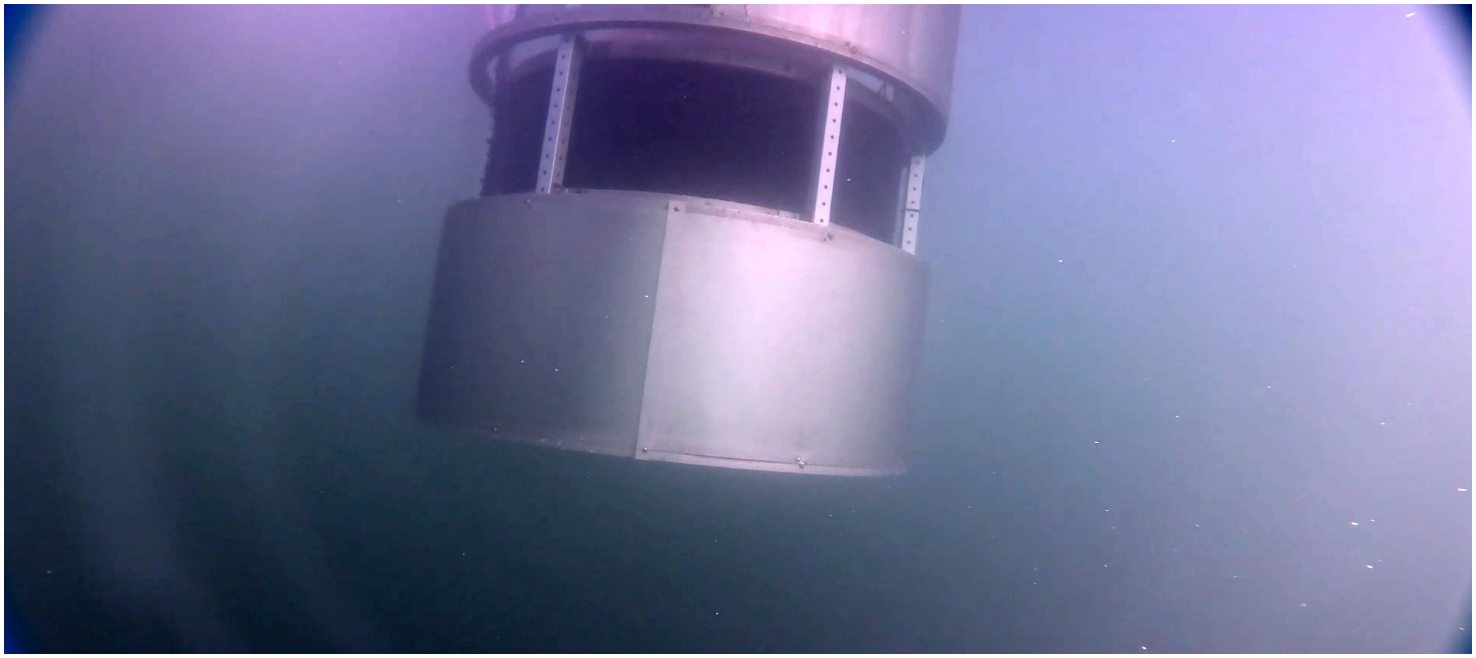
Desalination and Water Purification Research Program
Report No. R24AC00103-00 Final Technical Project Report

# Submerged Water Filtration: A Climate-Resilient, Eco-Friendly, Underwater Filtration Package



U.S. Department of the Interior

March 2026

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**Cover Photo** – *OceanWell Pod in-situ (OceanWell)*

## Desalination and Water Purification Research Program
## Report No. R24AC00103-00 Final Technical Project Report

# Submerged Water Filtration

A Climate-Resilient, Eco-Friendly, Underwater Filtration Package

**Project Completion:** September 30, 2025
**Applicant Name:** OceanWell (formerly NOWCo)
**City, County, State:** Menlo Park, San Mateo, California
**Project Manager:** Mark Golay, PE
**Email:** mark@oceanwellwater.com
**Phone:** 757-635-4355

Prepared by: **Mark Golay, PE:**
Prepared for: **Bureau of Reclamation under Announcement No. R23AS00282**

**U.S. Department of the Interior** **March 2026**

# Acronyms and Abbreviations

DP – differential pressure
DEE – dockside electrical enclosure
gfd – gallons per square foot per day
gpm – gallons per minute
gpd – gallons per day
LARS – launch and recovery system
LV – Las Virgenes
LVMWD – Las Virgenes Municipal Water District
NGO – non-governmental organization
ppm – parts per million
psi – pound per square inch
RO – Reverse Osmosis
rpm – revolutions per minute
SRO – Submerged Reverse Osmosis
SWF – Submerged Water Filtration
TDS – Total Dissolved Solids
ROV – remote operated vehicle

## Symbols

| | |
|---|---|
| cm | centimeter(s) |
| °F | degrees Fahrenheit |
| µg/L | micrograms per liter |
| kWh/m3 | kilowatt-hours per cubic meter |
| mS/cm | milliSiemens per centimeter |

## Metric Conversions

| Unit | Metric equivalent |
|---|---|
| 1 gallon | 3.785 liters |
| 1 gallon per minute | 3.785 liters per minute |
| 1 gallon per square foot of membrane area per day | 40.74 liters per square meter per day |
| 1 inch | 2.54 centimeters |
| 1 million gallons per day | 3,785 cubic meters per day |
| 1 pound per square inch | 6.895 kilopascals |
| 1 square foot | 0.093 square meters |
| °F (temperature measurement) | (°F−32) × 0.556 = °C |
| 1 °F (temperature change or difference) | 0.556 °C |

# Contents

Page

## Tables

Page

## Figures

Page

# Executive Summary

The need for alternative water treatment methods is paramount. To supply the increasing water needed for drinking, as well as for agriculture, cooling, and other uses, we must find solutions that are cost and energy effective, while minimizing harm to the environment. Legacy methods rely on costly nearshore construction, energy-intensive operation, and concentrated brines, solid wastes, or other harmful byproducts often released by water filtration facilities, affecting the environment and resulting in the accumulation of toxic pollutants, biodiversity loss, and harm to frontline communities. In addition, many land-based plants are large, noisy, smelly, expensive, and inefficient. This is because today's prevailing methods often use chemicals and high pressure pumps to treat and push water through downstream filters – processes that are unnecessarily land, energy, and capital-intensive. Moreover, land-based plants often use dead-end filters that entrain small lifeforms and dispose of them in landfills.

OceanWell's technology is a novel subsea desalination system that reimagines seawater desalination by submerging the reverse osmosis membranes 400m under the sea. At this depth, the natural pressure of the ocean drives the reverse osmosis process, cutting the required energy by as much as half. This lower pumping requirement reduces the cost, carbon footprint, and ecological impacts of harvesting freshwater from the deep sea. OceanWell's deep-sea location requires minimal land presence (>90% less than a typical onshore plant) and provides natural protection from climate-related risks to the water supply, by sheltering the system from extreme weather events.

OceanWell's technology can be broadly implemented to treat other water bodies. We successfully completed the submerged water filtration (SWF), also known as submerged reverse osmosis (SRO), pilot in August 2025 in the Las Virgenes (LV) Reservoir. The pilot exceeded expectations, allowing OceanWell to fulfill all objectives outlined in the Pitch-to-Pilot Proposal No. R23AS00282 and bringing our TRL from 4 to 6. The results validate our theoretical predictions of key performance indicators for SRO, including measurements of specific energy, conductivity, flow, pressure, temperature, oxygen, and turbidity. The pilot helped us prove that SRO is a practical and economic way to reduce the cost, energy, and environmental impact of water treatment applications across the nation. Furthermore, it validated that SRO can produce safe drinking water, which can be used for human consumption.

Highlights from the project include:

- **The SRO pilot produced >1 gpm for >3 months totaling >150,000 gallons** while maintaining an operational uptime >93%.
- **High quality water was produced, an order of magnitude purer**, with permeate conductivities starting at <0.015 mS/cm (<10 ppm TDS) while seasonal effects had big impacts on the reservoir's water quality with feed conductivities >0.5 mS/cm (>320 ppm TDS).
- **Low specific energy of ~1 kWh/m3 was observed, as predicted**, closely matching theoretical predictions for average energy use versus filter type, depth, and pump speeds in the freshwater reservoir with high levels of bioactivity, further validating the expected ~2 kWh/m3 for subsea desalination.
- **Backwashing proved to be a relatively safe and effective self-cleaning method**, with empirical data showing more entrained microorganisms were returned to their natural environment unharmed, providing good evidence that OceanWell's LifeSafe™ circulation system may dramatically reduce aquatic life mortality rates versus the 100% mortality rate of standard intakes that is currently tolerated by the open ocean intake and desalination industries.

# 1.0 Introduction

In the United States, we have more than 20 billion acre-feet of fresh water (reservoirs, lakes, and rivers) and virtually unlimited supplies of saline water (via desalination) that can easily provide the nation with reliable supplies of drinking water well into the future. However, today's prevailing land-based water filtration systems are unable to meet this opportunity. They are energy-intensive, susceptible to natural disasters, such as hurricanes, wildfires, and floods, and also negatively impact the environment because land-based facilities often use chemicals and dead-end filters that discharge harmful wastes and kill aquatic life.

In this project, we proposed a simple, modular, point-source filtration solution to the problems mentioned above: Submerged Water Filtration (SWF) or Submerged Reverse Osmosis (SRO). SRO is an unconventional water filtration method in which its process filters and pumps are submerged and operate deep underwater. This naturally protects SRO systems from atmospheric climate risks and, if designed thoughtfully, can eliminate ecological harms, such as waste accumulation and aquatic life mortality. Depending on its source salinity and depth, SRO can also cut energy requirements by as much as half compared to land-based systems, by leveraging the natural hydrostatic pressure of a water body. While this is not a new concept, challenges related to underwater access and servicing have so far kept SRO from being widely adopted.

