# Treatment Wetlands and Sea Level Rise:

# Ensuring the San Francisco Bay Water Board's Wetland Protection Policies are Climate Change Ready

White Paper

July 2018

California Regional Water Quality Control Board, San Francisco Bay Region &
The San Francisco Estuary Partnership

This white paper was produced by staff of the San Francisco Estuary Partnership (SFEP) with assistance from staff of the San Francisco Bay Regional Water Quality Control Board. SFEP received a grant award from U.S. Environmental Protection Agency (USEPA) in the amount of $90,402 (ABAG/SFEP Cooperative Agreement CD-99T34301-0, Wetlands Protection Development – Wetland Policy Climate - Change Update Project; Project) to work with the Water Board to support the evaluation of existing Water Board regulations and policies governing the permitting of multi-benefit projects designed to address sea level rise. SFEP is a coalition of resource agencies, non-profits, citizens, and scientists working to protect, restore, and enhance water quality and fish and wildlife habitat in and around the San Francisco Bay Delta Estuary. Working cooperatively, SFEP shares information and resources that result in studies, projects, and programs that improve the Estuary and communicate its value and needs to the public.

July 2018
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# Section 1: INTRODUCTION

Climate change in the San Francisco Bay Delta region is predicted to be accompanied by rising sea level and by an alteration in the timing, magnitude, frequency and distribution of precipitation events. Rising sea level will impact coastal ecosystems and water supplies and inundate low lying areas as well as push baylands and the transition zone landward and upward. Changes in rainfall and runoff patterns may increase flood magnitude and frequency. Stream and wetland systems can ameliorate some of the adverse effects of climate change through a variety of ecosystem services including flood water storage and attenuation, carbon sequestration, coastal buffering, and providing habitat for a diverse array of fish and wildlife. Protection, restoration and enhancement of the many wetland functions are important components of a regional strategy to reduce and mitigate the impacts of climate change within the San Francisco Bay Delta watersheds.

Local, State and federal agencies will need to utilize multiple tools to restore and enhance existing wetland sites as well as to design, construct and manage future projects, all while balancing fresh water flows and sediment needs. The Science Update to the San Francisco Baylands Ecosystem Habitat Goals Project (2015) recommends as a regional strategy to promote resilience, "Identify and implement opportunities for taking advantage of treated wastewater and stormwater to create salinity gradients and maximize peat accumulation in the baylands, while protecting water quality and minimizing nutrient loading." Coastal resilience references a system's adaptive capacity to external disturbances, which can be strengthened through the presence of natural features such as salt marsh and mudflats that act as buffers. Such natural features can reduce coastal erosion and saltwater intrusion from rising sea levels. Utilizing wastewater as a freshwater input to enhance bayland wetland environments as a component of a multi-benefit project can provide benefits including wetland creation or enhancement, pollutant load reduction, and flood protection.

Effluent discharges from the region's municipal wastewater treatment plants to the sloughs and shallower areas of the baylands may affect the condition of these areas, altering salinity gradients and species composition, impacting water quality where there isn't sufficient dilution and changing seasonal wetlands to perennial habitat. Expanding the use of multi-benefit projects such as horizontal levees and other constructed wetlands to provide additional treatment of wastewater may require policy changes to provide permitting clarity while ensuring protection of water quality. Horizontal levees provide flood protection and use treated wastewater to provide a source of water to support wetland vegetation. Understanding the human health and ecotoxicological effects necessitates continued study of what contaminants are present in effluent, which ones are attenuable, and what mechanisms drive removal. These factors will inform the design and ultimately the success or failure of projects to provide the multiple benefits needed of them while preserving, protecting, restoring and enhancing the State's wetlands.

The purpose of this white paper is to summarize the existing data on the efficacy of wetlands in removing contaminants of emerging concern. Treated wastewater is being proposed as an element of proposed tidal wetland projects to address nutrient removal and as a source of freshwater for marsh plant growth in horizontal levee proposals. Very little information is available about CEC removal in natural wetlands, so the focus of this paper is on what we have learned from the use of constructed wetlands to address pollutant removal.

# Section 2: Role of constructed Wetlands in Climate Change and pollutant removal

Changing climate patterns in the watersheds that feed the Delta and the Bay will increasingly alter precipitation events (frequency and amount), freshwater flows and salinity gradients, sediment transport, nutrient content, and tidal and wind action, and will result in higher sea levels forcing the migration of the estuarine-terrestrial gradient upland. Water quality will be of increasing concern due to decreased freshwater input, salinity intrusion inland, increasing algae blooms and large flushes of contaminants during storm events. Aquatic ecosystems that rely on certain physical, chemical and biological conditions within the Estuary are likely to be affected by water quality degradation that will in turn threaten many of the beneficial uses throughout the region. Improved water quality can help lessen the impact of many climate change stressors, making these ecosystems more adaptable to many of the other potential changes ahead.

Beneficial uses of surface waters, groundwater, and wetlands serve as a basis for establishing water quality objectives and discharge prohibitions to protect the uses from pollution and nuisance that may occur as a result of waste discharges. Beneficial uses are established through the Water Quality Control Plan for the San Francisco Bay Basin, which serves as the Water Quality Control Board's master planning document.

The role of wetlands within the context of climate change is potentially wide ranging, including carbon sequestration, flood and erosion control, tidal buffering, migration space for retreating baylands, as important habitat for local fish and wildlife, and as a water filtration system for stormwater and wastewater flows to the Bay. Projects offering multiple benefits are gaining ground as researchers and agencies understand more about nature-based treatments such as living shorelines and ecotone/horizontal levees. Proposals for using treated wastewater as a source of freshwater to enhance marsh plant growth and the use of wetlands to improve water quality has created a need to better understand the fate of any residual contaminants that might threaten the environment and beneficial uses. While not every treatment wetland type is appropriate to mitigate coastal vulnerabilities from climate change, designers can work with dischargers and regulators to implement projects that provide the most benefits, including the use of multiple treatment types together.

It is becoming increasingly important to understand which of the thousands of detectable chemicals present in treated wastewater effluent are of concern to wildlife and human health. Given that only approximately 200 of more than 100,000 chemicals approved or registered for commercial use are currently regulated and/or routinely monitored within the State, a much larger category exists of unregulated, unmonitored, undetected, or unknown chemicals that are potentially discharged to receiving waters (see Figure 1 below) (Sutton et al. 2017). These trace organic compounds, referred to here as contaminants of emerging concern (CECs), potentially expose aquatic and terrestrial organisms to risk through presence in both the water column and sediment.

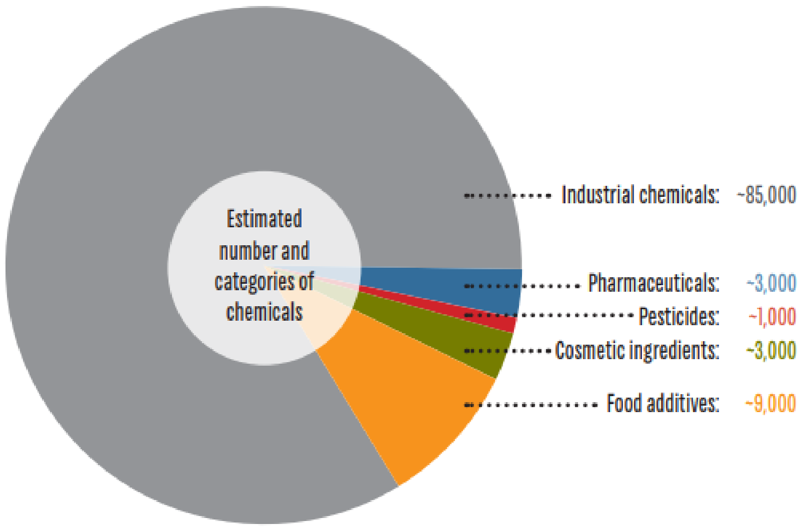



Figure 1. Estimated number and category of chemicals registered for use in the United States in the past 30 years. (From Sutton et al. 2017).

