DUAL-PURPOSE EQUALIZATION BASINS:
A SEASONAL SOLUTION FOR SUMMER NUTRIENT REMOVAL AND WINTER STORM EVENTS

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Empty FEB during dry season at Sewerage Agency of Sourthern Marin. Photo by Ellen Plane, SFEI.

INTRODUCTION

Nature-based solutions (NbS) can efficiently treat nutrient (i.e. nitrogen, phosphorus) polluted water bodies by harnessing the productivity and natural filtration capacity of wetland ecosystems.[1,2] Historically, wastewater treatment plants (WWTP) have not been designed to fully remove nutrients, resulting in high annual nutrient loads to the San Francisco Bay (Bay).[3] Partially in response to the Nutrient Watershed Permit, WWTPs are now exploring ways to augment nutrient reduction capacity.[4]

Excess nutrients in the Bay can lead to an increase in the occurrence of harmful algal blooms (HABs) and associated fish kills, such as the unprecedented *Heterosigma akashiwo* bloom of 2022.[5] Historically, the Bay has exhibited resilience to these types of phytoplankton blooms despite relatively high nutrient loading,[3] However, blooms have become more frequent, with a higher risk from April to October when warmer water, higher light irradiation, reduced turbidity, and increased hydraulic residence time promote algal growth.[6]

As part of the effort to reduce nutrient-rich discharge from WWTPs, the Nutrient Watershed Permit promotes the adoption of NbS to reduce nutrient loading. A previous study evaluating opportunities for implementation of NbS for nutrient removal found the major limiting factor to be available land area.[7] Most Bay Area WWTPs are situated next to heavily developed areas or sensitive coastal habitats that are prone to flooding, making land scarce and expensive.[7]

Constructing and maintaining flow equalization basins (FEBs) in available land at WWTPs is a priority to manage flows during winter storms. Sanitary sewer systems are designed to accommodate typical volumes of municipal wastewater and can exceed capacity when stormwater enters the system via inflow and infiltration (I&I).[8] FEBs are large basins often lined with clay, membrane, asphalt, or cement, that are designed to increase the overall capacity of the treatment infrastructure. FEBs temporarily store these wastewater surges until the storm passes and the excess flow can be fed back to the WWTP.[9] Often, the volume of the FEBs may be split across multiple basins to allow for cleaning and cycling between basins and for emergency extra capacity.[10]

As climate change increases the magnitude of storms, WWTPs will likely need to increase their FEB capacity to prevent overflows (i.e. excess untreated or partially treated wastewater discharging to the Bay).[11] This document outlines a strategy to maximize the co-benefits of new FEBs, maintaining and increasing storm resilience while addressing the growing nutrient discharge issue. This strategy can also be applied to retrofit existing basins to further enhance nutrient reduction without sacrificing wet weather capacity.

DUAL-PURPOSE EQUALIZATION BASINS

Previous studies by the San Francisco Estuary Institute (SFEI) identified existing FEBs as potentially suitable areas for the development of NbS.[7] Dual-purposed basins would consist of a temporary NbS in the FEB footprint, providing polishing functionality in the summer months while reserving the basin exclusively for wet weather holding capacity in the winter months. To account for the possibility of unexpected storms in the dry season as well, these basins will be designed with the ability to rapidly transition between operating modes (FEB, NbS) to use the basin as a wet weather storage facility whenever necessary. This design may reduce annual TIN loads to the Bay while retaining emergency basin capacity.

Figure 1. The wet weather FEB at Oro Loma Sanitary District, which was historically used as a pilot open-water wetland for pre-treatment. Left: summer condition (open water wetland). Right: winter wet weather storage. Photos by Ellen Plane, SFEI.

Core Basin Functionality (FEB)

During wet weather, WWTPs see a significant but temporary increase in total volume. This excess volume is composed of wastewater diluted by stormwater, containing pathogens and nitrogen typical of raw sewage along with micropollutants (metals, pharmaceuticals, pesticides, etc.) typical of stormwater.[12] Consequently, during the wet season plants receive a higher variability in flows and pollutant loads. FEBs are designed to temporarily store peak flows for subsequent treatment, to minimize the unanticipated discharge of stormwater- and wastewater-borne pollution.