OceanWell has developed a novel SRO technology package to simplify access to and extend the service life of a submerged filtration system. Our proposed project responds to Objective 1 in the NOFO – Reduce the costs, energy requirements, and/or environmental impacts of treating impaired and unusable water to standards necessary for an identified beneficial use. The SRO package not only addresses the need to reduce the costs, energy requirements, and environmental impacts of treating impaired and unusable water, but also has national significance where its benefits accrue to a large sector of the public. This is because SRO can produce safe drinking water from nearly any body of water, from fresh to brackish to saline, and can accept most commercially-available filter types. Project success was measured by proving that SRO can effectively clean a natural water source and resist fouling (extending its service life) over long runtimes >3 months. As mentioned, this cleaned water can have many beneficial uses, including for drinking, as well as for agriculture, cooling, or other water-intensive applications. Designed for easy intervention and dockside servicing, our SRO package was used to run head-to-head comparisons of different filters that can selectively reject impurities without the use of chemicals or dead-end filtration.

During the project, we installed our SRO package in the Las Virgenes (LV) Reservoir and monitored its performance/impacts over a 3-month endurance test. The LV Reservoir was a perfect environment for stress testing our system because it is >50-ft deep and suffers from surface algae and benthic metals.

# 1.1 Project Background

## 1.1.1 Objectives and Goals

The two main objectives we were responding to through this pilot were expanding access to impaired and unusable waters, and reducing the costs, energy requirements, and environmental impacts of water treatment.

As defined in the project proposal, four major objectives were accomplished: objective 1, a comparison of real-world water supply methods with SRO; objective 2, baseline testing of head-to-head comparisons of SRO filter types and cleaning methods; objective 3, longevity testing of the best-in-class filters, depth, and pump speeds; objective 4, performance mapping of SRO versus other water filtration methods. For reporting purposes, objectives 1 and 4 are combined and discussed together in Section 3.0. Section 2.0 summarizes baseline testing results, which were used to select the best-in-class filter types, depth, and pump speeds for longevity testing. Three independent variables – recovery rate, membrane flux, and feed pressure – were controlled during the trial to study their effects on the pilot system's specific energy, permeate quality, outfall strength, and other dependent variables of the produced freshwater, intake feedwater, outfall concentrate, and backwashed discharge.

## 1.1.2 Previous Research

In 2021, we developed the 1st-generation proof-of-concept prototype of our technology and tested it at the Naval Base Ventura County's Deep Ocean Simulation Facility. This successful test increased the technology readiness level to TRL 4 - lab scale validation. In a series of hyperbaric chamber tests, OceanWell varied the salinity, pressure, and temperature of the prototype's source water from 0-35 ppt TDS, 0-800 psi, and 7.5-20 °C, respectively. During the test, OceanWell produced high-quality freshwater, an order of magnitude purer than EPA drinking water quality standards of <500 ppm.

## 1.2 Project Overview

### 1.2.1 Overall Technical Approach and Concepts

Our approach followed systematic experimental protocols in which head-to-head tests of different filters were run simultaneously without needing multiple test beds. First, short duration baseline tests were run at different depths (25-50 ft) to measure performance changes under various hydrostatic pressures, pump speeds, and feed water qualities. Flow, pressure, water quality data, and post-test inspections informed which operating conditions were optimal for the reservoir environment. Then, a >3-month longevity test was completed to collect data required to map performance onto our prior test data in brackish and saline waters. Taking this approach allowed us to prove that SRO could be adopted to filter nearly any body of impaired or unusable water of sufficient depth across the nation to reduce the costs, energy requirements, and environmental impacts of SRO versus today's conventional land-based methods.

### 1.2.2 Overall Accomplishments

- **Objective 1:** A life cycle assessment of common water supply methods revealed that SRO has a lower cradle-to-grave impact than land-based seawater desalination and some wastewater recycling methods.
- **Objective 2:** The "best-in-class" filter types and cleaning methods identified for SRO were novel membrane crossflow constructions, polypropylene prefilters, backwashing to clean the intake, and light-duty pressure washing to clean the screens; the "best-in-class" depth and pump speed ratio required to maintain stable operational longevity in the lake were determined to be the deepest available depth of 50-ft and the lowest pump speeds.
- **Objective 3:** Post-test membrane autopsy reports, after >3 months of operation, revealed that, although there was substantial fouling (a feature of this study to accelerate learnings), the membranes performed better than expected in the highly bioactive freshwater lake environment.
- **Objective 4:** A detailed performance mapping of OceanWell's SRO technology versus other onshore and offshore desalination technologies suggests that OceanWell has the lowest overall environmental impact in seawater desalination.

As mentioned, for reporting purposes, objectives 1 and 4 are combined and discussed together in Section 3.0.

# 2.0 Technical Approach and Methods

In this section, the research approach to longevity testing is described. Three independent variables – recovery rate, membrane flux, and feed pressure – were controlled during the trial to study their effects on the pilot system's specific energy, permeate quality, outfall strength, and other dependent variables of the produced freshwater, intake feedwater, outfall concentrate, and backwashed discharge. **Figure 1** shows performance data collected during the >3 month trial.

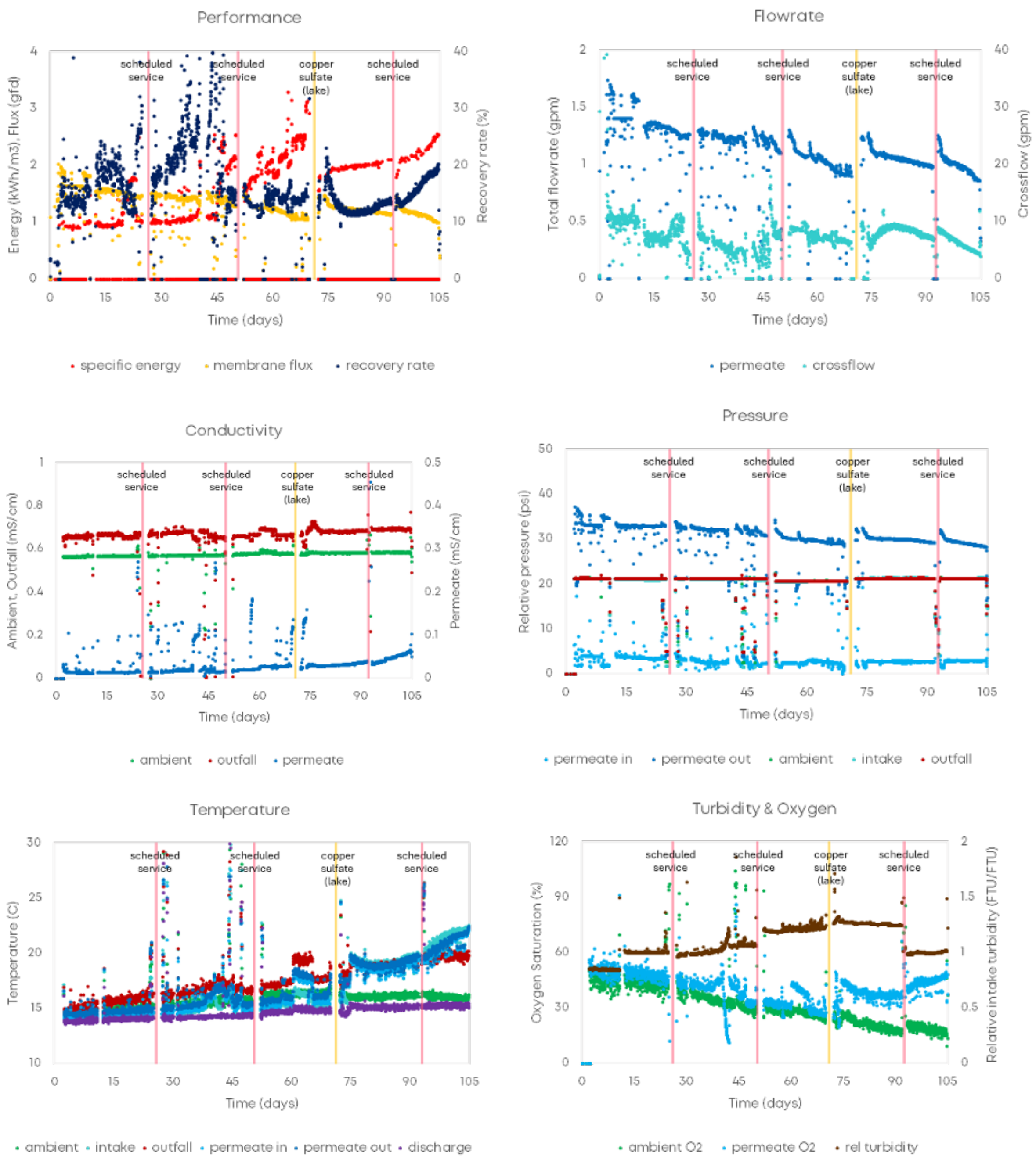

**Figure 1 | OceanWell SRO pilot system performance data** collected during the 3-month longevity testing trial. The vertical bars highlight scheduled service events for routine system maintenance, including one event which coincided with a copper sulfate seeding by the Las Virgenes Municipal Water District (LVMWD) staff to manage a seasonal algal bloom in the lake. Note, throughout the longevity trial, several hour-to-week long experiments were conducted to stress test the SRO system and understand its operational limits, resulting in the various trends and scatter seen in the data. Membrane performance did not show significant decline until the last several weeks of the trial, where an increase in average energy use and decrease in average permeate quality and flowrates were observed. This was likely due to membrane element fouling identified in the membrane autopsies (see Section 3). Post-processed data shown here was averaged hourly.

