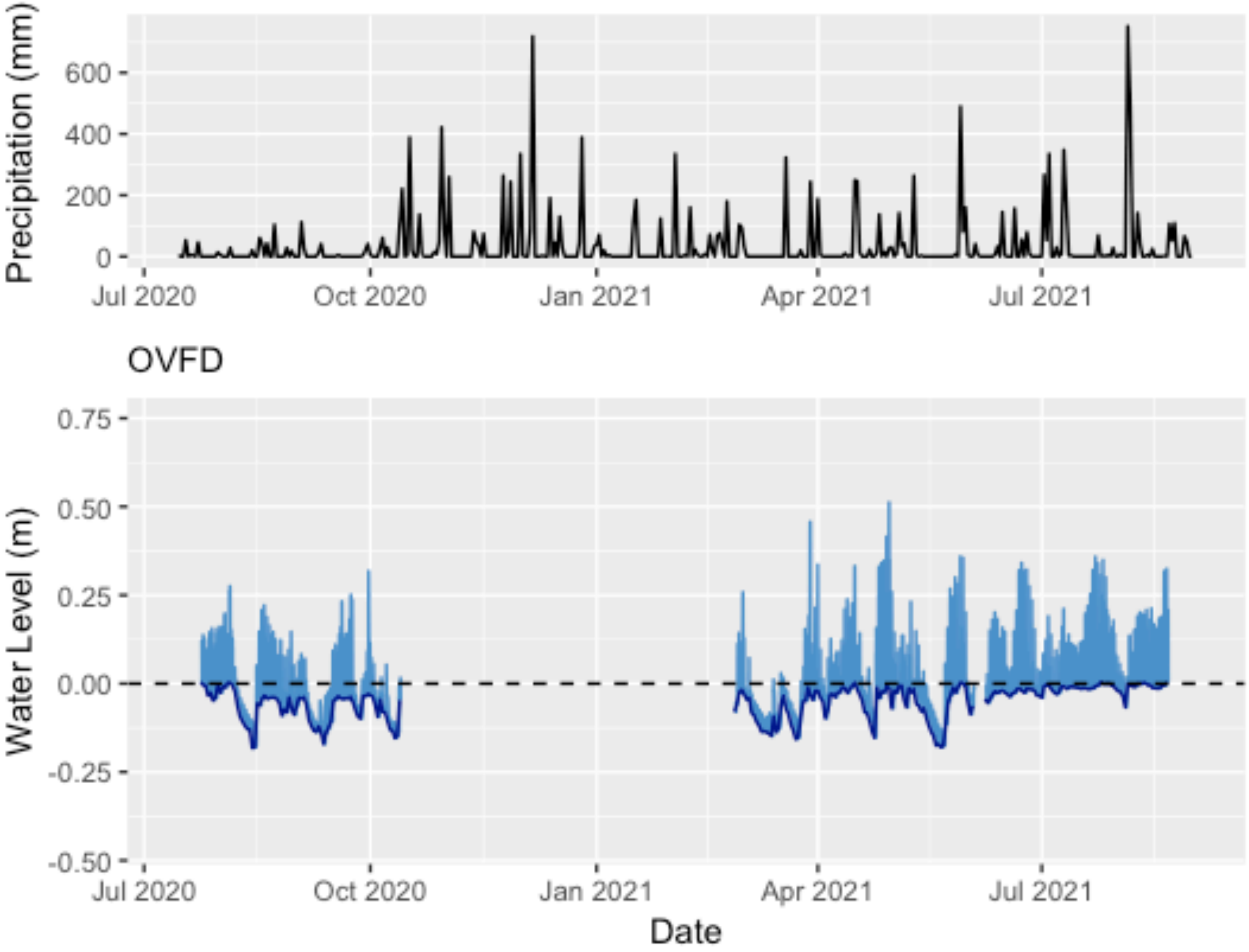


Figure 12. Before and after photograph at OVFF, Reference Site 2.

Figure 13. Local precipitation, and water levels from before runnels were installed (2020) and after (2021) at OVFF, Reference Site 2. Light blue line shows 15-minute data, and the dark blue line shows the water table height.

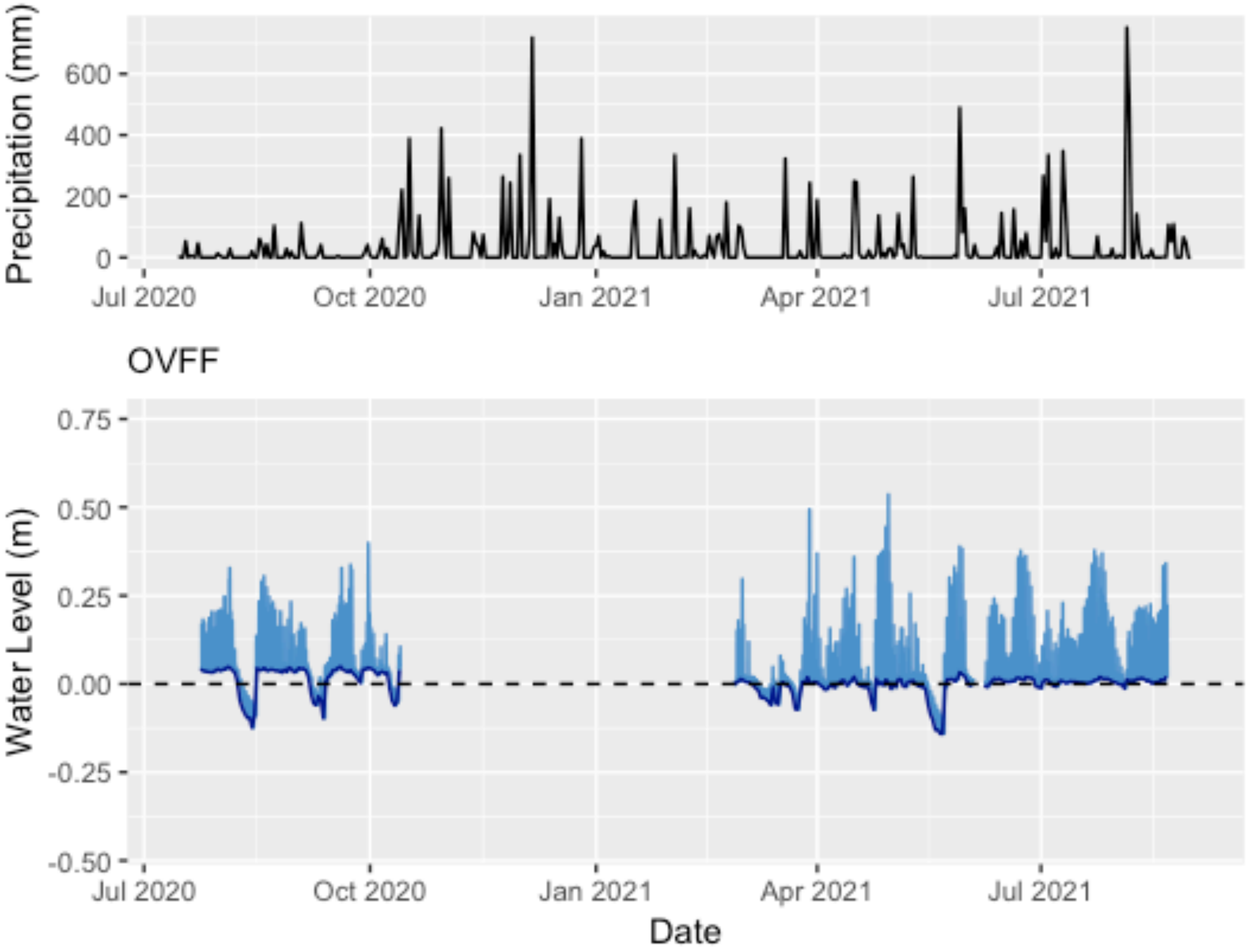


Figure 14. Before and after photograph at OVFG, Reference Site 3.

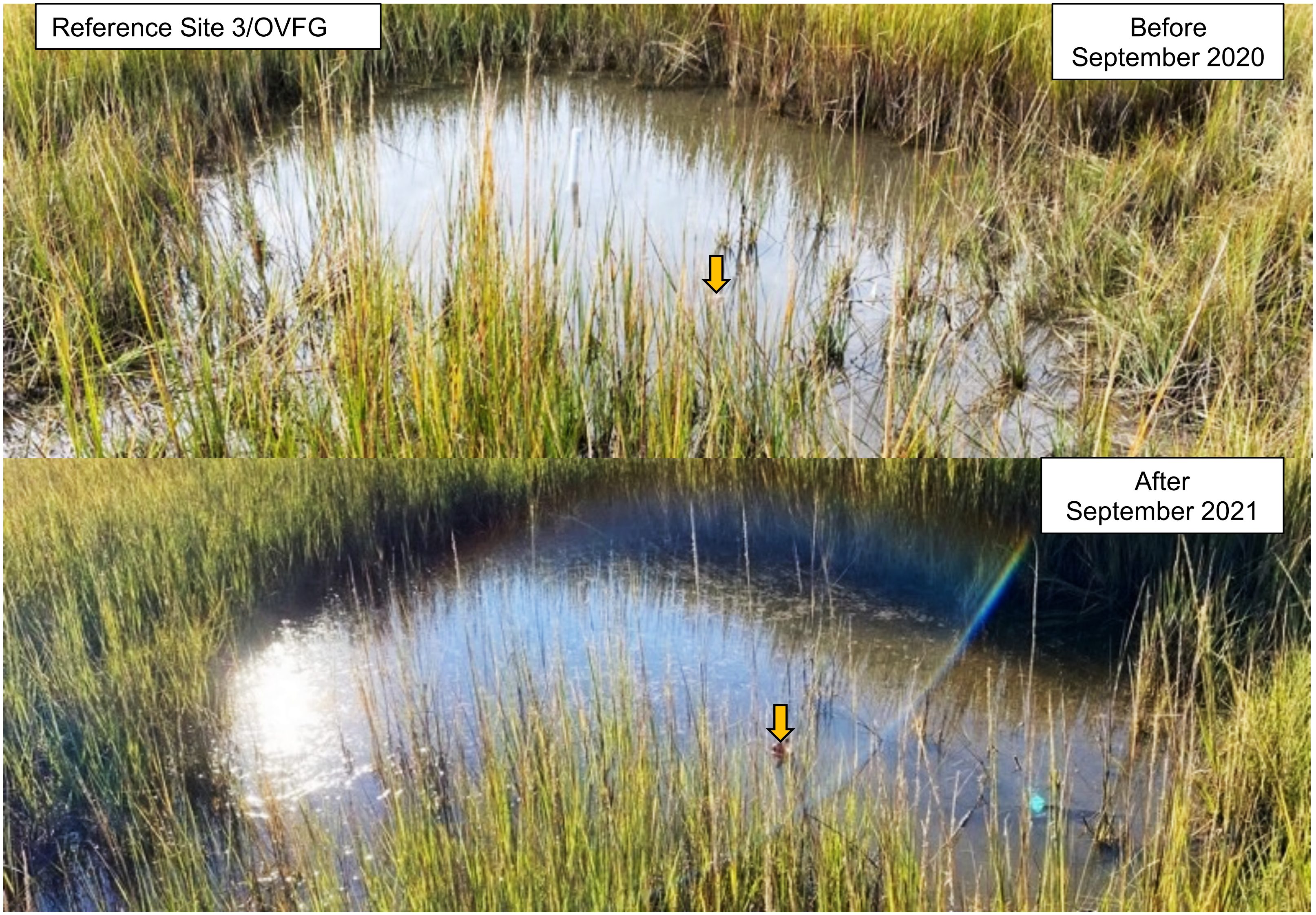


Figure 15. Local precipitation, and water levels from before runnels were installed (2020) and after (2021) at OVFG, Reference Site 3. Light blue line shows 15-minute data, and the dark blue line shows the water table height.

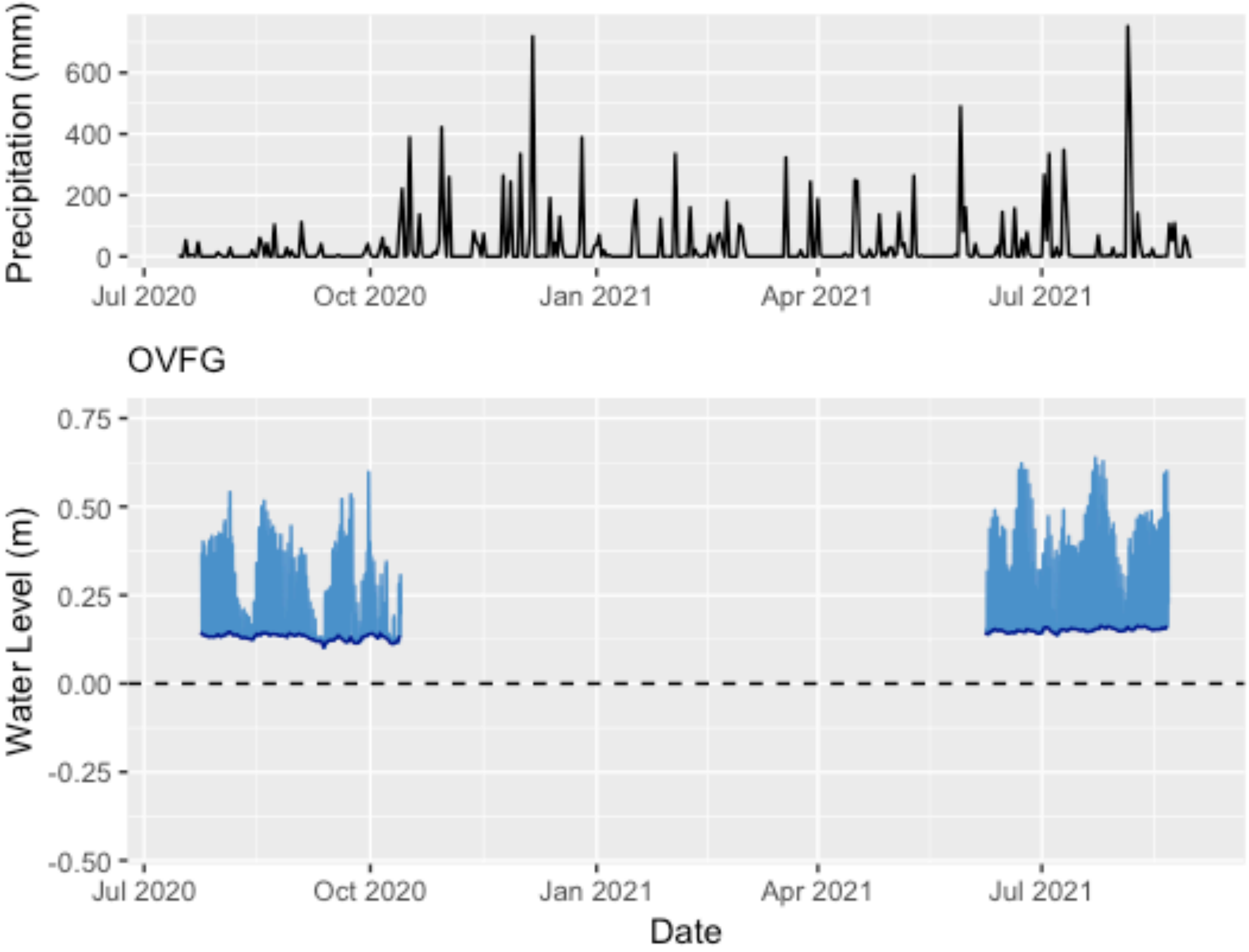


Figure 16. Before and after photograph at LBND, Runnel Site 4.