The fate of many of these CECs, which include personal care products, pharmaceuticals, pesticides, flame retardants and other domestic and industrial chemicals, is undetermined in many cases, with very little toxicological data or understanding of the ecological role or ramifications of accumulation. Estimating the harmful effects of compounds with unknown ecotoxicity may involve evaluation of biodegradability, carcinogenicity, and mutagenicity as well as potential pathogen resistance and endocrine disruption potential, with the end goal of identifying and monitoring compounds of particular concern. Risk assessment based on quantification of chemical concentration paired with biological characterization is a time-consuming process, particularly with the large number of potential chemicals. Constructed treatment wetlands offer the opportunity to remove many wastewater-derived contaminants including newer and lesser-understood compounds. Wetland design drives the removal processes and thus the efficacy with which CECs may be attenuated, although extensive research is still needed.

The transformation and removal of nutrients, pathogens and CECs is dependent upon a suite of physical, chemical and biological processes operating across different treatment types. Physical processes include sedimentation and volatilization of compounds; chemical processes include sorption, precipitation, transformation through ultraviolet (UV) radiation, and ion exchange; and biological removal mechanisms include microbial degradation/transformation/uptake, plant uptake, and die-off. Many factors (e.g. design, site geology and soil makeup, hydraulics) determine the ability and extent to which a contaminant may be transformed, degraded or sequestered within a wetland. To effectively utilize treatment wetlands as projects that provide multiple functions, these controls must be highly managed in the region's baylands, which are continuing to be squeezed between an increasingly built shoreline and marshes and mudflats subject to sea level rise and other effects from climate change.

Given the complexity of the processes in full-scale treatment wetlands that receive wastewater effluent, designing sites with predictable performance is a significant task. Energy flows from daily and seasonal temperature changes influence the short- and long-term ecological composition of a site. Abiotic factors such as dissolved oxygen, oxidation-reduction potential and pH fluctuate continually. How water moves through a treatment wetland will determine its ability to effectively remove pollutants. Water depth, flow rate, the length of time water spends within the system (hydraulic residence time), frequency and concentration of effluent loading, and the overall water budget must all be actively and flexibly managed. Site logistics such as land available to treat a specific volume of water and ongoing maintenance are also critical to achieving the desired water quality outcomes.

Different site designs and layouts produce distinct vegetation and flow regimes and thus impose constraints upon the processes that drive contaminant removal. Projects may be as diverse as vegetated levees that filter water while dissipating storm surge, open ponds that utilize sunlight or microorganisms to reduce persistent pollutants, or vegetated 'natural' wetlands that primarily provide habitat and nutrient filtering.

Free water surface wetlands (FWS) are similar to natural marshes that contain areas of open water and may or may not contain vegetation depending upon project goals. Shallow, open-water treatment cells can be utilized alone or in tandem for removal of specific compounds depending upon sunlight penetration and microorganism colonization. Treatment wetlands that treat flow underground using some combination of gravel, soil or sand for filtration can be categorized by flow direction into horizontal subsurface flow or vertical flow wetlands (HSSF and VF respectively). Each category has variations in layout, flow, media, plantings, etc. As research on treatment processes advances, it is becoming clearer that integrating multiple wetland types can optimize removal rates.

Open-water cells have been utilized as pilots at the Prado Constructed Wetlands in Orange County and in Discovery Bay California (Figures 2 and 3, below). These projects utilize sunlight and microorganisms for contaminant removal in shallow ponds. Maintaining function with this type of construction requires removal of vegetation and detritus that render photo- and biotransformation processes ineffective. The Prado wetlands additionally employ managed vegetated treatment ponds for highly cost-effective nutrient removal.

Figures 2 and 3. Shallow, open-water wetland cells at the Prado Wetlands in Orange County, CA (left) and Discovery Bay, CA (right). Credits: Scott Nygren (left), ReNUWIt (right).

The Oro Loma Horizontal Levee Project in Alameda County, California (Figures 4 and 5, below) is testing a horizontal subsurface flow model using a combination of native based soils and plant communities to filter and treat wastewater. Based on a naturally occurring sloping transition from wetland to upland areas, the experimental “ecotone slope,” referred to as a horizontal levee, also combines multiple treatment types to attenuate different pollutants.

Figures 4 and 5. Overhead and horizontal views (upper and lower, respectively) of the subsurface flow treatment at Oro Loma, in San Lorenzo, CA. Credit: ReNUWIt.

Additionally, the creation of treatment wetlands as part of a horizontal levee often involves significant use of fill in existing wetlands that can be a challenge for existing regulatory policies for instance, the State must balance goals of No Net Loss of wetlands, fill mitigation requirements, and resource agency concerns against the benefits of the projects. The No Net Loss policy refers to Executive Order W-59-1993 that establishes State policy guidelines for wetland conservation. The main goal of the policy is to ensure no overall net loss of stream and wetland system areas, functions, or beneficial uses. The policy also aims to achieve a long-term net gain in the quantity, quality, and permanence of wetland acreage in California.

## 2.1 Compounds of Interest and Pollutant Removal Mechanisms

Conventional pollutants such as biochemical oxygen demand, suspended solids, and coliform have generally high removal rates from secondary and advanced wastewater treatment, and wetlands can augment these reductions. Because conventional pollutants have been studied more than CECs and have effluent limitations applied to discharges, this paper will focus primarily on CECs, pathogens and nutrients. Nutrients are also of interest in the region since recent observations indicate that the San Francisco Bay's resistance to high nutrient loads may be weakening. Although the Bay receives high nutrient loads from treated wastewater, agricultural runoff, and stormwater, it has exhibited resistance to high phytoplankton biomass and low dissolved oxygen, which are common responses to nutrient overenrichment. More recently measured lower dissolved oxygen levels and more frequent detection of phytoplankton biomass are indicative of a weakening of the Bay's resistance (Senn and Novick 2014).

The United States Environmental Protection Agency (U.S. EPA 2010) compiled data on different wastewater treatment plant technologies and removal efficiencies for 246 CECs across laboratory, pilot and full-scale systems. Results indicate a wide range of removal rates across technologies (e.g. granular activated carbon adsorption removes 3.6% of the anti-inflammatory naproxen, versus 97% removal of naproxen through ultraviolet disinfection).

Determining the compounds of most concern in wastewater effluent and establishing water quality objectives, particularly around chronic toxicity, is a considerable task with such a wide array of chemicals and their associated unknowns (i.e. fate, transformation byproducts, etc.). The State has not developed water quality objectives for many CEC compounds. California's regulatory framework uses water quality objectives to define the appropriate level of environmental quality and to control the activities that can adversely affect aquatic systems. The State Water Resources Control Board is working on a framework for developing nutrient objectives that include narrative objectives along with numeric guidance, the goal of which is to address the complexity of establishing specific nutrient concentration criteria. Work on developing surface water quality objectives for CECs is much further out.

