# EVALUATING THE ECONOMICS OF A UNIQUE HYBRID RO DESIGN AFTER THREE YEARS OF TREATING BRACKISH GROUNDWATER

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## Abstract

In November 2008, the City of Oxnard, located sixty miles northwest of Los Angeles, commissioned its first, large scale, brackish water reverse osmosis (BWRO) desalination water treatment facility as part of its comprehensive regional water resources development program. The uniquely designed RO uses energy saving technologies in a hybrid configuration to minimize power consumption. The 7.5 MGD (28,400 m3/day) RO has been operating stably for three years and affords the opportunity to compare the tradeoff between its original capital cost and its operating cost based on actual performance data.

Downstream cartridge filtration, the two stage BWRO system treats ground water with an average salinity expressed in TDS of 1,500 mg/l and a temperature ranging between 18 $^{o}$C and 25 $^{o}$C. The plant employs a hybrid design by using two different RO membranes with differing permeabilities and rejections in each of the two stages. Contrary to a typical hybrid design, the Oxnard inverts the membrane installation by placing the higher permeability membranes in the first stage while higher rejecting membranes improve the permeate quality coming from the second stage. The flux imbalance that would normally occur in such an reversed hybrid is offset by the presence of an Energy Recovery Device (ERD) between the two stages. This leads to a more equitable flux throughout the system.

The selection of an ERD increased the capital cost of the plant. However, the use of a hybrid design in combination with the ERD, offers operational cost savings relative to a more conventional, lower capital, system. Placing the higher rejecting membranes in the second stage where they are needed most means that the overall permeability of the plant is lower than if the higher rejecting membranes had been located in the first stage. The operational savings associated with this unique membrane combination offsets the higher capital cost of the ERD which makes the design preferable both economically and technically.

This paper evaluates the capital and operating cost associated with the reversed hybrid design and compares the Oxnard design to other Brackish RO designs including a similar design that takes advantages of the latest RO membrane chemistry as well as manufacturing developments that were not available when Oxnard was commissioned in 2008. The evaluation is based on

actual operating data spanning the past three years, including actual feed and permeates water ion analysis. The difference in operating cost will be compared to the differences in capital cost, and a **2 year** return on investment will be shown. The technical and economic evaluation of the system, based on three years of operating data, illustrates the use of an innovative design employing the latest energy saving technologies to reduce energy consumption and operating costs. This evaluation can be used to design an RO system and evaluate the tradeoff between capital cost and operating cost, while seeking to tailor the element selection to meet specific permeate quality targets.

## Introduction

The city of Oxnard, California, located 60 miles north of Los Angeles is the largest city in Ventura County with a population of 200,000. Despite growing residential and commercial areas of Oxnard, the city remains largely agricultural. Oxnard's increasing population and agricultural needs have stressed the region's water supply, which comes from a combination of groundwater and surface water imported from Northern California. In response to the city's growing demand for water, Oxnard initiated a nationally recognized water resources project that combines wastewater recycling and reuse, groundwater injection, storage, recovery, groundwater desalination, and the restoration of local wetlands. The overall project, dubbed GREAT for Groundwater Recovery Enhancement and Treatment, is designed to increase the city's water supplies, particularly during droughts[1]. One component of the city's water management efforts is the Oxnard Desalter.

## Feed Source and Permeate Quality Requirements

The Oxnard Desalter consists of an RO system treating well water with an approximate salinity expressed in TDS of 1,500 mg/l and a temperature ranging between 18 $^{o}$C and 25 $^{o}$C. The typical well water composition prior to pretreatment is shown in **Table 1** below. Turbidity of the feed water to the BWRO ranges between 0.26 NTU and 0.36 NTU after the cartridge filters. The permeate water quality goals include total dissolved solids (TDS) concentration below 54 ppm and total hardness below 14 ppm as CaCO3.

