IMPLEMENTING NATURE-BASED SOLUTIONS FOR WASTEWATER MANAGEMENT

San Francisco Bay Area Examples

SFEI San Francisco Estuary Institute

BACWA BAY AREA CLEAN WATER AGENCIES

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INTRODUCTION

This report highlights key lessons learned from constructed treatment wetland projects across the San Francisco Bay Area. Such systems are a type of nature-based solution that integrates natural processes with engineered solutions to improve water quality. These systems may also be designed to provide additional benefits like wildlife habitat, flood protection, and recreational amenities.

In response to concerns stemming from wastewater-related nutrient enrichment of San Francisco Bay, the San Francisco Regional Water Quality Control Board (Water Board) issued the second iteration of its Nutrient Watershed Permit in 2019 (San Francisco Bay Regional Water Quality Control Board 2019). One term of this permit stipulated that the thirty-seven agencies that discharge treated wastewater to San Francisco Bay were required to perform a Regional Evaluation of Potential Nutrient Discharge Reduction by Natural Systems, focusing on nature-based solutions (NbS) to decrease nutrient loading from wastewater facilities.

In coordination with Bay Area wastewater agencies and the Water Board, the San Francisco Estuary Institute (SFEI) conducted a comprehensive evaluation of NbS opportunities. This supplemental report compiles case studies from five Bay Area wastewater agencies, showcasing their initiatives in applying NbS for water quality management. These projects provide critical insights for regional wastewater managers looking to incorporate NbS into their nutrient management strategies, offering additional benefits such as habitat enhancement, sea-level rise adaptation, and environmental education. Moreover, these projects highlight the challenges of NbS implementation and maintenance, a key concern for regulatory agencies and resource managers.

This report distills key background information and details the successes, challenges, and lessons learned from the case studies. Its primary aim is to enhance understanding of the opportunities and constraints related to NbS for nutrient reduction. The specific goals of these case studies include:

- Identifying viable NbS types suitable for wastewater facilities.
- Highlighting data gaps regarding nutrient load reductions from existing NbS in the region.
- Sharing operations and maintenance hurdles and potential solutions.
- Evaluating the feasibility and cost-effectiveness of various NbS strategies.
- Uncovering regulatory and governance challenges tied to implementation and ongoing maintenance.
- Highlighting ancillary benefits and potential adverse effects.

Bay Area agencies have a longstanding history of using NbS for wastewater treatment. Traditional methods like open water treatment wetlands have consistently proven effective in polishing municipal wastewater. Additionally, recent research underscores the effectiveness of horizontal levees in treating wastewater and the high-concentration waste products from the reverse osmosis process (known as reverse osmosis concentrate or ROC) (Cecchetti et al. 2020a, Stiegler 2022). As the region seeks resilient and sustainable approaches to reduce nutrient loading from municipal wastewater discharges and increases the rate of wastewater recycling for potable use, NbS represents a viable alternative to traditional gray infrastructure.

These case studies serve as a resource for regulatory bodies and wastewater managers, providing practical insights and demonstrating the potential of nature-based solutions for enhancing wastewater treatment in the San Francisco Bay Area. For additional information regarding the regulatory context of these and other projects refer to a 2017 Staff Report by the Water Board and a recent white paper developed by the San Francisco Estuary Partnership regarding regulatory pathways for shoreline NbS projects (California Regional Water Quality Control Board and San Francisco Estuary Partnership 2017, Sunahara and Nutters 2024).

LAS GALLINAS PONDS

Las Gallinas Valley Sanitary District successfully uses a system of freshwater storage ponds to circulate tertiary treated effluent, creating valuable freshwater habitat for diverse bird species and supporting a substantial water reuse program. Challenges include maintaining optimal water quality and vegetation management, underscoring the need for careful planning and dedicated funding to support ongoing maintenance.