### Depth & Pump Speed

The production of freshwater via SRO is best controlled by changing the system's operating depth and pump speeds. However, because of site-specific environmental limits, the deepest that the SRO system could operate was about 50 ft. At this depth the ambient pressure of the feedwater drawn into the system was about 20 psi, which was the best-in-class operating depth/pressure, as shown in **Figure 2**. As expected, the permeate-to-crossflow pump speed ratio also affected SRO performance. Higher permeate pump speeds led to higher permeate flowrates, while higher crossflow pump speeds led to greater crossflow rates, but at the expense of increasing specific energy, as shown in **Figure 2**. Therefore, the two pumps were tuned to operate at 1800 rpm (vs 3450 rpm max) for the permeate pump and 300-600 rpm (vs 1150 rpm max) for the crossflow pump. This resulted in the lowest specific energy of <1 kWh/m3 near the beginning of the trial. As the membranes began to foul, the crossflow pump speed was increased slightly up to 600 rpm by the end of the trial to maintain adequate crossflow. The permeate pump, on the other hand, was kept constant throughout most of the trial because its operation was dictated by the feed pressure at 50 ft (20 psi). Refer to **Figure 1** for long-term trends in total specific energy use. Importantly, the ratio of permeate-to-feed flowrate yields the recovery rate, and thereby, the outfall salinity. That is, the higher the crossflow (or feed) rate, the lower the salinity of the outfall, which is a key feature of OceanWell's LifeSafe™ circulation system. Throughout the trial, the recovery rate varied up to ~40% when stress testing the SRO system (refer to **Figure 1**). During normal operations, however, a stable 10-20% recovery was generally maintained, as targeted. For example, **Figure 3** shows plots of recovery and flux rates, critical pressures, and conductivities of the intake, outfall, and permeate streams during initial pump tuning experiments. As seen in the plots, the recovery rate and intake pressure (i.e., suction pressure feeding the RO membranes) decrease with increasing crossflow pump speed, while the membrane flux and permeate pump pressure differential (i.e., difference between the inlet and outlet of the permeate pump) increase with increasing permeate pump speed.

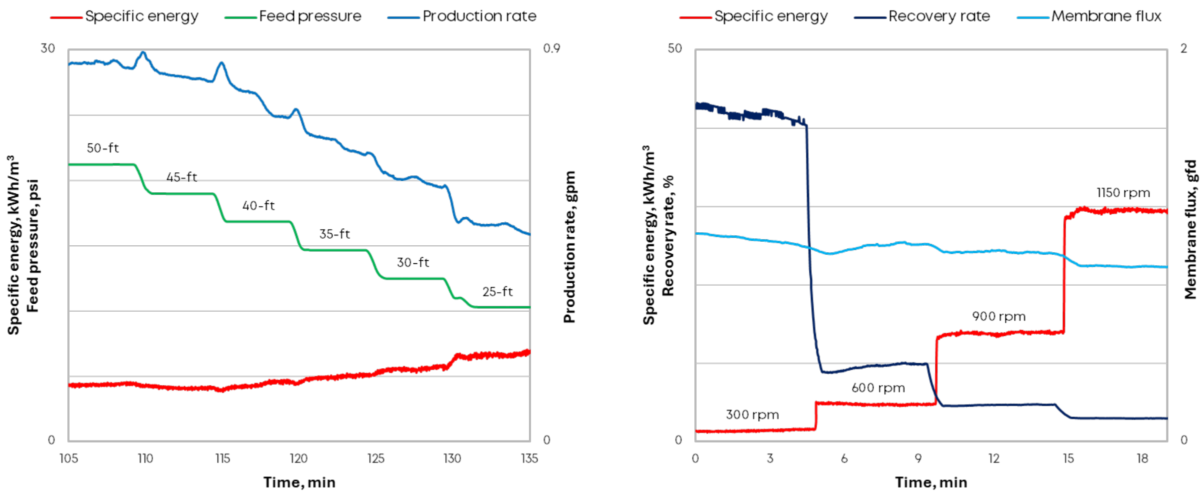

**Figure 2 | End-of-trial depth and crossflow pump speed experiments.** The depth experiment (left plot) was conducted across a range from 50 to 25 ft, showing a loss of feed pressure and production rate, while specific energy slowly increased, when held at different depths for 5-min intervals. The crossflow pump speed experiment (right plot) was conducted across a range of pump speeds from 300 to 1150 rpm, where the permeate pump speed was held constant at 1800 rpm for 5-min intervals to investigate the effects of different pump speed ratios. Note that higher specific energies (>1 kWh/m3), lower production rates (<1 gpm), higher recovery rates (>40%), and lower flux rates (<2 gfd) are observed in the plots because these experiments were conducted on the last day of the >3 month trial, just before the highly fouled membranes were removed for post-test autopsies. Refer to Figure 1 for complete data sets from the trial's start to finish.

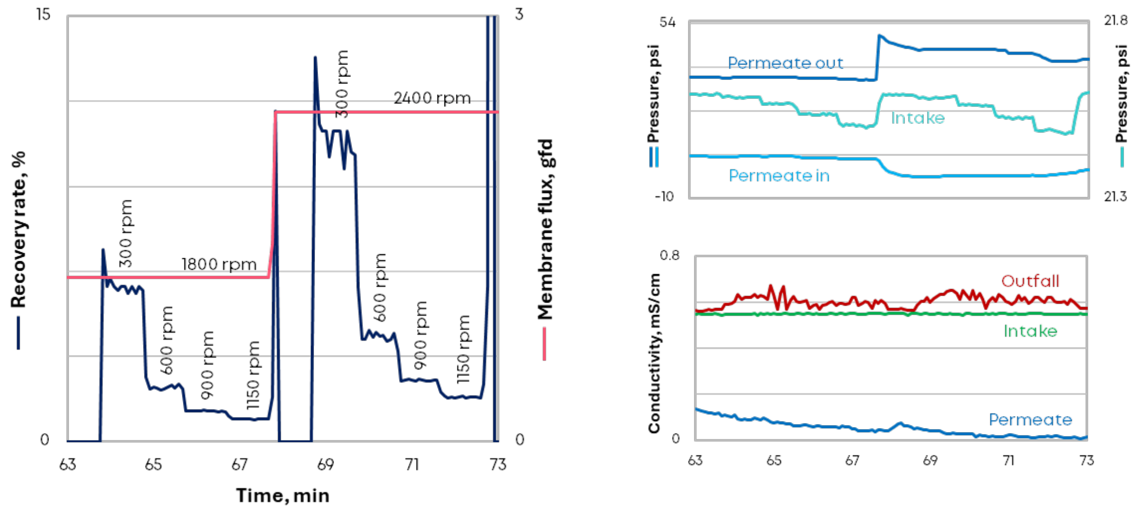

**Figure 3 | Start-of-trial pump tuning experiments.** The crossflow and permeate pump speeds varied between 300-1150 rpm and 1800-2400 rpm, respectively, to operate at different recovery rates and membrane flux rates, as illustrated on the lefthand plot. Permeate pressure at the pump inlet and outlet, intake pressure at the feed side of the RO membranes, and conductivity of the intake, outfall, and permeate streams are shown on the righthand plots. Refer to Figure 1 for complete data sets from the trial's start to finish.

## Membrane Elements

**Table 1 | RO membrane elements tested.** (Manufacturers not disclosed for their privacy.)

| Element | Manufacturer Specifications |
|---|---|
| #1 | Brackish water reverse osmosis (BWRO) membrane, 34 mil crossflow space, 400 sqft active area, 11,000 gpd permeate flow, 99.3% salt rejection |
| #2 | BWRO membrane, 34 mil crossflow space, 400 sqft active area, 12,000 gpd permeate flow, 99.2% salt rejection |
| #3 | BWRO membrane, 26 mil crossflow space, 505 sqft active area, 13,000 gpd permeate flow, 99.2% salt rejection, novel crossflow construction |

**Figures 4 & 5** compare RO membrane element performance at the end of the longevity test, including membrane flux, crossflow rate, and recovery rate drops (negative %) and gains (positive %), as well as post-test autopsy results. Notably, element #1 and #2 started with higher production rates, more than 2X greater than element #3, despite element #3's >25% larger active area. Initially, element #3 also had a lower crossflow rate, likely due to its tighter 26-mil spacing. Element #1, on the other hand, had a higher initial crossflow rate, approximately 2X greater than the others – an important feature of OceanWell's low recovery/low outfall strength operation. All elements started at recovery rates between 10-20%.

As expected, overall performance dropped throughout the longevity testing across all membrane elements but, interestingly, to a much lesser extent in element #3. This is especially apparent when comparing membrane flux and crossflow rate. Notably, membrane flux dropped by only ~25% in element #3 versus >50% for elements #1 and #2. Moreover, the crossflow rates for elements #1 and #2 dropped >90% versus element #3 which increased by >150%, likely to account for fouling in the crossflow spaces of elements #1 and #2. This suggests that differences in RO membrane materials may account for differences in flux, but element #3's novel crossflow construction allowed entrained debris to pass through its crossflow spaces more easily than those of elements #1 and #2. As a result, its recovery rate declined, while the recovery rates of element #1 and #2 increased by about ~300%. From these data (**Figure 4**) and the membrane autopsies (**Figure 5**), it is apparent that crossflow construction is a key parameter influencing the performance of SRO membrane elements.

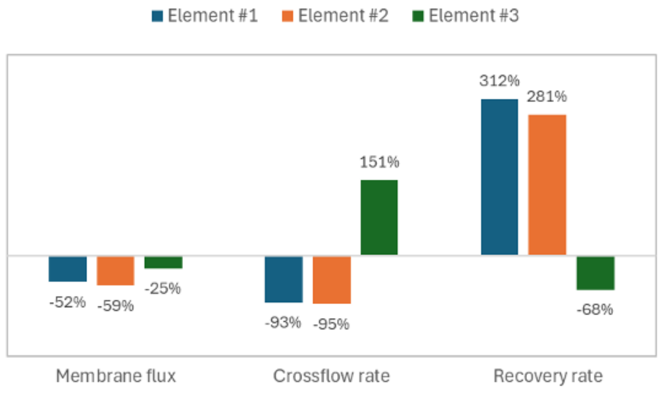

**Figure 4 | RO membrane element performance.** Graph shows changes at the end of the 3-month longevity testing trial, showing the percent drop (negative) or gain (positive) in membrane flux, crossflow, and recovery rates for elements #1, #2, and #3.