**Table 1**: Feedwater Analysis for Oxnard Desalter

| Parameter | units | Value |
|---|---|---|
| EC | umhos | 2,000 |
| TDS | ppm | 1,600 |
| pH | units | 7.2 |
| Temperature | Degrees C | 18-25 |
| Na | ppm | 130 |
| Ca | ppm | 230 |
| Mg | ppm | 80 |
| SiO2 | ppm | 35 |
| Cl | ppm | 70 |
| F | ppm | 0.55 |
| NO3 | ppm | 60 |
| SO4 | ppm | 740 |
| K | ppm | 6.2 |
| Alkalinity | ppm CaCO3 | 260 |

## Pretreatment

To achieve stable RO performance and high recoveries, both chemical and physical pretreatments were utilized. Oxnard has a unique plant layout. The treatment processes for most brackish groundwater application first uses well pumps to draw water from the aquifer that feed water directly to a reservoir or storage tanks. Transfer pumps are then used to convey water through cartridge filters at lower pressure, followed by high pressure pumps feeding the RO membranes. Oxnard's RO system eliminates this cascading series of pumps. In the case of Oxnard, groundwater is pumped directly through the 5 micron cartridge filters to the RO membrane system by the well pumps which acted as an RO high pressure pumps at the same time. This unique design eliminates the break tank, low pressure pumps and high pressure booster pumps by using larger wellhead pumps and high pressure cartridge filters. This design increases the efficiency of pumping and keeps the pumps outside of the building which reduces the building footprint and cost associated with noise control which can be generated by the high pressure pumps. The facility's noise level is much lower than traditional RO systems.

Antiscalant is injected at a dosage of 3 mg/l to reduce the likelihood of saturated salts precipitating onto the surface of the tail elements. The pH of the feed water is lowered from 7.5 to 6.7 in order to maintain an acceptable Langlier Saturation Index (LSI) of less than 2 in the concentrate. Recovery is 80%, Silica concentrations in the feed limit the level to which the brine may be concentrated without the occurrence of silica scaling.

## Energy Saving RO Design

The Oxnard RO is designed with three parallel trains to achieve a 7.5 MGD total permeate flow. Each train is designed for 1,736 gpm (2.5 MGD) of permeate flow. At 80% recovery, the required feed flow for each train is 2,170 gpm. The first stage consists of 46 vessels with 7 RO membrane elements in each vessel (46 x 7M). The second stage consists of 23vessels 7 RO membrane elements each (23 x 7M). To minimize operating cost, energy saving membranes were selected for the RO.

The Oxnard RO shown in **Figure 1a** utilizes a hybrid design of two different energy saving membranes used in one train to distribute flux more evenly throughout all elements in the system. An inherent inefficiency of any RO system is that the lead elements run at a higher flux than the tail elements. This is because the lead elements experience the highest feed pressure and the lowest feed salinities of other elements in the system. Subsequent elements see lower feed pressures due to the hydraulic pressure losses incurred as water flows from one element to the next. At the same time, elements downstream of the lead element treat a higher salinity stream since the water becomes more concentrated as it moves on from RO element to RO element along the pressure vessel.

Designing an RO system with highly permeable, energy saving membranes would further exacerbate the flux imbalance if not for the hybrid design. To realize the improved flux balance from a typical hybrid, the lower permeability membranes are installed in the first stage and the higher permeability membranes are installed in the second stage. The limitation of this approach is that the higher permeability, lower rejection membrane in the second stage is treating a feed stream that is concentrated by the first stage. Because this stream has a higher salinity, it should be treated by a higher rejecting membrane. At this point, the Oxnard design is unique. The Oxnard Desalter reverses the typical hybrid's placement of membranes and uses the more permeable, lower rejecting membrane in the first stage while the second stage contains the lower permeability, higher rejecting membranes. The large flux imbalance that would normally be expected from reversing the placement of the elements in the different stages is compensated by utilizing an energy recovery device (ERD) between the two stages and therefore boosting the feed pressure to the second stage while balancing membrane fluxes at the same time. The ERD shown in **Figure 1b** recovers the energy in the high pressure concentrate stream of the second stage and transfers it to the feed stream of the second stage. The use of and ERD provides several advantages:

1. The ERD harnesses available energy from the second stage concentrate that would otherwise be wasted (by a throttling valve), thus reducing energy consumption

2. The ERD increases the average flux through stage 2
3. The increased flux in the second stage improves overall flux distribution between the lead and tail elements of the system
4. The pressure boost provided to the second stage reduces the head requirements for first stage feed.
5. The improved flux distribution also reduces fouling in the lead element.
6. The increased flux through the second stage improves permeate quality from the second stage.