Figure 17. Local precipitation, and water levels from before runnels were installed (2020) and after (2021) at LBND, Runnel Site 4. Light blue line shows 15-minute data, and the dark blue line shows the water table height.

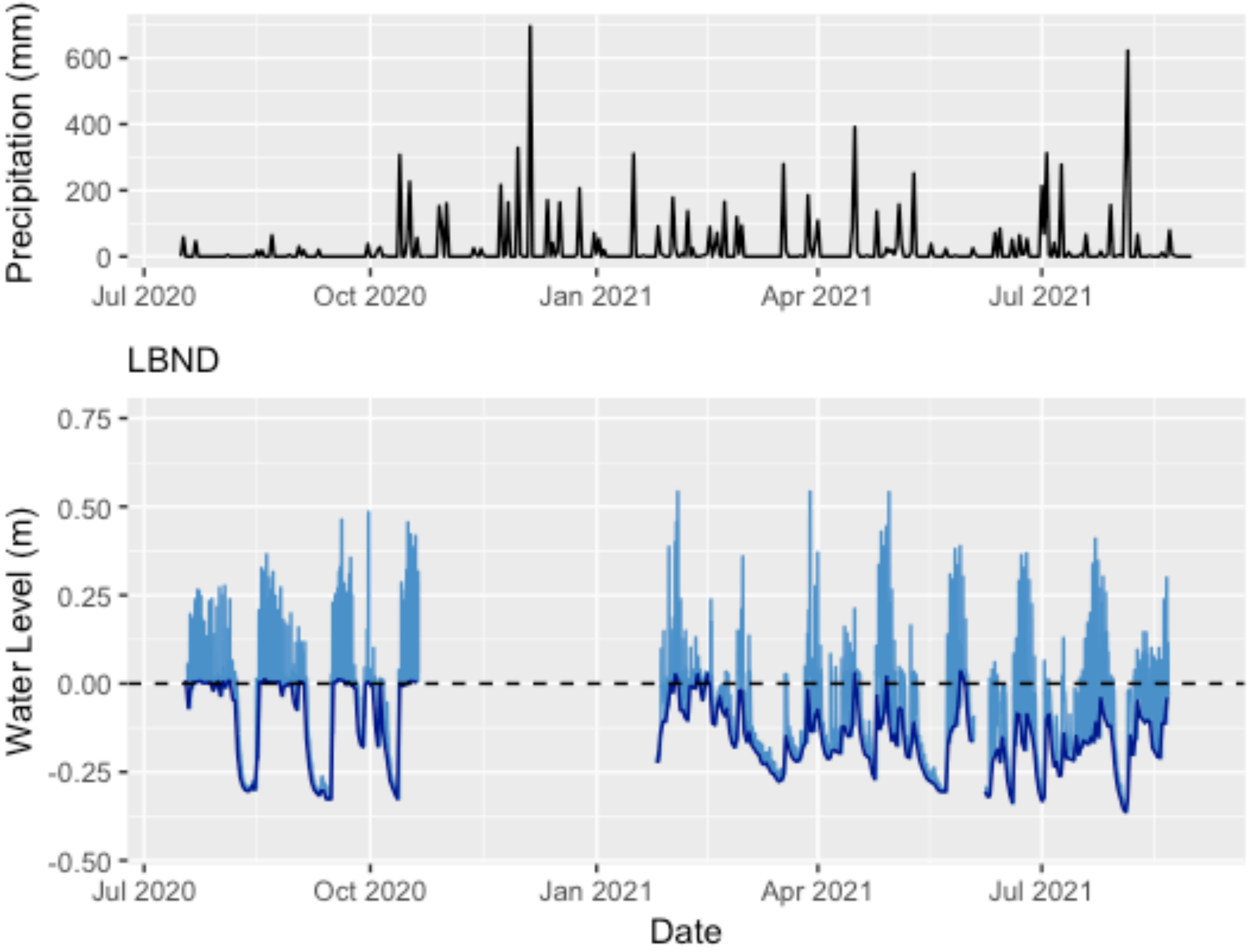


Figure 18. Before and after photograph at LBNF, Runnel Site 5.

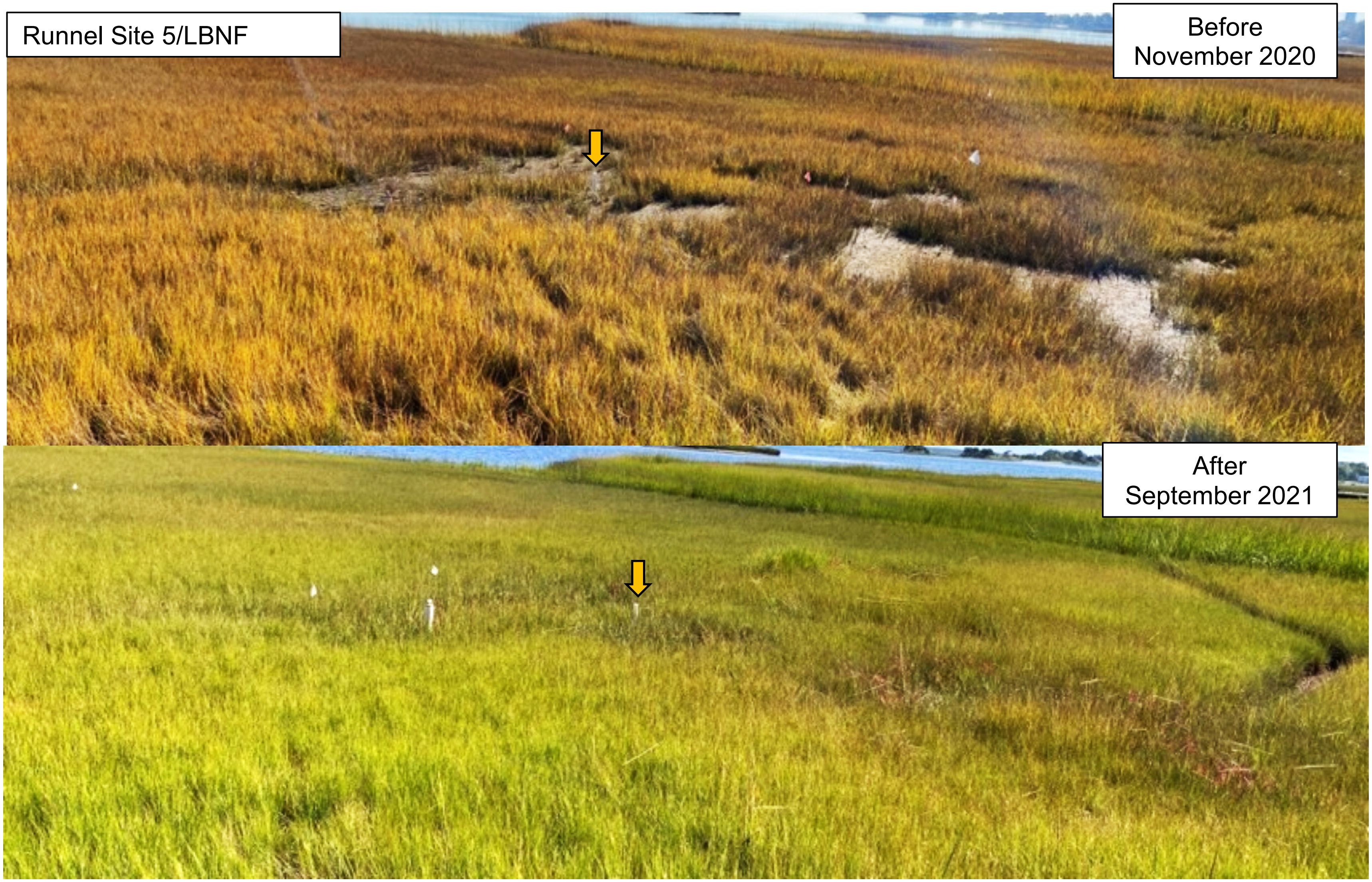


Figure 19. Local precipitation, and water levels from before runnels were installed (2020) and after (2021) at LBNF, Runnel Site 5. Light blue line shows 15-minute data, and the dark blue line shows the water table height.

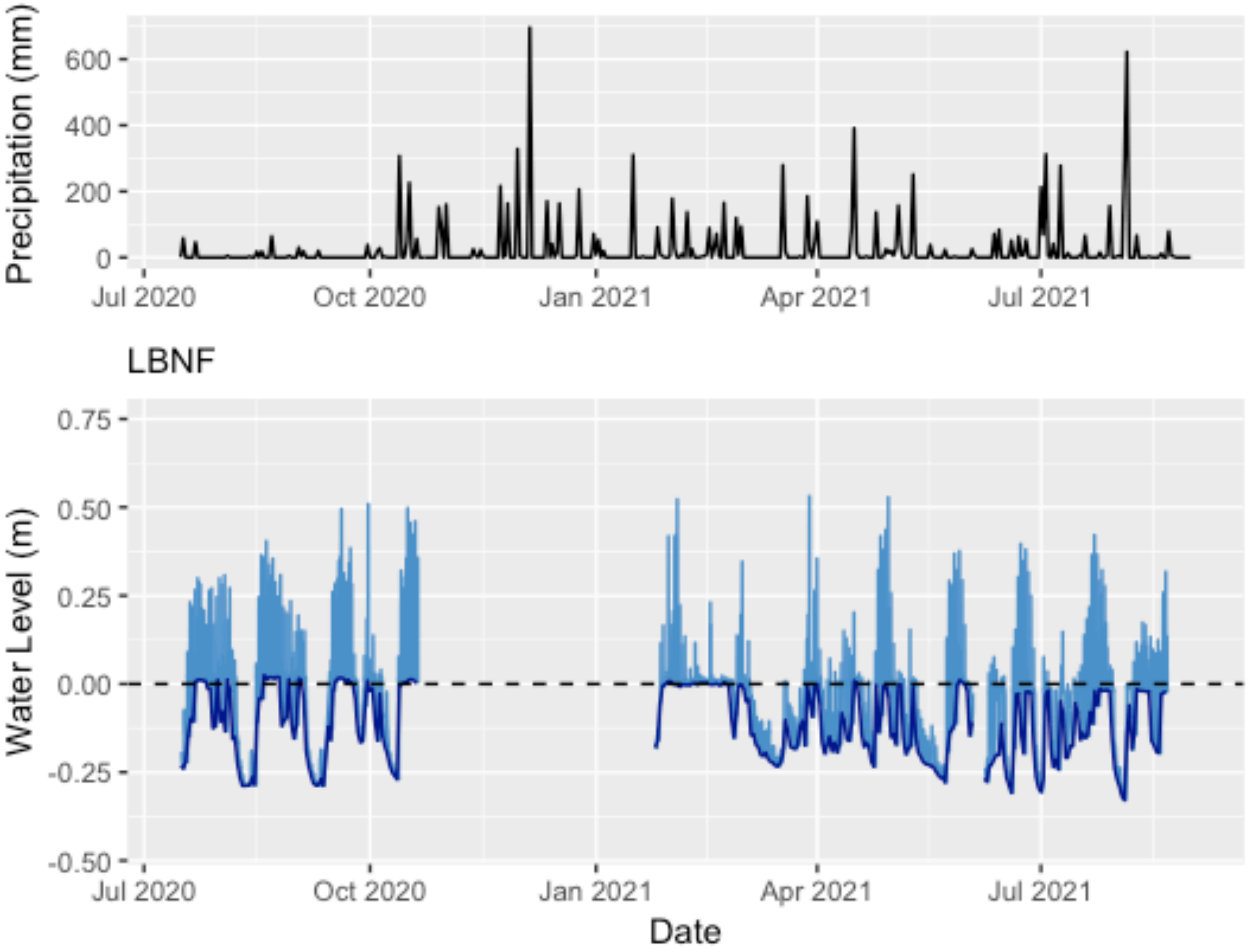


Figure 20. Before and after photograph at LBSM, Runnel Site 6.

Figure 21. Local precipitation, and water levels from before runnels were installed (2020) and after (2021) at LBSM, Runnel Site 6. Light blue line shows 15-minute data, and the dark blue line shows the water table height.