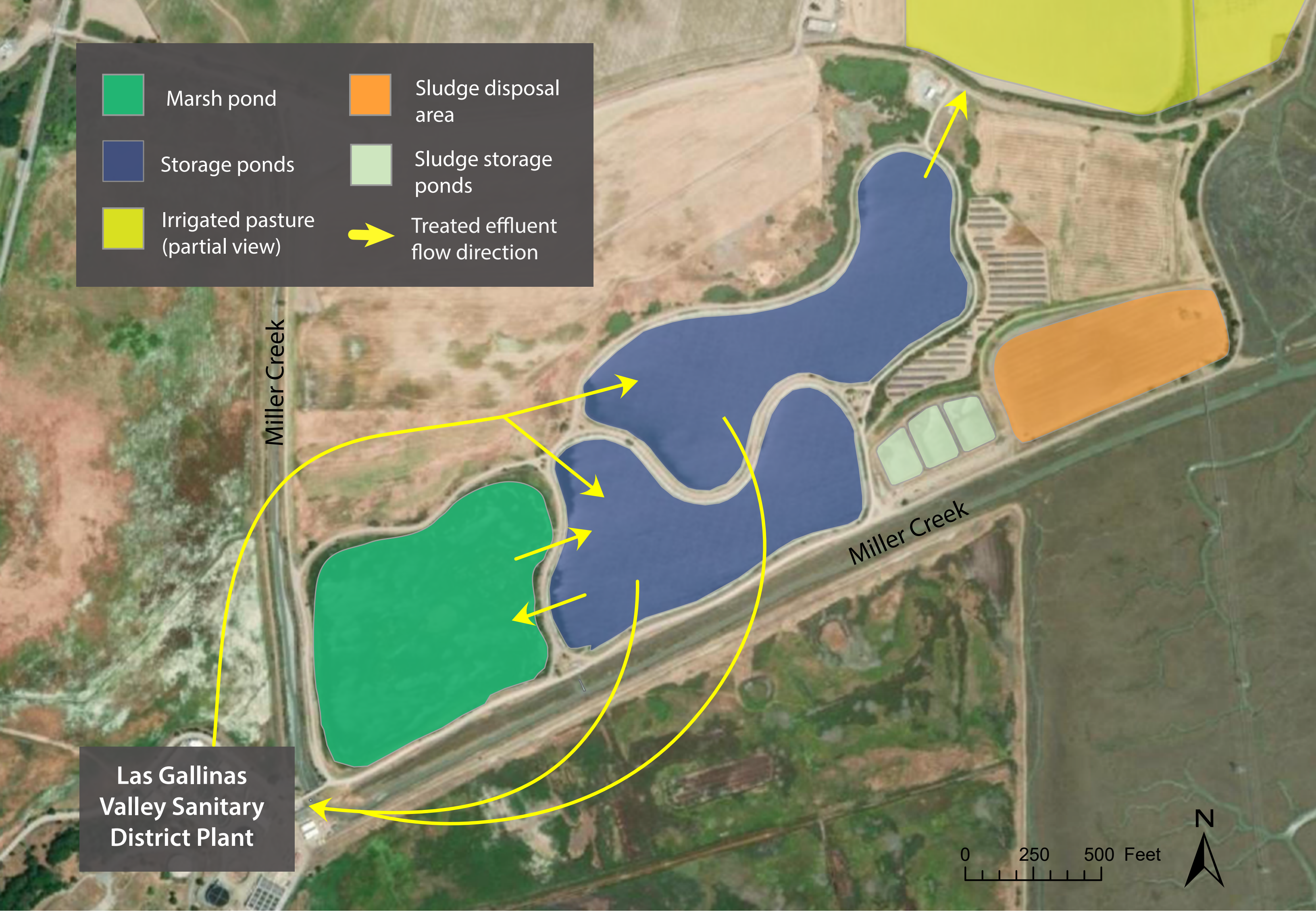
LOCATION: San Rafael, CA

MANAGED BY: Las Gallinas Valley Sanitary District

CONFIGURATION: The site features a 20-acre freshwater marsh pond and 40 acres of storage ponds.

OVERVIEW & HISTORY: In 1984, Las Gallinas Valley Sanitary District (the District) established ponds as part of its Wastewater Treatment Reclamation Project to meet a discharge permit requirement that called for reductions in dry season discharges to San Pablo Bay. This permit allows the District to discharge tertiary treated effluent into Miller Creek during the rainy season as an alternative to a deep-water discharge method. The chlorinated water from the treatment plant is sent to the storage ponds where it undergoes natural dechlorination. The effluent from the storage ponds is used for pasture irrigation and maintaining the freshwater marsh pond. During the dry season, some water from the storage ponds is returned to the District's Recycled Water Facility to undergo further treatment before being delivered to recycled water customers.

To maintain a steady flow volume through the treatment plant, during periods of low flow at night, water from these storage ponds is recirculated back to the plant. The District also actively manages water circulation by continuously pumping a small amount of water between the storage ponds and the marsh pond to prevent algal blooms and curb mosquito breeding. The storage ponds and the marsh pond provide essential freshwater habitats for a variety of bird species, with the marsh pond being specifically managed for wildlife conservation. Additionally, a section of the Bay Trail that wraps around the ponds provides public access and recreational opportunities.



The 20-acre freshwater marsh pond is connected to 40 acres of effluent storage ponds, with continuous water circulation between the two to maintain flow through the marsh.

SUCCESSES

HABITAT: The District works with the Marin Audubon Society to maximize habitat for birds, and the ponds are a popular birding destination. People have observed hundreds of species at the site, including a variety of waterfowl, shorebirds, songbirds, and raptors. Black-crowned night herons roost on the marsh pond islands, protected from predators. Rails, gallinules, and bitterns forage around the pond edges and shorebirds like the Wilson's Snipe visit the marsh pond when water levels are low. The ponds even attract mammals such as river otters.

WATER REUSE: The District has two successful water reuse programs. The first program uses treated secondary effluent to operate the marsh pond and storage ponds, as well as to irrigate the 200-acre pasture. The second program further treats plant effluent or water from the storage ponds in the District's Recycled Water Facility (RWF) to produce disinfected tertiary recycled water for delivery to Marin Municipal Water District and North Marin Water District, which distribute the water for a variety of approved uses. The RWF has the capacity to produce over five million gallons per day.

ENVIRONMENTAL EDUCATION: The District offers tours of the treatment plant and reclamation area. There is public trail system around the ponds, making it a valuable recreational amenity.T he trail is frequented by birders, hikers, bicyclists, and students on school field trips. The District estimates that roughly 20,000-30,000 people visit the ponds every year.

CHALLENGES & LESSONS LEARNED

VEGETATION: The marsh pond offers crucial habitat for wildlife; however, the dense growth of cattails has led to mosquito concerns. This issue necessitated a compromise between the Marin/Sonoma Mosquito and Vector Control District and the Marin Audubon Society regarding vegetation management. The extent of cattail growth and the operating water level both influence the types of bird species that live in the marsh pond.

KEY LESSONS: To mitigate mosquito populations, it is essential to proactively manage vegetation in marsh ponds, such as periodically trimming back cattails, to discourage mosquito establishment and ensure access for mosquito abatement districts to apply chemical or biological controls effectively.

Looking west across the marsh pond.

MAINTENANCE: The ponds and levees require regular maintenance, including the removal of invasive plants and overgrowth, dredging, and filling potholes in the levees. The District has a vegetation management plan, and it hires contractors as needed for certain maintenance activities such as cattail removal. While obtaining maintenance permits has been straightforward and unproblematic for the district, funding for these maintenance activities remains limited.

KEY LESSONS: Future projects should establish a dedicated funding stream to ensure the availability of financial resources for the inevitable maintenance costs of treatment wetlands.

WATER QUALITY: The Las Gallinas Wildlife Ponds face water quality concerns primarily due to high bacteria levels from bird activity. The bacteria levels prevent direct discharge into Miller Creek. Instead, water is cycled back to the treatment plant. Good circulation typically prevents significant blooms of algae and aquatic plants, although minor blooms have been noted during summer. While nutrient removal from these ponds has not been quantitatively assessed, documenting this could provide valuable insights into nutrient removal efficiencies, informing similar NbS projects.

KEY LESSONS: Future projects should prioritize effective water circulation and maintain higher water levels in ponds to prevent algal blooms and help manage emergent vegetation growth. Where possible, water quality parameters should be measured in open water treatment wetlands to enable discharges to receiving waters, rather than requiring recirculation through the treatment plant.

Levee and storage pond.