a b

**Figure 1**: Oxnard's (a) 3 RO Trains and (b) Energy Recovery Device (ERD)

Since the commissioning of the Oxnard Desalter in 2008, manufacturers have made improvements to the membrane chemistry and to the manufacturing of elements. These improvements can be used today to further improve the efficiency of a system such as the Oxnard Deslalter. The most notable improvement in element manufacturing is the now common use of automation to maximize area and allow of the use of thicker brine spacers. When manufacturing the spiral wound element, a trade off is inevitably made between the thickness of the brine spacer and the amount of active membrane surface area that can be packaged into the element. Historically, if a thicker 34 mil spacer were selected, the membrane surface area would be reduced from a typical 400 square feet down to 365 square feet. However, due to advances in materials and automated manufacturing, including the use of robotics for the precise placement of glue lines on the membrane sheet, today's elements can be constructed with the thicker 34 mil spacer while maintaining 400 square feet of active membrane area. **Table 2** compares the design and performance of different elements that were used in the Oxnard design with the latest elements that could be used today in a system such as Oxnard.

**Table 2**. RO Element Design and Performance Information at Standard Test Condition

| | Oxnard's Current Elements | | New Elements | |
|---|---|---|---|---|
| Stage | Stage 1 | Stage 2 | Stage 1 | Stage 2 |
| Element | ESPA1 | ESPA2 | ESPA4 LD | ESPA2 LD |
| Flow (gpd) | 12,000 @ 150 psi | 9,000 @ 150 psi | 12,000 @ 100 psi | 10,000 @ 150 psi |
| Rej (%) | 99.3 | 99.6 | 99.2 | 99.6 |
| Spacer (mil) | 26 | 26 | 34 | 34 |
| Area (sq ft) | 400 | 400 | 400 | 400 |

Using a thicker spacer in the Oxnard Desalter would further improve flux balance by reducing the differential pressure losses through each stage. **Figure 2** shows how the flux balance is improved when using a thicker spacer element. Less pressure loss would also reduce the overall feed pressure required.