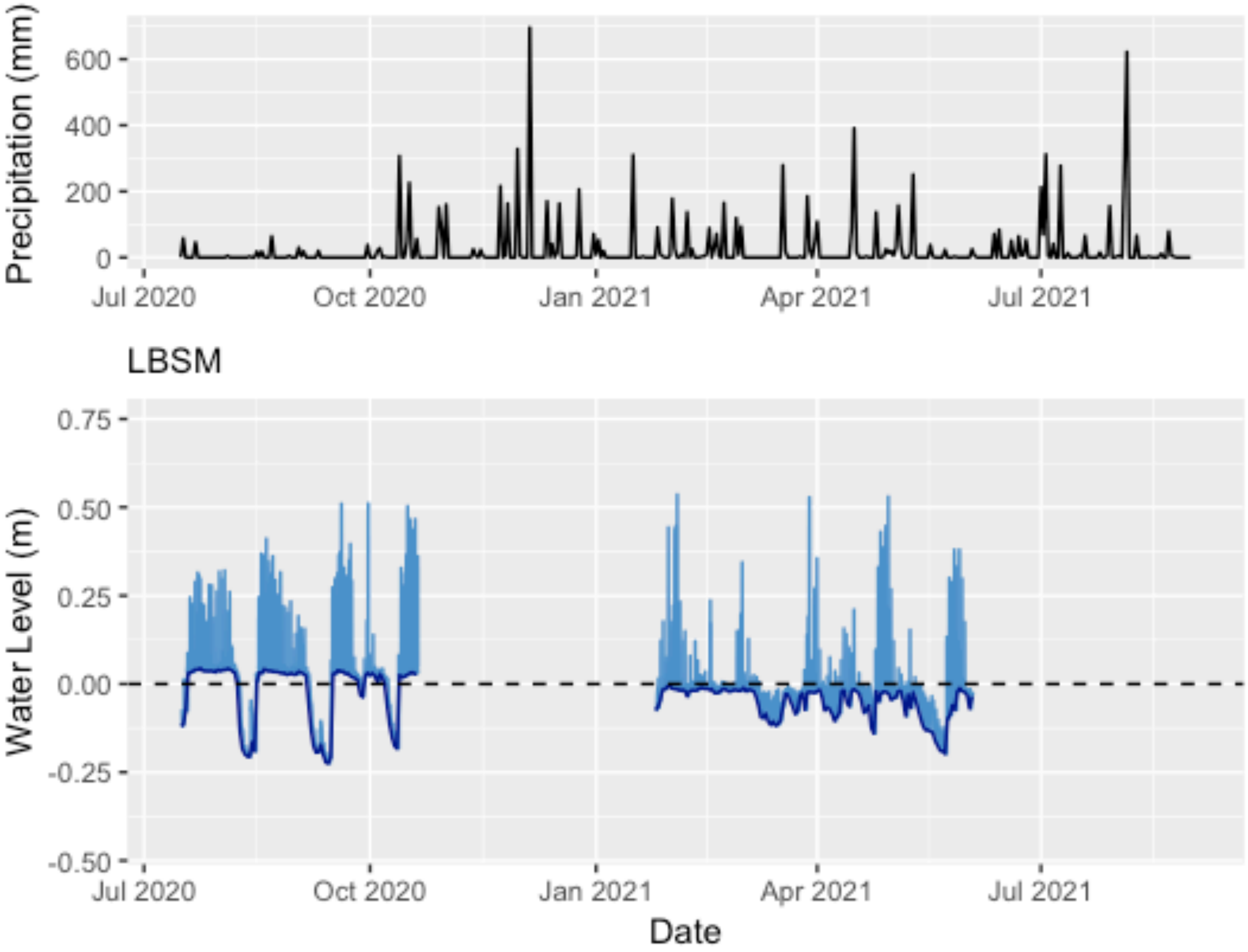


Figure 22. Before and after photograph at LBNA, Reference Site 4.

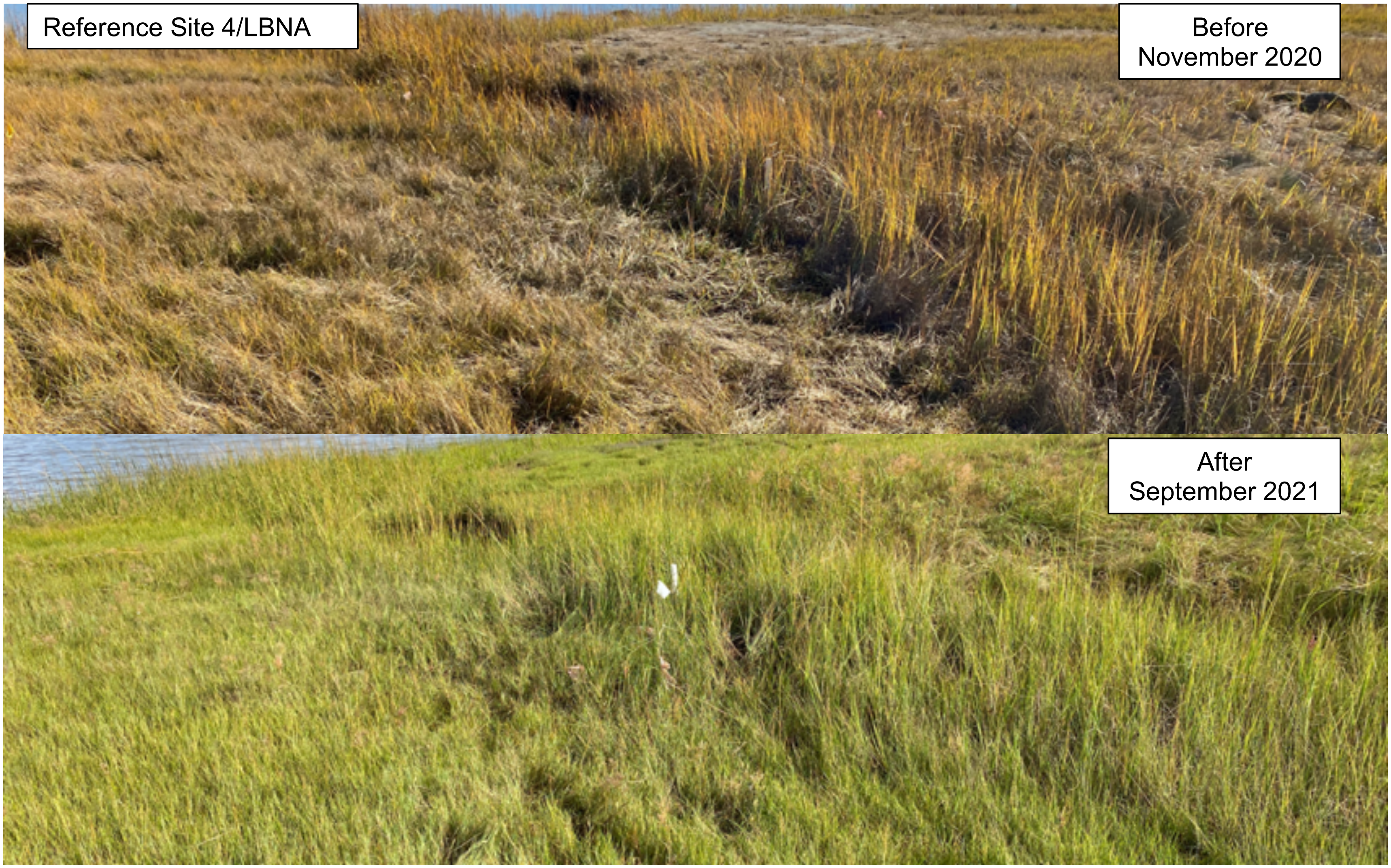


Figure 23. Local precipitation, and water levels from before runnels were installed (2020) and after (2021) at LBNA, Reference Site 4. Light blue line shows 15-minute data, and the dark blue line shows the water table height.

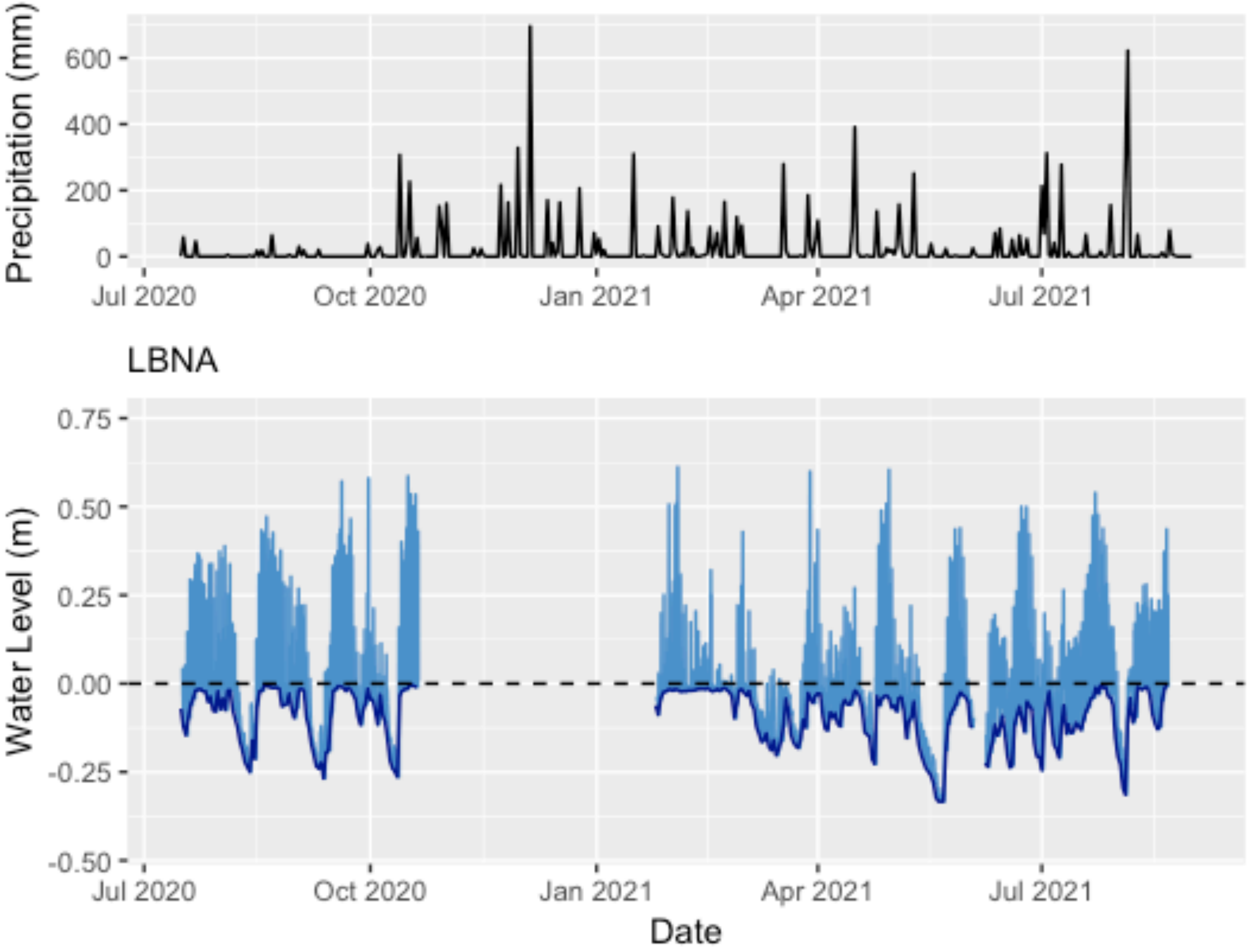


Figure 24. Before and after photograph at LBSB, Reference Site 5.

Figure 25. Local precipitation, and water levels from before runnels were installed (2020) and after (2021) at LBSB, Reference Site 5. Light blue line shows 15-minute data, and the dark blue line shows the water table height.

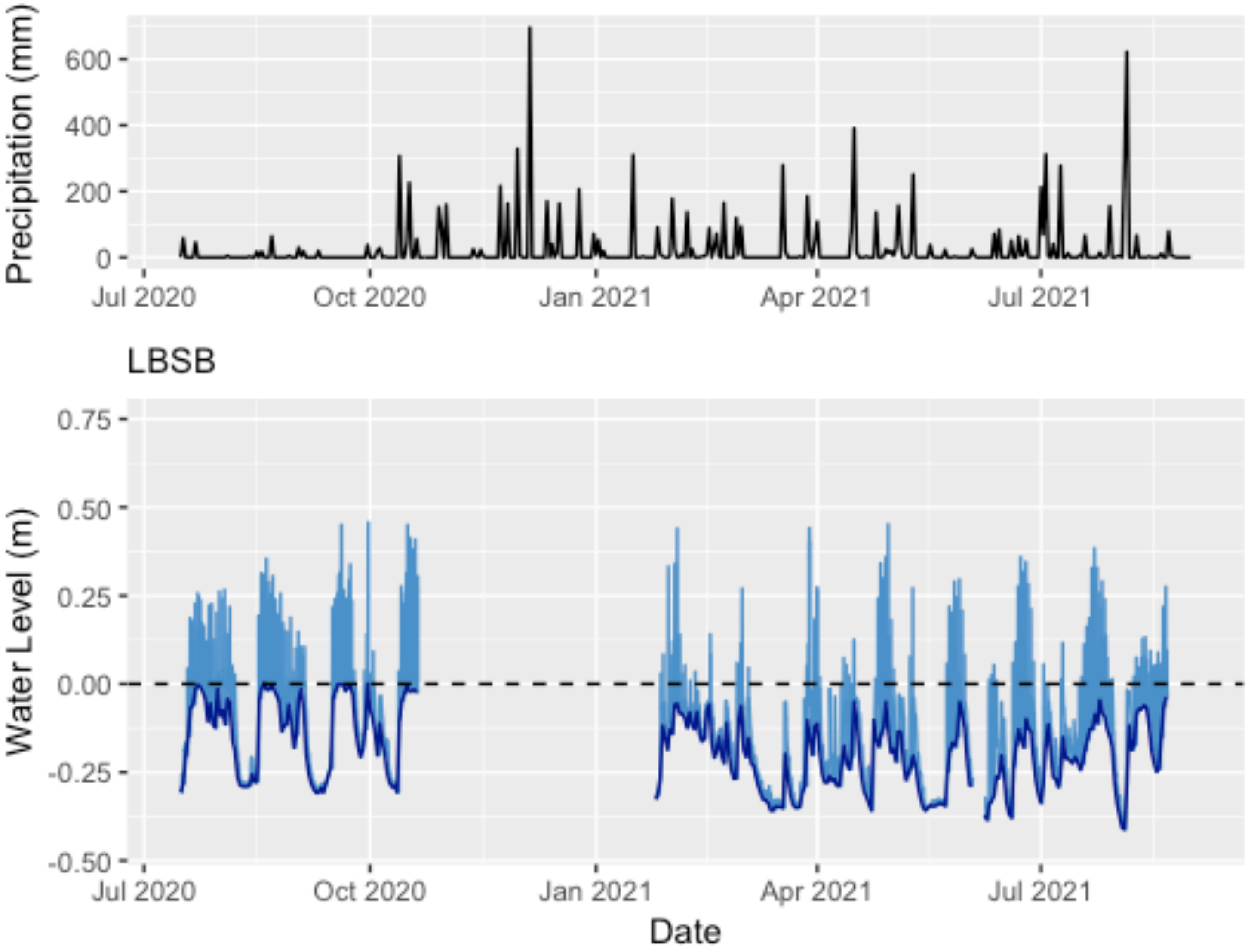


Figure 26. Before and after photograph at LBSC, Reference Site 6.