ELLIS CREEK WETLANDS

The Ellis Creek Treatment Wetlands demonstrate the critical importance of design in treatment processes. Aesthetic considerations in pond design must be balanced with functional needs to prevent issues like hydraulic short-circuiting and inadequate mosquito control. Designs should prioritize optimizing water flow and vegetation management to ensure both ecological benefits and operational efficiency.

LOCATION: Petaluma, CA

MANAGED BY: City of Petaluma

CONFIGURATION: The site features 15 acres of treatment wetlands, a 31-acre polishing wetland divided into four ponds, and 160 acres of oxidation ponds.

OVERVIEW & HISTORY: The City of Petaluma opened the Ellis Creek Water Recycling Facility in 2009, replacing Petaluma's Hopper Street wastewater treatment plant. Located southwest of Petaluma on Lakeville Highway, the site has a range of NbS elements, including ~160 acres of oxidation ponds created in the early 1970s. Construction of the Ellis Creek Facility in 2009 included the establishment of 30 acres of treatment wetlands (later reduced to 15 acres) and 31 acres of polishing wetlands. Treated wastewater first flows into the oxidation ponds, then into the treatment wetlands. Effluent from the treatment wetlands is pumped to the plant for tertiary treatment or to the polishing wetlands. The polishing wetlands are designed to remove algae, final traces of organic materials, and dissolved metals.

The site also features seasonal wetlands and tidal marshes, developed after a levee breach around 1999 (Sonoma Land Trust 2023). Ellis Creek runs between the polishing wetlands and other treatment ponds. Publicly accessible trails, including a connection to Shollenberger Park, provide excellent opportunities for wildlife viewing. The Ellis Creek Facility produces 6,800 acre-feet of recycled water annually, which is used to irrigate agricultural land, landscaping and playing fields at schools, golf courses, and parks in the summer. Effluent is discharged to the Petaluma River in the winter.

Diagram of the Ellis Creek wetlands. The site includes an aerated lagoon, oxidation ponds, treatment wetlands, and a 31-acre polishing wetland, with effluent discharged into the Petaluma River.

SUCCESSES

HABITAT: The treatment wetlands and polishing wetlands provide habitat for a wide range of wildlife. Roughly 120 bird species visit the site annually. These ponds recreate freshwater marsh habitat that historically existed in the area (Baumgarten et al. 2018). Point Blue Conservation Science conducts bird surveys in both the polishing and oxidation ponds.

PUBLIC ACCESS: The facility features a trail system around the polishing wetlands, which the public uses daily for recreation for activities such as bird watching, dog walking, exercising, and more. The trail system also connects to popular trails at Shollenberger Park and Alman Marsh. The Petaluma Wetlands Alliance offers a monthly tour of the area.

MAINTENANCE: Petaluma allocates about $400,000 each year to manage the vegetation and control mosquitoes at the oxidation ponds, treatment wetlands, and polishing wetlands. This budget covers mechanical and manual vegetation removal and the aerial dispersal of mosquito control chemicals via helicopter, in collaboration with the Marin/Sonoma Mosquito and Vector Control District. Petaluma budgets additional funds for years with larger vegetation removal projects. All maintenance activities are supported by a dedicated fund established for the upkeep of the entire facility.

WATER QUALITY IMPROVEMENT: The oxidation ponds at the Ellis Creek Wastewater Facility pre-date the polishing wetlands and serve as a critical element of the wastewater treatment process. Nutrient levels in these ponds are generally low, as monitored by the facility, and subsequent treatment wetlands help to further reduce nutrient levels and control algae growth before the water is pumped back to the plant for tertiary treatment or to the polishing wetlands. The polishing wetlands limit algal growth and reduce total suspended solids and copper concentrations, completing the final polishing step before the water is discharged to the river.

Additionally, the system significantly reduces the amount of chlorine and sodium bisulfite (SBS) required for treatment and permit compliance, thereby lowering both chemical use and maintenance costs. The polishing wetlands achieve high rates of dechlorination, thus reducing SBS demand. However, SBS is dosed continuously in order to document permit compliance with low residual chlorine limits.

CHALLENGES & LESSONS LEARNED

VEGETATION AND MOSQUITOES: The Marin/Sonoma Mosquito and Vector Control District applies a substantial amount of chemicals to control mosquito populations in the treatment wetlands and oxidation ponds. Dense tules within these areas facilitate mosquito breeding and obstruct mosquitofish from preying on mosquito larvae. City of Petaluma staff occasionally trims this overgrowth, although it proves challenging to completely clear. Additionally, the shallow depth of the polishing wetlands, at about two feet or less, precludes the use of an aquatic weed harvester. Due to a lack of aeration, which caused septic conditions in the wetland, the treatment wetland at Pond 10 (approximately 15 acres) was converted back into an open-water oxidation pond in 2015. Pond 9 is still a treatment wetland, but a swath of vegetation was removed to create an open water area that provides natural aeration.

KEY LESSONS: Vegetation and mosquito management challenges at the Ellis Creek ponds highlight the need for strategic design. Future projects should consider creating ponds with areas deeper than one meter to facilitate the use of aquatic weed harvesters or designing for adjustable water depths to enhance vegetation control and maintenance. Additionally, incorporating open water areas in planting designs can improve water circulation and reduce mosquito breeding. Also important is a dedicated maintenance fund to sustain these management activities.

The salt marsh harvest mouse-shaped polishing wetlands.

POLISHING WETLAND DESIGN: The design of the polishing wetlands was largely influenced by aesthetic considerations (the wetlands are intended to resemble a salt marsh harvest mouse from an aerial view), which has introduced functional challenges. The unique shape of the pond edges creates low flow zones, and the overall water flow within the ponds is suboptimal, leading to hydraulic short-circuiting. Moreover, managing water flow is difficult due to the almost triangular shape of the ponds; water enters at the narrowest part of the triangle and depends on natural circulation to move through the broader areas.

KEY LESSONS: The Ellis Creek Wetlands emphasize the importance of considering system flow and the ease of manipulating flow rates in future projects. A more linear and straightforward flow path, coupled with more open water and less densely planted areas, would facilitate better control of water flow rates and ensure more optimal circulation within the ponds.

MOORHEN MARSH

Moorhen Marsh was the first treatment wetland in the region and is a valuable local educational resource, offering schools and public tour groups the opportunity to explore the ecological and societal benefits of engineered wetlands. However, maintenance and permitting have become increasingly challenging over the past decade. Activities such as dredging, levee maintenance, and revegetation efforts have presented significant hurdles.