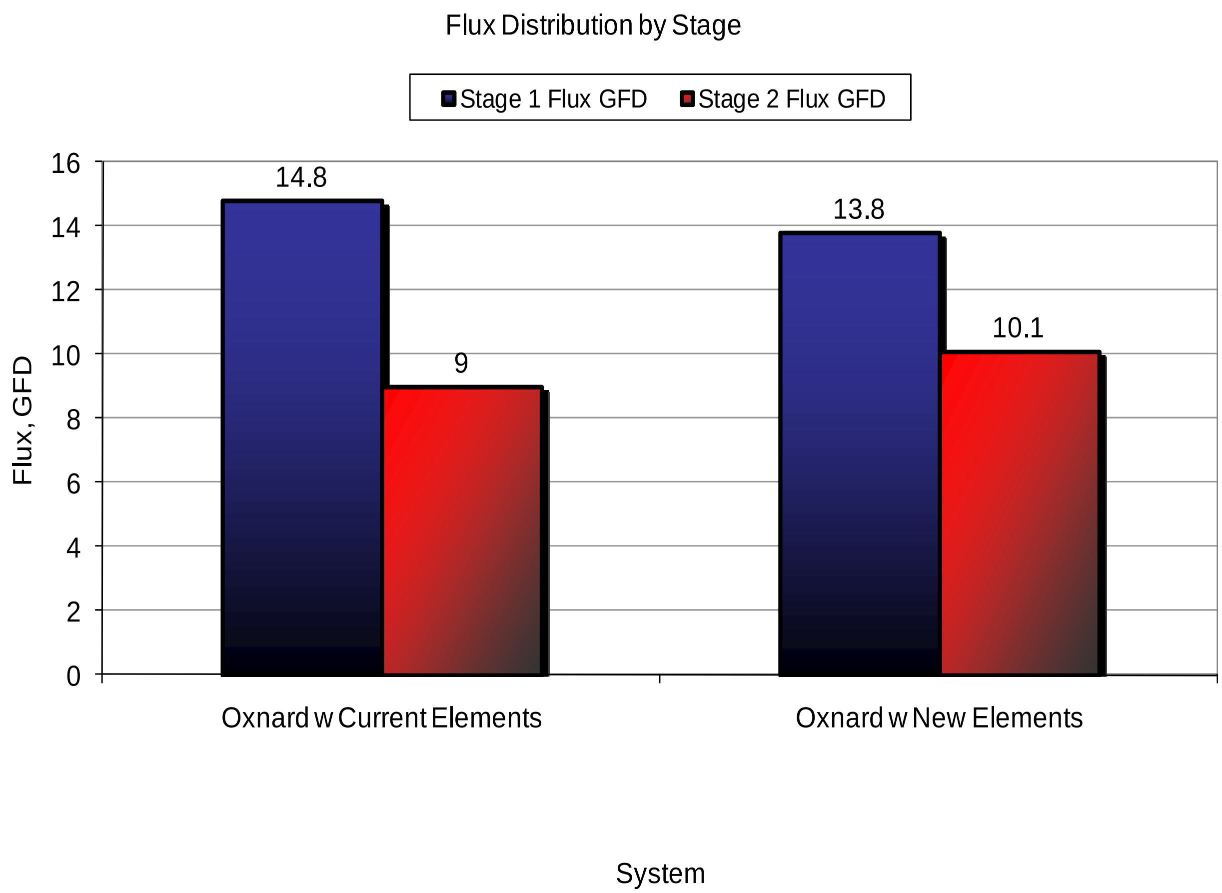


**Figure 2 Flux distribution between stage 1 and stage 2 for the Oxnard BWRO with current elements and with new, thicker brine spacer elements.**

Additionally, the use of thicker spacer elements has been shown to reduce the rate of fouling and increase the cleanability of a spiral element[2]. Particulates or biogrowth accumulating in the narrow feed channel of the spiral element with a 26 mil spacer will gradually increase differential pressure and subsequently feed pressure as well. If the feed channel width is increased by 30% with a 34 mil spacer, the rate of fouling is reduced. Normally in a low turbidity well water such as Oxnard's, fouling by particulates or biogrowth would not have a significant impact on system performance . However, as discussed below, Oxnard did eventually experience particulate fouling in the first stage and a subsequent loss in performance. The use of today's improved elements, with 34 mil spacer, would have reduced the rate of fouling experienced by the Oxnard system.

Determining the optimal combination of commercially available elements for the different stages of an RO system such as Oxnard requires an understanding of how each element, or combination of elements, affects the performance and operating cost of an RO system. For this reason, the following three designs, using elements found in **Table 2** are compared along with the economics of each design:

1. **Design 1 (Conventional Hybrid w/o ERD)** : Using higher rejection, lower permeable ESPA2 in stage 1 followed by the higher permeability ESPA1 in the second stage. No interstage ERD is required. This design is typically selected to balance flux without incurring the added capital cost associated with the ERD.

2. **Design 2 (Oxnard Hybrid w ERD)**: This is the current Oxnard configuration. Using higher permeability ESPA1 in the first stage followed by the higher rejection ESPA2 in the second stage with an ERD to balance fluxes by boosting second stage pressure.

3. **Design 3 (Oxnard Hybrid w ERD & New Membranes)**: This is the Oxnard design using current membrane chemistries and thicker 34 mil brine spacer in the element while maintaining the same 400 sq ft of membrane in each element.

Selecting the right elements for any RO system requires a balance between permeability and rejection. Permeability and rejection are opposite characteristics of RO membranes: the higher permeability, the lower rejection and vise versa. The elements should have the highest permeability possible (lowest feed pressure) while providing enough rejection to achieve the desired permeate quality. A comparison of feed pressure, differential pressure, and permeate quality for the three designs can be seen in **Figure 3**. All three designs meet the permeate quality requirement of 54 ppm TDS. The original Oxnard design (Design 2) achieves the lowest possible pressures, using the elements available at the time the plant was designed. Using the same elements in a conventional hybrid design (Design 1) increases both the feed pressure and TDS in the permeate. Design 1 requires a higher overall feed pressure to compensate for the absence of an ERD. The higher permeate TDS in Design 1 is the downside of placing higher permeability/ lower rejecting elements in the second stage to balance fluxes. The feed salinity to the second stage is double the feed salinity to the first stage and should be treated, not with lower rejection elements, but with the higher rejection elements (ESPA2).