### 2.1.1 Nutrients

Forms of nitrogen and phosphorus are the primary nutrients that in excessive quantities become surface waterbody pollutants. Nutrient removal from wastewater can have high capital costs and energy inputs, and treatment levels vary from plant to plant. Nitrogen compounds in treatment wetlands can include the inorganic forms of ammonia, nitrite, nitrate, nitrous oxide and nitrogen gas, as well as a variety of organic compounds including urea and amino acids. Phosphorus compounds consist primarily of dissolved phosphorus, solid mineral phosphorus and solid organic phosphorus (Kadlec and Wallace 2009).

Both nutrients are primary constituents within wetlands, and their many forms and transformation reactions produce both beneficial and potentially detrimental results that create complex challenges in engineering treatment wetlands. Wetland plants and bacteria have varying capacity for nutrient uptake and transformation, and chemical forms affect plant growth differently. Open-water wetlands without vegetation remove nitrates particularly effectively through photolysis and biotransformation and can be incorporated into other types of treatment wetland designs to augment removal rates (Jasper et al. 2014).

Treatment wetlands can be utilized for nutrient removal. Locally, the City of Palo Alto Regional Water Quality Control Plant utilizes Renzel Marsh along the Palo Alto baylands to reclaim treated wastewater and create 15 acres of seasonal freshwater marshes. The marsh also provides additional benefits in nutrient reductions post-treatment plant discharge. Baseline data from 2013 to 2014 indicate that the marsh acts as a nitrogen sink and is capable of reducing total nitrogen concentration by 40% via denitrification and cellular uptake (Engelage 2015).

### 2.1.2 Pathogens

Bacteria, viruses, protozoa and helminths are all pathogens present in wastewater that need to be removed before discharge or reuse. Different pathogen groups have removal rates that vary drastically depending upon removal mechanism, including sedimentation, attachment, predation and photoinactivation. Treatment wetlands can play a primary role in pathogen attenuation for non-disinfected effluent or can provide additional treatment for pathogens resistant to chlorine, UV or ozone disinfection. Additional processes such as longer hydraulic residence times can reduce pathogens by two to three orders of magnitude (Brooks et al. 2015). Wetland habitats can also attract animals, e.g., birds, that may reintroduce pathogens.

### 2.1.3 Trace Metals

Metal sequestration within treatment wetlands is a storage and removal process that involves sedimentation, precipitation, adsorption, microbial interaction and plant uptake. The accretion of new sediments combined with the precipitated material contribute to the layering of wetland substrate. Vegetation type and coverage play important roles in uptake, stabilizing flows, increasing hydraulic residence time, and building sediment. Even though wetlands can act as a sink for metals, they can also be a source, if contaminants are returned to the water column through decomposition of plant matter or sediment disturbance. Additionally, changes in hydrologic conditions, such as drainage or drought can alter the pH. Lowering of the pH creates acidic conditions and can impact metal forms and concentrations and become a source of metals. Wetlands remaining flooded can decrease metal export and bioavailability to aquatic organisms. Sequestration capacity may be reduced over time, and wetland vegetation and sediment must be periodically removed to avoid buildup and the release through plant detritus. With data coming primarily from studies on stormwater runoff, industrial wastewater/landfill leachates, and acid mine drainage, more research is needed looking at metal concentrations originating from wastewater treatment facilities.

### 2.1.4 Contaminants of Emerging Concern (CECs)

Broad new classes of trace organics, or CECs, are increasingly becoming of concern in treatment wetlands that are used for pollutant removal and wastewater polishing. These include pharmaceuticals and personal care products, pesticides, antimicrobials, antibiotics, and industrial chemicals such as fire retardants and plasticizers. Studied health effects range from endocrine disruption to antibiotic resistance to increased cancer rates.

Some of these diverse CECs have been around for many years, although many are newer chemicals that don't have toxicological data for understanding broader ecosystem or human health impacts. The lack of basic information on many of these CECs hampers the State's ability to assess their potential risk and develop regulatory protocols based on impacts to beneficial uses of water resources within the State.

Removal efficiency for CECs may be broken into three broad groups: high removal rate of 60% or higher, regardless of wetland design (for substances such as caffeine and the pain medication naproxen); partial removal rates generally between 40-60% depending upon design and hydraulic residence time (the hypertension medications atenolol and propranolol are examples); and low removal rates, generally under 40%, of compounds that are more recalcitrant regardless of wetland design (substances such as the anticonvulsant carbamazepine and the herbicide clofibric acid) (Jasper et al. 2013).

Figure 6 shows average removal rates of some commonly detected CECs across all treatment wetland types. Dominant removal mechanisms for CECs include sorption, biotransformation through microorganism interaction, and phototransformation through direct and indirect sunlight interactions. Compounds respond differently to different mechanisms, and a combination of processes (such as biotransformation and photolysis) can increase attenuation rates.

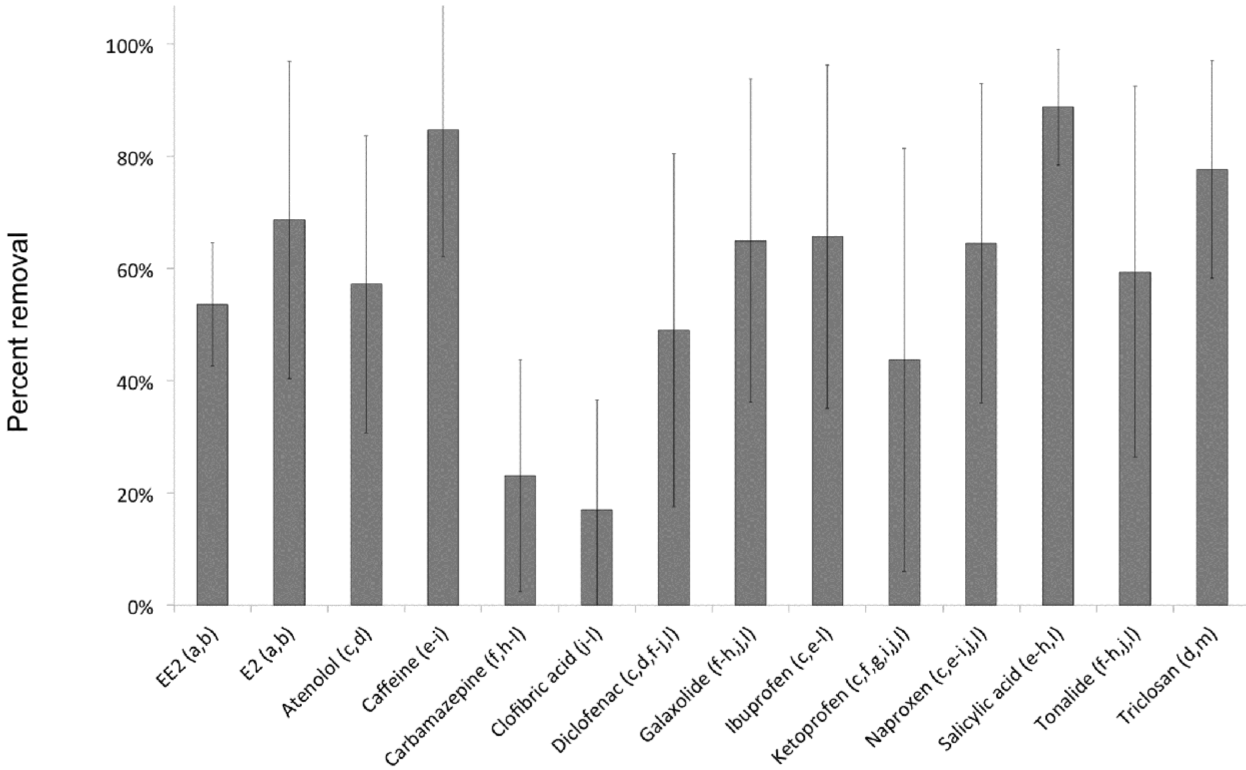



Figure 6. Average removal efficiencies of selected CECs in wetlands, compiled from recent studies. (From Jasper et al. 2013).