LOCATION: Martinez, CA

MANAGED BY: Mountain View Sanitary District

CONFIGURATION: The site features a 20-acre constructed wetland called Moorhen Marsh. It is made up of six ponds and a connecting slough.

OVERVIEW & HISTORY: Constructed in 1974, Moorhen Marsh was the first West Coast marsh entirely fed by wastewater effluent. Mountain View Sanitary District (MVSD) Wastewater Treatment Plant discharges treated wastewater to Moorhen Marsh, which then drains into Peyton Slough and McNabney Marsh. The marsh improves water quality, provides wildlife habitat, and offers opportunities for environmental education and recreation.

Diagram of Moorhen Marsh. The 20-acre constructed wetland is made up of six ponds and a connecting slough to McNabney Marsh.

SUCCESSES

PLANTING: In 2017-2018, MVSD carried out the Moorhen Marsh Western Pond Turtle Enhancement Project, which improved marsh conditions through levee repairs, pond dredging, and restoring native vegetation. The improvement project required the removal and replanting of native riparian and upland plants throughout the marsh. Afterward, the site was monitored for five years through annual plant counts to ensure plant establishment and survival as well as successful establishment of floating islands.

WILDLIFE: The wetland provides valuable habitat for wildlife in an area fragmented by an interstate highway and a neighboring refinery. The site hosts an array of wildlife, including numerous bird species, river otters, western pond turtles, beavers, deer, and foxes. The marsh is regularly used as a site for training biologists on methods for surveying and protecting wildlife.

WATER QUALITY IMPROVEMENT: Moorhen Marsh successfully removes nutrients from MVSD's wastewater discharge. Effluent containing ~25 mg/L NO3 decreases by roughly 13% to 40% in the winter and summer months respectively.

ENVIRONMENTAL EDUCATION: The site provides an excellent platform for environmental education. The marsh is open to the public by appointment and has several interpretive signs. MVSD also offers tours and educational programs to schools and community groups. Around 1,500 students visit Moorhen Marsh annually, where they learn about native wildlife and pollution prevention, tour the wastewater facility, and get hands-on experience with simple water quality testing.

CHALLENGES & LESSONS LEARNED

GENERAL MAINTENANCE: The pond designs and piping system at Moorhen Marsh present several maintenance challenges. The pipes that connect the ponds are positioned several feet away from the pond edges, rather than near the levees. This placement means that the pipes cannot be accessed from the shore for maintenance. Consequently, when the pipe screens become blocked, the only way to clear them is by deploying divers. This necessitates hiring divers approximately every three years to carry out routine maintenance. Additionally, some control valves are installed well above the water level, making them difficult to reach and operate from maintenance boats. These design elements complicate the overall upkeep of the system.

KEY LESSONS:
Placing infrastructure like control valves and pipes in easy-to-access locations can reduce maintenance costs.

VEGETATION: In 2017, MVSD initiated a series of pond and levee maintenance efforts, which triggered the need to obtain a Streambed Alteration Agreement permit from the California Department of Fish and Wildlife. Meeting the permit conditions has proved difficult. For instance, staff were required to clear much of the vegetation to properly inspect the levees. Post-replanting, MVSD was required to achieve an 85% vegetation survival rate annually. This target was challenging to meet without the ability to replant repeatedly. Additionally, local wildlife such as beavers and geese have damaged trees and native plants, and in drought years riparian and upland vegetation struggled to survive, requiring manual watering through the summer months.

KEY LESSONS: It is essential to consider permitting requirements and associated budget requirements for ongoing vegetation maintenance to ensure the site's success. Future projects might use protective measures like caging trees and other plants to prevent wildlife damage. Implementing irrigation systems may also be essential when planting species that are less drought-tolerant and unable to withstand prolonged dry conditions.

PERMITTING: The Western Pond Turtle Enhancement Project's Streambed Alteration Agreement was a five-year permit with possible extension if vegetation survival was not at least 85% at the annual plant count. Contracted biologists determined plant survival through hand counting, and they also assisted with the annual reporting requirement. MVSD used significant staff time and contracted support for manual weeding and invasive vegetation removal, so that the native vegetation was protected. Any work in the marsh had to be carefully scheduled to account for nesting seasons, and there were also provisions regarding the use of equipment and herbicide.

KEY LESSONS:

Future projects should budget and anticipate permitting needs for vegetation and site maintenance to help ensure success of the site. Irrigation needs must be considered if there is a plant survival requirement.

DOWNSTREAM FLOW: Downstream of Moorhen Marsh, a private company owns and operates a tide gate to help ensure adequate water levels at their pickleweed mitigation marsh (Rhodia Marsh). Rhodia Marsh requires frequent tide gate manipulations to ensure sufficient water for vegetation growth (California Regional Water Quality Control Board: San Francisco Bay Region 2017). However, this creates flow issues in Moorhen Marsh—namely, it raises the water level in McNabney Marsh, which then raises the water level in Peyton Slough. The higher water level in Peyton Slough slows or halts discharge from Moorhen Marsh, even pushing water upstream into Moorhen Marsh.

KEY LESSONS: Projects, even in distant areas of a marsh complex, can impact the function of the marsh. Site managers and authorities need to work with all stakeholders to develop projects in a collaborative manner to address the needs of the entire marsh complex. MVSD is currently working on a collaborative framework for a marsh complex management plan with other stakeholders, including the tide gate owner, East Bay Regional Park District (co-owner of McNabney Marsh), Contra Costa Mosquito Abatement District, and the Water Board.

Fat Slough.

MAINTENANCE FUNDING: Securing maintenance funding for treatment wetlands like Moorhen Marsh has historically been challenging. Initially, water quality compliance points were located upstream of where the water entered the marsh, resulting in minimal motivation to maintain the system effectively. However, MVSD has recently shifted the point of compliance from the effluent of the treatment plant to the effluent exiting Moorhen Marsh, which may help in prioritizing and justifying the need for consistent maintenance funding.

KEY LESSONS:

Site managers should consider formally including treatment marshes as components of the treatment process. This could potentially increase eligibility for established annual maintenance funding. Such planning could lead to sustained funding and better overall maintenance.

