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Constructed Wetlands Using Treated Membrane Concentrate for Coastal Wetland Restoration and the Renewal of Multiple Ecosystem Services

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Abstract: The management of reverse osmosis concentrate (ROC) poses a challenge to utilities as it requires expensive disposal methods and advanced treatment in order to comply with regulations. This paper presents studies of natural treatment approaches, such as constructed wetlands (CWs), that have been tailored to treat ROC. Conceptually, with testing and planning, these wetlands could meet regulatory criteria before discharging to the surface water and achieving multiple benefits. Lessons learned from pilot studies of wetland treatment of ROC point to the potential benefits of designing full-scale wetlands for concentrate management. Studies have illustrated the ability of CWs to reduce the concentrations of metals and simultaneously remove nutrients to meet state standards for aquatic and wildlife designated uses. Nutrient removal processes include denitrification for nitrogen removal (possibly supplemented with Annamox reduction of NO_3-N), labile carbon assimilation supporting oxidized nitrogen reduction, and phosphate-P uptake and precipitation. Because of the evaporative water loss, mass removal efficiencies were greater than concentration reductions. Studies illustrate how engineered wetlands help with the management of ROC produced from reclaimed water through reductions in concentration and volume for disposal through evapotranspiration. The associated creation of wildlife habitats and coastal wetland restoration could result in the renewal of multiple ecosystem services.

Keywords: RO concentrate; brine management; constructed wetland; tailored approach; evapotranspiration; metals and nutrient removal

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1. Introduction

The challenge of balancing water scarcity, increasing water demands, and rigorous regulations has drawn attention to the use of membrane technologies to produce potable water from non-potable sources [1–3]. Membrane processes have become a competitive option to conventional treatment technologies for desalination since the product water meets various water quality criteria and the small footprint of membrane technologies allows them to be combined with other treatment processes [1–5]. The major drawback to the implementation of pressure-driven membrane processes is the need for the management and safe disposal of highly polluted reverse osmosis concentrate (ROC), which presents a potential long-term limitation to water reuse as well as a financial burden for many applications [1–3,6–10].

The management of ROC requires the evaluation of the available management alternatives, regulations, costs, and site-specific conditions [1,3,11,12]. ROC, which is considered to be industrial waste, includes elevated concentrations of contaminants generated to make brackish groundwater or reclaimed water, such as wastewater treatment plant effluent, potable. Contaminants in ROC often include high concentrations of salts, metals, and nutrients that typically exceed water quality standards and must be removed or diluted before being discharged into surface waters or the ocean to meet the discharge criteria [4,8].

The water industry, particularly in inland areas where coastal waters are not available for relatively economical concentrate and brine disposal, continues to seek innovative solutions for disposal that are cost effective, provide a beneficial use of the water, and are environmentally sustainable. While the cost of RO-produced water or RO permeate has continued to drop over the previous decades, concentrate disposal can easily double the cost of constructing and operating an RO facility, particularly for the inland communities [3,6,7,11,13]. In the absence of a dedicated pipeline to bring the ROC to the ocean, many utilities find it cost-prohibitive to manage the ROC even if the facility is in the vicinity of a coast. Cost-effective and environmentally safe concentrate management is recognized to be the most important barrier to the widespread implementation of membrane technologies [3,9,11]. Wetland technology is a versatile approach to managing concentrate and achieving water quality, habitat creation, and recreation benefits [14,15]. Wetland treatment systems rely on naturally occurring processes to improve water quality through physical, chemical, and assimilative processes [16]. The ability of wetland and aquatic ecological systems to improve water quality has been recognized for more than 40 years, and their utilization for water quality treatment has grown from a research concept to an accepted pollution control technology [10]. The application of various types of wetlands using various substrates for ROC treatment with regard to meeting the finished water criteria for beneficial reuse has not been exploited extensively for various reasons, one being the challenge of treating highly toxic influent water. The available land for the creation of wetlands is a challenge for any area, particularly in an urban setting. Land acquisition for installing a natural treatment system in a city or urban area faces multiple challenges [15].

In a typical wetland treatment method, water moves slowly through the wetland, allowing for an extended contact time with micro-organisms. The velocity of the water in a wetland is adjusted so that the hydraulic residence time (HRT) increases and the particulate matter settles out. Microbes (microscopic organisms) provide most of the treatment. Suitable environments for both aerobic and anaerobic micro-organisms present in the wetland carry out the biological processes necessary to remove or transform pollutants, such as nitrates, phosphates, ammonia, manganese, sulfur, and carbon, carried by the water [17,18]. Plants in the wetland remove nutrients and improve aesthetics, but their primary function is to provide a surface area for the growth of microbial films. More plant stems in the water column translate into more microbes cleaning the water. System design and operation should be aimed at enhancing features that improve these characteristics of the wetland system [7]. Treatment wetlands have been used for decades to treat conventional wastewater pollutants, including the treatment of domestic sewage, industrial wastewater, and wastewater from mining and petroleum products [14,16,19–28]. Since the mid-2000s, wetland treatment of ROC has been piloted at several locations for the beneficial reuse of ROC as a natural management alternative [5,10,29]. The application of constructed wetlands (CWs) and the creation of brackish marsh wetlands would appear to be a benign method for concentrate management due to its low cost and minimal maintenance requirements, resulting in a lower life cycle cost and the ancillary benefits they provide, including creating aesthetically appealing spaces and wildlife habitats [3,18,30,31].

It has been proven that CW treatment is an efficient method for improving water quality for brackish groundwater and wastewater while being a natural alternative [12,18,28,32]. However, the question arises as to whether a CW can even treat metals, nutrients, and organic matter at the highly elevated concentrations found in ROC produced from secondary treated municipal effluent in order to create a source of reclaimed water. Chakraborti et al. [30] reported that ROC contains total dissolved solid (TDS) levels of 11,800 mg/L, a value 6.7 times higher than that in the feed water (1750 mg/L), i.e., the secondary treated effluent. The acuteness of the concentration of metals, salt, and nutrients in the concentrate along with other factors, such as temperature, pH, evaporation, hydraulic loading rate (HLR), and land area, must be addressed to confirm the suitability of CW treatment [26]. Therefore, prior to any type of CW application, it is recommended to investigate whether the performance of wetlands for ROC treatment is feasible and whether the wetland discharge meets regulatory limits.

This paper presents the performance of CW treatment of ROC and the impact of finished water for the restoration of a natural wetland. The objective of this study is to optimize and illustrate how the CW method could produce good-quality reclaimed water to create more brackish wetlands and enhance existing brackish wetlands for biodiversification and multiple ecosystem benefits. A case study is a powerful research strategy for investigating complex technical and managerial phenomena in real-life settings and a pilot study is a prototype of full operation. The focus of this study is to explore options under investigation in pilot studies to treat ROC by tailoring various types of CWs to solve particular problems, strategies for its reuse, and the achievement of multiple benefits with safe disposal and to illustrate the breadth of this approach from pilot studies to full-scale designs. In addition to the CW type, the media type, flow rate, sequence of treatment methods, and hydraulic adjustments, such as the hydraulic loading rate (HLR) and hydraulic residence time (HRT), of CWs were varied in pilot studies to optimize and achieve objectives for beneficial water reuse.

Natural treatment of high-strength ROC by CWs for reclaimed water use has many benefits. The removal efficiency of high-strength nutrients and metals by CWs to an acceptable level for reclaimed water use in a pilot study has been described by Chakraborti and Bays [31]. This paper focuses on the use of multiple pilot studies with brackish water and ROC as the source water for multiple benefits and explains with test results how the transfer of knowledge or the lessons learned from one pilot study can benefit another pilot study to help design a full-scale plant. Various design parameters, such as plants, size, hydraulic parameters, media, and source water, have been altered throughout the course of the studies to optimize the CW treatment performance to best meet the objectives of the advanced water treatment plant design.

These approaches using CWs have a general tendency to reduce the ROC volume and that alone may be a useful characteristic of this method of treatment. The natural treatment and application method for achieving multiple benefits demonstrates that an optimally used CW treatment method tailored for specific needs may be a viable and sustainable solution where it is appropriate.

2. Background

2.1. ROC Management Alternatives

In the RO treatment method, the feed stream is divided into two portions: (i) a permeate that contains the "cleaner" liquid that passes through the membrane, and (ii) a waste stream containing the retained constituents rejected by RO membranes. The characteristics of this waste stream or ROC or brine depend on the membrane technology used, the quality of the feed water, the quality of the water produced (percent recovery), the pretreatment method, and the cleaning and membrane storage procedures used [2,33]. The ROC volume depends on the source water quality and the membrane system used. Recovery from the membrane process to the high-efficiency RO (HERO) process could be anywhere between 80% and 95% [2,10,34,35]. The most commonly used concentrate disposal management options along with the applicable federal regulations for disposal are presented in Table 1.