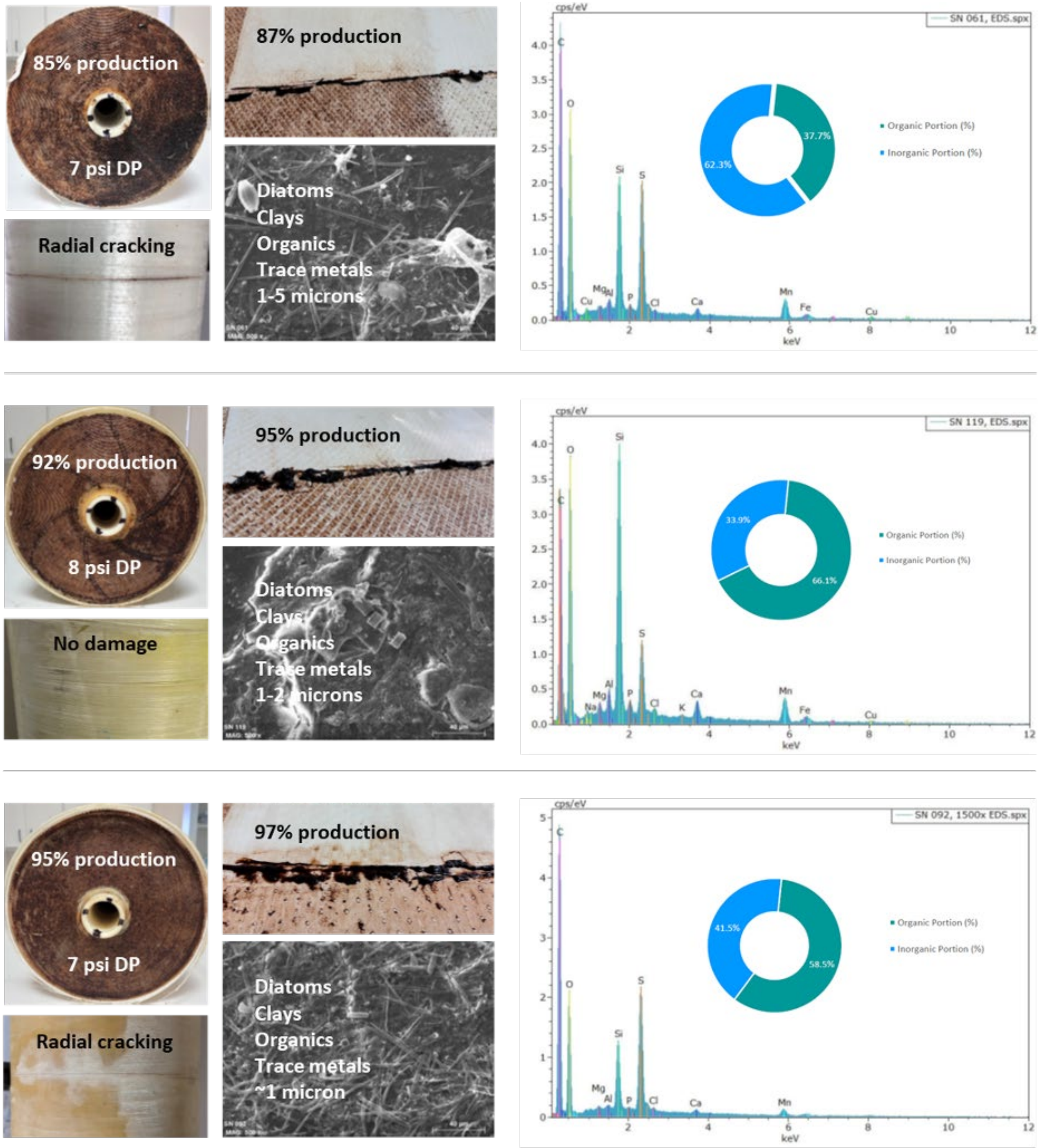

**Figure 5 | RO membrane autopsies** at the end of the trial, comparing (top) element #1, (middle) element #2, and (bottom) element #3. From left to right, top to bottom, images of the feed ends the elements showed substantial leading-edge fouling, highlighting reduced post-test permeate production (85-95% of original production) and crossflow pressure drop (7-8 psi DP); the membrane leaves showed superficial fouling easily wiped from the surfaces, resulting in 87-97% of original permeate flow after cleaning; the outer casing of elements #1 and #3 exhibited superficial radial cracking, likely caused by improper handling during interventions; and the types of foulants observed in the membrane crossflow spaces via scanning electron microscopy (in the grey-scale images and elemental analyses in the righthand plots) were composed of organic and inorganic debris, including diatoms, clays, and trace metals, typically in the 1-5 micron range. Notably, the foulants present in element #3 were generally smaller than those of the other two elements, further validating the theory that its novel crossflow construction allowed foulants to more easily pass through the crossflow spaces, resulting in a higher crossflow rate near the end of the trial.

## Prefilter Materials

**Table 2 | Prefilter materials tested.** (Manufacturers not disclosed for their privacy.)

| Material | Manufacturer Specifications |
|---|---|
| #1 | Polypropylene, 37 um nominal pore size, single layer weave, special calendared, 3.3 cfm/ft2 air permeability, 345 g/m2, 510-um thick |
| #2 | Polypropylene, 30 um nominal pore size, double layer weave, calendared, 26 cfm/ft2 air permeability, 360 g/m2, 740-um thick |
| #3 | Polypropylene, 41 um nominal pore size, double layer weave, special calendared, 21 cfm/ft2 air permeability, 550 g/m2, 1100-um thick |
| #4 | Polyamide, 38 um nominal pore size, single layer weave, special calendared, 11.7 cfm/ft2 air permeability, 400 g/m2, 470-um thick |

**Figure 6** shows the different prefilter materials investigated, with nominal pore sizes around 30-40 um, at the midpoint (time of the first cleaning; day 21) and at the end of the first experiment (day 42) conducted during the first half of the membrane longevity test (see **Figure 1**). Visual inspection showed that all polypropylene prefilters exhibited less fouling than the polyamide one. The 37-um polypropylene single layer weave (prefilter #1) clearly showed the least amount of fouling. However, it was initially unclear whether this prefilter was actually the highest performer or if its reduced permeability decreased its relative flow and thereby fouling severity, presenting as an experimental artifact. Following feedback from the manufacturer, prefilter #1 was installed as the only prefilter during the second half of the membrane longevity test (see **Figure 1**). One tradeoff was higher specific energy use during this phase of the trial, although this can be partially attributed to some degree of increased membrane fouling and increased bioactivity during the spring and summer months. In conclusion, prefilter #1 was selected as "best-in-class" for the shallow reservoir environment because it helped increase system longevity.

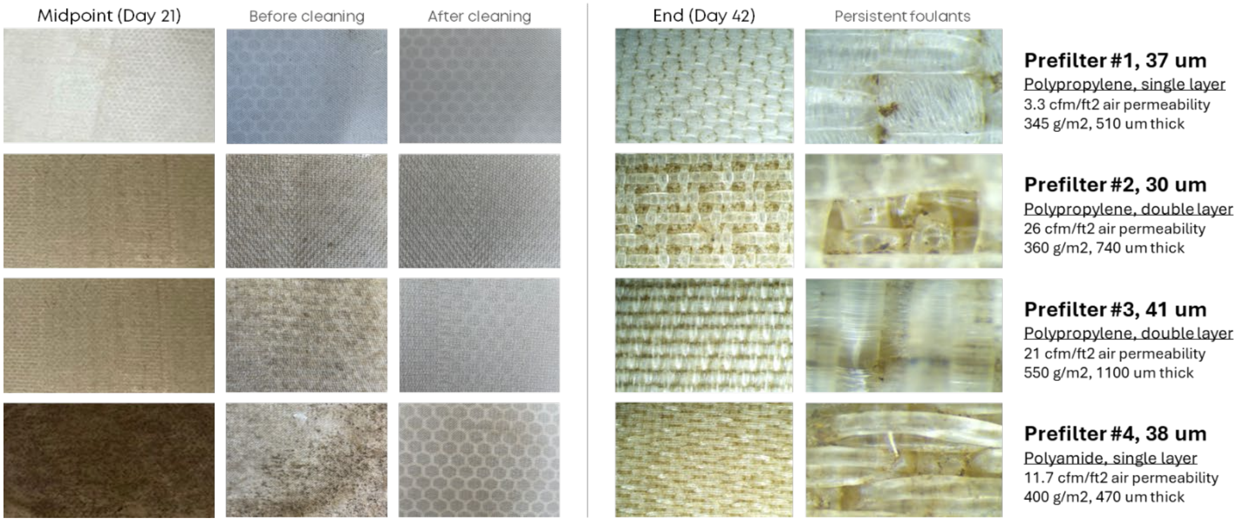

**Figure 6 | Fouled prefilters,** as observed before and after manual cleaning on day 21 at the experiment midpoint, and following removal on day 42 at the end of the experiment. Images were taken with a phone camera (day 21) and a stereo microscope at 3.5X and 180X magnification (day 42). The prefilters were only cleaned once, on day 21, via manual brushing and a light-duty pressure washer (550 psi max), which improved permeate production by >6%.

## Screen Cleaning

**Table 3 | Screen cleaning methods** compared during the first cleaning experiments on May 27-31.

| Method | Tool | Description |
|---|---|---|
| Water jet | Pressure washer | Dewalt 20V MAX 550 PSI cordless battery powered cleaner tested across different sweep patterns and positions |
| Brush #1 | Soft brush | Polypropylene, soft 0.3-mm OD x 65-mm L bristles, tested across parallel, perpendicular, circular, and poking sweep patterns |
| Brush #2 | Medium brush | Polypropylene, medium 0.4-mm OD x 60-mm L bristles, tested across parallel, perpendicular, circular, and poking sweep patterns |
| Brush #3 | Hard brush | Polyethylene, hard 0.4-mm OD x 25-mm L bristles, tested across parallel, perpendicular, circular, and poking sweep patterns |

The SRO pilot contains a two-stage intake system, composed of a 1st-stage 0.5-mm wedgewire screen followed by a 2nd-stage set of ~40-um prefilters in series ahead of the RO membranes. This relatively low level of prefiltration (40-um versus the typical 5-um common in onshore RO systems) was selected on purpose to accelerate the membrane fouling process, so that we could learn and improve the system's performance more rapidly. Throughout the trial, the intake system was maintained using automated backwashing and manual cleaning methods. **Figure 7** shows video screenshots of the different manual cleaning methods that are described in **Table 3**. During these experiments, water jetting with a light-duty pressure washer emerged as the clear "best-in-class" screen cleaning method. During the second half of the trial, with only prefilter #1 installed, the prefilters no longer needed topside cleaning and remained relatively untouched (excluding some residual spray from screen cleanings) because automated backwashing proved effective at keeping the prefilters operating within acceptable limits for ~2 months – much longer than expected. Results from backwashing experiments are reported in the following sections.