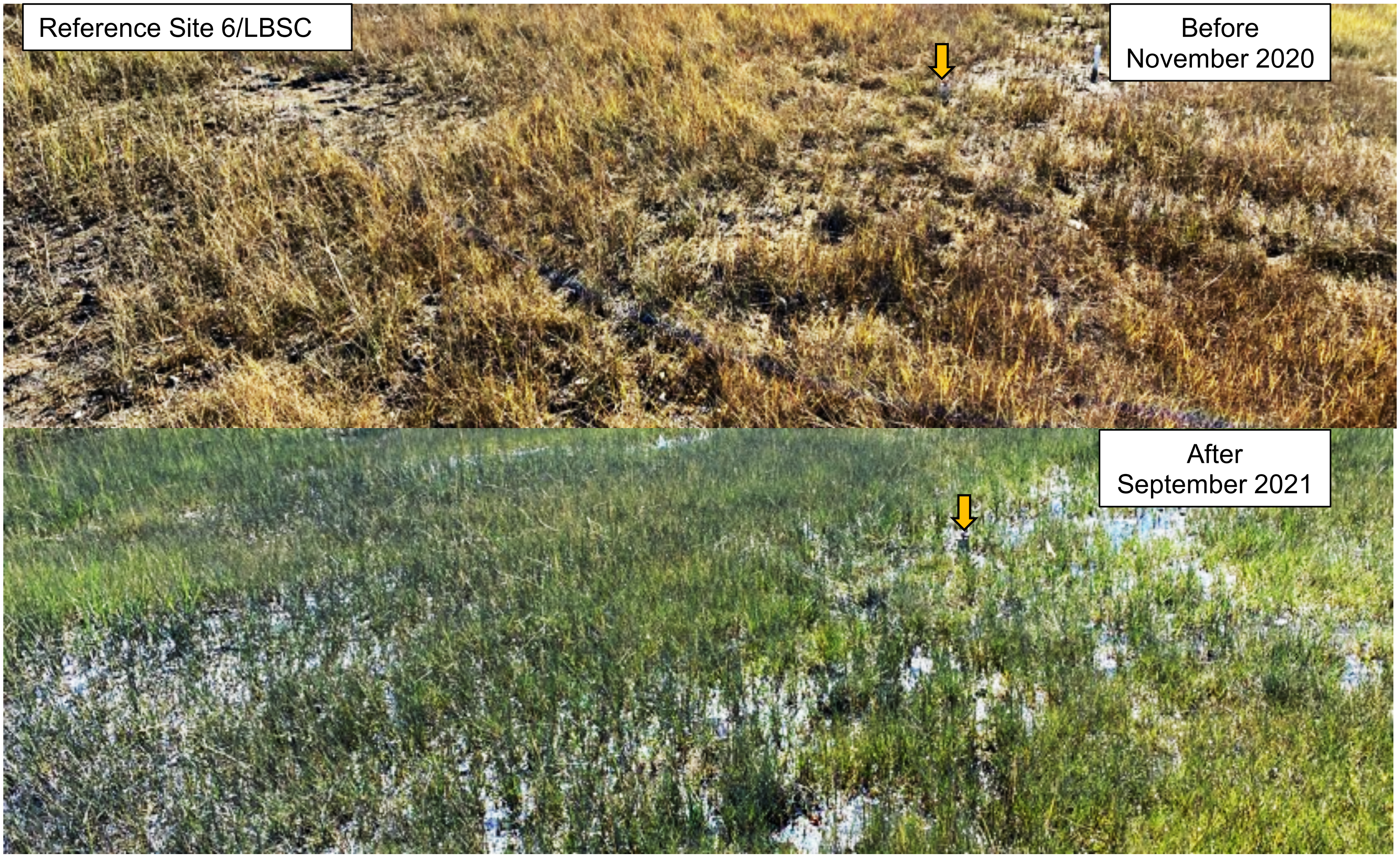


Figure 27. Local precipitation, and water levels from before runnels were installed (2020) and after (2021) at LBSC, Reference Site 6. Light blue line shows 15-minute data, and the dark blue line shows the water table height.

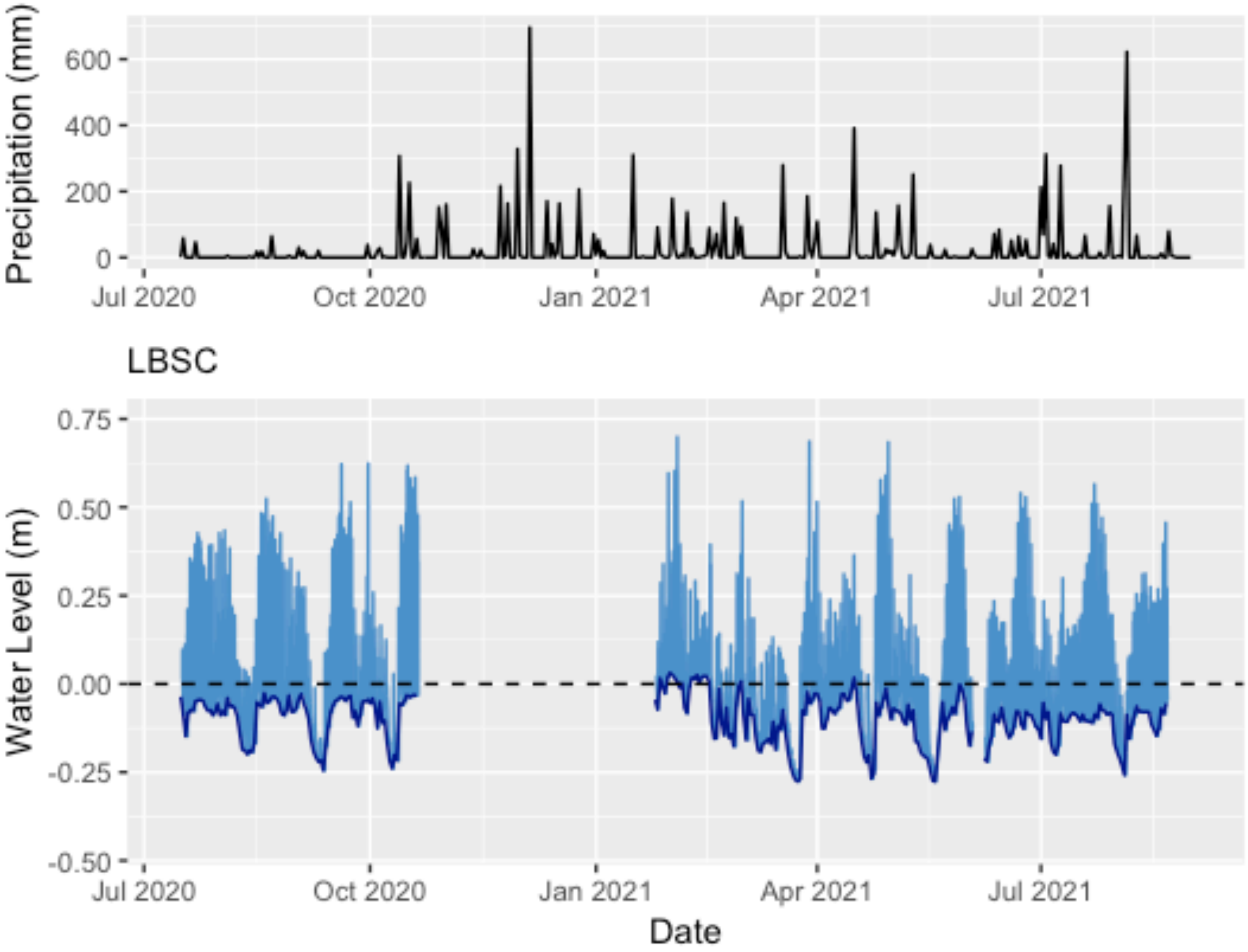


Figure 28. Results of statistical test for an effect of runnels on water table heights at LB and OVF. Displaying mean and water table heights and standard error for runnel and reference sites, before and after runnel-installation, and accounting for between-site differences. Model results indicated runnels decreased water table heights at OVF relative to reference sites, but not at LB ($p < 0.001$).

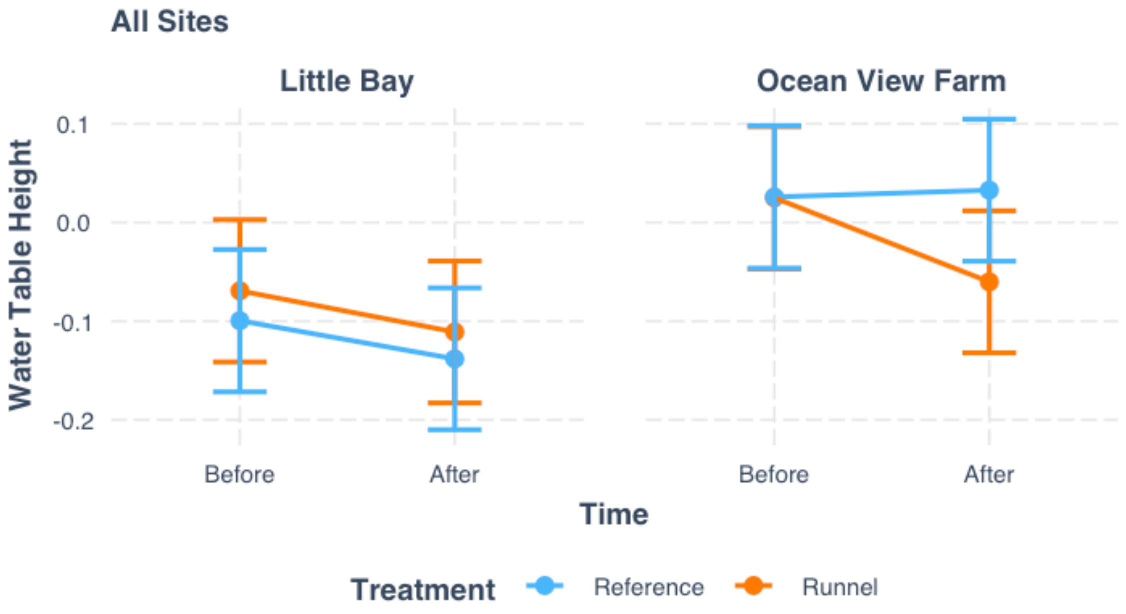


Figure 29. Soil moisture content as percent of wet weight of soil cores measured at a) OVF and b) LB sites. Boxplots show percentages before (purple, dark green) and after (gray, light green) runnel installation, in ‘Down’ (creekward), ‘Center’ (within dieback), and ‘Up’ (upland) experimental zones, at both runnel and reference sites.

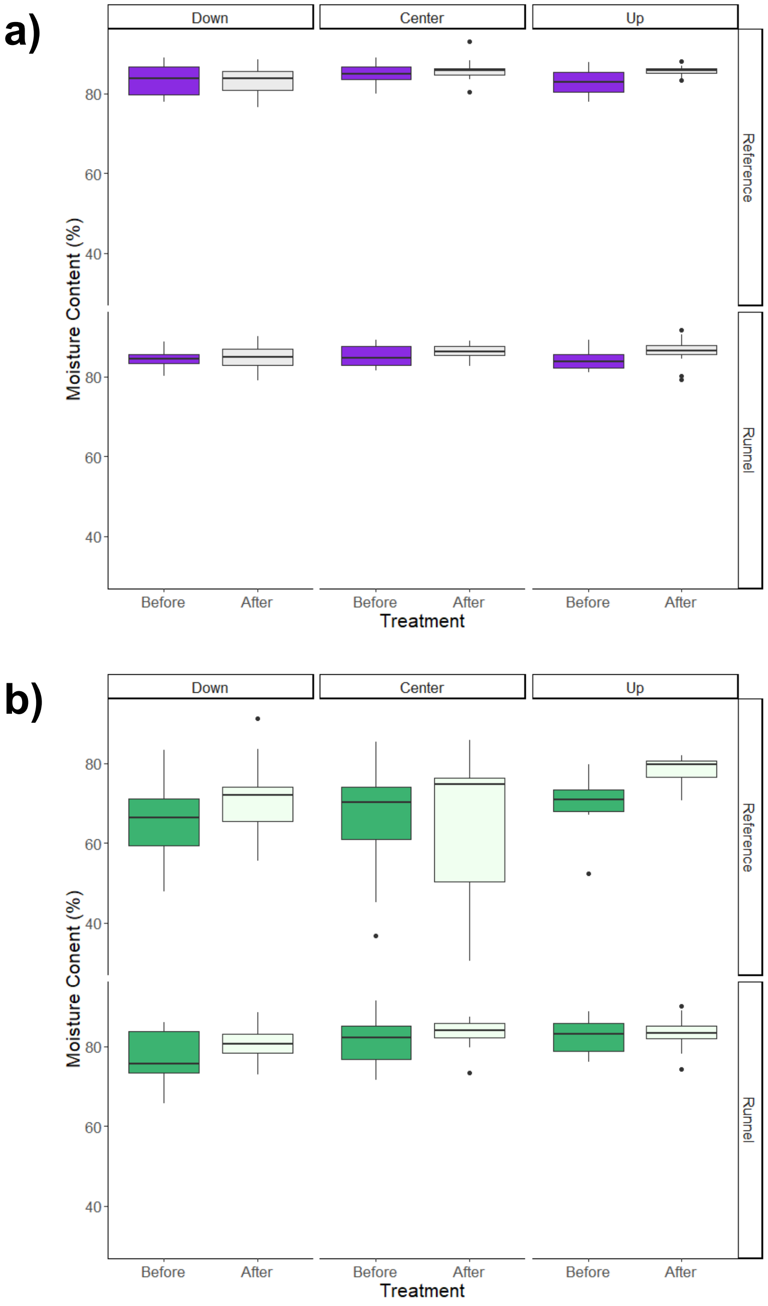


Figure 30. Porewater salinity as parts per thousand (ppt) measured at a) OVF and b) LB sites. Boxplots show percentages before (purple, dark green) and after (gray, light green) runnel installation, in 'Down' (creekward), 'Center' (within dieback), and 'Up' (upland) experimental zones, at both runnel and reference sites.