The most common disposal methods for ROC are disposal to water bodies that are already saline (an ocean or estuary), disposal to surface water (e.g., rivers, lakes with dilution potential), and disposal to sewers [36,37]. A few desalination plants dispose of their concentrate in deep wells, and only a very few facilities dispose of the concentrate in evaporation ponds and use spray irrigation [9]. These methods for disposal depend on the level of salt content in the concentrate and the ability of the water body to dissimilate the concentrate depending on the volume to treat and the available water for dilution. The concentrate's compatibility with the receiving water (surface water or sewer) is the major issue for determining whether surface water discharge is a feasible option. Proximity to water bodies and meeting federal regulation requirements are big factors in deciding on the appropriate disposal method. Conveyance costs (pumping, pipeline, and right-of-way costs) can be an important cost factor in determining the cost-effectiveness of any disposal option [2,37].

Table 1. The most common ROC disposal methods and regulations for discharge.

Disposal Methods	Requirements	Key Features	Applicable Federal Regulations [35]
Surface water discharge	Lake, river, or ocean	Proximity to a water body and a dedicated pipeline: Inland/coastal	CWA, RHA, NEPA, ESA
Land application (spray irrigation, percolation pond, rapid infiltration basin)	Area for recharge or irrigation	Availability of sufficient and suitable land for infiltration	CWA, HMTA, NEPA, ESA, RCRA, CERCLA, TSCA
Deep well injection where the receiving aquifer needs to be hydraulically confined	Suitable geology	Suitable geomorphology	SDWA, RCRA, CERCLA, TSCA
Sewer/effluent blending	Flow for dilution	Availability of good-quality water for blending	CWA, SDWA
Solar evaporation	Land area and the right climate	Sufficient land and a hot climate	HMTA, NEPA, RCRA, CERCLA, TSCA
Mechanical evaporation	High CAPEX and energy	Available funding and planning	HMTA, NEPA, RCRA, CERCLA, TSCA
Crystallization/Zero liquid discharge (ZLD)	High CAPEX and energy	Available funding and planning	HMTA, NEPA, RCRA, CERCLA, TSCA

Note: CWA, Clean water act; SDWA, Safe drinking water act; HMTA, Hazardous materials transportation act; RHA, Rivers and harbors act; NEPA, National environmental policy act; ESA, Endangered species act; RCRA, Resource conservation and recovery act; CERCLA, Comprehensive environmental response, compensation, and liability act; TSCA, Toxic substances control act; CAPEX, Capital expenditures.

Therefore, for inland communities with no access to brackish receiving water, the options for ROC management are very limited. With the growing challenges to concentrate disposal (regulatory challenges, environmental challenges, larger plant sizes, public perceptions, etc.), alternatives are needed that are environmentally appropriate as well as beneficial to society and nature.

2.2. Tailored Approach

With respect to optimizing the CW treatment efficiencies for solving the water quality problems of ROC, a better understanding of treatment efficiencies from the toolbox approach is needed so that wetlands as a unit process can be designed for the removal of pollutants (Figure 1). The system can be installed with individual wetland cells optimized for the removal of specific contaminants and connected in series or integrated with other engineered or natural treatment processes to achieve the targeted results most effectively. The different types of treatment processes within a toolbox range from an upland system comprising the land application of water consistent with water requirements and loading requirements to forests, pastures, and engineered plant systems, such as phytoremediation plantations.

The treatment units can be surface flow with the water on the surface growing marsh plants or sub-surface flow that may or may not be planted with wetland plants, but they use sub-surface media flow to provide treatment within the root zone of plants. Passive media beds use a biochemical reactor bed or a similar passive filtration bed where water is treated through natural processes. An open-water treatment system includes ponds and aquatics, such as ponds with floating wetland islands or aeration systems within ponds or lakes.

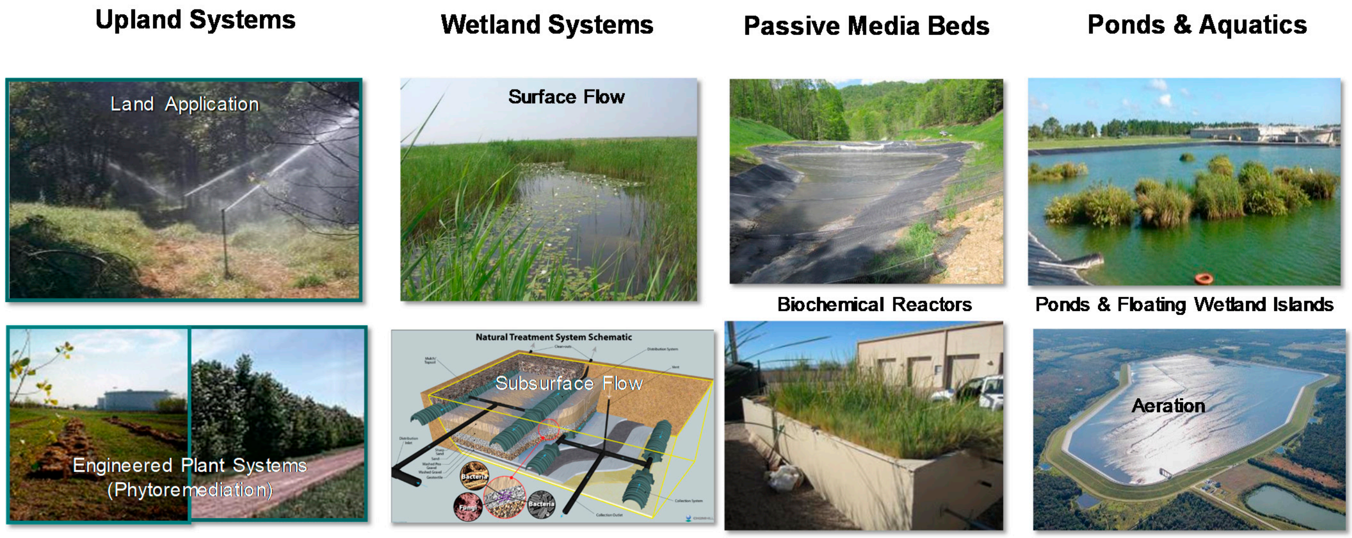

Figure 1. Various CW treatment options under the toolbox approach.

The general idea behind a wetland system's design is a landscape feature that holds enough water for a sufficient time so that natural processes take place and natural chemical, physical, and biological removal processes aided by microbial activities occur at a relatively natural rate to provide the treatment. Each one of these unit treatment systems may or may not be appropriate for a site but we certainly have a range of choices to pick from. The initial perspective of designing a CW system with any water quality issue is that there is probably a natural treatment system that can mimic nature and be applied to solve the problem. This includes a range of possibilities, from upland systems such as land application and engineered plant uptake systems to surface flow and sub-surface flow wetlands, passive media beds, such as anaerobic biochemical reactors, and ponds, which may include floating wetlands or aeration systems [27]. These types of systems and the benefits they provide can be reviewed and compared to see whether any of them "fit" the environmental setting of the project and treat the target compounds below the water quality criteria meeting environmental benefits. The plant types, substrates, types of wetlands, and sizes could easily be engineered with HRT, HLR, and flow paths to achieve the best treatment performance and meet the project's goal. The case study demonstrates how wetlands can be used to manage water resources through reclaimed water use.

2.3. Coastal Wetland Ecosystem Services

The wetland area loss to human activity over the last three centuries is estimated to be 85% globally [38]. Yet, the recognition of the need to protect, conserve, and restore wetlands for their ecosystem services has only recently been recognized [39]. These global trends are reflected in California, where more than 90% of its historical wetlands have been lost through agriculture, development, or hydrologic modification [40]. Of the remaining wetlands, it is noteworthy that there are less than 30 coastal wetlands in Southern California and they are subject to a large amount of variation in salinity (from fresh to saline) in response to seasonal flows [41]. Ecosystem services provided by wetlands are broadly categorized as regulating/balancing (e.g., the maintenance of essential ecological processes and life support systems for human well-being, such as pollutant attenuation, nutrient balancing, sediment retention, and species interactions), provisioning (e.g., the provision of natural resources and raw materials, such as an air supply, food, and materials for building and manufacturing), and cultural (e.g., enhancing emotional, psychological, and cognitive well-being, such as aesthetics, recreation, and education) [42]. In a recent review of ecosystem services provided by wetlands of the Gulf Coast in the United States, the top five ecosystem services provided by brackish marshes have been prioritized to include (in descending order): nutrient balancing, biological interactions, soil and sediment balance, climate balance, and food production [43]. Restoration of brackish marshes would provide a net increment in nutrient retention and processing, a greater area of habitat suitable for wetland avifauna and other wildlife, sediment retention, carbon fixation through photosynthesis, and a nursery for commercially important fish species. Consequently, the availability of a brackish source of water from treated ROC in a coastal setting offers the potential to augment these ecosystem services by restoring lost or degraded brackish marsh wetlands. The addition of a continuous flow of treated ROC could supplement the natural tidal flow and create an opportunity to restore, rehydrate, or create new brackish marshes, particularly considering the cumulative long-term loss in ecosystem services attendant with the decreasing trend in wetland area.