**Figure 7 | Screen cleaning methods,** left to right: water jetting, soft brush #1, medium brush #2, and hard brush #3.

## Longevity Testing

This section reports results on longevity testing of the RO membranes, defined as >3 months of continuous freshwater production at >1 gpm, or the equivalent of >150,000 gallons of total produced water. In addition to the stated deliverables, OceanWell also conducted preliminary analyses on its LifeSafe™ circulation system, including backwash and plankton experiments.

**Figure 8** contains screenshots of videos taken with a remote operated vehicle (ROV), showing the primary components of OceanWell's LifeSafe™ circulation system. Attached along the crossflow path were multiple cameras and sensors measuring key water properties, including turbidity, conductivity, temperature, pressure, and flowrate. During plankton experiments, an 180-um mesh plankton net was attached to the bottom of the backwash discharge valve to collect backwashed debris for biological identification and microscopic characterization.

### Sustained Operations

At the pseudo-start of the membrane longevity test, the average permeate and crossflow rates were maintained around 1.4 gpm and 10 gpm, respectively. Three months later (just after the final scheduled maintenance), the respective recoverable flowrates fell to 1.2 gpm (~14% drop) and 9 gpm (~10% drop), as seen in **Figure 1**. This exceeded OceanWell's goal of maintaining recoverable permeate and crossflow rates of >75% for at least 1 month of continuous operation. That is, OceanWell successfully maintained recoverable flowrates of >85% over 3 months of continuous operation at >93% uptime, proving the effectiveness of the system's maintenance strategy.

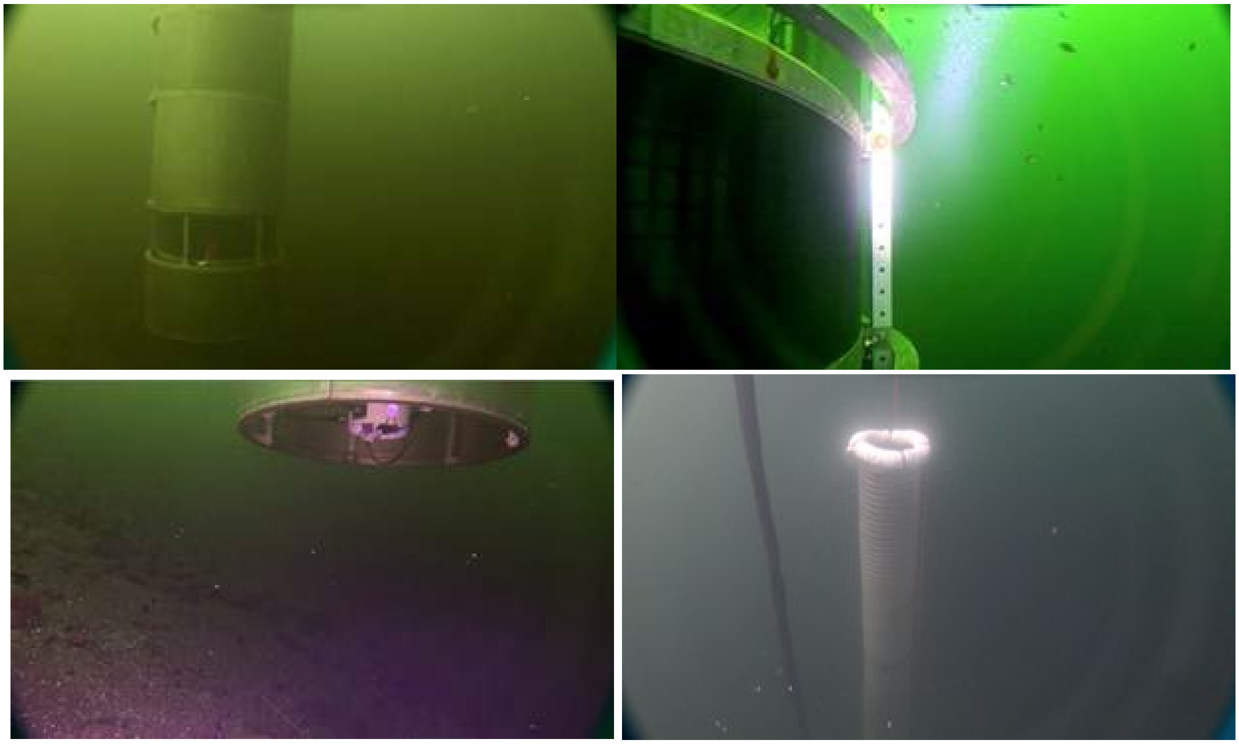

**Figure 8 | SRO pilot system,** from left to right, top to bottom: pilot pod, intake screen, backwash discharge, outfall riser.

**Figure 9** highlights some key parameters that were tracked throughout the 3-month longevity test. Interestingly, the average permeate conductivity generally rose throughout the trial because higher temperatures (as observed in the spring and summer months) are known to loosen RO membranes leading to lower rejection rates. Regardless, permeate quality remained very high at <50 ppm TDS throughout the trial, an order of magnitude lower than World Health Organization limits of <500 ppm TDS. Perhaps most significant was the nearly 2X jump in power use from ~0.3 kW when the four different prefilters #1-4 were installed to ~0.5 kW when only prefilter #1 was installed. This is because prefilter #1 had a lower permeability leading to an increased pressure drop that the crossflow pump had to overcome. Notably, total system power use did not seem to change with ambient environmental conditions. Though, the increasing temperature and decreasing oxygen saturation levels observed in the spring and summer months seemed to correlate with visible screen occlusions teeming with algal blooms and copepod activity. In fact, the Las Virgenes Municipal Water District (LVMWD) staff seeded the lake with copper sulfate midway through the second half of the trial to help control the blooms. Membrane autopsies revealed some trace copper residue (see **Figure 5**), confirming the copper sulfate treatment was ingested by the membranes near the end of the trial, but seemed to have only minor effects on overall SRO system performance (refer to **Figure 1**). These observations, along with OceanWell's hands-on operational experience, suggest that prefilter selection (material and weave), membrane element construction (particularly the crossflow design), and environmental conditions play major roles in SRO performance and system longevity.

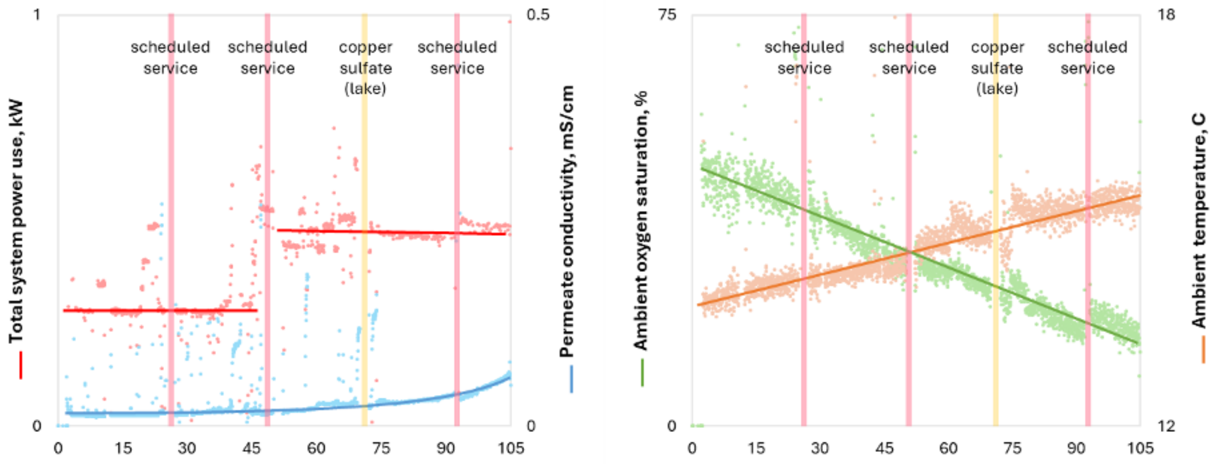

**Figure 9 | Total power, permeate quality, and ambient environmental conditions** during the trial from day-0 to day-105.

## Backwash Experiments

Automated backwashing involves reversing the system's crossflow through a set of control valves to backwash the intake system (screens and prefilters). Entrained debris, such as nano/micro-particulates and plankton, small enough to pass through the 0.5-mm screens, but too large to pass through the prefilters are safely caught by the prefilters and removed during a backwash event. In different backwash scenarios, the flowrate, pressure, and relative turbidity (among other less critical parameters) of the backwashed fluids were recorded across different pump speeds, durations, and frequencies. Realtime videos streaming from cameras located at several points along the crossflow path also revealed key characteristics about the different backwash events, providing a path to fine tune the processes. Once the different backwash events were better understood, various component upgrades were incorporated into the system, including the replacement of actuated valves with passive valves that reduced the overall complexity and total power use of the SRO system. These upgrades allowed the OceanWell team to optimize the backwash protocols near the end of the trial, leading to less scattered operational data during the last couple months of the trial (refer to **Figure 1**).

**Figure 10** shows a representative plot of successive backwash cycles run at different pump speeds. A characteristic "saw-tooth" pattern is clearly observed in the flowrate and pressure measurements as the pressure drop across the prefilters increased while operating normally (i.e., an intake cycle) until a backwash event "reset" the prefilters. During these resets, impinged debris is gently dislodged from the prefilters and washed back into the ambient environment from the bottom of the SRO system and sufficiently far from the approach field of the intake screen to avoid reingestion of the discarded debris.

Depending on local environmental conditions present in the lake, the typical frequency of backwash events was on the order of ~1 cycle per hour.