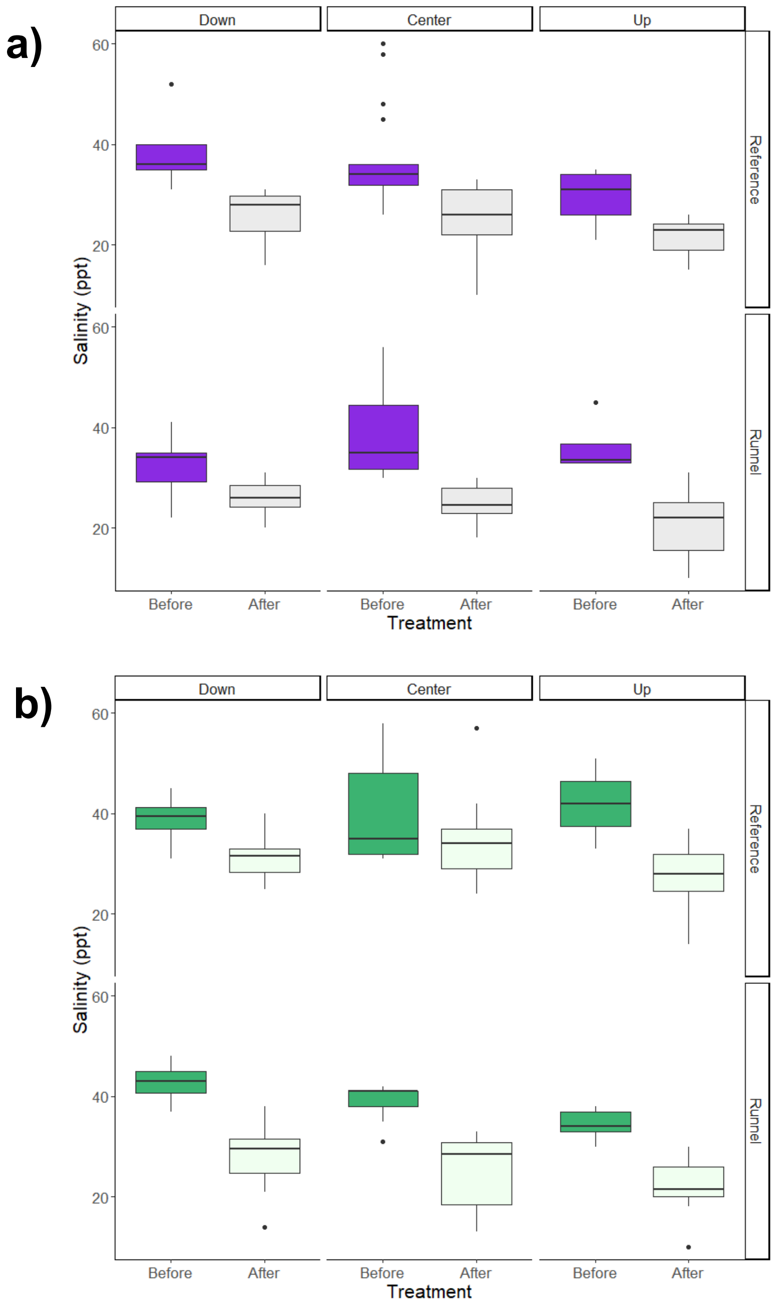


Figure 31. Illustration of method to estimate hydroperiod. 15-min water level data in m shown as a time series, identified high and low tide points identified using software indicated with open circles, and reference minimum water level used to identify low tide points shown as blue dashed horizontal line.

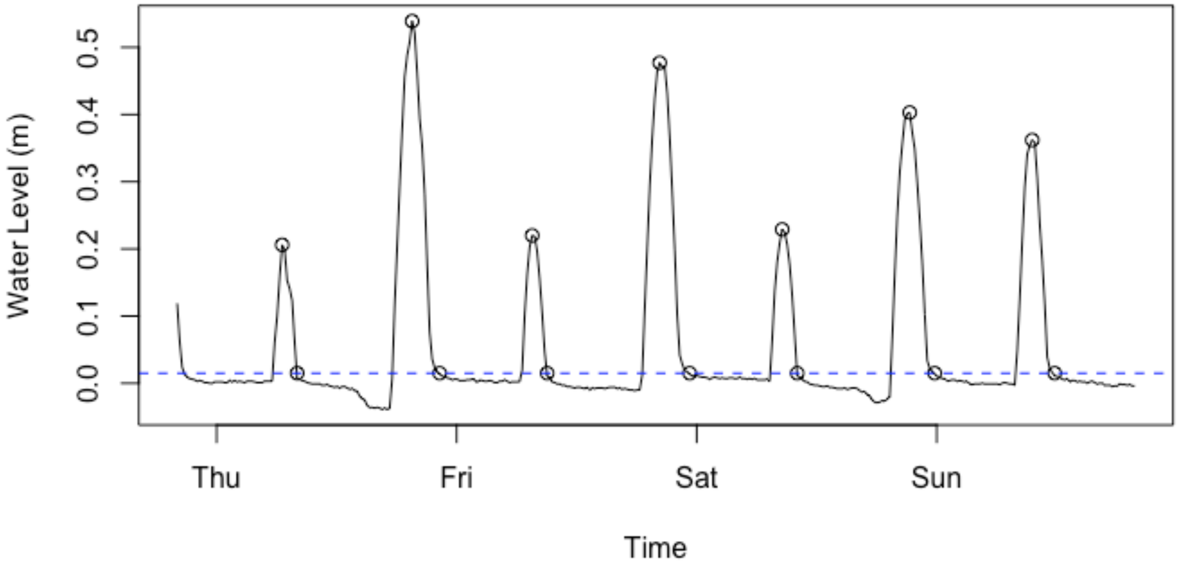


Figure 32. Redox potential measured as millivolts (mV) at a) OVF and b) LB sites. Boxplots show percentages before (purple, dark green) and after (gray, light green) runnel installation, in 'Down' (creekward), 'Center' (within dieback), and 'Up' (upland) experimental zones, at both runnel and reference sites.

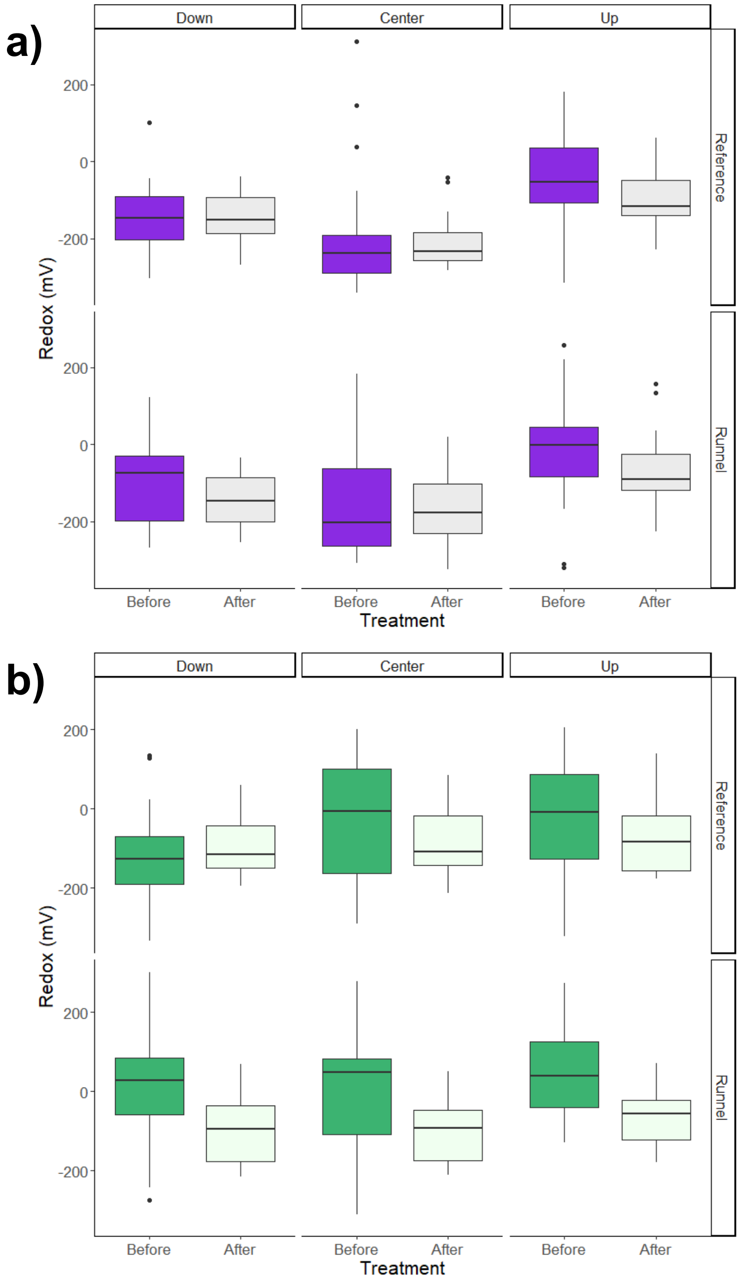


Figure 33. Decomposition of tea bags expressed with the K constant at a) OVF and b) LB sites. Boxplots show percentages before (purple, dark green) and after (gray, light green) runnel installation, in ‘Down’ (creekward), ‘Center’ (within dieback), and ‘Up’ (upland) experimental zones, at both runnel and reference sites.

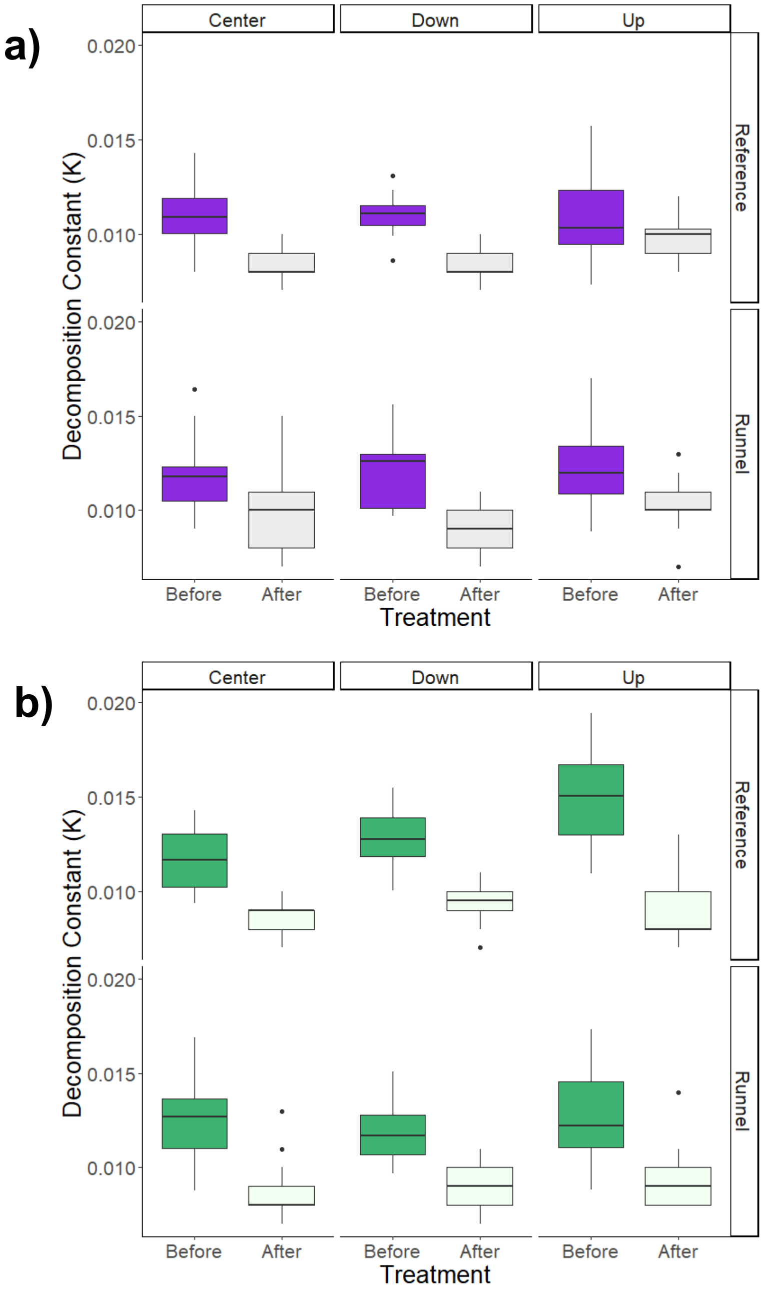


Figure 34. Upper panel: Wind speed at BUZM3 (entrance to Buzzards Bay), lower panel: turbidity at Little Bay channel site (red) and Ocean View Farm channel site (blue). Large peaks at LB represent resuspension of bed material during storms, with perhaps slight export of sediment from the marsh during events (but overall neutral transport over the entire time period). OVF shows no response to wind-wave resuspension.