3. Case Study

The application of CWs for the treatment of ROC and the disposal of ROC to a marsh wetland to augment the water supply is presented through a case study of the Oxnard Wastewater Treatment Plant in California (Figure 2). The case study presents the treatment potential of CWs under a tailored approach for water quality improvement and the beneficial reuse of ROC with relatively high salt contents and high metal and nitrate concentrations.

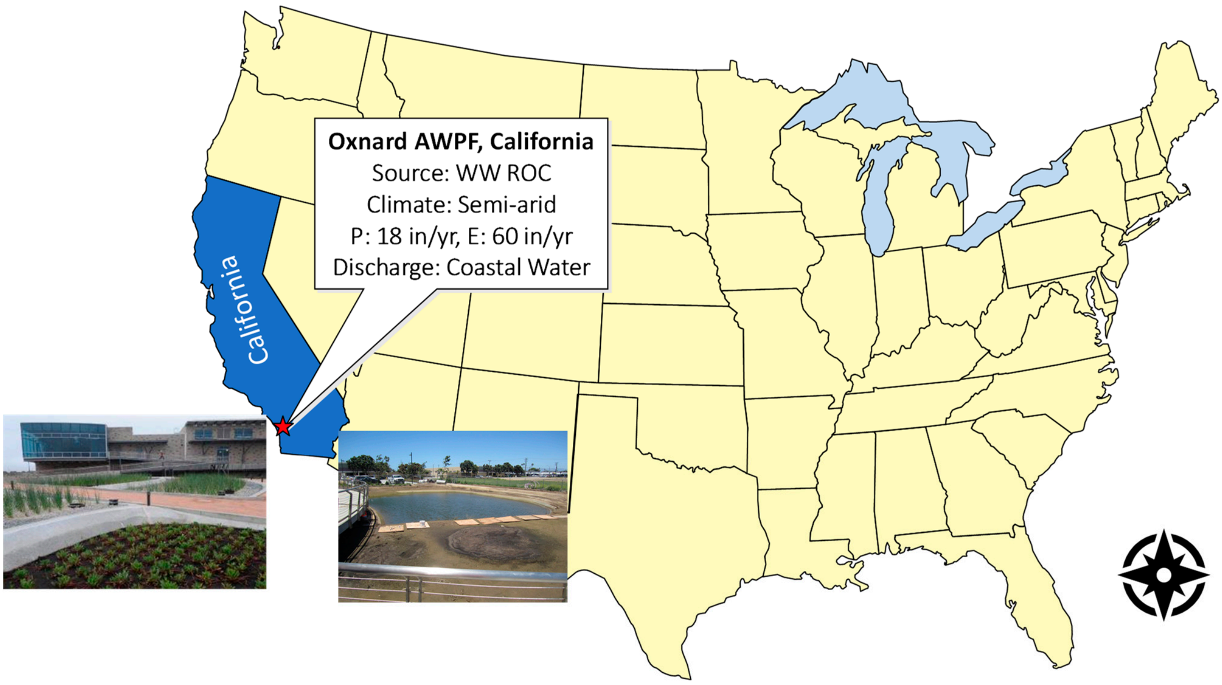

Figure 2. Location of the Oxnard AWPF in California on a map of the USA.

Background

The City of Oxnard, California, USA has embarked on the Groundwater Recovery Enhancement and Treatment (GREAT) program to make efficient use of its water resources. This program develops additional sources of alternative water by combining wastewater recycling and reuse with groundwater injection, storage, and recovery and groundwater desalination to supply water to the Oxnard region, continue meeting the City's goal of providing current and future residents and businesses with a reliable and affordable source of high-quality water, solve overdraft conditions, and minimize the cost of imported water [44–46].

According to the Advanced Water Purification Facility (AWPF) plan (Figure 3), the secondary effluent from the wastewater (about 75% domestic and 25% industrial wastewater) plant produces high-quality recycled water that meets the water quality criteria for groundwater recharge (GWR) and unrestricted irrigation as specified by the State of California, Department of Public Health Title 22 guidelines [47]. To meet the GWR water quality permitting requirements, the treatment options for the AWPF include microfiltration (MF), reverse osmosis (RO), and ultraviolet (UV) disinfection, including advanced oxidation (UV/AOX) capabilities, degasification, and water stabilization [47].

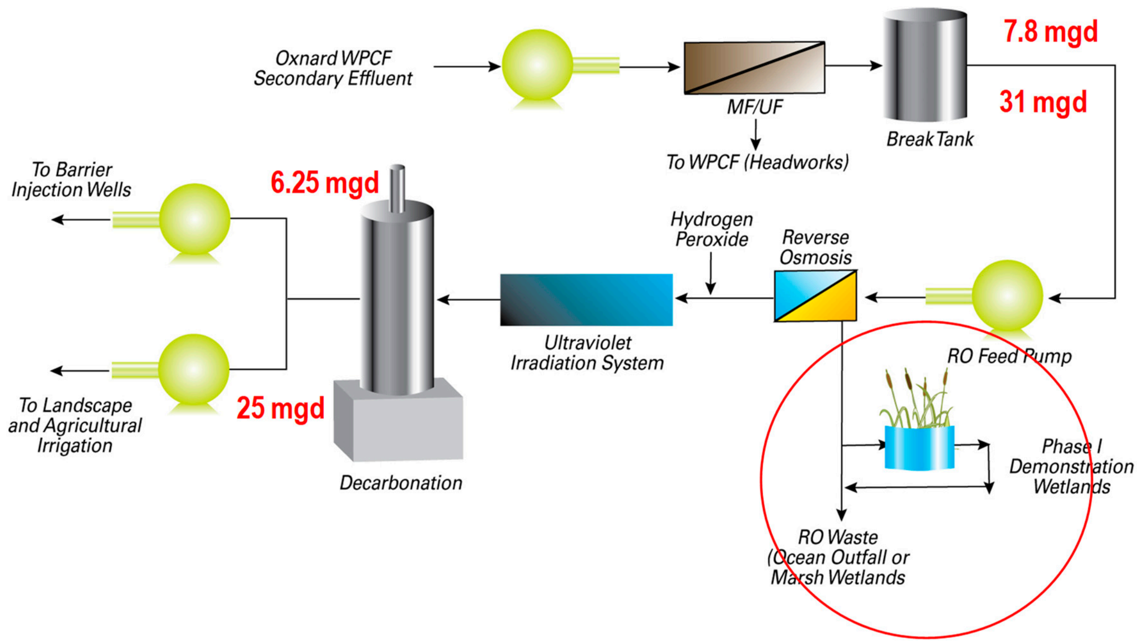

Figure 3. Oxnard Advanced Water Purification Facility (AWPF) Process Schematic. The red circle shows the pilot constructed wetland receiving ROC.

The Oxnard wastewater treatment plant is on the coast of Ventura County, California, USA, which is known as a center for agricultural production, mostly strawberries and oranges. Oxnard's annual total pan evaporation averages 1524 mm and its annual rainfall averages approximately 380 mm, occurring mostly during the winter months between December and April in 2010 [46]. The total evapotranspiration (ET_0) in 2010 was 1168 mm, varying from 5 to 10 mm during October through March and from 10 to 15 mm during April through September [48]. The climate is semi-arid, and the temperature ranges between 6 °C and 24 °C.

As presented in Figure 4, the GREAT program requires a portion of the RO concentrate to be discharged to the Pacific Ocean and the other portion of the concentrate stream (highlighted with a circle) to be directed through a demonstration-scale engineered natural treatment system (a CW). Conceptually, the treated ROC could become a water source to create or restore brackish or salt marsh wetlands at the adjacent Ormond Beach [39]. Ormond Beach is the beach that fronts the Ormond wetlands and coastal farmlands near Oxnard in Ventura County, California. By augmenting the water supply to the Ormond wetland with a source of treated brackish water, the ecosystem of the wetland and the coastal area could be enhanced. The Ormond Beach wetland is home to many rare plants, is an important resting site for hundreds of migratory birds, including the endangered snowy plover and the western least tern, and is a host for many ecosystem activities. Since a limited number of coastal wetlands remain, the Ormond wetland represents a critical beachfront and open space for the coastal communities and needs to be protected and restored [48]. The Ormond Beach is one of the few areas in southern California with an intact dune-transition zone–marsh system. It is also an important public access and beach recreation area that balances habitat restoration and the protection of sensitive plant and animal species by providing multiple ecosystem benefits with improved and increased public access.