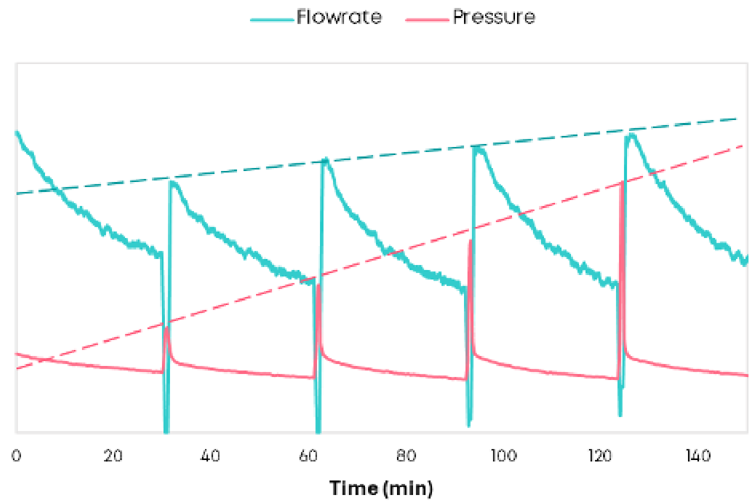

**Figure 10 | Backwash cycles run at different pump speeds** showing the characteristic saw-tooth patterns of relative feed pressure and flowrate measurements at the RO membrane inlets.

## Plankton Experiments

In addition to longevity testing and backwash experiments, OceanWell also conducted plankton experiments as preliminary analyses of its LifeSafe™ circulation system. During these experiments, a 180-um mesh plankton net was attached to the bottom of the backwash discharge valve to collect backwashed debris for biological identification and microscopic characterization. Water samples after each event were photographed and analyzed using an inverted phase-contrast compound microscope with up to 1000X magnification (AmScope, IN300 Series). Variations in backwash protocols were compared against control samples where the SRO system sat at its operating depth with its valves open and no pumps running for 10 mins. **Figure 11** shows representative microscopic images of copepods, algae, and diatoms collected during the tests. Although there was some evidence of planktic mortality, there was also substantial evidence of sustained life, suggesting that OceanWell's LifeSafe™ system is an improvement over the existing art, which assumes 100% entrainment mortality.

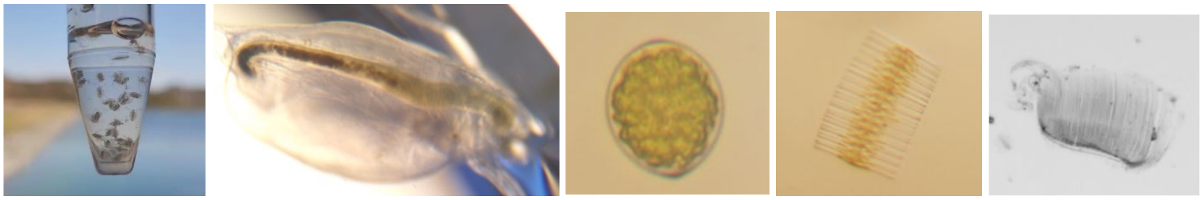

**Figure 11 | Specimens collected from plankton experiments,** from left to right: a test tube showing visible signs of some life and some death of collected samples after a backwash event, a living copepod, a living alga, and a living diatom, and a copepod part (shown in grey) suggesting some degree of microorganism mortality and, more importantly, some degree of microorganism vitality was retained during backwash cycles.

## 2.1 Project Facility/Physical Apparatus

### 2.1.1 Design Criteria

The SRO pilot system was designed and built by OceanWell's in-house engineering team. The only major component that was outsourced was the system's dockside electrical enclosure (DEE), subcontracted to InterOcean Systems. A few other independent contractors were also hired on a part-time basis to assist in the design, construction, testing, transport, installation, and commissioning of the SRO and DEE systems. Factory acceptance testing of the fully integrated system was completed at InterOcean's facility to ensure OceanWell's permeate and crossflow pumps were properly tuned.

Prior to installation, the project site was prepared. To provide access to water deep enough for SRO operations, an existing dock at the LV Reservoir was extended about 80 ft. Notably, at the end of the dock extension, the maximum depth of operation was about 50 ft, instead of the originally proposed 100 ft. This compromise was necessary to accommodate site constraints related to ease of access; the dock extension made it possible for OceanWell's engineering team to work onsite after hours without needing LVMWD's workboat or crew. The tradeoff of operating at a shallower depth (closer to shore) limited the feed pressure to about 20 psi (50 ft), instead of the original 40 psi (100 ft) proposed. This was acceptable because the membranes could still produce water at these depths, just with reduced flowrates. At 50 ft deep, the permeate flowrate was maintained >1 gpm throughout the trial.

After the dock extension was in place, a launch and recovery system (LARS) was assembled at the end of the dock. The LARS consists of a double gantry with two battery-powered winches plus one installed spare winch. 480V power and communications cables were run from the nearby water treatment facility to the DEE at the end of the dock, and a kill switch was installed onshore at the control room in case of emergency. After the SRO system was lifted and towed via crane and barge to the LARS, the SRO and DEE systems were connected via umbilical for transferring power, communications, and water. **Figure 12** shows images of the complete pilot system.

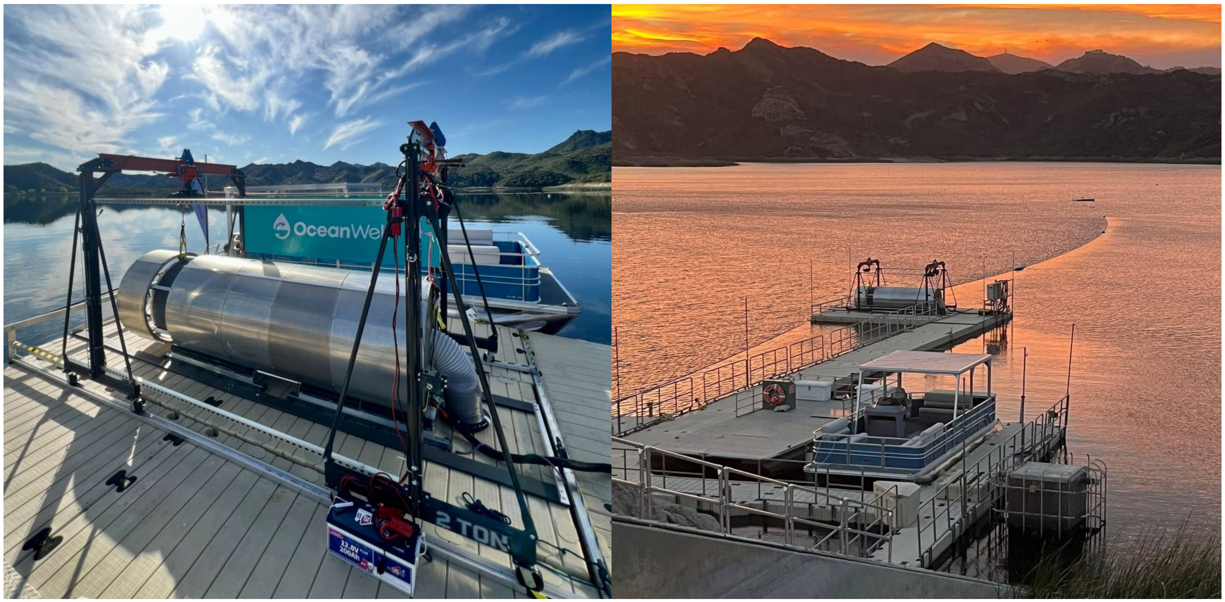

**Figure 12 | OceanWell's pilot system,** (left) the pilot pod and launch and recovery system, and (right) the 80-ft dock extension.

### 2.1.2 Source Water

The source water used was from the LV Reservoir, which is stored fresh water supplied by the California State Water Project. The water quality of the lake varied throughout the trial due to seasonal changes and maintenance activities conducted by the LVMWD staff at the Westlake Filtration Plant. **Table 4** provides example water quality data of the feed and product waters collected at the end of the trial. Throughout the trial, the conductivities of the feed, product, and concentrate were measured in situ with nominal values generally in the range of >0.5 mS/cm (>320 ppm TDS) for the feed, <0.015 mS/cm (<10 ppm TDS) for the product, and ~0.7 mS/cm (~450 ppm TDS) for the concentrate. **Figure 1** shows this time series data.

Table 4.—Summary of water quality data collected at the end of the pilot study

| Parameter | Units[1] | Feed | Product |
|---|---|---|---|
| TDS | mg/L | 466 | 73 |
| Sodium | mg/L | 143 | 22 |
| Calcium | mg/L | 337 | 25 |
| Magnesium | mg/L | 425 | 50 |
| Chloride | mg/L | 256 | 40 |
| Sulfate | mg/L | 100 | 100 |

[1] mg/L = milligrams per liter.

### 2.1.3 Setup

*See Section 2.1.1*

### 2.1.4 Runs and Experiments

*See Section 2.0*

# 3.0 Results and Discussion

## 3.1 Results

Highlights from the project include the following key performance indicators:

- **The SRO pilot produced >1 gpm for >3 months totaling >150,000 gallons**, while maintaining continuous operations through several acute weather systems, seasonal blooms, and other environmental changes, providing good evidence that submerged water filtration applications, such as subsea desalination, will be less impacted by changes in climate, atmospheric weather, and surface water conditions, such as droughts, fires, floods, high winds, waves, algal blooms, and other coastal events that put onshore water supply systems at risk.
- **Operational uptime was maintained >93% over the 3-month longevity test**, where scheduled maintenance every 2-3 weeks and unscheduled maintenance to repair or upgrade components, such as valves, resulted in the only downtime experienced during the trial.
- **Recoverable membrane flowrates were maintained >85% over the 3-month longevity test**, with permeate production dropping from 1.4 gpm to 1.2 gpm (~14% decline) and crossflow rates dropping from 10 gpm to 9 gpm (~10% decline), validating the effectiveness of OceanWell's maintenance strategy and far-exceeding the trial's initial target of >75% over 1-month.
- **High quality water was produced, an order of magnitude purer**, with permeate conductivities starting at <0.015 mS/cm (<10 ppm TDS) while seasonal effects had big impacts on the lake's water quality with feed conductivities >0.5 mS/cm (>320 ppm TDS).
- **Low specific energy of ~1 kWh/m3 was observed, as predicted**, closely matching theoretical predictions for average energy use versus filter type, depth, and pump speeds in the freshwater lake with high levels of bioactivity, further validating the expected ~2 kWh/m3 for subsea desalination.
- **Low recovery rates were maintained between 10-20%** when operating parameters were stabilized, where the lower recovery resulted in a lower outfall strength of ~0.7 mS/cm (~450 ppm TDS), a key environmental advantage of OceanWell's subsea desalination process.
- **Different membranes, prefilters, and screen cleaning methods impacted SRO performance**, providing effective tools for enhancing system longevity, resisting significant fouling, and protecting aquatic life. Standout performers included novel membrane crossflow constructions, polypropylene prefilters, and light-duty pressure washing.
- **Backwashing proved to be a relatively safe and effective self-cleaning method**, with empirical data showing more entrained microorganisms were returned to their natural environment unharmed, providing good evidence that OceanWell's LifeSafe™ circulation system may dramatically reduce aquatic life mortality rates versus the 100% mortality rate of standard intakes that is currently tolerated by the open ocean intake and desalination industries.
- **Techno-economic analyses reveal SRO is commercially attractive**, particularly for subsea desalination applications where the specific energy of reverse osmosis is reduced by 30-40% because the hydrostatic pressure of the deep sea provides the necessary feed pressure for the process.