RO system performance would further improve, as design 3 shows, if the current Oxnard system were to install the latest, high permeability membranes manufactured with 34 mil spacer.. The 24 psi lower differential pressure and subsequent lower feed pressure would result in a 24% reduction in energy consumption relative to the current Oxnard system. Permeate quality would be 10% higher, but would still remain well below the target requirements of 54 mg/L TDS.

The energy savings realized by the hybrid design with ERD leads to a reduction in the operating cost of the system which would eventually pay for the additional capital investment associated with installation of an ERD. In terms of capital cost, the greatest difference between the current Oxnard design and the conventional hybrid design comes from the cost of the ERD. The cost for each of the low pressure ERDs installed would be approximately $90,000. Based on literature, the cost for the RO system would total approximately $4,000,000 [3,4]. **Figure 4** uses these values as a reference to compare the initial capital combined with the cumulative operating cost of the three designs. Design 1, without ERD, begins at year zero with a capital cost $270,000 lower than the other two designs with ERDs. However, Design 1 cost increases at the greatest rate due to the highest feed pressure. Design 2 with older membranes, increases in cost at a greater rate than Design 3 due to its relatively higher feed pressure and higher energy consumption. The pumping energy for Design 1 is 1.54 kwhr/kgal. The pumping energy for Design 2 is 18% lower at 1.26 kwhr/kgal and the pumping energy of Design 3, with improved elements, is 38% lower at 0.96 kwhr/kgal. The more rapid accumulation of operating cost for Design 1 begins to exceed the accumulated operating cost of Design 2 after 2.2 years. The payback is shorter when considering Design 3. After about 1 year, the lower operating cost of Design 3 has recovered its higher capital investment. These differences illustrate not only the cost savings of the Oxnard design but also the cost savings of the currently available brackish water RO membrane chemistry and RO element design.