### 2.1.5 Transformation Byproducts

Wetland transformation processes can produce unintended degradation products, form mixtures with synergistic or unknown effects, or bioaccumulate without the risks being well understood. Transformation does not necessarily equate to detoxification, and byproducts can potentially reform into parent compounds, or form new ones. Many chemicals fall into broader classes of compounds that have similar persistence, bioaccumulation or toxicity, which can help researchers determine which compounds to evaluate and potentially monitor (Sutton et al. 2017).

One example of some of the unknowns around byproducts is the hypertension medication atenolol, which degrades to the highly stable human metabolite metoprolol acid. While the byproduct is less toxic to mammals, it does not undergo further transformation, indicating a need to study its persistence further (Jasper et al. 2014b). Other research shows that byproducts of the antiviral drug acyclovir reduce the reproduction ability of the planktonic crustacean *Daphnia magna* and inhibit the growth of green algae (Li et al. 2016). Many unrelated compounds disrupt human health systems through similar pathways such as endocrine disruption, so risk assessment must include toxicological and epidemiological data where possible.

# Section 3: CASE STUDIES

The following case studies highlight different design elements and mechanisms for effluent contaminant removal. The range of benefits for each project is different depending upon location, available area, wastewater treatment needs, and overall project goals. The most compelling projects will be those that are integrated into a multi-benefit project designed to provide water quality and ecosystem benefits and shoreline sea level rise protections.

The case studies and research presented here include contaminant remediation processes observed from different waste streams (urban runoff, agricultural uplands, etc.), as many of the processes are the same. The results from these case studies should be cautiously interpreted, as research is still preliminary and, in some cases, ongoing. More broadly, research is needed with differing variables such substrate and planting regime to more fully understand what factors may be standardized and included in policy and permitting changes.

## 3.1 ORO LOMA: SUBSURFACE TREATMENT OF CECS AND A RESILIENT LEVEE DESIGN

### 3.1.1 Design

Threats to bayland habitats and critical infrastructure from sea level rise have increased interest in projects that mimic the natural ecological gradient between mudflats, tidal marshes, and adjacent freshwater wetland/floodplain habitats. The concept of a "horizontal levee" includes using treated wastewater to irrigate a gradual slope along the Bay shoreline and re-create a gradient between non-tidal freshwater (wet meadow) and tidal salt marsh habitats (Figure 7). Such a system deployed around the Bay could attenuate wave energy at the Bay shoreline (thus reducing the height of flood control levees landward of the marsh) and reduce the potential for shoreline erosion/overtopping/flooding.

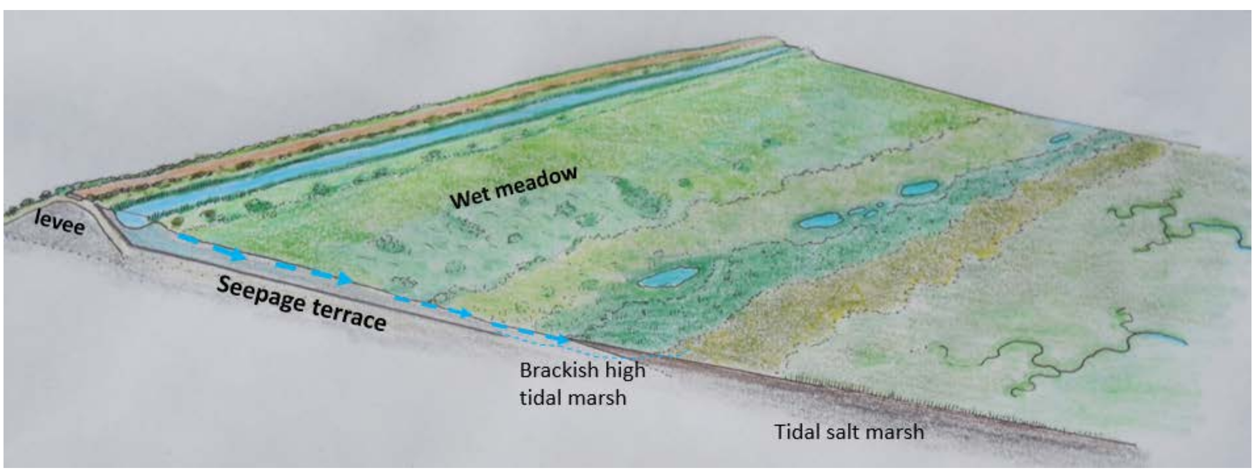



Figure 7. Conceptual drawing of a horizontal levee fed by treated wastewater along the shoreline. Courtesy of Dr. Peter Baye.

The Oro Loma ecotone slope uses an experimental "horizontal levee" to examine the feasibility of establishing these features along the San Francisco Bay shoreline, and to determine their effectiveness at removing nutrients, contaminants of emerging concern (CECs), and other pollutants from treated wastewater. The current phase of Oro Loma experimentation utilizes the ecotone slope as a component of a closed system with no tidal influence. Effluent from the wastewater treatment plant is filtered through both a free water surface wetland and twelve parallel horizontal subsurface flow cells, testing a range of media porosities, varying hydrologic regimes, and different plant communities. The project site contains a denitrification trench that sends water in parallel to both the surface water wetland and the horizontal levee, utilizing different removal mechanisms at each phase, and returning tested effluent back to the wastewater treatment plant (Figure 8). Future phases of research intend to deploy similar ecotone slopes around the Bay margins to examine their effects on wave attenuation, flood risk reduction, and ecosystem dynamics.