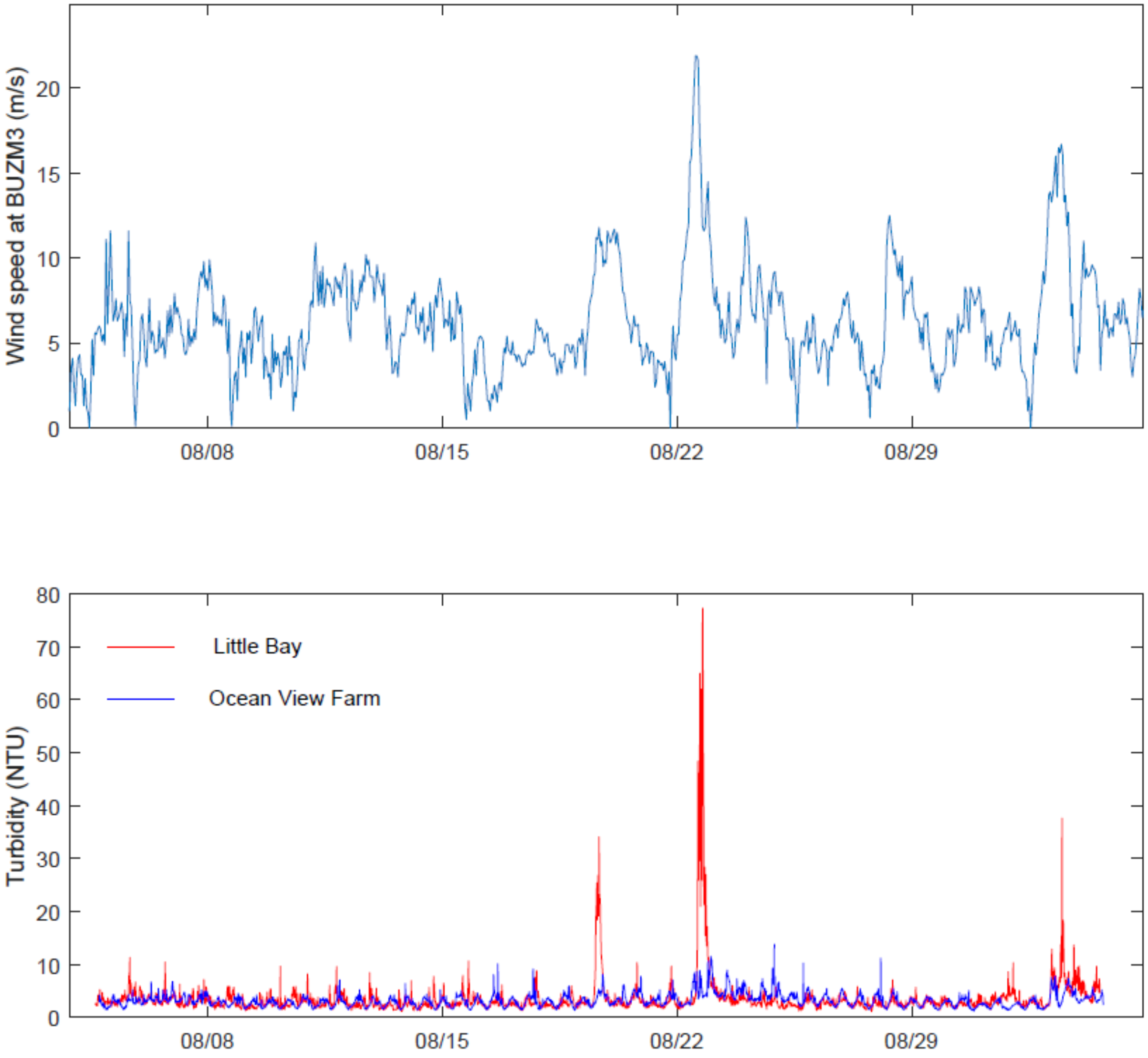
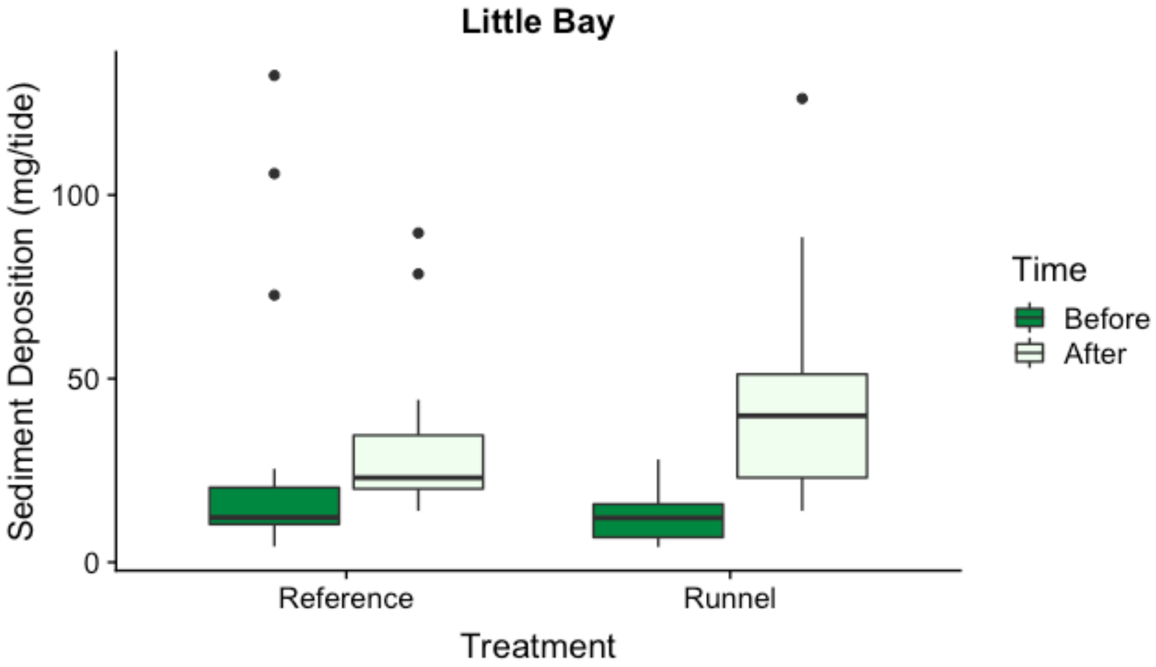


Figure 35. Sediment deposition as milligrams (mg) of inorganic sediment accumulated per flooding tide of 10-cm depth or more at LB. Boxplots show sediment deposition in before (dark green) and after (light green) periods, at both reference and runnel sites. Initial data exploration indicates that sediment deposition might increase within shallow water areas after creating runnels (p = 0.01).



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Salt Marsh Conservation and Adaptation in Allens Pond: A Case Study in Buzzards Bay

Suggested Citation: Besterman, A.F., W. Ferguson, R. W. Jakuba. 2022. Salt Marsh Conservation and Adaptation in Allens Pond: A Case Study in Buzzards Bay. 13 pages.

SUMMARY: The salt marshes around Allens Pond demonstrate how historic alterations and current stressors are degrading salt marsh habitat throughout the Northeast U.S. They are also illustrative of the multiple strategies at different scales that can be used to facilitate adaptation in order to retain valuable salt marsh habitat. This report describes the existing conditions and stressors facing this marsh and the various conservation activities undertaken by multiple organizations and agencies.

1. Background

Figure 1. Salt marsh at Ocean View Farm within Allens Pond provides habitat and resources for people and animals, including the threatened species Saltmarsh Sparrow (nest shown here). Photos: Alice Besterman

Coastal wetlands including salt marshes are critical ecosystems providing benefits to fish and wildlife, invertebrate animals, and people through resource provisioning, water quality improvement, and coastal defense (Fig. 1). Salt marshes around the world, and especially in the Northeast U.S., are experiencing rapid loss as a result of complex, interacting factors. Accelerating sea level rise is the primary stressor for southeastern New England marshes. Higher high-tides increase the frequency and length of inundation. As a result, soils become waterlogged, and plants become stressed and begin to die back. While some marshes have the natural ability to increase their vertical elevation at the same pace as sea level rise, many marshes in southeastern New England do not have this capacity. This is because these marshes are experiencing especially high rates of sea level rise, have low suspended sediment supply in flooding waters, and are not vertically accumulating biomass at a sufficient rate to match rising seas.

Horizontal migration of a salt marsh can compensate for an inability to vertically accrete — with the marsh moving inland as an alternative adaptation to sea level rise. Migration is possible where there is a gentle slope between marsh and adjacent uplands. However, in New England the transition between marsh and upland is too steep in many places to allow migration. Along many coastlines hardened infrastructure has been placed into this migration zone, including walls, roads, and buildings, further limiting migration. Rising seas and hardened infrastructure create a "coastal squeeze" on salt marshes, leading to erosion and reducing capacity for adaptation.

Marsh loss is exacerbated by interactions between sea level rise and historic modifications made to marshes by people. Modifications including ditches, "open marsh water management", culverts, and agricultural infrastructure such as embankments have altered the fundamental shape and structure of marshes. Interactions between sea level rise and these modifications can lead to ditch expansion and conversion of vegetated marsh to shallow water areas (Fig. 2).

Figure 2. Types of marsh loss affecting southern New England marshes: ditch expansion (left), interior shallow water expansion (center), edge or bank loss (right). Photos: Rachel Jakuba, Alice Besterman, and Chris Neill.

Other stressors also negatively impact marshes. Nitrogen from agriculture and sewage enters estuaries and floods marshes, decreasing marsh resilience. High nitrogen can enhance microbial decomposition, oxidizing the organic peat in marshes which provides critical elevation capital. High nitrogen also leads to a weakened root structure, and marsh edges can fracture and cleave off as a result. Marsh edges can erode from wind-waves that undercut banks and lead to marsh cleaving (Fig. 2). An overabundance of herbivorous crabs has degraded some New England marshes. There is additional concern among resource managers that extensive burrow networks created by crabs might weaken soil structure in areas where vegetation is stressed or has already died back.

Addressing the problem of marsh loss requires an adaptive, systems approach that considers multiple stressors acting at different spatial and temporal scales. Individual conservation organizations must decide how to invest limited resources, and therefore which marshes and which stressors are most critical to address. Partnership and collaboration provide a mechanism to tackle multiple issues at once. In Buzzards Bay, multiple organizations and agencies working across southern New England have partnered to conserve, adapt, and restore a large salt marsh complex in Allens Pond. In this short report we detail the existing conditions and stressors facing this marsh, the various conservation activities undertaken, and the rationale behind decisions.

2. Allens Pond: Current Condition

Allens Pond is a back-barrier salt pond connected to Buzzards Bay by a narrow tidal inlet (Fig. 3). The marsh in Allens Pond is one of the largest contiguous systems of salt marsh in Buzzards Bay. In addition, it provides some of the most important habitat for Saltmarsh Sparrows in Buzzards Bay, and is used by other marsh-dependent wildlife such as Willet, Diamondback Terrapin, and Seaside Sparrows. The marsh is surrounded by extensive, low-lying, and mostly undeveloped upland and agricultural hay fields.

The salt marshes in Allens Pond exhibit signs of stress similar to many southern New England marshes. The vegetation and elevation within the Ocean View Farm marsh (main focus of this report, Fig. 3) has been studied in detail (Jakuba et al. 2022), and is likely similar to marshes across the Allens Pond complex. Ocean View Farm is dominated by the "low marsh" species *Spartina alterniflora* (73% relative cover), while "high marsh" species less tolerant of flooding (*Distichlis spicata, Juncus gerardii, Spartina patens*) represent only 27% relative cover.

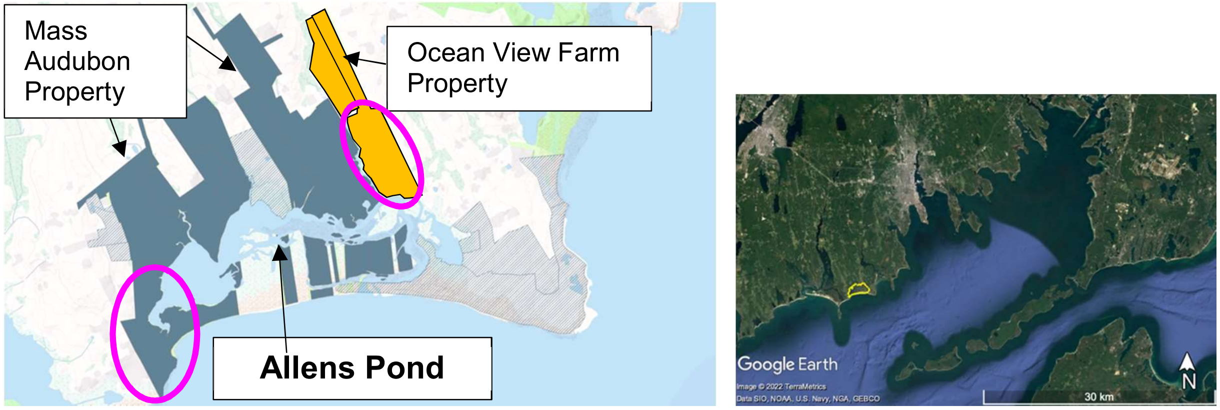

Figure 3. Left: Map of Allens Pond properties and focal zones for conservation. Blue-gray polygons show Mass Audubon-owned properties, the gold polygon shows the Ocean View Farm property with parcels owned by Dartmouth Natural Resources Trust and Round the Bend Farm outlined (boundaries approximate). Magenta circles show the conservation focus areas within Ocean View Farm (upper right) and the western side of Allens Pond (lower left). Map adapted from Mass Audubon Land Conservation StoryMap. Right: Buzzards Bay with Allens Pond marshes outlined in yellow.

The marsh surface is 84% vegetated, with 16% covered by bare peat or shallow water. The Buzzards Bay Coalition (BBC) is currently studying marshes around Buzzards Bay, and the vegetative cover at Ocean View Farm is below the 25th percentile of these marshes. The marsh sits at a relatively low elevation, with only 53% of the platform above mean high water (based on field surveys of elevation). This elevation also places Ocean View Farm below the 25th percentile of marshes around Buzzards Bay.

Despite current conditions at Ocean View Farm, the marsh remains an ecologically important resource. As a result, multiple conservation organizations have recognized Allens Pond as a priority salt marsh within Buzzards Bay for conservation and adaptation projects. These projects address stressors with scale-specific conservation strategies operating at three levels: a watershed-scale inclusive of the entire Allens Pond sub-estuary and sub-watershed, a landscape-scale inclusive of the marsh and its surrounding upland habitats, and a marsh-scale inclusive of the marsh platform (Fig. 4). Organizations have worked individually and in collaboration to tackle multi-scale stressors through land protection, watershed management, and adaptation and restoration.

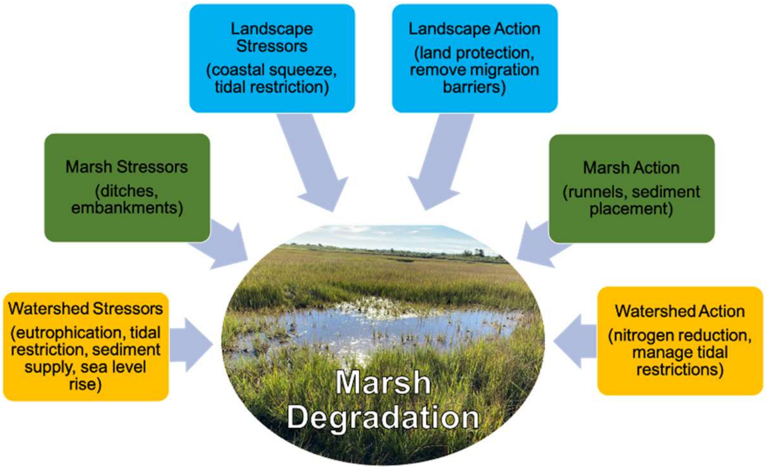

Figure 4. Main stressors on southern New England marshes at three spatial scales (watershed, marsh, landscape), and examples of conservation strategies applied at these same three scales. Note tidal restrictions can stress marshes at a landscape scale (e.g., undersized culvert), or at the scale of a watershed (tidal inlet).