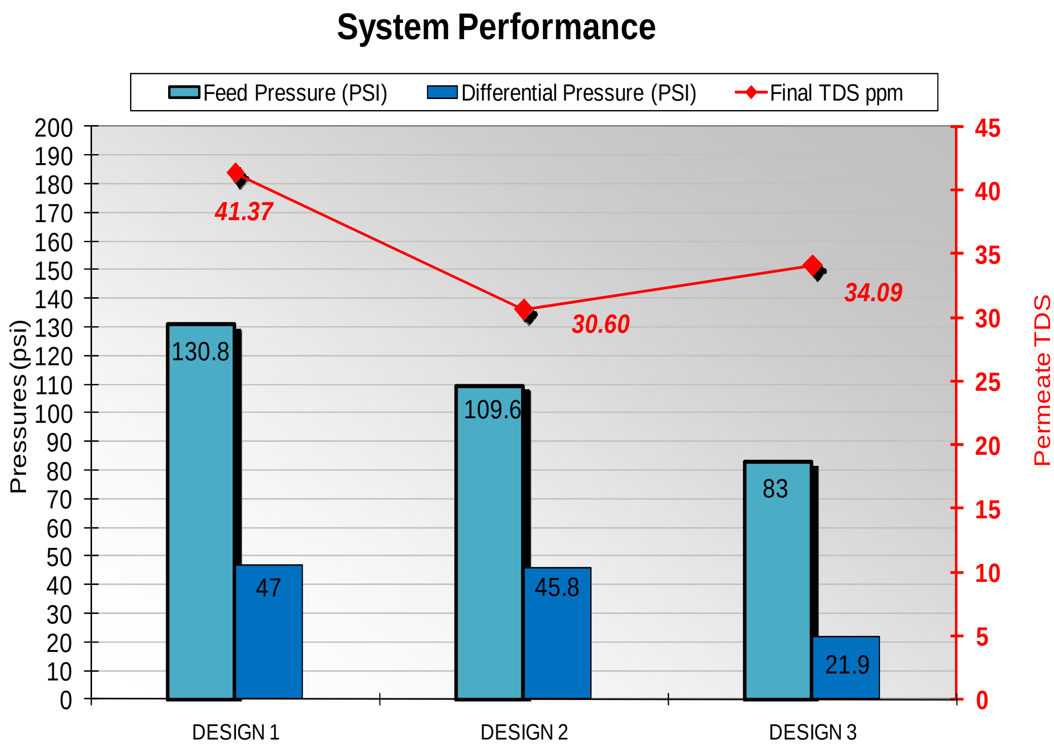


**Figure 3** Feed Pressures, Differential Pressures, and Permeate TDS of three different BWRO designs

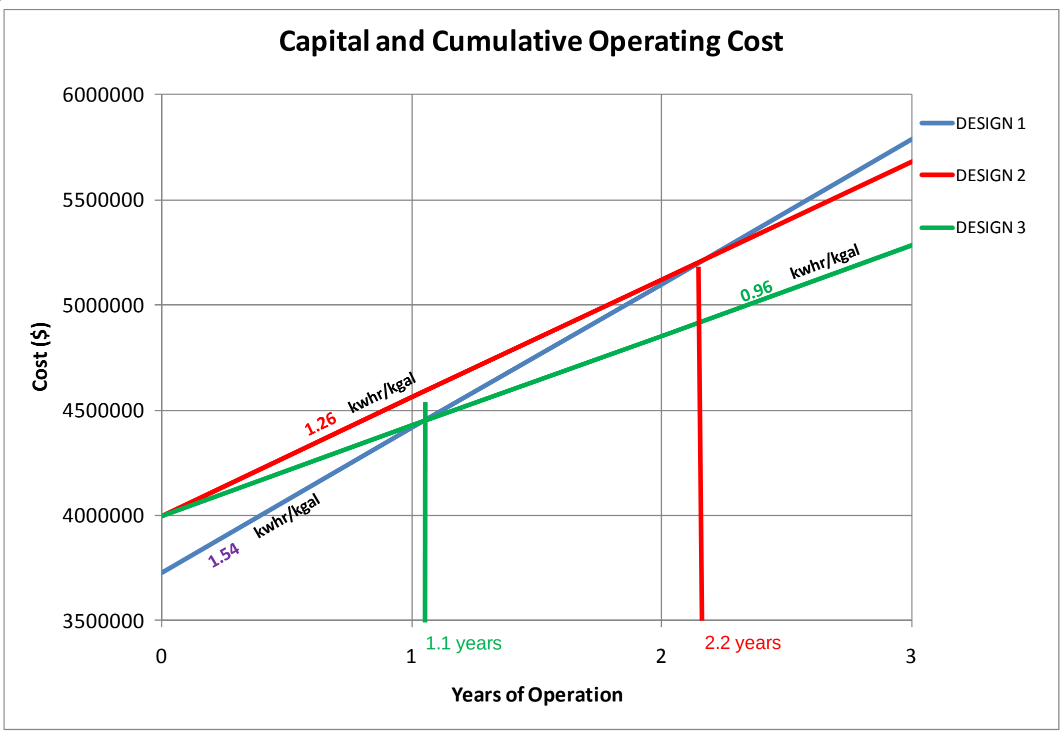


**Figure 4** Capital and Cumulative Operating Cost for 3 Designs

## RO Operation

The Oxnard Desalter performed stably with little change in performance and no cleanings during the first two years of operation. **Figure 5** shows normalized permeate flow started at 1,700 gpm and remained constant until late 2010 when it began a 21% flux decline which occurred through most of 2011. Membrane manufactures typically recommend cleaning an RO when flux declines 10% to 20%. Foulants that were removed or not present in the feed during the first two years of operation began to reach the membranes in 2011.

Further evidence of the fouling comes from the trends in differential pressure from stage 1 and stage 2 as shown in **Figure 6**. There is a 50% increase in stage 1 differential pressure, while stage 2 differential pressures remain stable. This trend is characteristic of particulate fouling which accumulates in the first stage lead elements while having little effect on elements in the second stage. Permeate quality TDS from the system was 31 mg/L based on full ion analysis (**Table 3**). This is well below the required 54 ppm TDS.

**Table 3: Ion Analysis for City of Oxnard Startup Train1**

| Sample ID | Na (ppm) | Ca (ppm) | Mg (ppm) | SiO2 (ppm) | K (ppm) | Cl (ppm) | F (ppm) | NO3 (ppm) | SO4 (ppm) | Alk (ppm as CaCO3) |
|---|---|---|---|---|---|---|---|---|---|---|
| Feed Stage1 | 134 | 231 | 79.5 | 34.7 | 6.21 | 70.7 | 0.553 | 62.2 | 737 | 258 |
| Perm Stage 1 | 7.74 | 0.594 | 0.212 | 1.11 | 0.147 | 2.22 | <0.05 | 9.65 | 2.83 | |
| Perm Stage 2 | 8.93 | 0.850 | 0.313 | 0.82 | 0.154 | 2.44 | <0.05 | 9.40 | 4.90 | |
| Total Perm | 8.23 | 0.654 | 0.235 | 1.03 | 0.165 | 2.32 | <0.05 | 9.62 | 3.36 | 4.0 |