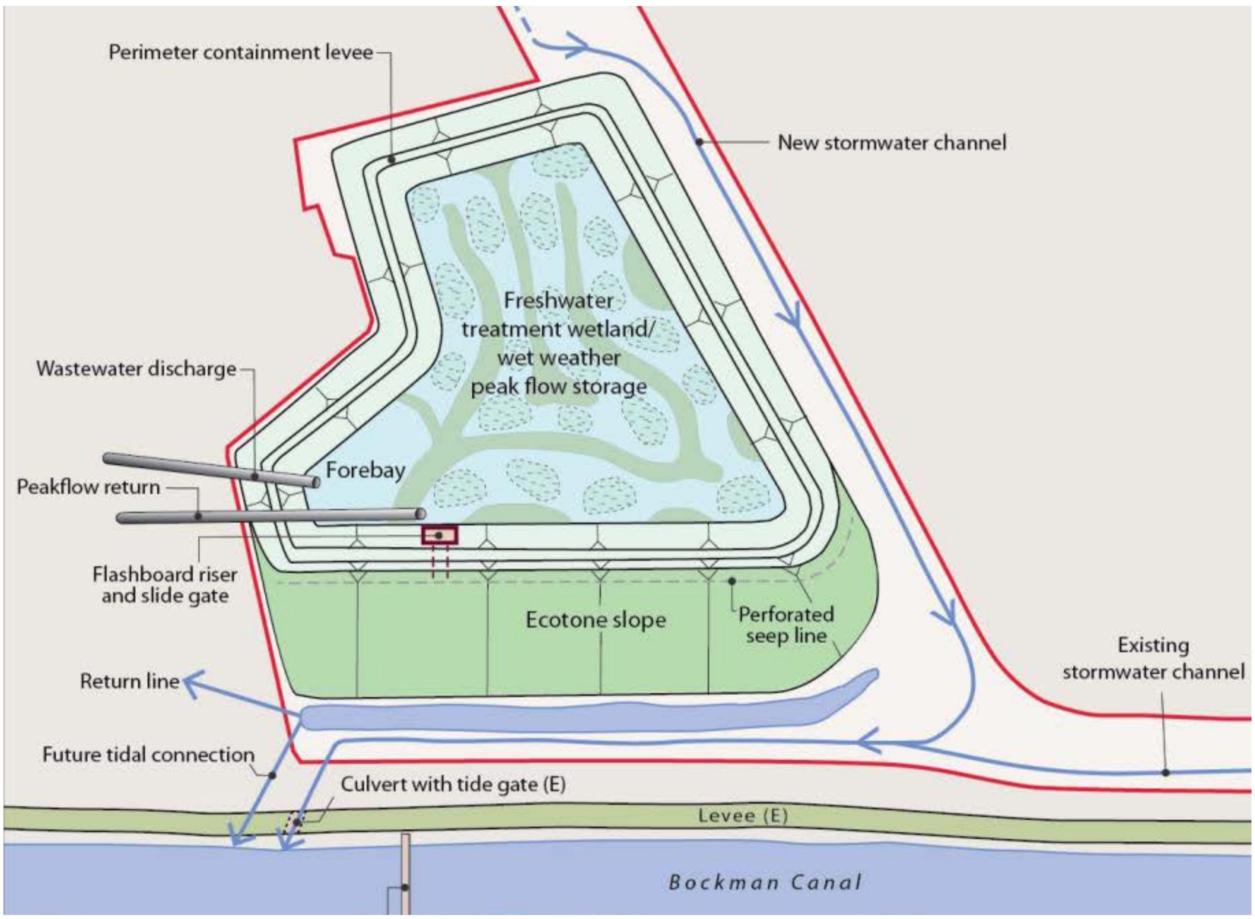



Figure 8. Conceptual diagram of the experimental horizontal levee at the Oro Loma treatment plant.

### 3.1.2 Contaminants of Interest and Results

Researchers are currently monitoring a range of CECs at Oro Loma to determine their treatment wetland attenuation rates (Table 1, below).

| COMPOUND | USE |
|---|---|
| ATENOLOL | Beta blocker, used in heart attack and hypertension treatment |
| METOPROLOL | Beta blocker |
| ACYCLOVIR | Antiviral |
| EMTRICITABINE | Antiviral |
| TENOFOVIR | Antiviral |
| SULFAMETHOXAZOLE | Antibiotic |
| CARBAMAZEPINE | Anticonvulsant, used to treat seizures |

Table 1. CECs studied at the Oro Loma treatment site. (UC Berkeley personal communication Sept 6, 2017).

U.C. Berkeley researchers anticipate nutrient removal of 10-30% through treatment in a vegetated wetland, and additional removal via the gravel denitrification trench (Oro Loma 2015). CECs are removed through the different treatment phases via photolysis, sorption, plant uptake and microbial transformation. Initial results show high removal rates of both nitrate nitrogen and CECs (UC Berkeley personal communication Sept 6, 2017). Figure 9, below shows the fraction of the compound removed from influent to effluent over a two- to six-day hydraulic residence time. Early results show efficient removal of even the seizure medication carbamazepine, which has been shown to be difficult to remove in other studies. Sulfamethoxazole appears to be impacted by seasonality, but the trend for carbamazepine shows consistency through the winter months (UC Berkeley personal communication Mar 15, 2018).

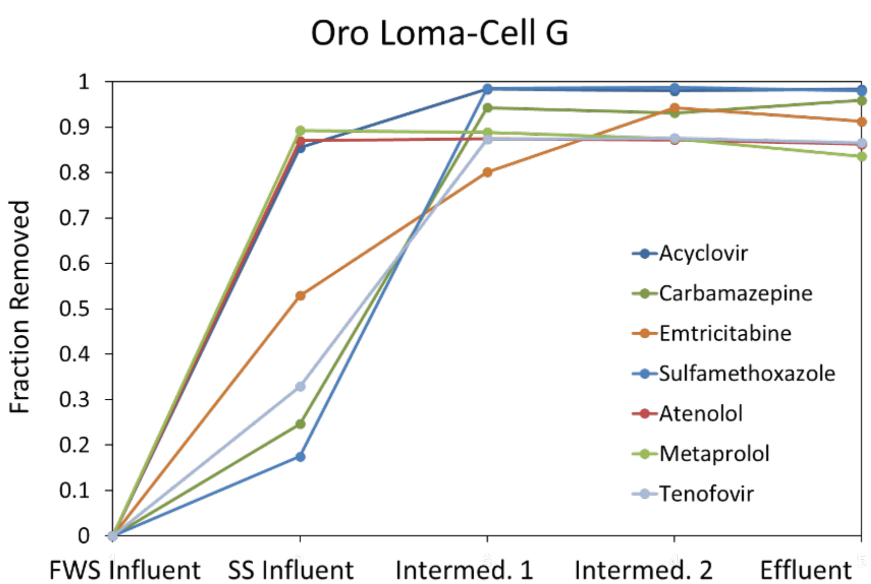



Figure 9. Preliminary (unpublished) Oro Loma CEC removal rates through multi-phase treatment steps. (UC Berkeley personal communication Sept 6, 2017).

### 3.1.3 Challenges

High CEC removal rates have been found initially, although long -term performance will not be understood for some time. Short-circuiting has been found to be a challenge, and as much as 1 mm of overland flow can interfere with efficient removal. An important consideration is that the volume of effluent that can be treated for additional pollutant removal is based on the available amount of land; the pilot site currently treats around 50,000 gallons per day (the Oro Loma wastewater treatment plant by comparison has an average dry weather flow of 12.4 million gallons per day) (personal communication, (UC Berkeley personal communication Mar 15, 2018, Oro Loma 2017). Scaling up to treat significant quantities from working wastewater treatment plants poses land acquisition and capital cost issues. It may be possible to address higher flows by rethinking the treatment matrices, but this is still under consideration. In addition, soil conditions at the site are not static, and vegetation growth and maturity can alter the matrix through which contaminants are filtered.

One of the main observations at Oro Loma thus far has been that, while multiple years are needed to confirm data, removal rates are highly dependent upon controlling overland flow. Researchers have determined that because hydrology controls removal, proper design and monitoring must be careful to ensure adequate performance.