Dry-Season Nutrient Management (NbS)

During the dry season, WWTPs receive base sanitary flows with higher nutrient concentrations.[3] Nutrient reduction is most important during these months when the Bay is most sensitive to nutrient loading.[3] Conveniently, during these dry summer months, storm events and the need for FEBs is unlikely. FEB layouts tend to be amenable to the installation of a constructed wetland (CW) in their footprint. CWs rely primarily on biological nutrient removal, the kinetics of which reach their maximum during the summer months.[13] The CWs identified below represent efficient means of reducing nutrient loading in wastewater-effluent-dominated waters (Table 1).[2]

Ancillary Benefits

Constructed wetlands offer a multitude of ancillary benefits beyond their primary treatment function.[2] These systems play a crucial role in the removal of emerging contaminants, such as pharmaceuticals and personal care products, through natural processes.[14] Additionally, they support ecosystem function, supporting biodiversity by providing habitat for various aquatic and terrestrial species.[15] Aesthetically, these areas enhance the surrounding landscape, creating serene environments that can be used for educational and recreational purposes. Like other types of constructed wetlands, dual-purpose FEB wetlands could be designed according to the desired co-benefits of the system. For example, they might include habitat islands for nesting birds, walking trails, or educational signage. Such spaces not only educate the public about the importance of sustainable water management but also provide community members with recreational opportunities, fostering a deeper connection with the local environment.

DESIGN CONSIDERATIONS

First Flush Tank

The concentration of pollutants in stormwater runoff is generally highest in the first few hours of a storm when contaminants are first mobilized from impervious surfaces.[16] A first-flush tank (FFT) may be employed to capture the first predetermined volume of influent water in which organic contaminants and heavy metals will be at their peak concentrations to minimize direct toxicity to wetland vegetation.[17] Such a FFT would function as a small conventional FEB and can be operated and cleaned accordingly, with no concern for environmental release of settled stormwater pollutants. During smaller storm events, only the FFT will need to be utilized for flow equalization. During larger events, excess flow would be routed into the emptied seasonal constructed wetland portion of the basin. This will further minimize disruption to the CW biology. It is recommended in all cases that a FFT be the first module in the dual-purposed FEB treatment train.

Wastewater - Constructed Wetland Interactions

Many types of CWs lend themselves well to a modular design strategy, in which multiple wetlands of the same or different type can be operated in series. This approach allows for adaptation based on the specific WWTP footprint, operational constraints, and design priorities.

There is precedent for adapting constructed wetlands to mitigate combined sewer overflows (CSOs) in Europe.[17] Combined sewer systems represent a small proportion of municipal sewer systems in the Bay Area and California as a whole.[1] The City and County of San Francisco maintains the only CSO system in the Bay Area. However, the water chemistry of a CSO is likely similar to the effluent entering FEBs in the wet season. Thus, the efficacy of treatment wetlands in CSO mitigation serves as an indicator of treatment performance in our proposed design.[12]

The constructed wetlands in a dual-purpose basin must not be sensitive to rapid loading during storms and must be resilient to wastewater and stormwater derived contaminants. Wet-weather flows have a high biological oxygen demand (BOD) due to the high bacterial load from waste solids combined with contaminants derived from stormwater runoff, notably heavy metals, which will be higher at the onset of the storm.[17] While the capacity of CWs to treat BOD and reduce pathogen load is not a necessary consideration for this effort since the FEBs will pipe the storm-wastewater back into the wastewater treatment plant during storm events, potential toxicity to wetland vegetation is an important consideration as is the potential environmental release of wet-weather contaminants upon transitioning to dry-season discharge directly from the CW.

NbS Removal Comparison

Nutrient removal is the dry season priority, when summer nitrification is efficient and most other pollutants are already removed by the conventional WWTP.[6] Three major CW categories: (Free Water Surface (FWS) planted, FWS unplanted, and Vertical Flow (VF), are evaluated for their nutrient removal performance and flexibility to be dual-purposed. The most efficient type of unvegetated wetland is known as the unit-process open water wetland, which is a shallow unplanted flow-through basin that supports the growth of a benthic microbial community with a high denitrification potential.[13,18] Unit-process open-water wetlands are the specific type of unplanted FWS considered (Table 1). While horizontal flow (HF) wetlands represent an important class of NbS, due to sizing and operational requirements a HF wetland isn't feasible in the footprint of a FEB, so our analysis focuses only on comparing the three aforementioned CW types.

Table 1 provides an overview of the CW types in our assessment and outlines major design and operational considerations for wet and dry season needs. A treatment train could consist of one or more of these CW in series.

Specific wetland type choices will be site-specific given treatment goals, maintenance capacity, expected flow rates, and land constraints. Unit-process open-water wetlands are the most efficient at dry season nitrogen removal yet are the most sensitive to disturbances. Vegetated wetlands are less sensitive to disturbances and provide habitat and potential recreation or educational benefits however their nitrogen reduction potential will be smaller. VF wetlands will provide the best buffer against storm-events by preventing infiltration of solids but may reduce FEB volume since a portion would have to be filled in to provide sub-surface flow. Depending on each WWTPs specific goals, some combination of the above CW types in series after a FFT may provide a robust approach to dry and wet season flow management.