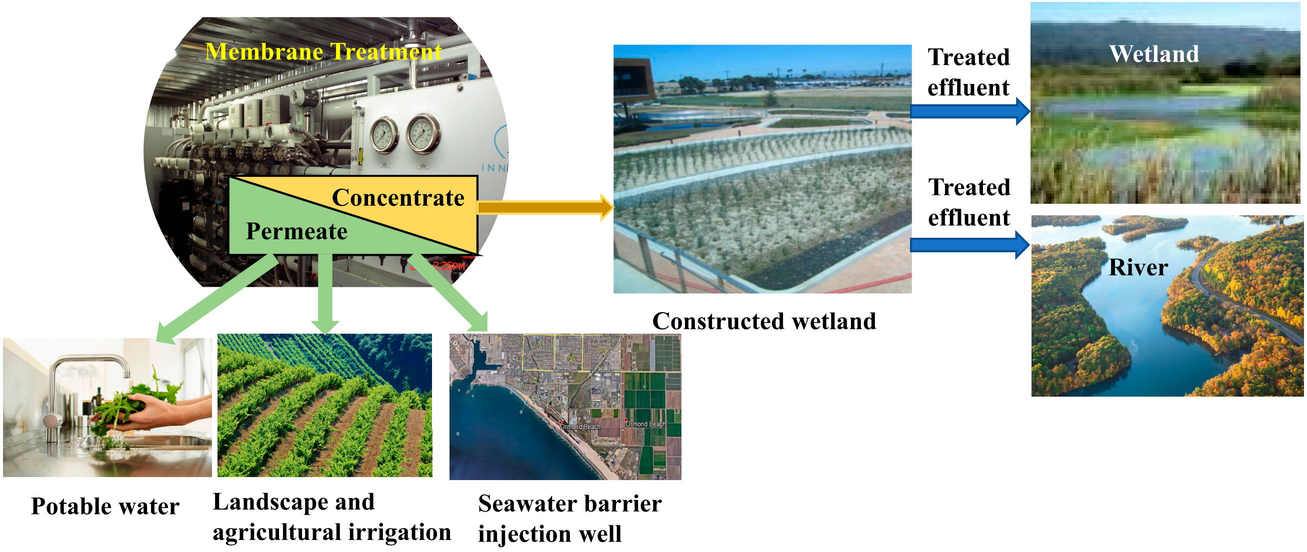

Figure 4. Schematic of the management of the membrane treatment for the permeate and concentrate at the AWPF.

Two pilot studies were performed prior to the design of the demonstration-scale CWs using both groundwater and wastewater concentrate in two phases. To investigate the performance of the CW to tailor the full-scale plant design, Pilot Study 1 was conducted between 2003 and 2006 using brackish groundwater from the Port Hueneme Brackish Water Desalination Facility and Pilot Study 2 was performed in 2008–2009 to investigate the treatment of ROC derived from the secondary effluent of the Oxnard wastewater treatment plant.

Various lessons were learnt from the pilot studies and that knowledge was used to design full-scale CWs for the treatment of ROC. Considering the variability in the flow and chemical constituents in the effluent from the wastewater treatment plant, those pilot studies provided helpful details on how to set performance criteria for a conceptual full-scale wetland system.

The objectives of the pilot studies were to:

- Determine whether the wetland-treated water can meet the performance requirements and comply with the guidelines of the State of California, Department of Public Health;
- Demonstrate the system's performance under full-scale design and operating conditions;
- Confirm the survival and growth of brackish marsh plants receiving the ROC;
- Confirm that the aesthetics of the treatment wetland would be acceptable (i.e., that no offensive odors or colors would be generated);
- Assess whether the pollutant removal performance of the wetlands treating the ROC is similar in quality to the full-scale operations.

4. Analysis Methods

4.1. Pilot Study 1

Because the membrane concentrate from the AWPF includes metals, nutrients, and salts, there was a need to develop removal rates and toxicity characteristics under mesocosm tests before considering the use of the concentrate for wetland treatment in the AWPF [49].

Initial testing, including the construction, operation, and testing of pilot wetland mesocosms, was conducted from June 2003 to May 2004. The goal of this testing was to demonstrate the safety and potential beneficial use of the concentrate for wetland restoration. Additional testing was conducted by re-configuring the initial pilot wetland mesocosms over a 6-month period from September 2004 to March 2005. The goal of this testing was to assess the treatment effectiveness of an optimized series of pilot wetland mesocosms. Final sampling of the mesocosms was conducted in July 2006 to quantify the distribution and accumulation of salts.

To evaluate design parameters, this pilot study consisted of twelve 1 m^3 wetland mesocosms comprising six wetland types with two replicates of each, randomly arranged (Figure 5). The test was performed with the concentrate for treating local brackish groundwater containing between 1000 and 5000 mg/L of total dissolved solids (TDS).

Figure 5. Configuration of Oxnard membrane concentrate Pilot Study 1.

Groundwater was encountered at shallow depths during geotechnical investigations conducted near the AWPF project site. The groundwater table was at a depth ranging from 7 to 15 feet below the ground surface at the proposed project site. The six flow-through wetland types included: surface flow high marsh (SFHM), surface flow low marsh (SFLM), horizontal subsurface flow (SSF), peat-based vertical upflow (VF), submerged aquatic vegetation (SAV), and saltgrass evaporation bed (SE). Of the wetland types selected, the SFHM, SFLM, and SAV cells represented the major brackish water plant communities known to exist within local coastal salt marsh wetlands. The SSF, VF, and SE cells represented treatment systems designed to eliminate or minimize the potential for wildlife exposure to the concentrate. Water, sediment, and plant and fish tissue were monitored, and chronic and acute toxicity testing was performed.

4.2. Pilot Study 2

Because the water source for the membrane treatment process will be reclaimed water, with significantly greater concentrations of nitrogen, phosphorus, selenium, and TDS, instead of groundwater, it was determined that another pilot CW study would be conducted with the ROC from the AWPF to confirm the treatability characteristics of the reclaimed water concentrate. The objectives of the CW treatment in the pilot study were to (i) use the membrane concentrate as an additional water source to create or restore brackish or salt marsh wetlands, if found to be compatible with the local environment, and (ii) use the membrane concentrate for the beneficial creation of new coastal marshes or for enhancing flow to existing marshes.

The RO unit in Pilot Study 2 included membrane elements, pressure vessels, feed, permeate, and concentrate headers, system support frames, and numerous valves and instruments and is shown in Figure 6. The RO system had three stages, in which the concentrate from the first stage was the feed water to the second stage, and the concentrate from the second stage was the feed water to the third stage. The permeate from the three stages was blended into the final product water. The RO pilot unit was continuously fed with MF filtrate from the break tank using an RO booster pump.

Figure 6. The RO pilot unit for Pilot Study 2.

The RO pilot unit was designed to treat 169 L/d (or 31 gpm) of filtrate from the MF and operate at 85 percent recovery. The unit was arranged as a three-stage configuration comprising seven 10 cm (or 4-inch) diameter pressure vessels configured in a 4:2:1 array arrangement using six elements per pressure vessel to simulate the same array arrangement as proposed for the full-scale system. Each vessel was fitted with six 10 cm (or 4-inch) diameter by 102 cm (or 40-inch) long spiral-wound membrane elements. Two types of low-fouling, low-pressure brackish water RO elements were trialed during the pilot study prior to receiving the MF-treated secondary effluent from the Oxnard wastewater treatment plant. The pilot system had a total permeate output of approximately 142 L/d (or 26 gpm) based on an average flux of 427.8 L/m^2 (or 10.5 gallons per square foot per day, gfd). The first-stage permeate piping was fitted with a back-pressure valve and a flow meter to allow for flux balancing in the first stage. All of the equipment and components were mounted on a common skid with the exception of the chemical carboys and housed inside a container. The RO unit was equipped with the Hydranautics ESPA2 element. All performance requirements for feed pressure were achieved during the pilot study.

In Pilot Study 2, the AWPF effluent was tested on a portable sub-surface flow-type wetland developed by Mobile Environmental Solutions (MES) of Tustin, CA (Figure 7). The MES portable wetland was constructed in such a way that both the sub-surface flow (SSF) and the vertical flow (VF) could take place simultaneously [30]. The MES portable wetland was a trailer with a surface area of 8.9 m^2 (or 96 ft^2) and an internal volume of 11.9 m^3 (or 420 ft^3) containing soil and gravel as a substrate for the growth of a mature stand of bulrush (*Schoenoplectus californicus*). The plant was fully grown in with sufficient time for a microbial biofilm community to develop on the inert matrix and the root system. Secondary effluent was recycled through the wetland for the first week. Over the next three weeks, sea salt (Instant Ocean brand) was added to the wetland to attain a total dissolved solid (TDS) of 5 g/L and finally 11 g/L. During this time, the water continuously recycled through the wetland at a rate of 1.9 L/min. All components of the study were operational by the end of September 2008. The wetland received ROC continuously with average HRTs estimated to range from 1 to 5 days. During the initial acclimation period of 23 days, an HRT of 1.3 days was achieved. The HRT was increased to 2.5 days during the first period of sampling for 110 days, followed by a 5-day HRT during the final period of sampling of 40 days. Generally, the testing conditions involved relatively higher HLRs and shorter HRTs than most wetlands [26].