## 3.2 Discovery Bay: Shallow, Open-water Wetland Cells Targeting Contaminants

### 3.2.1 Design

Open-water unit process cells are shallow, modular wetland cells that may be utilized alone or placed within existing wetlands to complement the removal processes already at work. The constructed treatment wetland at Discovery Bay in Contra Costa County, California was a five-year pilot-scale project consisting of open-water unit process cells that received treated wastewater effluent from a nearby treatment plant. The cells were 15 to 20 cm in depth and utilized a short hydraulic residence time of 1 to 3 days (Jasper and Sedlak 2013). As is typical for open-water cells, surface vegetation was periodically cleared to keep the water column shade-free, and emergent vegetation was discouraged by lining the bottom of the ponds to harvest reactions that require sunlight. The bottom layer of the ponds was colonized by a biomat of microorganisms that varied depending on effluent content. Nitrate removal occurred through microbial activity within the biomat. Photolysis, biotransformation and sorption (least important of the three) were the dominant removal mechanisms for CECs in Discovery Bay's open-water cells.

### 3.2.2 Compounds of Interest and Results

Researchers at Discovery Bay studied the removal efficiency of nitrate and CECs in open-water cells specifically. Nitrate accounted for 95% of the nitrogen species monitored by Jasper et al. (2014b), and 60% of this was removed on an annual basis over a two-year study. Figure 10 shows seasonal nitrate removal, indicating higher removal rates in summer and fall when abundant sunlight drives photolysis and microbial activity is higher from warmer temperatures.

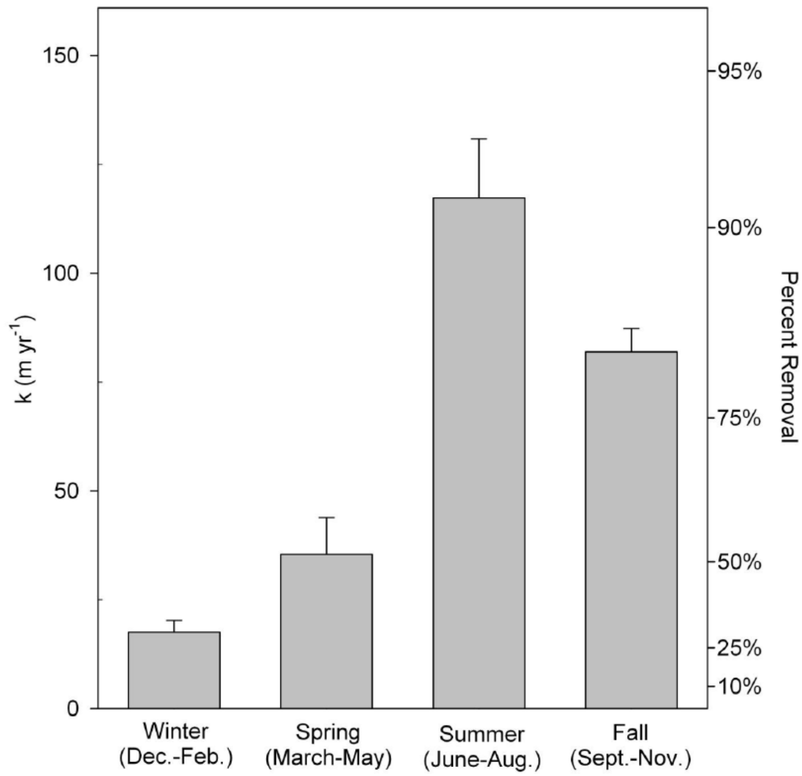



Figure 10. Average nitrate removal rates at Discovery Bay by season, based on a 1 ½ day hydraulic residence time (from Jasper et al. 2014b).

Based on experiments conducted with water collected at Discovery Bay, photolysis was shown to be an important mechanism in the removal of the beta blocker propranolol and the antibiotic sulfamethoxazole. Biotransformation appeared to be more dominant in removing the beta blockers atenolol and metoprolol, and the antibiotic trimethoprim. The anticonvulsant carbamazepine was recalcitrant, resisting attenuation via both photolysis and biotransformation. Combining biotransformation and photolysis accelerated transformation rates by 10 to 100 times faster than previous studies in vegetated wetlands, with over 90% attenuation of all observed compounds with the exception of carbamazepine (Jasper et al. 2014a).

### 3.2.3 Challenges

Balancing conditions needed for optimal contaminant removal through photolysis and biotransformation requires maintaining the proper depth, residence time and vegetation management scheme to maximize sunlight penetration and biomat thickness. Seasonal fluctuations in CEC reductions are an important factor when considering a site, in that a larger treatment area may be needed due to slower transformation rates in winter. The availability of land is key in this type of project. Wastewater quality will also need to be continually monitored and controlled for factors that can influence CEC attenuation rates, such as ammonium and nitrate concentrations, pH, and dissolved organic carbon.

## 3.3 PRADO WETLANDS: NITRATE AND CEC REMOVAL FOR AN EFFLUENT-DOMINATED RIVER

Figure 11. Prado Constructed Wetlands. Photo: Orange County Water District.

### 3.3.1 Design

Nutrients and dissolved solids have been identified as water quality concerns in the Santa Ana River Basin by the Regional Water Quality Control Board (Santa Ana Regional Water Quality Control Board 1995). The 450-acre Prado Constructed Wetlands in Riverside County, California (Figure 11, above) are the largest constructed wetlands on the West Coast and include a series of vegetated shallow ponds for contaminant removal from the dry season effluent-dominated Santa Ana River. Water sources for the wetlands include the river itself, which receives mountain and urban runoff and municipal tertiary wastewater, and creek water passing through a highly dense cattle ranching area. The wetlands were originally constructed for nitrate removal within vegetation-managed ponds and to provide wildlife habitat for rare and endangered species. Once pollutants are removed from the water during a 5 to 7 day residence time, the outflow recharges basin groundwater (Orange County Water District 2015).

Three open-water units were added in 2013 to begin testing CEC removal through bio- and phototransformation. The demonstration-scale cells are lined to prevent emergent macrophytes and to encourage colonization by a biomat of microorganisms. Hydraulic residence times varied between one and four days.

### 3.3.2 Compounds of Interest and Results

The Prado Wetlands have been operating since the mid-1990s to remove nitrate, the nutrient of highest concern to water managers in the Santa Ana Basin. Nitrate levels fluctuate seasonally, with lower levels found higher up in the watershed and during stormwater-diluted winter months. Higher levels (up to and greater than the USEPA's drinking water standard of 10mg/L as nitrogen) were found downstream from wastewater inputs (USGS 2004).

In a study of water quality and microbial composition based on plant density, Ibekwe et al. (2006) found that ponds with 50% plant cover could produce removal rates as high as 96.3%, contrasting with ponds with 100% plant cover resulting in nitrate removal around 11.4%. Overall removal rates were between 50-60% of nitrate and 40-50% of orthophosphate (reactive phosphates that give an estimation of the amount available for algae and plant growth).

The open-water unit study has more recently examined wetland removal rates of nitrate, selected trace organics and bacterial indicators. Microbial activity within the biomat appeared to be the main mechanism for nitrate removal, particularly during summer months that resulted in a 90% decrease in concentration (Bear et al. 2017).

The beta blocker atenolol was removed primarily by biotransformation, with reductions of over 70% in summer months. Propranolol, another beta blocker, was more effectively removed via photolysis due to its structure, with removal rates around 90% in summer months. The antiviral acyclovir showed modest rates of removal but increasing hydraulic residence time from two to four days improved biotransformation rates from 50% to 70%. The anti-epileptic carbamazepine showed lesser rates of removal and appears to respond to a removal mechanism that requires the nitrate that is concurrently being removed within the wetland. Pathogen concentrations decreased in summer, as indicated by *E. coli* and enterococci which were amenable to photolysis (Bear et al. 2017).