3. Land Protection

Land protection is a critical first step in conservation for watershed, landscape, and marsh scales. Mass Audubon has been growing the Allens Pond Wildlife Sanctuary for decades by acquiring donated parcels of land and establishing conservation restrictions that provide permanent protection for conservation values. The Ocean View Farm property was a key missing piece of protection within Allens Pond. When this property became available for purchase, BBC led a fundraising effort so collaborating organizations could buy the land, and create conservation restrictions. Ownership was transferred and conservation restrictions went into place in 2017. The property includes two parcels, one owned by Round the Bend Farm, and one by Dartmouth Natural Resources Trust (DNRT) (Fig. 3). The conservation restriction for the Round the Bend-owned parcel is held by BBC, and BBC and the Town of Dartmouth jointly hold the conservation restriction on the DNRT-owned parcel. Ocean View Farm includes marsh and upland habitat within the Allens Pond system. Protecting and conserving uplands adjacent to salt marsh is important for enabling marsh migration. The slope between Ocean View Farm marsh and adjacent upland is favorable, so protecting this upland has created an opportunity for migration. Upland land protection mitigates future potential risk from development, including stressors operating at larger spatial scales such as nitrogen-loading.

4. Watershed Management

Conservation strategies applied at a watershed-scale can reduce stress for all of the marshes within that watershed. While the effects of these conservation strategies may be less obvious than in-marsh restoration, they are equally important as a way to reduce stress (e.g., eutrophication, tidal restrictions), and bolster resilience (land-use change, tidal inlet management). For example, land-use change can be an effective tool to reduce nitrogen-loading within a watershed. And while tidal restrictions may apply to smaller-scale features such as undersized culverts, in Allens Pond the entire watershed is affected by the management of the inlet connecting the pond to Buzzards Bay.

4.1. Land Use

After DNRT took ownership of Ocean View Farm they transitioned land-use practices on the property. Previously, the upland was used for traditional agriculture (corn, with fertilizer use). In April 2018 DNRT converted fields from corn to hay (seed mix of 40% alfalfa, 45% timothy, 15% clover), and ceased any use of fertilizers. Mowing was only practiced twice per year, after nesting season to allow fields to be used by migratory birds such as Bobolink. Land use change stopped inputs of nitrogen from this property that would have resulted from traditional agriculture. The vegetation changes also provided habitat for songbirds and other wildlife. A second phase of conversion is underway now, with the goal of facilitating marsh migration. This is described in Section 5.2 below.

4.2. Inlet management

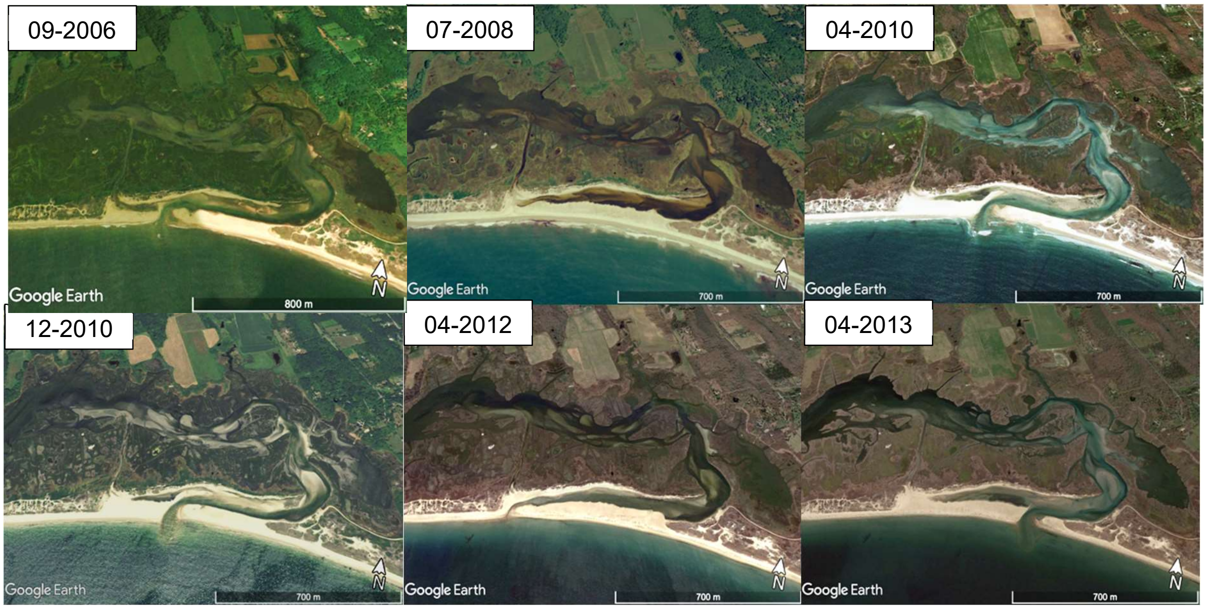

Figure 5. Time series of inlet closure and reopening. Full closures occurred in 2008, 2013, 2017, and 2021. The inlet is reopened at the eastern end of the barrier spit; it then migrates west, narrows and closes.

The tidal inlet presents one of the most direct threats to the salt marshes in Allens Pond; restricted tidal flow into and out of the pond can lead to the system holding water and stressing plants. This process would be stressful on its own, but in interaction with sea level rise presents a serious threat to Allens Pond marshes. The inlet naturally closes every few years and must be dredged to reconnect the pond to Buzzards Bay (Fig. 5). Based on existing documents, current managers believe the inlet has been managed by the local community and Town of Dartmouth cyclically for around 100 years. This cycle may be speeding up (thought to historically occur every 5–8 years, but more occurring every 3–5 years). Current management is led by the Allens Pond Association, a homeowner's group, and Mass Audubon who assists with the reopening and monitoring needed for permits.

Managing flow through the inlet is necessary for conserving salt marsh habitat in Allens Pond. Early in 2008 a full closure occurred, and the inlet remained closed through the growing season (Fig. 5). Back-barrier areas flooded from April through October. The consequences were dramatic[1]. Piping plover nesting was < 25% of a typical year (unpublished data, Mass Audubon), and Saltmarsh Sparrow, Seaside Sparrow, and Willet populations declined. Mass vegetation die-off occurred in the back-barrier salt marshes. It is unknown the exact extent of die-off, and how much of the Ocean View Farm marsh was lost — but the die-off included much of the low marsh throughout the Allens Pond complex. It took around 3 years for vegetation to recover. Saltmarsh and Seaside Sparrow populations took several years to recover. Mosquito breeding increased significantly during the closure, creating public health concerns. Given the ecological and public health importance of managing the inlet, several organizations and regulatory agencies have been

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[1] Buchsbaum, R. 2021. Responses and Recovery of Salt Marsh Vegetation and Birds in Southeastern Massachusetts to Two Hydrologic Events: a Tidal Restoration and an Inundation Event. *Estuaries and Coasts*. https://doi.org/10.1007/s12237-021-00918-1

engaged in conversations about how to streamline permitting and ensure sustainable management of the inlet. Since the inlet was reopened in late-2008, it has fully closed and been reopened three times (2013, 2017, 2021).

5. Adaptation and Restoration

Direct techniques can be used within the marsh complex and in adjacent upland areas to help restore salt marsh ecological function and adapt marshes to changing environmental drivers (e.g., climate change). At Ocean View Farm, and other marshes within Allens Pond, adaptation and restoration activities are underway both within the marsh (e.g., runnels to facilitate vegetation and hydrologic restoration), and in adjacent uplands (e.g., vegetation management, runnels to facilitate migration).

5.1. Marsh Platform

Across Allens Pond, marshes are experiencing interior shallow water expansion. On the DNRT-owned Ocean View Farm in-marsh conservation activities have focused on hydrologic restoration. BBC, working in collaboration with Woodwell Climate Research Center (Woodwell), Save The Bay (Narragansett Bay), and Bristol County Mosquito Control Project created runnels to drain surface water (reducing plant stress and mosquito-breeding habitat), and restore tidal hydrology and vegetation in 2020. In addition to creating runnels, clogged ditches were cleared to improve drainage, but only to the depth of a runnel (~ 12"). Runnels and ditch maintenance are also planned for the Mass Audubon-owned western side of Allens Pond (Fig. 3). Sites were selected according to the characteristics listed in Table 1 (Fig. 6).

Figure 6. Wenley Ferguson, Director of Habitat Restoration at Save The Bay, performs initial assessments at a shallow water area, measuring depths across the feature and testing the texture and firmness of the underlying peat. Photo: R. Jakuba.

Figure 7. Creation of runnels at Ocean View Farm. Top and Bottom Left: Bristol County Mosquito Control operator creates a runnel with a low-ground pressure excavator. Bottom Center: Staff and volunteers hand-dig a runnel. Bottom Right: Wenley Ferguson hand digs a runnel. Photos: R. Jakuba, A. Besterman, W. Ferguson.

Table 1. List of characteristics used to select runnel sites within Allens Pond marshes.

Marsh Characteristic	Good Candidate	Poor Candidate
Shallow water areas	• Impounded shallow water area is firm, with intact peat • Evidence of recent formation • Evidence of horizontal spread/expansion	• Impounded shallow water area is soft and covered with layer (>15 cm) of unconsolidated material • Evidence of older formation (40+ years) • Stable border, no signs of horizontal spread/expansion
Microtopography and water flow	• Embankments, levees, ditch spoils, and/or ditch plugs that create barriers to flow	• No evidence of topographic barriers to flow
Elevation	• Platform around shallow water feature is at or above mean high water • Impounded water is less than 20 cm deep	• Platform around shallow water feature is close to mean sea level • Bed of shallow water area sits greater than 20 cm below the platform

Five areas of shallow water were treated with runnels as a part of a controlled experiment (five reference and five runnel sites at Ocean View Farm). Runnels were created in phases, monitoring flow between phases to assess if depths, widths, and lengths of runnels were sufficient to drain shallow water areas. Runnels were excavated to a maximum depth of 12”, and maximum width of 12”. These maximum dimensions were used because they were the best option available using the low-ground pressure excavator. However, other runnel projects in New England have found that runnels dug wider than 12” but dug with the same maximum depth more successfully maintain drainage without regular maintenance, as they do not clog with sediment as easily. A sill was left in each runnel during the initial phase of excavation, acting as a “speed bump” to slow water flow and trap any unconsolidated sediments eroded off the platform. Runnels were constructed to be narrower and shallower where they intersected with unvegetated soils to limit the risk of erosion. Excavation was performed using a combination of a low-ground pressure excavator and hand-digging (Fig. 7). Bristol County Mosquito Control Project led the excavator-work, while staff and volunteers from BBC, Save The Bay, DNRT, and Bristol County Mosquito Control worked to complete hand-digging (Fig. 7).

Peat and salt marsh vegetation excavated from runnels and ditches at Ocean View Farm were used to create small elevated “habitat islands” that revegetate with low or high marsh vegetation depending on elevation (Fig. 8). Once revegetated, these islands can function as future habitat for marsh-nesting birds. The USFWS Atlantic Coast Joint Venture's Saltmarsh Bird Conservation Plan for the Atlantic Coast[2] identifies creating habitat islands, referred to as “microtopography”

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[2] Salt Marsh Bird Conservation Plan for the Atlantic Coast. 2019. Atlantic Coast Joint Venture.

or “mounds”, as a method to provide nesting area that is less prone to flooding. The methods described above used to create runnels (working in phases, leaving sills, specific depths and widths, and habitat-islands) are best practices developed through more than ten years of runnel projects led by partners. A more in-depth discussion of the theory and practice of runnels is available[3].

Runnels and hydrologic restoration can offer many benefits. The primary goal of this in-marsh technique is to restore tidal hydrology and restore vegetation. Shallow water areas can expand through reinforcing cycles; draining them can stop this process of expansion and prevent further losses. Runnels benefit public health by reducing mosquito larvae through draining water and providing fish better access to the upper marsh platform. They also can be used to reduce the height and density of *Phragmites australis* by increasing salinity of surface water in an area, and the habitat islands created from excavated peat have the potential to benefit nesting birds. As a part of the runnel study at Ocean View Farm, BBC and Woodwell are leading an intensive monitoring program to help quantify runnel efficacy across a range of initial conditions (Fig. 9).

In addition to these ecosystem functions, runnels can “prepare” sites for other adaptation techniques. If upper marsh areas convert to open water, then marsh migration may be less likely to occur even with a favorable slope. Techniques such as sediment placement (not used in Allens Pond) are less likely to be successful when applied to waterlogged soils. Thus, by restoring hydrology, other techniques are more likely to be successful. Using runnels to reconnect tidal flow through topographic barriers (e.g., embankments, ditch spoils) also helps mitigate flooding stress from sea level rise.


Figure 8. A newly created “habitat island” formed from peat excavated while digging a runnel. Photo: A. Besterman.

5.2. Migration Zone

With rising sea level, the need for marshes to increase their elevation is inevitable. This can either occur by increasing elevation *in situ* through natural (sediment and biomass accretion), or human-assisted (sediment placement) methods. *In situ* accretion is unlikely to be sufficient to combat rising seas because sediment supply is low in Buzzards Bay, biomass accretion is likely less than the rate of sea level rise, and sediment placement is not currently an approved technique in Massachusetts. Marshes can also increase their relative elevation through horizontal migration into uplands. Facilitating marsh migration is a major focus of adaptation work in Allens Pond marshes and includes runnels, vegetation management, and hardened-barrier removal. Each of these approaches is described in greater detail below.