Figure 7. The MES wetland system for Pilot Study 2. The white trailer on the left is the AWPF pilot system and the wetland trailer is equipped with a solar cell to operate the pump used for water circulation. The right top photo shows lively bulrush plants after the 9-month-long pilot study with intense ROC pollution and the bottom photo shows the pilot study layout plan at the AWPF. The red circle shows the pilot plant at the AWPF.

Between 17 September 2008 and 5 March 2009, the inflow and outflow to the MES wetland was sampled weekly for analysis of ammonia-N (NH_3-N), nitrate-N (NO_3-N), total Kjeldahl nitrogen (TKN), orthophosphate (OP), biochemical oxygen demand (BOD), total organic carbon (TOC), total nitrogen (TN), and total selenium (Se). Weekly samples of concentrate, which essentially represented the characteristics of the wetland influent, were also analyzed. Field measurements of temperature, specific conductance, pH, and ammonia-N were taken periodically throughout the study.

5. Results

5.1. Pilot Study 1

All of the mesocosms were planted with local species typically found in southern California and assigned to each mesocosm by hydroperiod tolerance. For example, the surface flow marsh systems were planted with species of bulrush and mixed emergent species commonly found in brackish marshes, such as bulrush (*Schoenoplectus californicus*, *S. americanus*, and *S. maritima*). The sub-surface flow wetlands were planted with species typically found at the highest elevation within a tidal flooding gradient where soils would be saturated or inundated infrequently, such as saltgrass (*Distichlis spicata*), yerba mansa (*Anemopsis californica*), jaumea (*Jaumea carnosa*), and pickerelweed (*Salicornia virginica*).

HLRs were gradually varied by system type from 0.8–1.6 cm/d to 6.4 cm/d and 17 cm/d. Volumetric evapotranspiration (ET) losses ranged from as little as 23% in the SSF systems to as much as 98% in systems with the greatest macrophyte densities. Most salts and TDS became more concentrated as water evaporated within the different mesocosms for all of the wetland types studied but exhibited mass removals between 23% and 78% through evapotranspiration and the precipitation of calcium compounds.

The iron (Fe^{+3}), selenium (Se^{-2}), nitrate, and phosphorus concentrations decreased measurably in all systems. Based on inlet/outlet differences in flow, the estimated concentrations and mass removals for the non-conservative parameters (nitrate, Se^{-2}, and Fe^{+3}) were 67–83% and 93–96%, respectively. In contrast, TDS concentrations increased by 15% from 2350 to 2695 mg/L, presumably through the evaporative concentration of solids, but the overall mass of TDS decreased by 76% because of the evapotranspiration of flow.

With regard to metals, data from this pilot study indicate little or no risk of accumulation to ecotoxicological thresholds. All selenium and mercury samples were below the reporting limit, even in the vertical flow wetland, which had the greatest selenium removal rate [50]. Plant roots showed measurable concentrations of selenium but shoots generally did not. Another factor affecting the longevity of a concentrate wetland may be more pragmatic, in that the precipitation and accumulation of salts in pipes and gravel and soil media may ultimately impede flow and cause an unacceptable level of hydraulic head loss or short-circuiting. However, visual inspections of the pipes and valves used in the pilot study found no indication of excessive salt build-up and flows were maintained throughout the study. After three years of operation, the plant tissue and soil concentrations indicate that a full-scale system would likely have a lifespan similar to that of other wastewater treatment wetlands, which have been found to be on the order of decades or longer [19].

To summarize, results from Pilot Study 1 include the following: (1) the concentrate supported healthy plant communities for over three years, (2) both metals and nutrients were effectively removed through natural biological and chemical transformation processes and varied among wetland types, and ET was a major loss process, (3) concentrations of key constituents, such as nitrate and selenium, decreased to levels at or below regulatory thresholds and the discharge is ecologically safe for wetland biota, (4) the mass removal was higher than the concentration-based removal efficiency, (5) the wetland effluent was less toxic to indicator organisms than the raw concentrate, (6) the concentrate can sustain viable native plant communities, and (7) salts and other contaminants did not accumulate outside of ranges found in natural systems and it is expected that such a system would have a lifespan comparable to that of other common natural treatment systems.

5.2. Pilot Study 2

From the field measurements (number of samples, 11), it was found that the mean pH decreased marginally throughout the wetland by 3% from 7.4 to 7.2, indicating alkaline water, as expected given the high inorganic ionic content of the concentrate. Influent temperatures during this period were warm, ranging from 14 °C to 22.5 °C with an average temperature of 18.2 °C. Samples were generally collected between 10 a.m. and 2 p.m. on each sampling day. The specific conductance in the influent water measured with a handheld instrument at the pilot study location varied between 11,460 and 16,210 µS/cm, indicative of the concentrate source, while effluent values averaged between 16,320 µS/cm and 19,150 µS/cm during the study period. This 17% increase in inorganic solids content throughout the wetland is attributable to the evapoconcentration caused by water loss through plant evapotranspiration. Ammonium concentrations showed an apparent decrease of 38% from 150 mg/L to 94 mg/L during this same period. The actual concentration reductions may be greater given the significant water loss and evapoconcentration effect.

Figure 8 presents box and whisker plots of NO_3-N, NO_2-N, NH_3-N, TKN, BOD5, TOC, and orthophosphate as P concentrations in the influent and effluent during HRT1 and HRT2. These plots represent the spread of data from the median (the 50th percentile). The concentration reductions of constituents varied. The nitrate and nitrate concentration reductions were about 60%, whereas the NH_3-N, orthophosphate as P, and TOC concentration reductions were in the range of 20%. The TKN concentration reduction was in the range of 10%. The decrease in concentrations for NH_3 –N, TKN, and TOC was not significant ($p > 0.05$) between HRT1 and HRT2 compared with NO_3-N and NO_2-N (for HRT2).

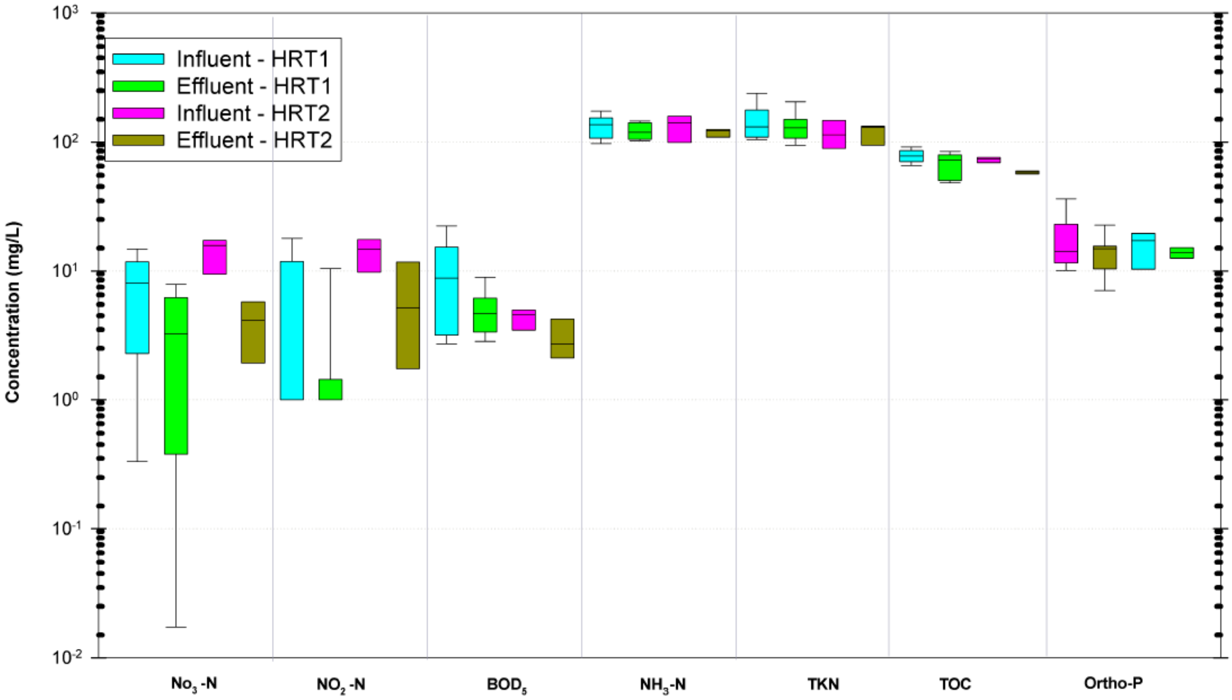

Figure 8. Range of concentrations of nutrients measured at the outflow of the wetland.