One of the major lessons of the Prado study has been that the overall performance at full-scale matched well with models developed at pilot scales such as Discovery Bay. The results indicate that contaminant removal in large-scale open water wetlands is fairly well predictable for conditions similar to those at Discovery Bay and Prado both (wastewater effluent and effluent-dominated waters in California).

### 3.3.3 Challenges

Vegetation management at the Prado site involves clearing floating vegetation that blocks sunlight penetration into the water column, reducing photolysis and microbial activity within the biomat. This shows that ponds will need continual maintenance to maintain productivity. Vegetation management includes controlling emergent plant, surface plants and edge plants within the open-water cells, as well as desired and invasives within the vegetated wetland portion. Other maintenance includes draining and removal of silt and sand, and restoring areas damaged by normal flooding and erosion (Santa Ana Regional Water Quality Control Board 2012). Vector management also poses a significant challenge in terms of vegetation selection and water chemistry impacting mosquito and predator abundance (Jiannino and Walton 2004).

# Section 4: Challenges

Treatment wetlands have historically been utilized to remove conventional pollutants, however their value in reducing emerging contaminants while providing ancillary benefits is gaining appreciation. One basic consideration in the use of treatment wetlands relative to other methods of removing pollutants from wastewater is the presence of environmental factors that add increased variability and unpredictability to the system. Policymakers, regulators, dischargers and researchers have much to address if wetlands are to be used regionally on a useful scale.

Some of the challenges include technical and economic feasibility such as the availability of publicly owned land in which they could be placed, competing demands for fill material from other bayland wetland restoration or sea level rise adaptation projects, competing demands for recycled or otherwise treated wastewater, the cost of ongoing operations and maintenance, and regulatory and permitting issues such as fill and mitigation requirements. Occurrence, fate and effects of CECs are not well understood, and monitoring and assessment efforts need to be refined to include multiple categories of compounds while balancing resources already allocated to non-CEC chemicals. Additionally, different wetland types (FWS, HSSF, VF) have fundamentally different mechanisms for removal, thus different design requirements (e.g. direct sunlight breaks down compounds in open water cells, versus encouraging plant growth and uptake in vegetated cells) as well as determining appropriate performance standards for these units. More research is needed around ecotoxicity, removal processes and rates, and long-term performance in order to maximize performance of the limited potential sites within the region, and to develop appropriate performance standards for these systems.

The case studies previously discussed focus on increased water quality and pollution control through contaminant removal, which is one important aspect of the hydrological changes potentially facing the region's baylands. The potential effects of sea level rise on the water quality and flood reduction benefits of these systems also require further study and consideration. For example, sea level rise could cause many of the tidal salt marshes bayward of potential horizontal levee locations to drown, resulting in a loss of their functions and values. Hardened shorelines in the form of residential, industrial and commercial development already preclude the migration of many bayland habitats upslope, regardless of the speed of sediment accretion and wetland conversion. Addressing these landscape-scale challenges will require a broader regional planning context to address multiple climate change scenarios and their potential consequences.

A wetland's ability to attenuate specific compounds depends on many environmental factors, some of which will determine the size needed based on water quality objectives. Site considerations initially involve issues of hydrologically appropriate land being available. Full scale designs must be such as to discourage hydraulic short-circuiting or inefficiencies (i.e. avoiding factors that reduce hydraulic residence time, create preferential flow paths, encourage overland flow, or any other scenario that reduces removal rates).

Seasonal and daily cues including sunlight hours, intensity and temperature, as well as effluent concentration, level of treatment and loading rates all play distinct roles in different wetland types. Warmer climates and seasons with greater sunlight penetration into the water column generally result in greater contaminant removal in open water systems, as will designs that increase hydraulic residence time or decrease hydraulic inefficiencies. Higher flushing rates from increased precipitation and fewer algal blooms in winter add to the complexity of designing systems built around specific processes, stressing the need to incorporate multiple wetland types.

Subsurface wetlands need enough area so that maximum flows are given adequate time to filter through the vegetation and soil matrix. Vegetation, sediment and salinity management and their associated costs can be significant, particularly over the long-term. The determination of scale based on pollutant removal in cooler seasons will need to balance greater loading rates from storm events, land and constructions costs, and fundamental site considerations such as shoreline hardening and policy limitations.

Seasonal variability in open water systems is demonstrated in Figure 12 below, which shows the predicted area needed for removal of various compounds over the course of a year, comparing flow rates at the Easterly Wetlands in Orlando, Florida and the Prado Constructed Wetlands in Southern California. Note that wetlands built to attenuate a more recalcitrant compound such as carbamazepine would likely allow effective removal of easier-to-remove compounds.

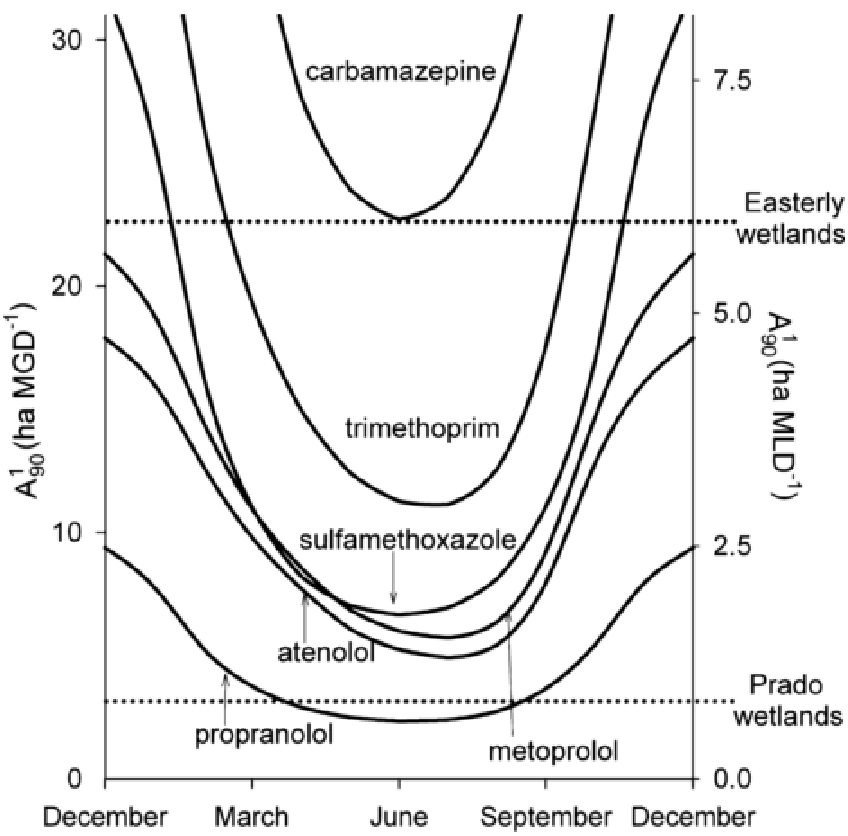


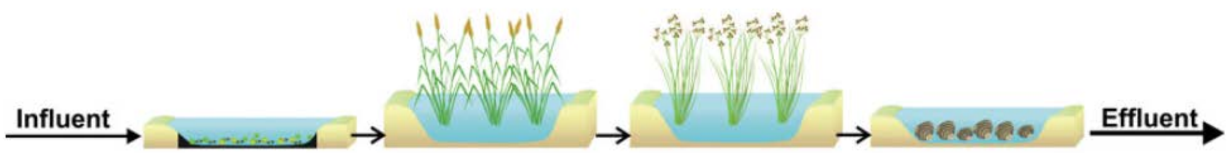

Figure 12. Area predicted to provide 90% removal of contaminants from 1 million gallons per day (MGD) or 1 megaliters per day (MLD) of wastewater effluent in open-water treatment cells throughout the year. Dashed lines for Prado and Easterly wetlands show the area per flow rate at existing full scale wetlands (from Jasper et al. 2014a).