## 3.2 Analysis

The performance of the SRO pilot was stress tested during several short (hours to days) and long (days to weeks) experiments conducted throughout the trial. System inputs included variations in operating depth, pump speeds, backwash protocols, and changing environmental conditions caused by high wind and rain events, seasonal algal blooms, and standard control measures taken by LVMWD staff. Notably, the floating dock extension and LARS were put to the test during the week of January 6 when wind speeds at the lake surface topped 50 mph, some of the highest winds ever recorded onsite. Also, rising temperatures and algal blooms during the months of June-July became so severe that LVMWD staff seeded the lake with copper sulfate on July 15. Despite these challenging conditions, OceanWell's SRO pilot continued to operate throughout the 3-month trial (refer to **Figure 1**).

### Life-Friendly Intake

Additionally, a remote operated vehicle (ROV) and underwater cameras were deployed near the end of the trial. Cameras viewing the pilot's intake screens, outfall riser, life-friendly discharge, and internal plumbing captured clear evidence in support of OceanWell's claims around its LifeSafe™ circulation system. In one instance, a Grebe (a freshwater bird that frequents the lake) was filmed hunting a school of fishes near the system's intake, highlighting the fact that OceanWell's SRO system is fish (and bird) friendly. **Figure 13** shows screenshots of the activity.

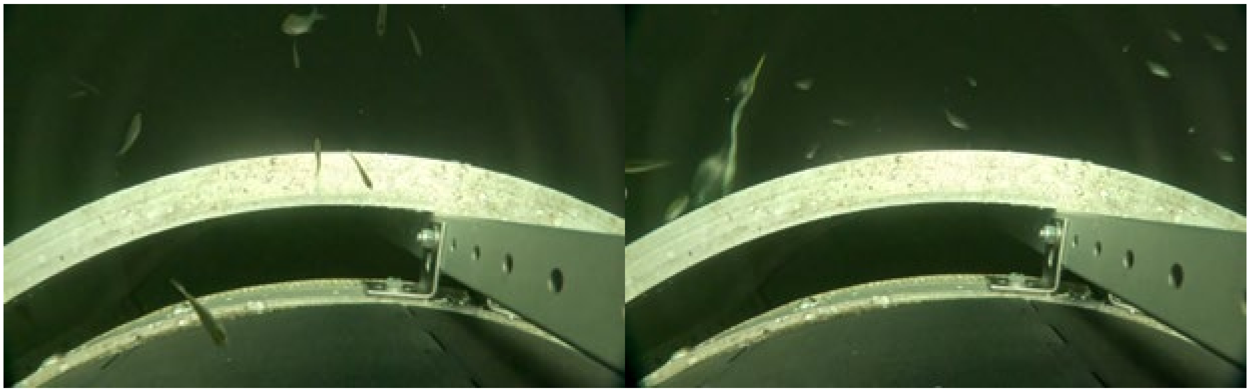

**Figure 13 | Underwater video** of the fish (and bird) friendly intake system where fishes were filmed freely swimming around the intake screen during both intake and backwash operations, and a grebe (freshwater bird) was filmed hunting fishes near the intake during standard operations. These videos provide some empirical evidence that the low velocity intake eliminates the impingement (getting sucked onto the screen surfaces) of aquatic life larger than the screen exclusion size of 0.5-mm.

### Specific Energy

An important parameter to consider when comparing the cost and environmental impact of SRO versus land-based RO is specific energy use. OceanWell claims that subsea desalination (seawater SRO) can lower energy use by 30-40% compared to traditional seawater RO conducted onshore. To validate this claim, OceanWell carried out additional high-pressure seawater testing (beyond the scope of this project) in a hyperbaric test chamber in the Deep Ocean Simulation Facility at the Port Hueneme Naval Base in Ventura, CA. There, OceanWell recorded **specific energies for seawater SRO as low as 2.0 kWh/m3** when desalinating seawater. They also demonstrated sustained operations during a 100-hr trial, producing high quality permeate (~200 ppm TDS) from seawater extracted from the Pacific Ocean (~35,000 ppm TDS) with a >98% uptime, using no chemicals, and generating a brine only ~20% above the ambient salinity of the feed seawater.

**Figure 14** shows the recorded hyperbaric tank test data along with data from this reservoir pilot study, which resulted in specific energies of ~1 kWh/m3. Adjusting the data to account for the measured inefficiencies of the lab-scale pumps used in these tests (50-60%) versus the theoretically viable efficiencies claimed by manufacturers for fit-for-purpose pumps (~75%), OceanWell expects to achieve the ~2 kWh/m3 target for sustained commercial operations in the deep sea. This is because the circulation pump requires approximately the same amount of energy regardless of depth, while the permeate pump uses more energy the deeper it operates (e.g., at 50 ft deep in the lake, the energy split between the permeate pump and circulation pump is about 50:50; while at 1500 ft deep in the ocean, the energy split is expected to be about 90:10). Whereas ~1 kWh/m3 is relatively high compared to many onshore freshwater treatment systems, like the diatomaceous earth filters used at the Westlake Filtration Plant operated by LVMWD, this number is very close to the expected energy consumption for SRO operated at 50 ft deep in a freshwater lake – providing validation that OceanWell's circulation pump, which drives the crossflow intake-to-outfall subsystem, performed as expected with efficiencies approaching 75%.

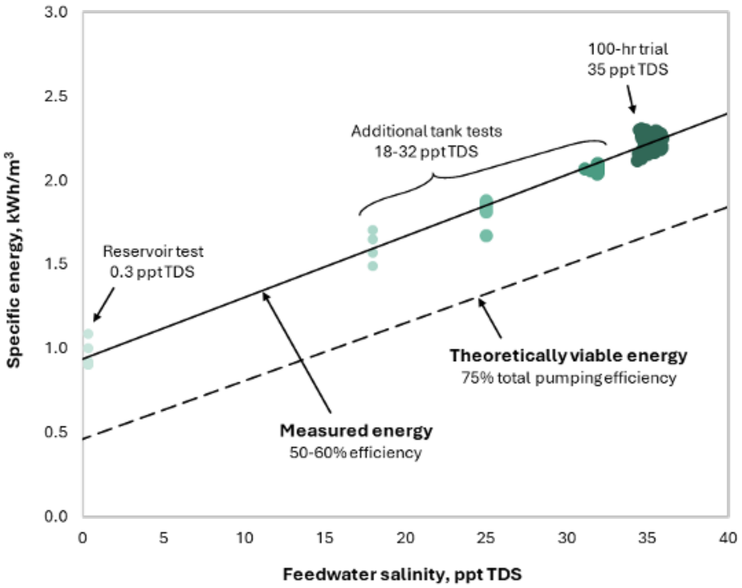

**Figure 14 | Specific pumping energy of OceanWell's SRO system** in fresh, brackish, and saline water bodies. The solid line and dots show measured data (50-60% pump efficiencies), and the dashed line shows expected data (75% pump efficiencies).

## Life Cycle Assessment

Key comparisons from a life cycle assessment (LCA) to evaluate the cradle-to-grave environmental impacts of SRO versus other water supply methods, including RO technologies used for seawater desalination, wastewater recycling, and surface water treatment are compared in **Figure 15**. The LCA analysis considered all major life-cycle stages and operations, including material extraction, manufacturing and construction, specific energy, land use, chemical use, solid and liquid waste, effluent strength, produced water quality, membrane replacement, end-of-life disposal, and total equivalent carbon footprint. Because system performance and resource intensity vary significantly with feedwater salinity and system configuration, only a few dominant contributors to the environmental burden of water supply methods emerged from the analysis. These include the high-pressure energy consumption and brine strength of desalinated water, the land use requirements for recycling and importing water, the chemical demand of surface water treatment, and the unsustainable nature of groundwater (in some locations groundwater is a nonrenewable resource). In general, seawater SRO is a more attractive method of water production versus traditional desalination via onshore RO; and in some cases, freshwater SRO is attractive because it uses less land and no chemicals.

While SRO is still an emerging technology with some unproven operational limits, the LCA analysis conducted in this pilot study shows promise that the total carbon footprint (cradle-to-grave impact) of SRO is likely to be less than traditional seawater desalination and on par or better than wastewater recycling. In arid regions where drought is common, reliance on water from the sky, surface, ground, or imported from afar is risky and unsustainable. Therefore, many communities are beginning to turn to recycled and desalinated water to bolster water resilience. This study proves that SRO could deliver more sustainable, drought-proof sources of new water to coastal regions in need.