As shown in Figure 8, the influent loading during HRT2 was higher than that during HRT1, but the effluent data for HRT2 had less spread over the median value. Similar observations can be made for NH_3-N and TKN influent and effluent data for HRT1 and HRT2. There are significant ($p < 0.05$) differences in NO_3-N, NO_2-N, and TOC concentrations ($p < 0.05$). This illustrates that the heterotrophic assimilation of organic carbon and the anaerobic reduction of oxidized nitrogen are the major processes in the wetland.

The mass removal efficiency for nutrients by the CW is shown in Figure 9. The loss of water through evapotranspiration and plant uptake caused a considerable amount of mass removal. The key findings from this study show that plants survived well, vigorous plant growth was observed, and no odor was detected. On average, the treatment removed 61% of the NO_3-N (0.5 g/d/m^2), 32% of the NO_2-N (0.1 g/d/m^2), and 42% of the NH_3-N (7 g/d/m^2). The NO_2-N and NO_3-N removal seemed to follow expectations from other wetlands [26]. The average concentrations of orthophosphate decreased by 29%. The removal of a significant amount of phosphorus is not normally expected in sub-surface flow wetlands [26].

Under the mass-based analysis, the treatment removed an average of 43% of the BOD5 (0.5 g/d/m^2) and 61% of the selenium (1 µg/d/m^2). This was due to multiple wetland processes occurring naturally through the water flowing through the gravel bed and root system of the plants. An increase in the removal rate could be anticipated with a reduction in the hydraulic loading rate and a further increase in HRT given the understanding that nitrate will be used as an electron source preferentially by the bacteria that create the anaerobic conditions appropriate for a reduction in selenium before the oxidization of selenium. The evaporation rate varied from 1.4 mm/d to 3.9 mm/d with an average of 2.7 mm/d (38 inches/year or 3.2 ft/year). As with the other parameters, the concentration of selenium may increase in part due to the evaporative concentration caused by the plants.

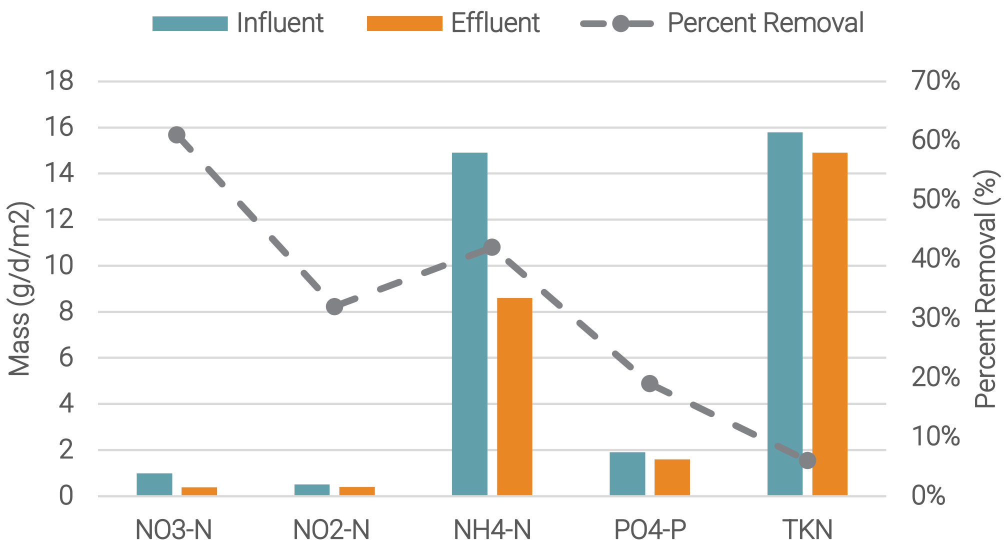

Figure 9. Nutrient percent removal by mass between the influent and effluent (number of samples, 6).

Since the demonstration wetlands will be part of a public display, one of the initial concerns was that the concentrate would generate unpleasant odors in the aerated wetland cells. Throughout the study, no unpleasant odors were given off by the water in the aeration tank.

5.3. Demonstration Wetland Design

Borrowing from the results of Pilot Studies 1 and 2, a demonstration wetland facility was designed and built at the AWPF with the CWs tailored to three types of systems: horizontal subsurface flow with a capacity for aeration and recirculation, vertical upflow for anaerobic treatment, and an open surface flow (SF) wetland pond in a 1.2-acre (4856 m^2) area. Wetlands are set up in series; however, both of the vertical flow systems included several individual cells of that type in parallel. Water flows below the ground in these two types of systems, preventing the potential for odor or vector concerns to develop. Using the same types of wetland technologies evaluated in the pilot studies, the ROC is treated first by an aerated horizontal sub-surface flow wetland for nitrification and ammonia reduction, followed by a vertical upflow wetland for denitrification and selenium reduction, with the objective of achieving a water quality level that can be discharged safely to an emergent marsh suitable for aesthetic public use.

Figure 10 presents the layout of the demonstration CW, which was designed to wrap around the AWPF visitor center and to be incorporated into educational outreach programming for the facility. Various key environmental processes that take place in the individual cells of the wetland are also presented. The final polishing of the contaminants takes place after excess nutrients and metals are removed from the water through VUF and SF wetland cells. The VUF cells are intended to provide an anaerobic environment for the bacterial reduction of nitrate and selenium. Cells have a lower layer of gravel and an upper layer of peat moss that supports a diverse list of brackish plant species. The SSF cell nitrifies ammonia in a sand-and-gravel-based filter bed planted with wetland plants. The final SF cell provides final nutrient removal through denitrification and biological assimilation in an aesthetic aquatic wetland habitat that can be used as an environmental education component while providing additional contaminant polishing. Based on the pilot studies, it is expected that reductions in two common contaminants (selenium and nitrate) in the concentrate could be achieved in the anaerobic VF upflow cell, and other improvements in water quality could be expected in SF-type marsh cells and open pond-like SAV cells.

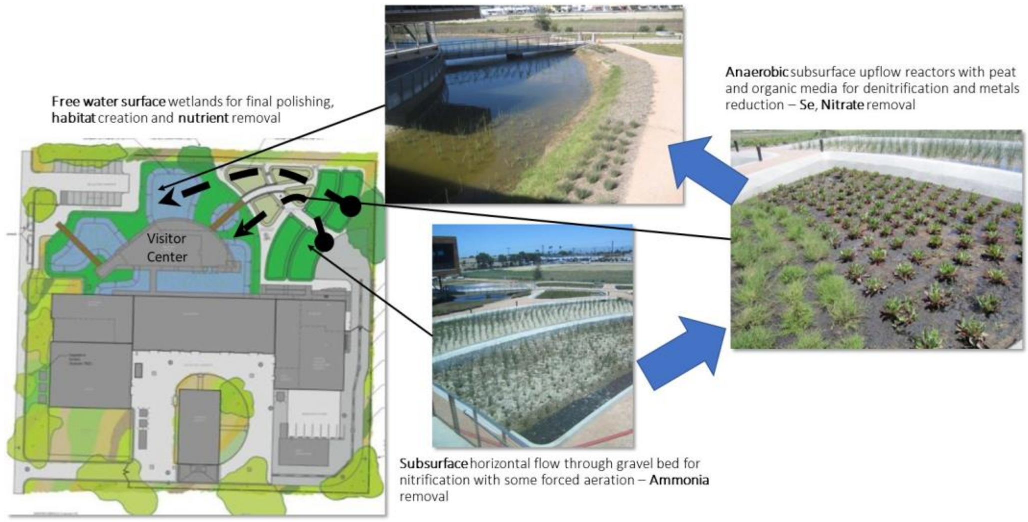

Figure 10. Layout of the constructed wetland around the visitor's center of the AWPF.

The horizontal sub-surface flow wetlands were configured to allow for supplemental aeration of the gravel bed to reduce the BOD content and support the natural nitrification of the ammonia. The vertical upflow beds were configured as thick beds of peat and compost supplemented with reduced carbon to facilitate the denitrification of the nitrified effluent from the horizontal sub-surface flow wetlands and the reduction of biological selenium, where selenium in the form of selenate will be reduced to selenite and, eventually, elemental selenium and precipitate to the bottom of the wetland. Because the high concentrations of salts will precipitate and lead to scale formation and clogging, four cells are planned for each sub-surface flow wetland to create two flow paths of two cells each to minimize the short-circuiting potential and to allow for wetland cells to be taken off-line for maintenance as needed, a recommended feature in wetland design [19]. The treated water from the sub-surface flow wetlands will flow to an open pond interspersed with alternating bands of marsh vegetation, submerged aquatic vegetation, and open water. This final marsh pond system was designed and maintained as an aesthetic public use, education, and research facility.