FLOATING ISLANDS: Floating islands were originally installed to help reduce algal blooms at Moorhen Marsh. The islands successfully reduced algae, but are difficult to maintain. Though they are anchored, they still move around during storms or high winds, and because they are anchored separately in the middle of the ponds, they are only accessible via boat. The floating islands provide valuable wildlife habitat, but wildlife have also become a significant nuisance as they eat newly planted vegetation, making it hard to establish native plants on the islands. Although originally installed for algae control, the floating islands also contribute to nutrient reduction, which has prompted investigation into modifying the islands to increase nutrient reduction efficiency. A project was identified to install additional islands using a different shape that would allow for them to be anchored together and installed in a narrow slough area where all flow would be forced through their root systems. The project also includes defining a monitoring system to better quantify the effectiveness of the new islands' nutrient removal efficiency. With the island anchored together, a floating walkway will be incorporated to allow for ease of maintenance and easier installation of exclusionary fencing.

KEY LESSONS:

Floating islands can reduce algae blooms, but site managers should carefully consider their design. Exclusionary fencing or similar methods should be considered to protect vegetation from wildlife. The location and logistics for accessing the islands for maintenance should also be considered.

Floating islands.

HAYWARD MARSH

Hayward Marsh, which no longer functions as a treatment wetland, illustrates both the value and challenges of using treated wastewater for habitat and water quality enhancement. To avoid some of the pitfalls encountered at Hayward Marsh, future projects should clearly identify the priority management goals of the wetland and ensure dedicated maintenance funding in shared management contexts.

LOCATION: Hayward, CA

PROJECT PARTNERS: East Bay Regional Park District, Union Sanitary District

CONFIGURATION: This facility featured a 145-acre treatment wetland with five managed basins and 15 islands.

OVERVIEW & HISTORY: In 1985, the East Bay Regional Park District (EBRPD) constructed Hayward Marsh within a repurposed salt pond, intending for it to serve as a demonstration wastewater polishing wetland. The design included three freshwater treatment basins aimed at improving water quality and two basins for brackish wetland habitat. Union Sanitary District (USD) was responsible for supplying the marsh with secondary treated wastewater from the East Bay Dischargers Authority pipeline. During its operational phase, the marsh typically processed about 15% of USD's total discharge, equating to around three million gallons per day in dry weather and up to 43 million gallons during wet conditions, with an average detention time of about 14 days.

However, over the years, sediment from the Bay accumulated in the culverts between basins, significantly impeding water circulation. By 2019, at EBRPD's request, USD ceased discharging into the marsh due to deferred maintenance and other escalating maintenance challenges and growing concerns regarding potential risks to wildlife health. Today, Hayward Marsh no longer functions as a treatment wetland. Instead, EBRPD is converting the area back to a tidal marsh, restoring its natural ecological functions.

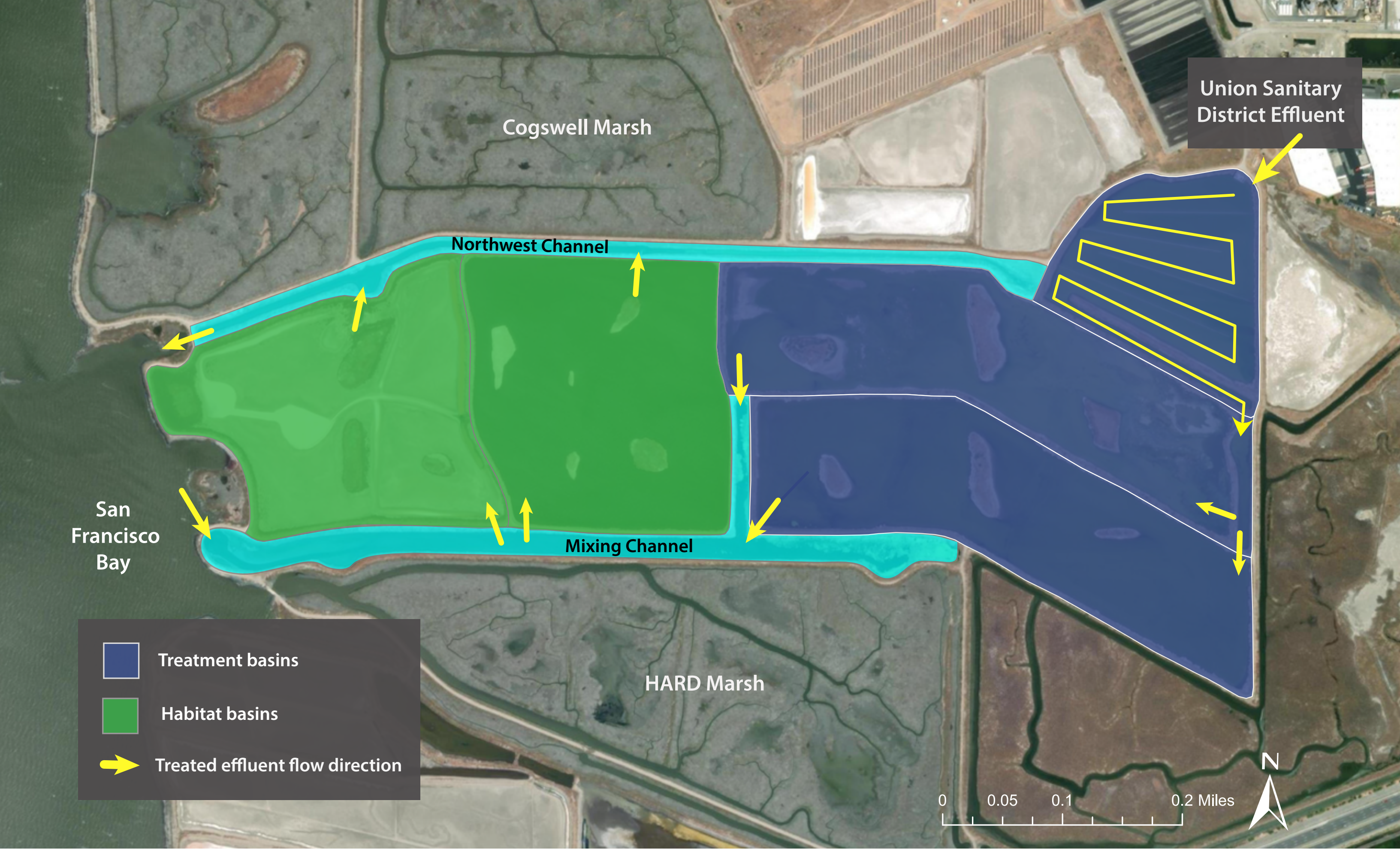


Diagram of Hayward Marsh. The marsh featured three freshwater treatment basins and two brackish habitat basins. Treated effluent flowed through these basins, mixed with Bay water in the southern channel, and exited into the Bay through the Northwest Channel.