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[3] Besterman, A.F., Jakuba, R.W., Ferguson, W., Brennan, D., Costa, J.E., & Deegan, L.A. 2022. Buying Time with Runnels: A Climate Adaptation Tool for Salt Marshes. *Estuaries and Coasts*. https://doi.org/10.1007/s12237-021-01028-8

A second phase of runnels is planned on the Ocean View Farm property that will extend higher into the marsh, and into waterlogged areas with high *Phragmites* cover. Bristol County Mosquito Control will lead this phase of excavation in coordination with Save The Bay. Introducing runnels into higher elevation zones can increase salinity and lower the water table, in addition to reducing the cover of invasive *Phragmites*. Runnels can prepare higher elevation soils, hydrology, and vegetation communities for marsh migration.

Figure 9. Buzzards Bay Coalition and Woodwell Climate Research Center Staff study vegetation, invertebrate fauna, and soils at a site with a runnel in 2021. Photo: R. Jakuba

DNRT, Mass Audubon, and Save the Bay have partnered on a project to facilitate marsh migration through multiple methods on both the Ocean View Farm property and western side of Allens Pond. On the Ocean View Farm property, efforts are focused on transitioning and preparing vegetation in the upland and ecotone between marsh and upland. Woody invasive species had colonized the shrub-dominated ecotone between the marsh and hay fields at Ocean View Farm. DNRT, Mass Audubon, and a team of volunteers removed large swaths of invasive woody shrubs (> 2 acres), leaving only native plants along much of the border of Ocean View Farm marsh in 2020. By reducing the density of woody vegetation in this zone, DNRT and Mass Audubon hope to give marsh grasses a competitive advantage to migrate. The next phase of conversion will occur in 2022, when an area of upland currently vegetated with hay will undergo an organic herbicide treatment to remove the hay grasses, and be replaced with native, more salt-tolerant grass species typically found in the marsh transition zone. The seed mix will use 12 species, including Coastal Panic Grass (*Panicum amarum*), Winter Bent Grass (*Agrostis hyemalis*), and Wild Rye (*Elymus canadensis*), as some examples. By re-introducing native, salt tolerant plants, the fields may be more likely to transition to salt marsh as sea level continues to rise than if they remained planted with species that would die with more frequent tidal flooding.

On the western side of Allens Pond, migration facilitation is planned using runnels and by removing hardened barriers to migration. Runnels have not yet been installed, but are planned to extend into the brackish marsh adjacent to the salt marsh in several locations. Removing hardened barriers is an important and widely practiced tool to facilitate migration. This could include the complete removal or relocation of walls, sheds, parking lots, and even buildings. On the western side of Allens Pond, remnant stone walls from historical agricultural-use border the marsh perimeter. Sections of these walls are planned for removal in four locations to allow better opportunity for vegetation transgression with sea level rise, and to reduce the height and density of *Phragmites australis* that dominates the brackish wetlands.

6. Synthesis and Conclusions

6.1 Synergy and Prioritization of Conservation Strategies

Using multiple conservation strategies acting at multiple spatial and temporal scales provides the best chance for helping salt marshes persist through the 21st century and beyond. Some strategies work well in combination, and some may be better to prioritize over others due to trade-offs in time and resources.

Large, watershed-scale hydrologic stressors can supersede landscape- or marsh-scale conservation strategies to affect salt marsh condition and resilience. In the case of Allens Pond, an unmanaged inlet could negate any restoration or conservation actions implemented within the marshes or uplands. The inlet needs to be managed to accommodate present-day and future sea level. If tidal flow becomes too restricted relative to regional sea level much of the intertidal zone could convert to open water. Similarly, watershed-scale stressors such as nitrogen-loading can impact how in-marsh actions like runnels perform. Watershed-scale drivers are important to consider independent from and in interaction with landscape- and marsh-scale conservation strategies.


Figure 10. Staff and interns from Buzzards Bay Coalition, Mass Audubon, Save the Bay, and Dartmouth Natural Resources Trust meet to discuss runnels and other conservation strategies at Ocean View Farm. Photo: R. Jakuba

Landscape-scale and marsh-scale strategies work well in coordination. Land protection is of primary importance among these, without which none of the work currently ongoing or planned at Ocean View Farm could occur. With both marsh and upland protected, coordinated strategies can be used across habitats to promote conservation and adaptation. Runnels are used as both a marsh-scale strategy to restore marsh vegetation, and as a landscape-scale strategy to help facilitate migration. Runnels are used in combination with vegetation management, and hardened-barrier removal to restore current conditions and accommodate future changes. However, it remains important to consider how runnels interact with landscape-scale stressors. For example, interactions between runnels and tidal restrictions from culverts, and between runnels and freshwater inputs from adjacent freshwater wetlands or groundwater seeps, remain important areas of research.

Where marshes are severely degraded, an organization may consider focusing on landscape-scale actions rather than smaller-scale, in-marsh strategies. For example, in one area of Ocean View Farm the marsh platform elevation is low (only about 0.25 m above local mean sea level). As a result, in-marsh runnels may only “buy” a small amount of time for the marsh. Where BBC and partners installed a runnel in this zone, water has successfully drained and some revegetation is occurring. However, the water table is still very high, sitting just below the soil surface. With expected sea level rise and the degraded condition of the peat in this area, the platform may convert to open water much sooner than other parts of the marsh (at the scale of decades), with or without the runnel.

Meanwhile, just upland of this runnel is one of the zones where DNRT removed extensive invasive woody vegetation. Without any additional action or planting, this zone has largely converted to native, salt-tolerant herbaceous species, e.g., Seaside goldenrod. In this example, where a low elevation platform is adjacent to a gentle, favorable slope for migration, an organization with limited resources might preferentially focus on facilitating migration through vegetation management, rather than try to restore tidal hydrology.

A significant benefit to the integrative work occurring at Allens Pond is the expanded pool of resources, expanded community of staff, members and volunteers, and opportunity for knowledge transfer. Our organizations have held site meetings, calls, and workshops through which we have strategized conservation actions (Fig. 10). We have begun sharing data in addition to general knowledge, and have shared volunteer and staff time to accomplish goals together. This model of synergistic conservation work tackling issues across multiple spatial and temporal scales has been productive, and as our efforts begin to show results over the next few years will hopefully prove to be a successful approach to conservation.

Evaluating Management Actions to Promote Salt Marsh Resilience

Rachel Jakuba, Linda Deegan, Joe Costa, Wenley Ferguson,
Neil Ganju, Diana Brennan, and **Alice Besterman**

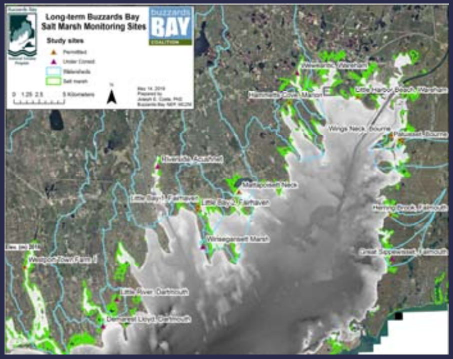
THE ISSUE

Salt marshes provide nutrient removal, storm and flood protection, carbon sequestration, and essential habitat for waterfowl and marine life. Currently salt marshes are adversely affected by sea level rise, eutrophication, legacy ditches, increased storm intensity, tidal restrictions, and low sediment supply.

Our recent work in the Westport Rivers revealed that by 2016 about half of the salt marsh area had been lost from six marsh islands. The recent rate of loss (2012–2016) was twice as high as earlier rates (1938–1962), which is alarming. Communities urgently want solutions to slow marsh loss.

PROJECT PARTNERS

buzzards BAY COALITION
Woods Hole Research Center
Buzzards Bay Project
SAVE THE BAY. NARRAGANSETT BAY est. 1970
USGS science for a changing world
BRISTOL COUNTY MOSQUITO CONTROL



Map shows the salt marsh areas (green) and locations of long-term salt marsh monitoring that began in 2019.

Conceptual diagram of runnel experiments (left). Before (top right) and after (bottom right) photos of a runnel project.

WHAT WE'RE DOING

This project brings together a unique team of researchers and practitioners to promote saltmarsh resilience: Buzzards Bay Coalition, Woods Hole Research Center, Buzzards Bay National Estuary Program, Save The Bay (Narragansett), U.S. Geological Survey, and Bristol County Mosquito Control Project. This project will take a two-prong approach to evaluate different types of management actions.

First, the use of runnels (shallow, meandering furrows that drain water off the marsh surface), will be assessed by synthesizing current knowledge and by performing new field experiments. In Rhode Island, runnels have drained impounded water off marshes, reversing marsh vegetation loss. However, the approach has not been tried across marshes in the various stages of degradation found in Buzzards Bay.

Second, the relationships between conservation strategies in the watershed, nutrient enrichment, marsh elevation, and salt marsh stability will be evaluated by combining geographic information with long-term water quality data and new data on the marsh areas. Salt marsh loss and watershed conservation land will mapped for nine sub-estuaries of Buzzards Bay. Models will be used to estimate nitrogen loading, sediment supply, and erosion pressure from wind and waves.

PROJECT FUNDING

SNEP Southeast New England Program
United States Environmental Protection Agency

FINDING SOLUTIONS

The significant loss of salt marsh habitat is a concern for natural resource managers as well as the public — both are seeing rapid changes in recent years throughout southeast New England. This project will provide guidance for communities struggling to slow marsh loss by testing runnel use and by developing information on what characteristics are associated with marsh resilience in Buzzards Bay. The results will provide a holistic picture of salt marsh status and aid strategic planning to promote salt marsh resilience in Buzzards Bay.

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New technique to save Buzzards Bay salt marshes being piloted in Dartmouth and Fairhaven

NEW BEDFORD, Mass.—The Buzzards Bay Coalition is working to address the problem of salt marsh decline on Buzzards Bay by assessing a restoration technique that has been shown to be effective in other places in the Northeast.

The project is a partnership involving the Coalition, the Woodwell Climate Research Center, the Buzzards Bay National Estuary Program, Save The Bay in Rhode Island, the U.S. Geological Survey, and the Bristol County Mosquito Control Commission. The team is working with local landowners—the Dartmouth Natural Resources Trust (DNRT) and the Town of Fairhaven—on the study.

The technique being tested could reverse losses in some marshes and help guide new restoration projects. The work is critical because salt marshes are not only beautiful but also vital natural resources. Marshes filter out pollution from reaching the Bay, provide habitat for wildlife, and protect homes from flooding. However, increasing stress from pollution and sea level rise is leading to the dramatic loss of many of these critical habitats, which further endangers the long-term health of the Bay.

“We can never fully improve and preserve Buzzards Bay and its water quality, if we stand by as the Bay loses its salt marshes. These marsh habitats play an essential role in sustaining a healthy Bay ecosystem, and over the past two decades, we’ve seen dramatic and accelerating losses of marshlands,” said Mark Rasmussen, president of the Coalition.

Rachel Jakuba, Ph.D., the science director for the Coalition, notes that some of the challenges facing salt marshes come from what are known as interior “die back areas”—places where increasing high tides are leaving more water stranded on the marsh, rather than draining away when the tide recedes. The standing salt water kills marsh plants that are adapted to dry conditions at low tide. In addition, these areas of impounded water create mosquito breeding habitat that can pose public health threats.

“These die back areas threaten the marsh. They expand over time, effectively eating the marsh from the inside out as these areas grow,” said Alice Besterman, Ph.D., the Coalition’s post-doctoral researcher who is coordinating the research of this promising restoration technique to shrink die back areas.

The restoration technique being tested to combat die back areas is known as runnelling, a process in which shallow, channels are dug in the marsh to aid the natural tidal flow and drain impounded water.

“The idea is for the standing surface water to drain out of these die-back areas, which should allow for vegetation to begin growing back, restoring other ecosystem properties,” said Besterman. The strategy has been employed in Rhode Island by project partner Save The Bay, but this marks only the second time it is being tried in Buzzards Bay.

The project team worked with local officials, conservation agents and landowners to evaluate twelve sites for their potential to benefit from runnelling, settling on salt marshes on Allens Pond in Dartmouth and Little Bay in Fairhaven, both of which have multiple die back zones. The pilot runnels were completed at Ocean View in late October; work at Little Bay will take place the week of Nov. 9.

“The salt marsh here at Ocean View Farm is home to several rare and endangered species,” said Linda Vanderveer, Land Manager for DNRT. “Seeing die back in the marsh is concerning, especially for the wildlife that depend on it for nesting, feeding, and shelter. We are excited to work with the Coalition and all of the project partners to try and restore the health of the marsh not only for the benefit of wildlife, but also so that others may benefit. It’s our hope that the runnelling technique will advance the science of salt marsh restoration on the Southcoast.”

The installation of the runnels takes place partly by hand and partly through the use of a specialized excavator operated by the Bristol County Mosquito Control Commission. The equipment is designed to minimize impact on marsh vegetation. In fact, it exerts less pressure per square foot than a human foot, making it possible to install the runnels quickly and with minimal impact to the environment.

The effect of the created runnels will be assessed as a part of multi-year study, including monitoring on “treatment” areas where runnels have been created, and “reference” areas where no action was taken. Before the runnels could be installed, Besterman and colleagues conducted a months-long study of the salt marshes— including soil composition, water levels, marsh levels, and plant surveys as well as other ecosystem properties. In all, the team gathered 69,000 water level measurements, 680 marsh elevation readings, and vegetation surveys at 400 plots. Gathered data will be used to assess whether and how the technique contributes to strengthening the health of the marshes and which marshes are good candidates for using runnels.

In addition to this project, the Coalition also is conducting long-term monitoring of 11 salt marshes from Westport to Falmouth in partnership with the Buzzards Bay National Estuary Program. “Looking at all of the salt marshes around Buzzards Bay, we have noticed areas of really rapid degradation in recent years. In some places, it’s happening very fast, and we’re trying to understand what factors are involved so that we can develop strategies to slow or reverse marsh loss,” Jakuba said.

Halting the decline of the Bay’s salt marshes not only will help efforts to improve water quality, but it will also protect critical habitat for myriad fish and shellfish species that spawn, grow and live in these areas. Coastal developments will also benefit, as marshes help to absorb the energy of ocean waves and absorb the temporary flooding caused by storm surges.

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The Buzzards Bay Coalition is a nonprofit organization dedicated to the protection, restoration, and sustainable use and enjoyment of Buzzards Bay and its watershed. The Coalition works to improve the health of the Bay ecosystem for all through education, conservation, research and advocacy, and is supported by more than 10,500 members.