The AWPF demonstration CW was built based on the results of pilot studies (Figure 11). As a consequence of the results of Pilot Study 2, aeration lines were installed in the first series of sub-surface flow wetland cells to meet the BOD in the concentrate and the conversion of ammonium to nitrate.

Figure 11. Construction of the constructed wetland around the visitor's center of the AWPF.

6. Discussion

The influent water characteristics in Pilot Studies 1 and 2 are very different, reflecting their origin as groundwater or wastewater (Table 2). The concentration of ROC is 5 to 12 times higher than the secondary effluent produced in the wastewater plant's operation (Figure 12).

Table 2. Influent concentrations for the CW in Pilot Studies 1 and 2 and the secondary effluent.

Parameter	Range of Influent Concentrations		WWTP Operation: Average Concentration of Secondary Effluent
	Pilot Study 1: Brackish Groundwater	Pilot Study 2: RO Concentrate	
TDS (g/L)	2–5	12–15	1.75
NH_3-N (mg/L)	0.1–0.5	100–150	22.2
NO_3-N (mg/L)	30–50	20–40	1.2
Se (µg/L)	20–30	30–60	6.0

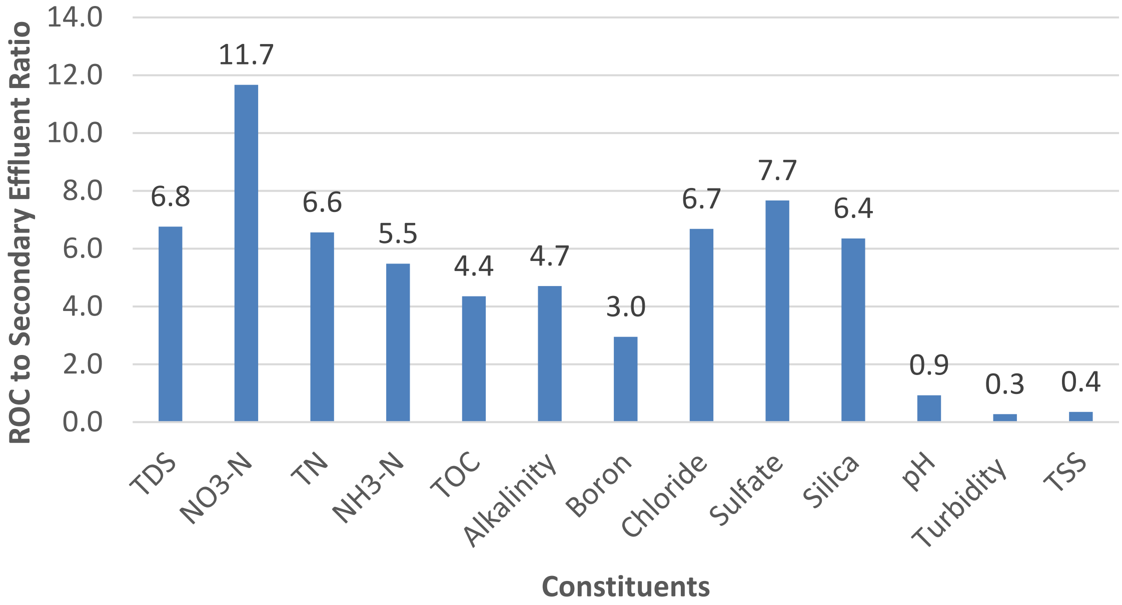

Figure 12. Constituents in the ROC to the WWTP secondary effluent ratio (number of samples, 6).

It was realized that, in order to gain confidence in the performance of the wetlands to treat ROC and to confirm that the demonstration wetland would present no aesthetic nuisances, Pilot Study 2 was performed before the full-scale design. A step higher in the concentration of pollutants in the concentrate from brackish water (Pilot Study 1) to reclaimed water treated with MF/RO was needed since the CW in the full-scale plant will treat the concentrate from the reclaimed water. Therefore, Pilot Study 2 was developed as a prototype of the full-scale plant.

We learned from Pilot Study 1 that a constructed brackish wetland creates an opportunity for treatment and habitat creation. Multiple processes take place in CWs, including nutrient (such as nitrate and phosphorus) removal and metal (such as iron and selenium) immobilization. The wetland plants (bulrush) in Pilot Study 2 were found to tolerate the high levels of salts and grow in the ammonium-rich water from the MF/RO plant with no indications of adverse health at the conclusion of the study. There were no indications of stress to the plants, including tip browning, shoot necrosis, and shoot pigment loss, or other indications of plant mortality or injury. Normal flowering and fruiting characteristics were observed. No odor was detectable from the ROC influent to the wetlands.

Reductions in nitrate, nitrite, and total nitrogen concentrations and masses were measured throughout the study at levels consistent with findings from other studies [17,26]. Nitrite concentrations were detectable in the wetland effluent, indicating a carbon limitation or hydraulic short-circuiting in the test wetland. The estimated mass removal of pollutants by the CW was about 42% of the NH_3-N mass and 25% of the orthophosphate mass. The sub-surface flow treatment wetlands reduced nitrogen levels through the plant concentration of nitrogen as ammonium and nitrate, the biological nitrification of ammonium, and the biological denitrification of nitrate. Phosphorus interacts strongly with wetland soils, media, bed aggregates, and biota, which provide both short-term and sustainable long-term storage of this nutrient [26]. The removal of phosphorus is not normally expected in sub-surface flow wetlands because the removal of phosphorus in this type of wetland is due to bacterial growth and plant uptake and the formation and precipitation of various phosphate salts, including calcium phosphate (apatite or hydroxyapatite) [26]. Both surface flow and sub-surface flow treatment wetlands have a limited ability to remove phosphorus [25]. The modest removal of orthophosphate is consistent with the possibility of exporting organic matter in the form of bacterial biomass and root exudates and material and is compounded by the evaporative increase in parameter concentrations. The room for adsorption in the sediment (soil) and plant root surface was limited in the relatively small-size MES wetlands with the small surface area available from soil particles and vegetation (volume and density) and, therefore, the removal of phosphorus seemed to be predominantly due to the precipitation process.

Ammonium concentrations decreased but, given the high inflow concentrations, the removal of addition ammonium is needed to complete nitrification. The production and export of organic matter by the macrophyte and microbial biomass may account for some of the export of the organic nitrogen given the high rate of enrichment and the relatively dense condition of the root mat within the MES wetland. The lack of oxygenation in the wetland bed may be due to the fact that the plant root structure may not have fully penetrated into the full depth of the wetland. Without continual exposure of the water to the oxygen from the root hairs, a critical step in nitrification could have been missed in Pilot Study 2. Because this was anticipated, the proposed design includes the provision of aeration of the sub-surface flow horizontal wetlands, which will support the microbial conversion of ammonium to nitrate and, subsequently, to gaseous nitrogen in the anaerobic second-stage wetlands.

A limited reduction in the selenium concentration was observed in the pilot test. Mass removals were estimated to be in the order of 36%. The pilot system was configured differently than the proposed demonstration wetland, which includes anaerobic wetlands. The reducing conditions in the vertical flow cells of the demonstration wetland are designed to remove the selenium to meet the 5 μg/L regional limits. The use of various types of substrates and media to remove metals from the ROC using wetlands is a future research goal.

The pilot studies were tested with the hypothesis that a sequence of varied types of wetland treatment cells would provide higher mass removal rates for trace metals than individual cells. Results indicate that the iron, selenium, nitrate, and phosphorus concentrations decreased in all systems; and, through evapotranspiration (ET) losses, all four salts showed a net mass removal through the series. The principal processes through evaporation or sinks within a wetland can be described as an evapotranspiration/evapoconcentration loss process (Figure 13). These data suggest that a pretreatment train of wetland systems could be constructed for the treatment of concentrate in order to safely discharge it into a natural system.