SUCCESSES

HABITAT: The treatment wetland attracted a diverse range of wildlife. At least two hundred bird species used the marsh, including the federally and state-listed endangered California Least Tern and Western Snowy Plover. Up to 20,000 birds visited the basins at times, drawn to the freshwater conditions at the site, which are now rare along the Bay shoreline. The constructed islands in the habitat basins also served as protected nesting grounds for birds such as the California Least Tern, Western Snowy Plover, and Black Skimmer.

NUTRIENT REMOVAL: Hayward Marsh was primarily constructed to provide wildlife habitat, but the site also successfully removed nutrients and always met National Pollutant Discharge Elimination System permit requirements. Water quality monitoring showed the treatment basins removed up to 99% of ammonia during the summer. The system also removed significant levels of nitrate and total inorganic nitrogen, though the exact removal rate is unclear.

RECREATION: Hayward Marsh has trails around the bayward part of the site as well as a longer trail system that connects surrounding marshes and the Hayward Shoreline Interpretive Center. Hayward Marsh is part of EBRPD's Hayward Regional Shoreline.

CHALLENGES & LESSONS LEARNED

VEGETATION: The original planting of Hayward Marsh had mixed success. EBRPD planted vegetation in some basins to improve nutrient removal, but many of the plants did not survive due to high soil salinity and foraging birds. EBRPD also planted tules in two basins to help increase nutrient removal, but these areas became breeding grounds for mosquitoes due to low water flow. Eventually, the mosquito abatement authority ordered the removal of the tules.

KEY LESSONS: Future projects should install protective cages, avoid dense vegetation, and maintain constant water flow to help plants establish and limit mosquito populations.

WILDLIFE: Wildlife management at Hayward Marsh presented several challenges, including outbreaks of avian cholera and avian botulism, likely driven by high bird density at the site, which affected the bird populations and required significant time and resources from EBRPD to control. Additionally, the marsh faced issues with raccoons, exacerbated by people relocating trapped raccoons to the area. As raccoons are predators of birds, EBRPD was compelled to implement measures to remove these invasive raccoons to protect the local avian community.

KEY LESSONS: Effective wildlife management at treatment wetlands requires proactive measures to prevent and control diseases like avian cholera and botulism, which may have stemmed from the project's success in periodically attracting birds in high density. Additionally, strategies to manage non-native species such as raccoons are crucial to protect native wildlife.

Black-necked Stilt at Hayward Regional Shoreline

SEDIMENTATION: Site design did not allow for easy dredging when sediment built up. Bay water entered through a flap gate, depositing sediment near the inlet of one of the habitat basins. Sediment buildup eventually cut off flow into this basin and limited flow into the mixing channel. Sediment buildup also occurred near the islands, which ultimately gave predators access to the islands via the nearby road.

KEY LESSONS: Future projects should consider adding a catchment basin or sediment trap to facilitate the removal of sediment buildup.

LEVEE SYSTEM: The levees around the basins were constructed out of clay and did not have any riprap protection. Over time, the earthen levees eroded and could not handle vehicle traffic, which limited access for maintenance. Eventually, the East Bay Regional Park District added riprap to some levees to reduce further erosion.

KEY LESSONS: Site managers should ensure vehicle access and material staging space are available for levee maintenance work.

PERMITTING: EBRPD had difficulty getting maintenance permits, and ultimately did most levee repairs under emergency permits. Endangered species (California Least Tern and Western Snowy Plover) resided in the basins, which made permitting even more challenging.

KEY LESSONS: Site designs should consider potential maintenance challenges, and avoid them when possible. Site managers should apply for permits well in advance. A site maintenance plan and dedicated maintenance fund will also help with obtaining permits before large maintenance issues occur.

MANAGEMENT & GOVERNANCE: EBRPD prioritized protecting biological resources and providing public access at the site, which often conflicted with Union Sanitary District's priority to polish treated wastewater. At times, EBRPD requested to drain the ponds or perform other maintenance activities incompatible with wastewater treatment needs. Overall, the two agencies had a cooperative relationship but their goals didn't always overlap.

KEY LESSONS: If multiple entities plan to co-manage a treatment wetland, they should agree upon a financial plan, a maintenance plan, and overall goals in advance. Even with these agreements in place, co-management can still be challenging if there are multiple goals for the system.

ORO LOMA HORIZONTAL LEVEE

The Oro Loma experimental horizontal levee has demonstrated the promise and limitations of horizontal levees as a wastewater treatment solution. This project highlights the need for internal champions at the staff level and partnerships for effective implementation.

LOCATION: San Lorenzo, CA

PROJECT PARTNERS: Oro Loma and Castro Valley Sanitary Districts, East Bay Dischargers Authority, University of California-Berkeley, San Francisco Estuary Institute, San Francisco Estuary Partnership, Environmental Science Associates, Peter Baye, The Bay Institute, Save The Bay, Valley Water