These types of innovative projects may be more complicated for dischargers from a regulatory standpoint. Discharges will need to be consistent enough and/or planned to support project goals such as habitat creation, adding a level of temporal complexity to releases. Wetlands can also complicate permitting compliance issues if flow is significantly adjusted, or if increased biological activity results in changes in other parameters such as total suspended solids or turbidity, and may, depending on design and level of treatment, raise questions about where the point of compliance should be.

Additional concerns arise around issues as diverse as existing cultural resources and environmental justice factors associated with a site, anticipated ancillary uses of a site, long-term performance and increasing uncertainty in changing climate patterns.

## 4.1 Using Multiple Treatment Types Together

Because wetland design and type drive specific pollutant removal rates, and because of the wide array of processes unique to each wetland type (e.g. photolysis, biotransformation), utilizing multiple treatment types together could optimize removal rates, build in needed redundancy and potentially provide more predictable and manageable results. The Prado wetlands utilize vegetated wetlands for nutrient removal, and the more recently added open-water test cells to contribute to higher CEC removal. Figure 13 shows an example of how different wetland cells might be designed to operate in series.




| Open-Water Cell | Cattail Cell | Bulrush Cell | Bivalve Cell |
|---|---|---|---|
| •Direct photolysis<br>•Indirect photolysis via •OH produced by $NO_3^-$ and ROS from CDOM<br>•Sorption and biotransformation in periphyton mat | •Denitrification<br>•Precipitation of metal sulfides<br>•Biotransformation fueled by plant-derived carbon | •Sorption to peat formed by slow-decaying bulrush lignin<br>•Precipitation of metal sulfides<br>•Biotransformation fueled by plant-derived carbon | •Ingestion of pathogens and particle-associated chemical contaminants<br>•Inactivation and transformation of ingested contaminants |

Figure 13. An example of different treatment cells used together and the processes occurring in each (Jasper et. al 2013).

## 4.2 Further Research and Questions

While many CECs have been present but undetected for years, new compounds are continually being developed for residential, commercial and industrial products. Widespread use of chemicals with potential long-term persistence and effects on natural systems should spur further research as well as State and federal water quality criteria. Wastewater treatment plants in the Bay area currently do not have effluent limits for CECs. The Regional Monitoring Program for Water Quality in San Francisco Bay (RMP), a collaborative effort between the San Francisco Estuary Institute and the regulated discharge community, has been looking at CECs since 2000, and has outlined a strategy for CEC management that includes prioritization of known and identification of unknown compounds. It includes a strategy of taking actions commensurate with the risk posed by the CEC (SFEI 2013). The approach is based on a tiered-risk framework, from Tier 4, high concern to Tier 1, possible concern. At present, the management focus is on pollution prevention, low cost control actions and informing State and federal decision-making about product usage and controls. This is because no CECs have been identified in Tier 4, high concern, which would require more aggressive control actions.

Recent monitoring in San Francisco Bay has identified a number of pesticides and flame retardants that have elevated toxicity potential and have been found in fish, bird egg and seal blood throughout the region. Based on other regional water quality programs' prioritization, other CECs recommended for potential study include common fragrances and dyes found in many household products (Sutton et al. 2017). Because of the diversity of regional wastewater treatment plant processes (e.g. activated sludge, granular activated carbon, various disinfection methods, reverse osmosis), understanding which methods are effective in removing which compounds will be instructive. Further research involving plant uptake, transformation products and treating reverse osmosis concentrate could assist current pilot project work (UC Berkeley personal communication Mar 15, 2018).

A recent sampling of California wastewater treatment plants detected pyrethroid compounds used in many common insecticides in the effluent of 28 of the 31 sites examined, and the most commonly found pyrethroid, bifenthrin (highly toxic to fish and aquatic invertebrates), was detected in 96% of biosolid samples (Markle et al. 2014). Fipronil and imidacloprid are two newer insecticides that have begun replacing pyrethroids. The widespread and increasing use of these as tick and flea control agents (one potential primary source), their persistence in conventional wastewater treatment, and their toxicity to aquatic invertebrates have shown the need for further risk assessment (Sadaria et al. 2017).

Poly- and perfluoroalkyl substances (PFASs) are another large group of over 3,000 compounds used industrially in automotives, textiles, aerospace, food packaging and firefighting materials. These compounds can be very stable in the environment, and while some such as PFOS have been phased out by manufacturers, the RMP recommends monitoring PFOS (which has been detected in Bay Area wastewater) and a dozen other PFASs (Sutton et al. 2017).

While many gaps exist in monitoring and assessment, policy, and the technical and economic components, the State has begun research and policy work on CECs both in recycled water and their effects on aquatic ecosystems (SWRCB 2009, SCCWRP 2012). Recommendations from the science advisory panels convened by the State Water Board to provide guidance on CECs can address some of the same questions necessary for policy changes on CECs in wastewater such as *what are the appropriate constituents to be monitored, would the constituent list change based on level of treatment, what potential indicators represent a suite of CECs, and what levels of CECs should trigger enhanced monitoring* (SWRCB 2018)

# Section 5: SUMMARY

The increase in interest in permitting and building multi-benefit projects involving some type of treatment wetland necessitates changes in policy. Constructed wetlands can be highly effective at removing nutrients and CECs, but there are a great number of considerations before they may be used at a scale that will significantly benefit water quality on a regional scale. We have learned from the ongoing pilot projects that both nutrient and CEC removal in constructed wetlands can be successful. There is a larger body of knowledge around the ability of natural wetlands to assimilate nutrients; there is however, little information about the fate of CECs in natural wetlands. Modelling may be the most efficient way to evaluate the fate of CECs in wetlands (D. Sedlak, personal communication 2018).

Continued research should occur around what chemicals of concern are in effluent and what their effects are on receiving waters and the ecosystems that rely on this water. Initial considerations begin with land availability and the high costs of acquisition and construction. The San Francisco Bay Water Board is evaluating the policy considerations around shallow water discharge requirements, level of treatment, mitigation of impacts to existing wetlands, point of compliance, and monitoring with input from the regulated community and other relevant stakeholders. What is clear is that a set of performance standards for these innovative approaches would be helpful to support the permitting needs. We are also working regionally to develop a set of core monitoring requirements that would create the foundation for a regional approach to wetlands monitoring. Developing a set of indicators and metrics as part of performance standards for these types of projects would be helpful to inform the regional program for wetlands monitoring. All this, in the context of protecting water quality and, where possible, using best knowledge and judgement to allow projects to best help address the many challenges facing the baylands from climate change.

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