Table 1. Comparison of constructed wetland types that could be implemented in a flow equalization basin footprint.

		Free-water Surface Flow Wetlands		Sub-surface Flow Wetlands
		Unvegetated	Vegetated	Vertical Flow (VF)
Design and Operation		 Photo Source: Scarlet Kilpatrick	 Photo Source: SFEI	 Photo Source: SFEI
Design and Operation	Description	Shallow-unplanted flow through basin with geotextile liner to prevent emergent vegetation and promote growth of a microbially active benthic biomat. The lack of vegetation allows for improved hydraulic efficiency.	Surface water flows through a vegetated cell. Faster growing species (cattails) have a slower nutrient uptake rate but higher tolerance for ammonia than faster growing species (bulrush).	VF wetlands act as planted filters. Flow is subsurface and can be oxic or anoxic depending on saturation. Planted vegetation (reeds) enhances aeration and nutrient uptake. Intermittent saturation provides the most flexible treatment.
Design and Operation	Maintenance	Removing floating vegetation, emergent vegetation, and excess sediment buildup Re-seeding biomat if necessary after disturbance	Controlling excess vegetation as necessary	Periodically de-sludging top layer to reduce clogging potential
Dry-Season Considerations	Treatment Mechanism	Sunlight Biological	Sunlight Biological Sorption	Sorption Biological
Dry-Season Considerations	Nitrate Removal	**High** Efficient denitrification	**Moderate** Plant uptake	**Varies** Denitrification if saturated Plant uptake
Dry-Season Considerations	Phosphorus Removal	Sediment formation Plant uptake	Sediment formation Plant uptake	Sorption Sediment formation Plant uptake
Dry-Season Considerations	Ammonium Removal	**Low** Small degree of uptake by periphyton possible	**Moderate** Oxidation to nitrate if unsaturated Plant uptake	**High** Oxidation to nitrate if unsaturated Plant uptake Sorption
Wet-Season Considerations	Stormwater Contaminants	Photo-inactivation of pathogens Photo-degradation of organic contaminants	Cattails and reeds are tolerant to metals	Sorption of metals
Wet-Season Considerations	High Flow Rate	Design must take care to minimize biomat disturbance	Vegetation less sensitive to disturbance	Intermittent loading doesn’t affect capacity

Example Process-Flow Diagram

While a FFT is recommended in all cases, the specific processes flow should be determined by a site-visit and assessment of current infrastructure and predicted flow-equalization needs. One possible configuration is depicted in Figure 2 for a theoretical FEB with a large enough footprint to dedicate some portion to a VF wetland to protect the downstream open-water wetland from solids.