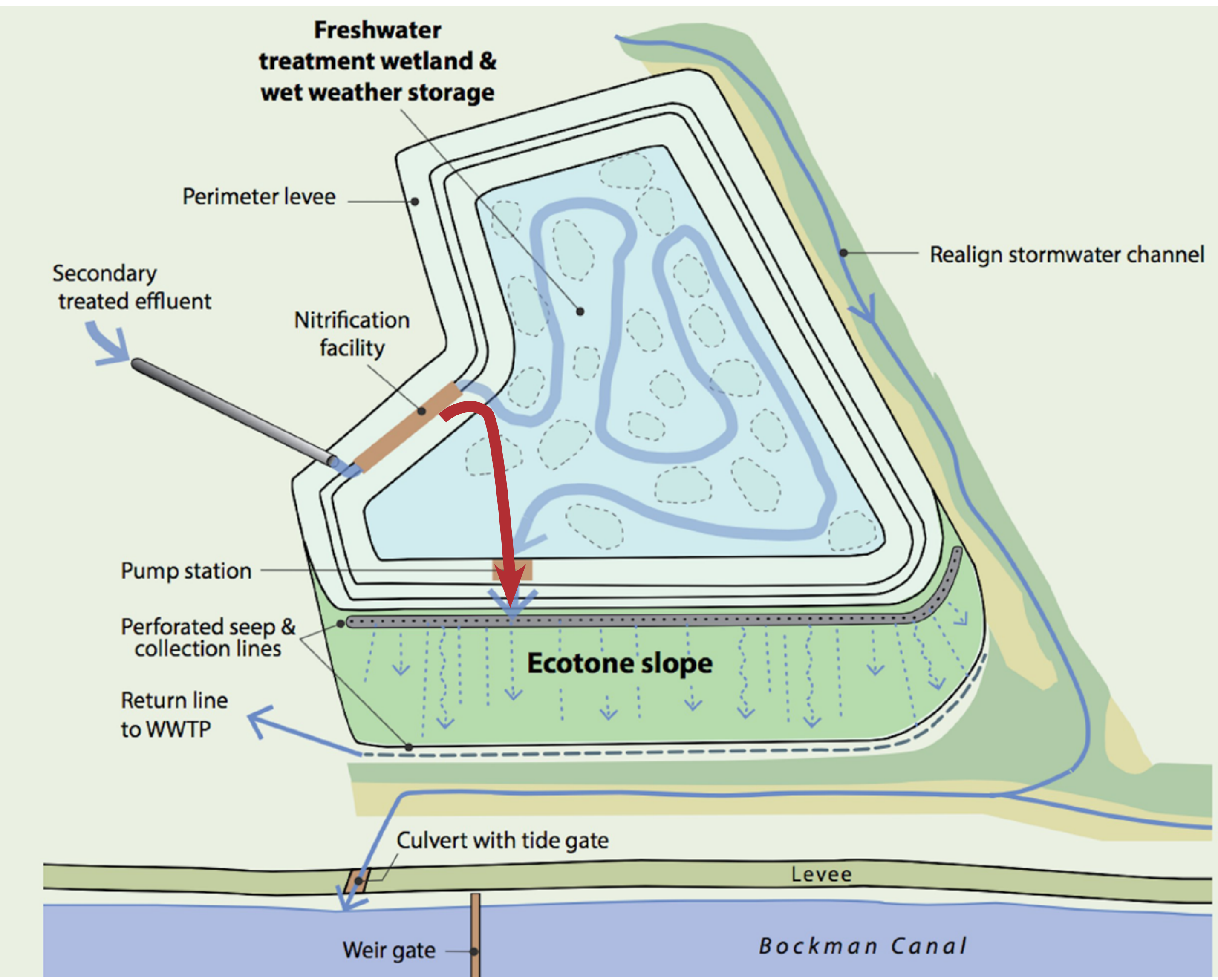
CONFIGURATION: The site features a 1.4 acre horizontal levee and an 8 million gallon wet weather basin.

OVERVIEW & HISTORY: Oro Loma Sanitary District (OLSD) hosts the innovative Oro Loma Horizontal Levee, also known as the Oro Loma Living Laboratory, which was constructed between 2015 and 2017. The horizontal levee has a 30:1 slope covered with a range of vegetation types and substrate engineered to enhance wastewater treatment processes and nutrient removal. This project was the culmination of partnerships spanning OLSD, non-profits, regulatory agencies and multiple funders. OLSD staff championed this project for years and proved critical in building support for this project, which has demonstrated the potential of horizontal levees at providing benefits in the areas of flood risk, water quality, and habitat enhancement.

The levee system comprises twelve hydraulically isolated treatment cells, each layered with gravel/rock, coarse sand, and varying finer loam soils, supplemented with wood chips to foster microbial activity. An impermeable clay layer at the base directs the flow of water through these granular media, enhancing filtration and treatment. The site has been intensively researched to determine how different substrate, slope and plant combinations affect pollutant transformation and removal (Cecchetti et al. 2020a). The treated water from this experimental setup does not discharge into the Bay but is instead recycled back into the treatment system.

Initially, the site included a vegetated serpentine-style constructed wetland/dual-purpose equalization basin. During high-flow storm conditions it was used for storing primary treated wastewater, which was later recirculated back to the treatment plant. During normal conditions, it was used as a treatment wetland. Before entering the treatment wetland, plant effluent flowed through a trickling filter for oxygenation and nitrification. From the treatment wetland, water was directed to the horizontal levee. The dual-purpose wetland was so effective in removing nutrients that eventually it was removed from the treatment train, with a bypass flowpath directing treated effluent directly to the horizontal levee to better test its efficacy.

Ongoing research at Oro Loma by UC Berkeley and Valley Water aims to test more efficient designs and treatment strategies, including the management of reverse osmosis concentrate (ROC), the byproduct of an advanced water purification process. Project partners recently reconstructed two of the twelve treatment cells into smaller sub-cells and used information gathered from the first phase of research to optimize the specifications for the sub-cells. Construction was completed in early 2024 and is now undergoing continued research by the UC Berkeley team. Such efforts are critical for refining future horizontal levee designs for improved replicability, treatment capacity, and cost-effectiveness, potentially influencing similar environmental projects regionally and beyond.



Layout of Oro Loma experimental horizontal levee. Water from the system does not flow into the San Francisco Bay, but instead recirculates back into the wastewater treatment plant. The red arrow shows the bypass flowpath, which skips the open water wetland and goes directly to the horizontal levee. Supplemental figure from Cecchetti et al (2020).

SUCCESSES

VEGETATION ESTABLISHMENT AND MAINTENANCE: Save The Bay led the plant propagation and planting project at the site, establishing seventeen raised beds to cultivate plants destined for the dual purpose treatment/wet weather basin and horizontal levee. Seeds and rhizomatous divisions were collected from multiple locations across the East Bay, allowing for a fifteen-month propagation period before the actual planting. In total, over 68,000 plant materials (rhizomes, shoots, clumps) were propagated, with careful attention to ensure that no more than 5% of the population was taken from any single location (Save The Bay 2017).