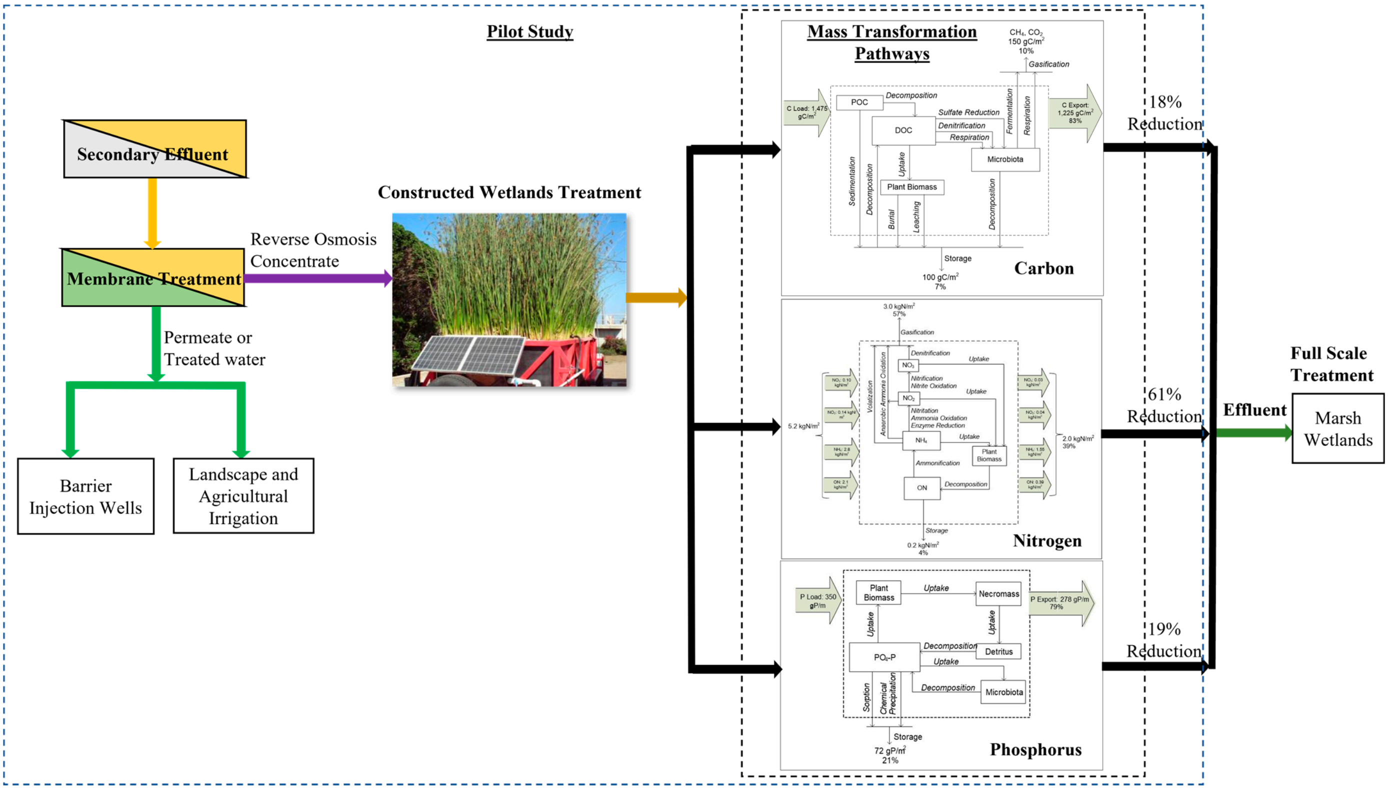

Figure 13. Summary of processes and results from Pilot Study 2 for the full-scale design.

Although the treated water that emerged from the CWs in the pilot studies, which lasted only for a few months, is within the discharge limits, the discharge and potential accumulation of pollutants in the plants, water, and media of a CW for a longer period of time need to be addressed through regular maintenance of wetland components and the periodic removal of sediments in which metals and emerging contaminants may potentially accumulate over time. Revitalization and replanting will become necessary if any kind of stress in the plants in the CW is noticed.

The pilot studies demonstrated the importance of the HLR and HRT as the key operational controls over wetland performance to (i) improve the water quality of the concentrate for disposal, and (ii) benefit the wetland habitat for local species of birds, mammals, and plants as well as a myriad of other living organisms. Moreover, this study indicated that the elevated concentrations of nitrogen, phosphorus, and selenium in the reclaimed water concentrate can be treatable by CWs under a tailored approach and the performance of CWs is consistent with expectations from the treatment wetland literature [17,51–54].

The restoration and renewal of coastal wetlands in southern California are needed for various reasons. Climate change and the growth of the population and businesses have driven away many coastal wetlands. The water supply to coastal wetlands has become unreliable in a semi-arid region such as southern California with a Mediterranean climate. The water produced from the demonstration wetland project could help the flora and fauna of the coastal wetland to survive with a steady supply of good-quality water. The dwindling supply of natural water due to the climate effect could be easily compensated for by the water produced from the secondary effluent of a coastal wastewater treatment plant through the CW treatment processes as presented in this study. The drought-prone area in coastal California could be aided by the reclaimed water source as demonstrated in this study. It could be one of the nature-based, environmentally friendly, and cost-effective solutions for concentrate management.

The pollutants carried through the non-point-source discharge from agricultural and urban areas and the pollution coming from the first flush effect after rainfall to the coastal wetland could be managed and alleviated when good-quality CW-treated water is supplied through some dedicated pipelines. The dilution effect could help the wetland plants to survive in the coastal areas. The steady daily supply of water from the local treatment plant as presented in this study could serve multiple ecosystem services and create a resilient coastal wetland system.

The supplemental water produced by the CW treatment plant could help sustain coastal wetland activities by stopping erosion and providing soil retention. The steady and robust water source will promote biological productivity and diversity, provide wildlife habitats, and help to maintain recreational activities, including educating visitors during the year.

These pilot studies support the prospect of using membrane concentrate for the beneficial creation of new coastal marshes or for enhancing flow to existing marshes. This is consistent with the overall project vision, and, assuming the future testing in the demonstration wetlands continues to support these results, this effluent could possibly serve as a water source for the Ormond Beach Brackish Wetland Restoration Program.

7. Conclusions

The following can be concluded from this study:

- The wetland plants were found to tolerate the high levels of salt and grow in the ammonium-rich water from the ROC;
- No odor was detectable from the ROC influent to the wetlands;
- Significant reductions in nitrate, nitrite, and total nitrogen concentrations and masses were measured consistently throughout the study at levels consistent with findings from other studies. Nitrite concentrations were detectable in the wetland effluent, indicating a carbon limitation or hydraulic short-circuiting in the test wetland;
- Ammonium concentrations decreased significantly but, given the high inflow concentrations, the removal of additional ammonium will be required to complete nitrification. Because this was anticipated, the proposed design includes the provision of aeration of the sub-surface flow horizontal wetlands, which will support the microbial conversion of ammonium to nitrate and, subsequently, to gaseous nitrogen in the anaerobic second-stage wetlands;
- The final TDS in the wetland effluent is projected to fall within the range of 15–25 g/L. This is consistent with the overall project vision, and, assuming that future testing in the demonstration wetlands continues to support these results, this effluent will serve as a water source for the Ormond Beach Brackish Wetland Restoration Program;
- The pilot test demonstrated the importance of the hydraulic loading rate and hydraulic retention time as the key operational controls over wetland performance;
- Wetland technology is a novel approach to managing ROC and achieving water quality, habitat creation, and recreation benefits in a sustainable way;
- If tailored to the specific suite of pollutants in the ROC, engineered wetlands could meet surface water quality standards using a train approach with various media types in series. The management of ROC through a natural treatment system, such as a CW, may open many sustainable treatment avenues meeting the discharge limit regulations and generating an additional water source for reuse if the tailored approach is optimized for the flow conditions;
- Wetland treatment could be a cost-effective alternative for ROC management (low energy and operational requirements; thus, a lower lifecycle cost);
- Pilot studies are required to facilitate a full-scale plant design;
- The water produced from a CW treatment plant could assist with coastal wetland restoration services by providing a supplemental and steady reclaimed water source as presented in this study. Restoration as a nature-based climate change adaptation approach provides ecological benefits and promotes natural habitats as a form of

protection to coastal areas ("green infrastructure") and as an alternative to human-built structures such as concrete channels and seawalls ("grey infrastructure").

In all pilot studies, evapotranspiration was observed to increase the salt concentration but reduce the mass (plant and media water uptake) through water volume reductions. While a natural treatment approach has shown to be ineffective in removing biologically conservative salts and elements in the ROC, the creation of a brackish marsh as a part of or predecessor to evaporation ponds or as a conditioning step before deep injection wells or ocean discharge appears to be a reasonable technology. Salt-tolerant plants grew vigorously and thrived on high TDS in the ROC through natural bio-geochemical and physical processes under high nutrient conditions (N and P). Additional blending with low-salinity surface waters (such as municipal wastewater) may be an appropriate solution for inland settings.

In summary, wetland technology shows potential as a versatile approach for managing ROC from reclaimed water to achieve water quality, habitat creation, and recreation benefits and, thereby, promote the widespread use of membrane technologies. If land is available near a facility, wetland treatment offers a cost-effective and environmentally sustainable means to treat and discharge ROC for beneficial reuse. In locations near coastal areas, wetlands represent a promising method for treating concentrate whilst simultaneously providing environmental benefits.

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