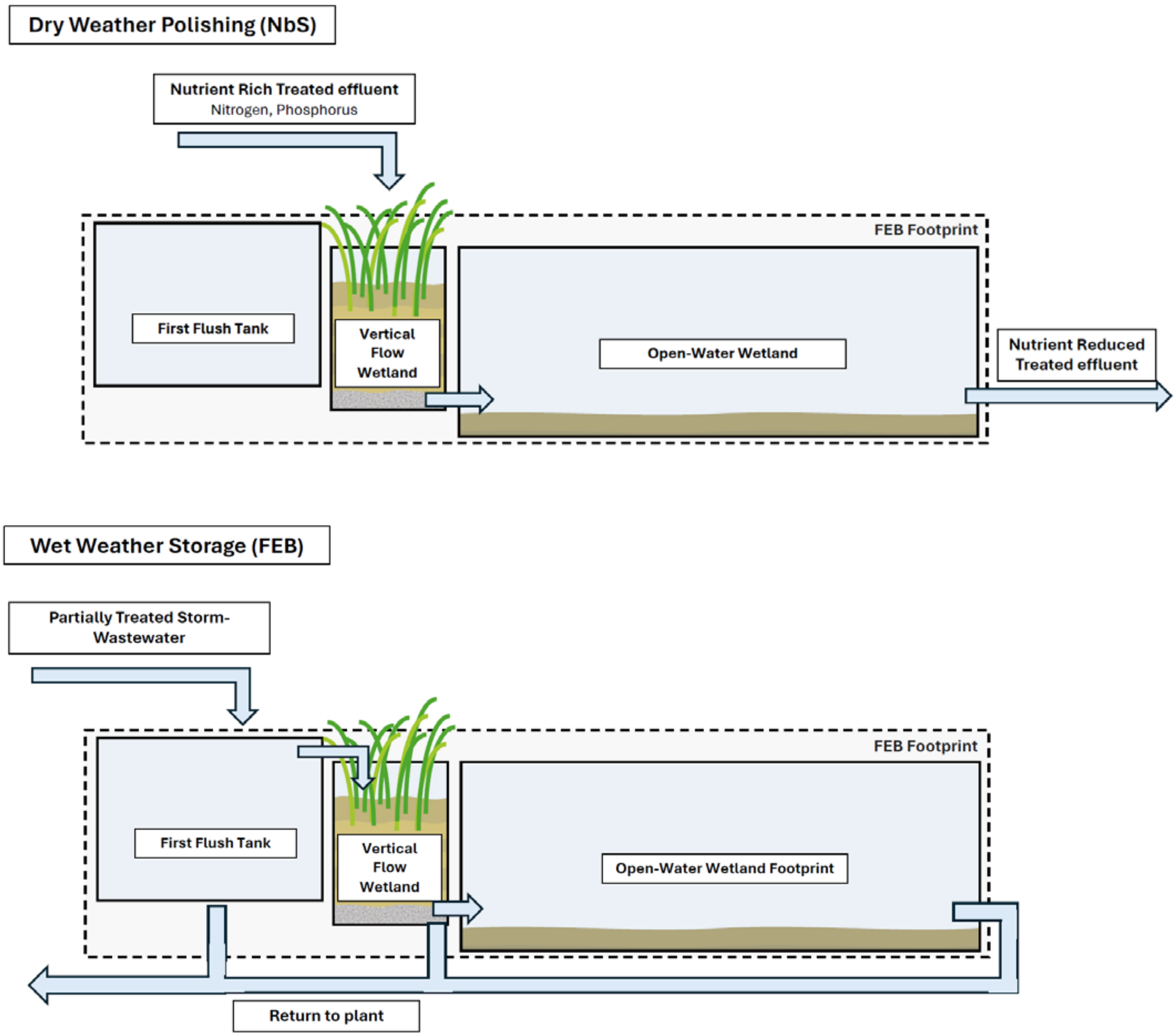

Figure 2. Process-flow diagrams representing wet and dry season operation for constructed wetlands in series in a flow equalization basin footprint.

APPLICATION FEASIBILITY

Nutrient Reduction Potential

The additional nutrient removal capacity that a dual-purposed basin adds to the WWTP will depend on the basin size and chosen process flow configuration. To remain consistent with recent literature regarding the performance of California-based open water treatment wetlands, the estimated wetland area needed to remove 90% of nitrate from 1 million gallons per day (mgd) of effluent was utilized to estimate flow capacity of the available acreage.[14,18,19] This value, termed the A90, is considered a useful metric for wetland design, to enable comparison with technologies that offer the highest technically feasible level of treatment of municipal wastewater.[18] In practice, a less conservative ratio of wetland area to flow may be chosen, driven by space constraints and water quality regulations.

The A90 varies considerably based on season and wetland type. In a dual-purposed FEB wetland, the majority of nitrogen removal is expected to come from a unit-process open-water wetland portion. A90 values for such wetlands are maximized in the summer, corresponding with the dry season when dual-purposes wetlands will be operating, with A90 values of ~1.2 X 10^{-3} ha (m^3 d) $^{-1}$.[18,19] This corresponds to a summertime A90 of 11.2 acres per MGD of treated wastewater. Given the wide range of existing FEB sizes (<1 to 50+ acres), the amount of achievable nitrogen reduction will vary.

Permitting

Based on conversation with SF Bay Regional Water Quality Control Board staff, the main permitting requirement unique to dual-purposed basins is ensuring that bacteria discharge thresholds are not exceeded after transitioning from wet season to dry season operation and resuming surface discharge. This can be accomplished with a combination of system flushing after use for flow equalization and benchmark monitoring to confirm sufficient flushing to avoid bacteria remobilization. Concerns regarding the remobilization of other stormwater associated contaminants do not pose additional regulatory hurdles but will nonetheless be mitigated by flushing during transition to ensure immobilized contaminants are routed through the treatment plant.

Transitioning between FEB and NbS operating modes

To prevent remobilization of settled and sorbed contaminants when dry-season flows resume, a flushing step is recommended after the FEB is emptied (Figure 4).

The specific flushing requirements will be a function of basin hydraulics and bacterial count in effluent routed to the FEB for temporary storage. These can be refined during an operational pilot period wherein a required number of flushes before resuming surface discharge is determined based on monitored bacteria counts. This flushing time could be reduced if other cleaning mechanisms (i.e. spraying to remove solids after FEB use) are part of routine maintenance.