Additionally, about four million seeds were collected and cleaned to create a cover crop mix, which was spread across the levee slopes to reduce invasive and non-native species. Over a six-week period, Save The Bay's trained staff and volunteers densely planted these slopes, aiming to foster rapid habitat establishment. The effort was highly successful, with vegetation establishment not only meeting but exceeding expectations, as the plant community developed faster than anticipated (Save The Bay 2017).

SUBSTRATE: Soil and media layers below the surface of the Oro Loma Horizontal Levee are strategically designed to optimize water flow and contaminant removal within the system. The finer topsoil layer is crucial for supporting robust plant growth, while the coarser granular layer beneath it facilitates the flow of water. This configuration helps limit the diffusion of oxygen into the subsurface, promoting anaerobic processes that facilitate effective contaminant removal. Additionally, the incorporation of organic materials such as roots and woodchips within these layers enhances microbial activity. Notably, the woodchips play a vital role in establishing a bioreactor within the substrate, significantly enhancing the denitrification process, resulting in nutrient load reductions (Addy et al. 2016).

WATER QUALITY IMPROVEMENT: The Oro Loma Horizontal Levee effectively reduces contaminants from treated wastewater, serving as a critical testing ground for design parameters. The combination of plants, microbes, and a subsurface woodchip layer significantly enhances denitrification, with the system achieving greater than 98% nitrogen removal (Cecchetti et al. 2020b, Cecchetti et al. 2022). The levee also effectively removes other contaminants, including pharmaceuticals, phosphate, and viruses (Cecchetti et al. 2020a, Stiegler et al. 2022). Current efforts to reconfigure the project aim to reduce its footprint while maintaining efficiency.

In the context of regional utilities exploring reverse osmosis technology for potable water reuse, the OLSD, UC Berkeley, and Valley Water are investigating the treatment of ROC at the Oro Loma levee (Stiegler 2022). ROC, with its higher concentration of contaminants in a smaller volume of water, presents a unique opportunity to overcome space constraints associated with using horizontal levees for wastewater polishing. Preliminary results indicate that horizontal levees could be effective in removing not only nutrients but also copper, organic contaminants, and per- and polyfluoroalkyl substances (PFAS) from ROC, indicating the system's potential in handling higher contaminant loads.

CHALLENGES & LESSONS LEARNED

PLANTING AND VEGETATION MANAGEMENT: The dual-purpose equalization basin was initially planted with cattails and tules, chosen for their ability to enhance nutrient removal during the summer months. The design also included 8 deep pools for mosquitofish. Despite this strategic planting, the cattails and tules experienced higher mortality rates in the equalization basin compared to those in the horizontal levee, although some individuals of each species managed to survive. Eventually, overgrowth led the Alameda County Mosquito Abatement District to require vegetation removal in 2022 to allow better movement of mosquitofish.

Research by San Jose State University involved an assessment of vegetation dynamics within this system, particularly focusing on two distinct planting strategies employed on the horizontal levee slope: a wet meadow and a riparian scrub community (Fishman 2022). Despite the survival of most planted species from 2015 to 2021, plant diversity within these communities declined over the study period. This reduction in diversity was notably influenced by habitat fragmentation, which facilitated the encroachment of invasive non-native species, particularly within the wet meadow community. This fragmentation also coincided with a decrease in the diversity and cover of native species, especially in areas dominated by native plants like willow and cattails. This research highlights the complex interactions between plant management strategies and ecological outcomes in the context of horizontal levees and other NbS types (Scholes et al. 2020, 2021).

KEY LESSONS: The Oro Loma experiment indicated that the survival rates of vegetation like cattails and tules were hindered by deep water depths, supporting findings from other treatment wetlands that water depth plays a role in promoting or hindering plant establishment. Additionally, the study showed that constructed wetlands often evolve into ecosystems dominated by a few species due to fragmentation and substantial edge exposure. To counteract this, it is crucial to clearly define habitat and wastewater treatment objectives, select plant palettes resistant to ecological succession, and design plantings in larger patches with lower edge-to-area ratios. Implementing these strategies can enhance biodiversity and ensure the sustainability and effectiveness of nature-based solutions in urban coastal environments.

Vegetation removal at the dual purpose basin in 2023.

WATER FLOW: At the horizontal levee, periods of hydraulic short-circuiting—where water took the most direct overland path from the inlet to the outlet—resulted in less water flowing through the subsurface of the horizontal levee and a decrease in contaminant removal. During these times, only a small percentage of the influent flow was effectively polished by the levee. To enhance the system's efficiency, managers reduced the flow to 30,000 gallons per day to ensure 100% subsurface flow, maximizing the time available for contaminant removal. Experimental results also showed that most contaminants are removed within the first few meters of the slope, suggesting that even if the the site's footprint is reduced, the horizontal levee could still perform well in removing nutrients if hydraulic loading rates are adjusted by increasing the slope (e.g. to 15:1) or increasing the depth of drain rock.

KEY LESSONS: To optimize contaminant removal in horizontal levees, it is crucial to maintain subsurface water flow, which can be achieved by enhancing the hydraulic conductivity of the media and controlling the flow rate to allow sufficient contact time for purification. Additionally, modifying the structural design, such as increasing the slope or increasing the depth of woodchip media and drain rock, can effectively increase hydraulic loading rates while maintaining efficient nutrient removal within a reduced footprint.

Wet meadow cells at the horizontal levee in 2017.

Willow cells at the horizontal levee in 2017.

CELL DESIGN: Initial cell designs considered including ponding areas, but this was ultimately abandoned due to concerns about mosquito breeding. The cells planted with willows demonstrated the highest treatment capacity; however, the rapid growth of the willows led to a dense canopy that shaded out nearby cells with different vegetation types. Additionally, there were concerns that the willow roots might extend into the distribution pipes, potentially causing maintenance issues.

KEY LESSONS: Designs for horizontal levees should avoid standing water to reduce mosquito breeding grounds. While willows are effective in supporting contaminant removal, their vigorous growth can lead to unforeseen complications. Future projects should consider limiting willow plantings and carefully plan for the extensive horizontal and vertical spread of their roots to prevent potential damage.

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