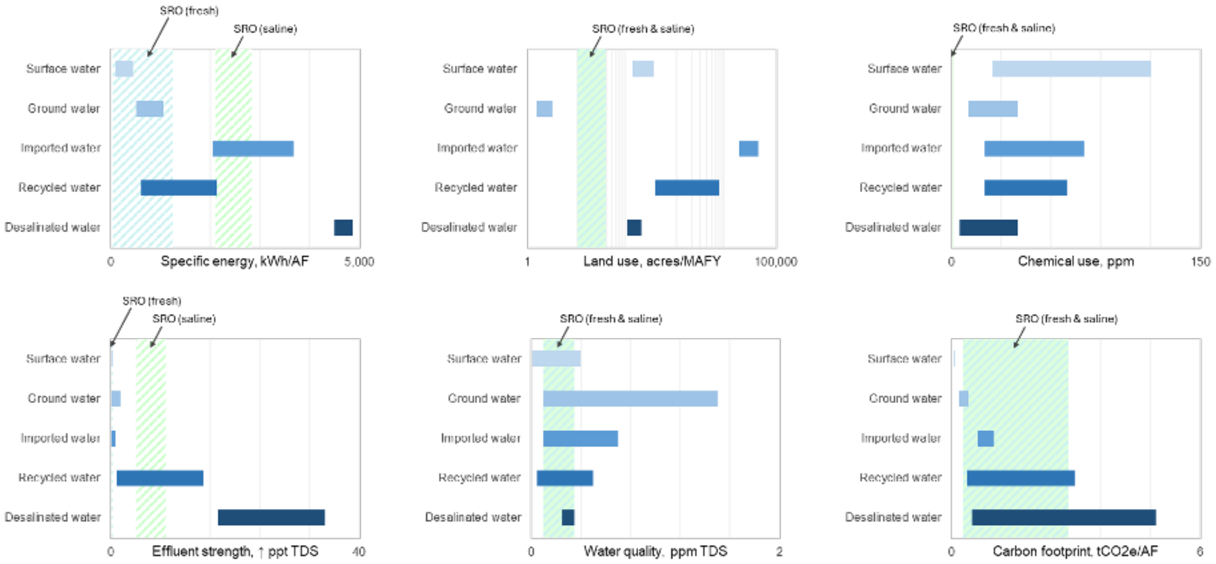

**Figure 15 | Environmental impact of different water supply methods versus seawater SRO,** highlighting key results from a life cycle assessment (LCA) of water supply methods common in California and around the world. Data on the five dominant methods of water supply (surface, ground, imported, recycled, desalinated) were collected from numerous academic, industry, and publicly accessible sources. SRO impacts, when operated in fresh (blue crosshatched area) and saline (green crosshatched area) water bodies, are highlighted against the ranges of data on the other water supply methods. All data is expressed in specific quantities per acre-foot (AF), million acre-feet per year (MAFY), parts per thousand (ppt), or parts per million (ppm).

## Performance Mapping

As highlighted by the LCA analysis in **Figure 15**, OceanWell's SRO technology is most environmentally attractive for seawater desalination applications because of its significant reduction in specific energy use and effluent (brine) strength versus traditional desalination via seawater RO. That is, as the salinity of a water body increases, SRO becomes more attractive. To further emphasize this point, **Figure 16** shows performance maps on the evolution of desalination from today's state-of-the-art land-based technologies (traditional open ocean and subsurface intakes) to new emerging offshore technologies (floating and submerged versus OceanWell). By collecting real-world operations data, this pilot study helped build more confidence around projections on the cost, energy use, environmental impacts, and climate risks of SRO versus other seawater desalination methods. OceanWell's novel SRO technology represents a potential step-change innovation in the seawater desalination sector, reducing not only the environmental impact of desalination, but also its cost. Its core underwater filtration package and LifeSafe™ circulation system were developed with an environment-first approach, guided by the California Ocean Plan and active engagement with key regulators, non-governmental organizations (NGOs), water agencies, and other relevant stakeholders in the Southern California region. The OceanWell solution is a version of SRO that was thoughtfully designed to reduce impacts on human life and marine life by minimizing the required inputs and outputs of the system, as illustrated by the performance maps in **Figure 16**.

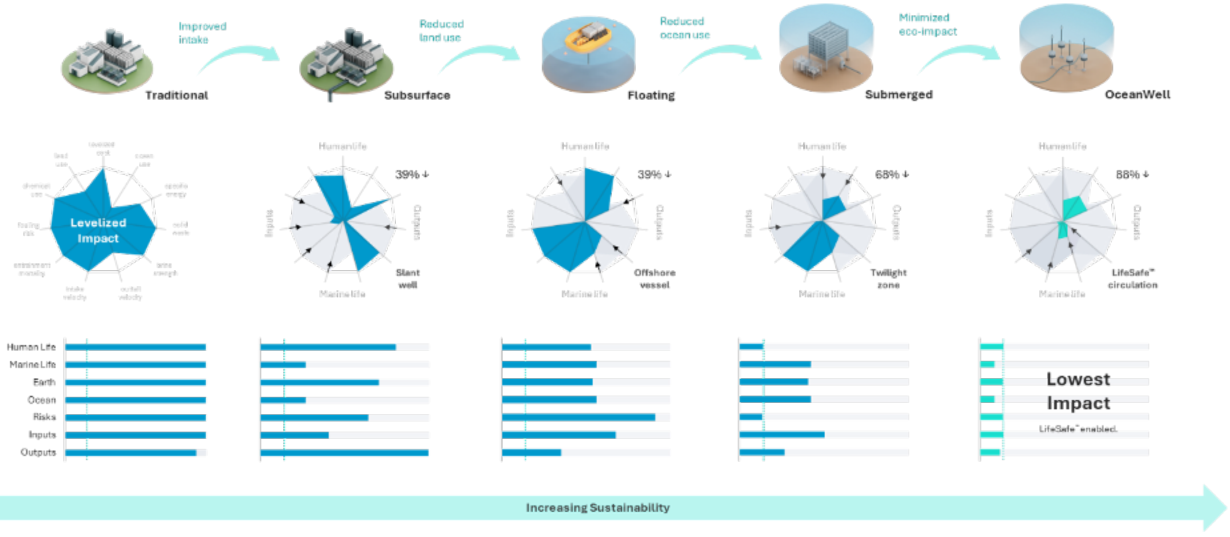

**Figure 16 | The evolution of seawater desalination** from a heavy industrial process conducted onshore, typically on the coast, drawing in seawater from the shoreline through open water intakes (Traditional) or slant wells (Subsurface) to offshore systems that float on the surface (Floating) or operate deep underwater (Submerged) to the OceanWell solution – a form of submerged desalination with improved ecologically-conscious intake and outfall designs. The radial plots display negative environmental impact data collected from publicly available sources and environmental impact reports, including on cost, land and ocean use, specific energy, solid wastes, brine strength, intake and outfall velocity, entrainment mortality, fouling risk, and chemical use. By sorting the plotted data according to their relevant impact on human life (top) or marine life (bottom) and by their classification as an input (left) or output (right), the total plotted area becomes a proxy for the levelized holistic negative environmental impact, i.e., the larger the plotted area, the greater the total impact. Thus, quantifying the plotted area as a proxy for environmental impact via multidimensional data mapping, it can be shown that the OceanWell solution has an ~88% lower impact than traditional desalination; in contrast, subsurface and floating desalination are only ~39% lower and competing submerged desalination technologies are ~68% lower.

## 3.3 Conclusions

As proposed, Objectives 1-4 were completed by the end of the trial. Key performance indicators and unique learnings are outlined in the introduction of this report. For completeness, key results from each of the four objectives are outlined below:

- **Objective 1:** A life cycle assessment of common water supply methods revealed that SRO has a lower cradle-to-grave impact than land-based seawater desalination and some wastewater recycling methods.
- **Objective 2:** The “best-in-class” filter types and cleaning methods identified for SRO were novel membrane crossflow constructions, polypropylene prefilters, backwashing to clean the intake, and light-duty pressure washing to clean the screens; the “best-in-class” depth and pump speed ratio required to maintain stable operational longevity in the lake were determined to be the deepest available depth of 50-ft and the lowest pump speeds.
- **Objective 3:** Post-test membrane autopsy reports, after >3 months of operation, revealed that, although there was substantial fouling (a feature of this study to accelerate learnings), the membranes performed better than expected in the highly bioactive freshwater lake environment.
- **Objective 4:** A detailed performance mapping of OceanWell’s SRO technology versus other onshore and offshore desalination technologies suggests that OceanWell has the lowest overall environmental impact in seawater desalination.

Additional results from the backwashing and plankton experiments also provide more confidence that OceanWell’s LifeSafe™ circulation system may dramatically reduce marine life mortality in the ocean. In conclusion, SRO remains a very promising new technology for sustainable freshwater production.

## 3.4 Challenges

We faced two main challenges throughout this pilot:

- The highly bioactive lake environment, particularly in the spring and summer months, created somewhat unpredictable feed water quality.
- The low-budget valves and flowmeters sourced proved to be problematic, requiring more frequent maintenance and troubleshooting than desired.

## 3.5 Recommended Next Steps

The pilot set us up for our next step in development, which will be an ocean test to validate SRO performance for desalination applications.

# 4.0 References

James, I. 2025. California is testing a new way to turn seawater into drinking water. Will it work? Los Angeles Times. https://www.latimes.com/environment/story/2025-03-21/desalination-tech-tested

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Mark Golay, PE

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**14. ABSTRACT**

In this project, we advanced our technology package from TRL 4 “lab validation” to TRL 6 “pilot validation”. Our pilot system was built, factory tested, and installed in the Las Virgenes Reservoir, a private fresh water body with easy access and low operating costs. The reservoir’s current issues with surface algae and benthic metals allowed us to stress-test our system’s life-safe intake (self-cleaning screens and life-friendly return), as well as establish a foundational understanding of its operational longevity in a relevant, natural water environment. The pilot proved the following:

- A life cycle assessment of common water supply methods revealed that submerged water filtration (SWF) has a lower cradle-to-grave impact than land-based seawater desalination and some wastewater recycling methods.
- The “best-in-class” filter types and cleaning methods identified for SWF were novel membrane crossflow constructions, polypropylene prefilters, backwashing to clean the intake, and light-duty pressure washing to clean the screens; the “best-in-class” depth and pump speed ratios required to maintain stable operational longevity in the reservoir were determined to be the deepest available depth of 50-ft and the lowest pump speeds.

- Post-test membrane autopsy reports, after >3 months of operation, revealed that, although there was substantial fouling (a feature of this study to accelerate learnings), the membranes performed better than expected in the highly bioactive freshwater lake environment.
- A detailed performance mapping of OceanWell's technology versus other onshore and offshore seawater desalination technologies suggests that OceanWell has the lowest overall environmental impact.

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