While the open-water wetland portion is unlikely to receive untreated wastewater except in extreme conditions, these basins may be designed with the ability to store and re-introduce biomat to speed up nutrient reduction capacity once storms have passed and allow complete FEB use without biomat disruption. This is currently an un-evaluated design idea and a likely topic of future research.

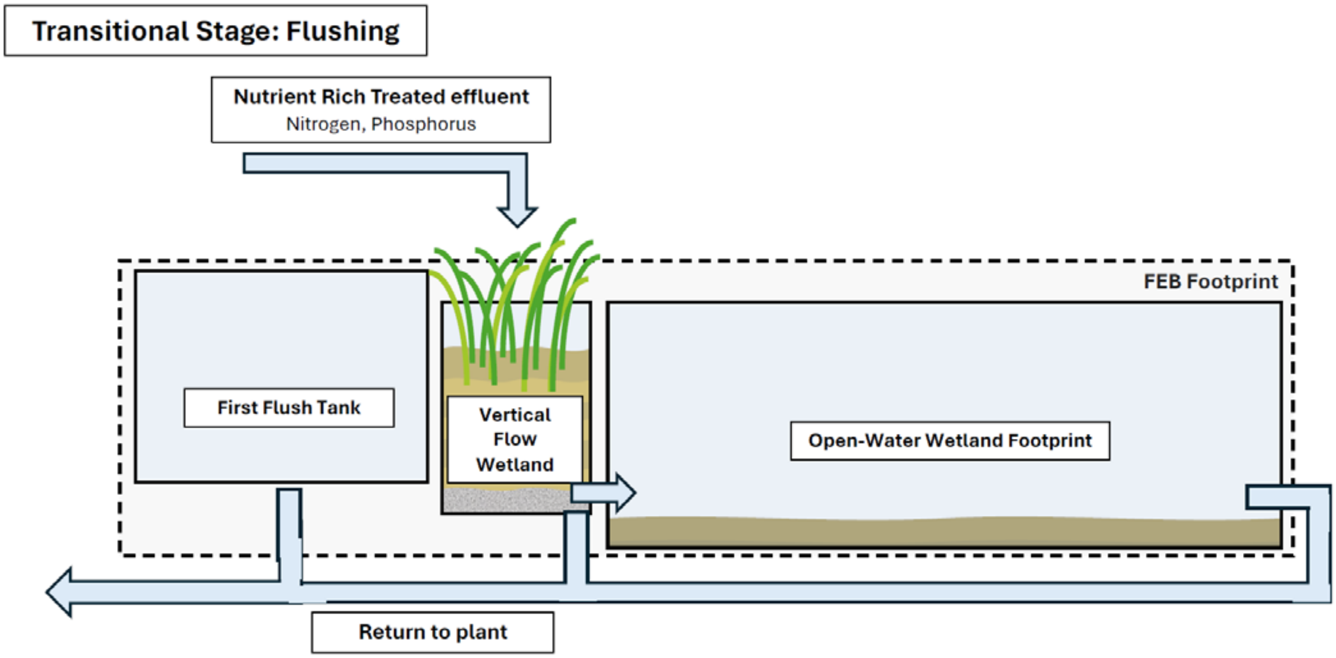

Figure 4. In the transitional/flushing stage, treated effluent flows through the wetland and is returned to the plant.

Routine Cleaning and Maintenance

FEBs typically only remain full for a few hours to days after a storm event before being emptied and cleaned if needed. Specific cleaning and maintenance during the wet season will depend on whether the FEBs receive raw or primary treated wastewater. Routine cleaning guidelines for the dual-purposed basin will mirror those of a traditional FEB, with the additional consideration that vegetated CW modules only be considered if the basins receive primary treated wastewater for ease of cleaning. Dry season NbS maintenance follows that of typical CWs listed in the table above.

Retrofitting Existing Basins

Existing FEBs can be dual purposed to retain their historical water storage capacity while operating seasonal NbS in their footprints. The modularity of this proposed dual-purposed system is useful for fitting the design into the unique footprints of existing FEBs. Specific design choices will be based on site-evaluations and can be selected with consideration for existing infrastructure (i.e., basin size, current piping). Multiple CWs can be placed in series in the existing flow paths to maximize space.

New Dual-Purpose Basins for Expanded Capacity

WWTPs may consider the construction of new FEBs to increase holding capacity in the face of anticipated future increases in storm severity. This presents an opportunity to optimize the design strategies discussed above to create a plant-specific nutrient reduction strategy that simultaneously increases FEB capacity. Dual-purposes basins can allow WWTPs to develop climate resilience with regards to both nutrient management and storage.

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