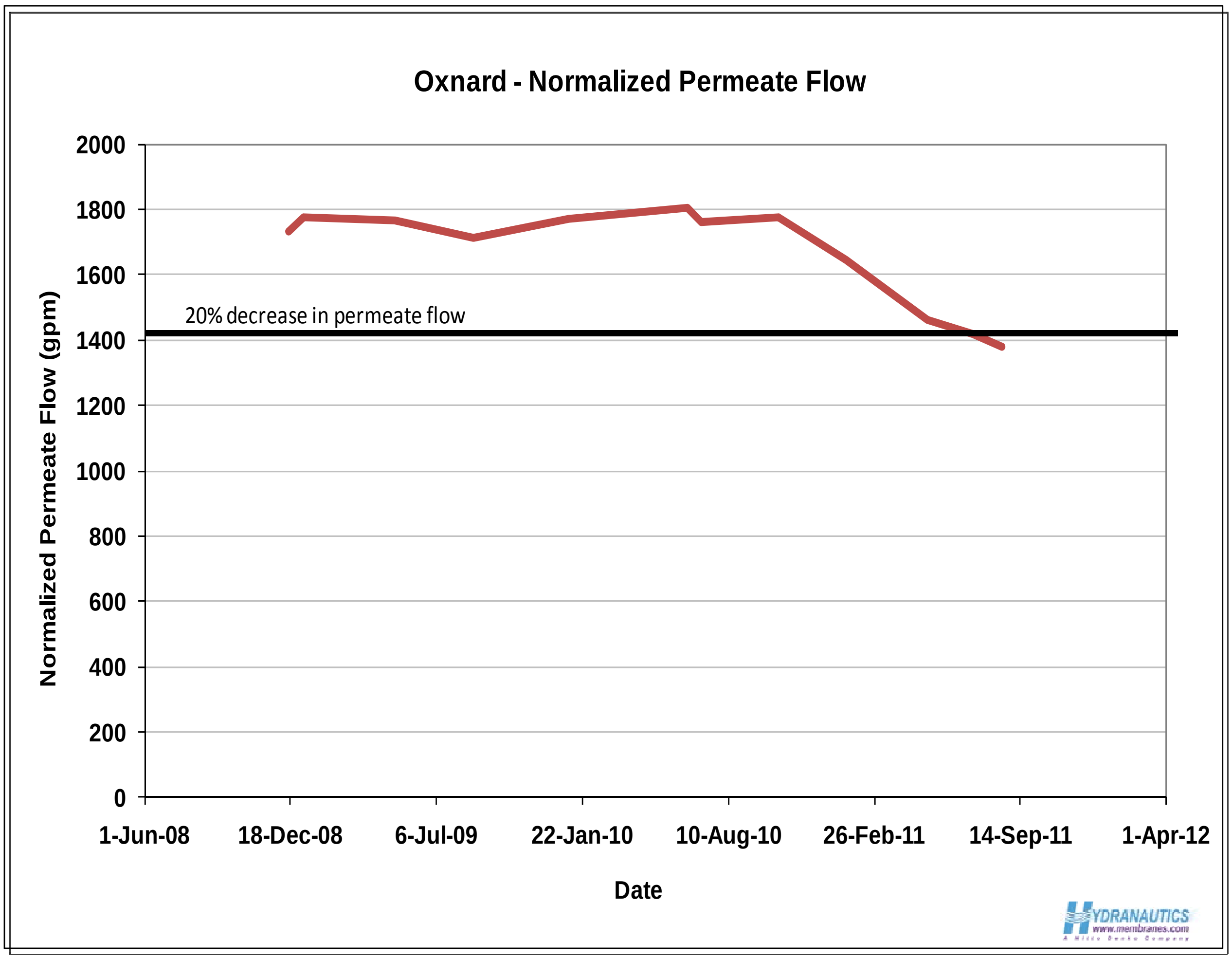


**Figure 5:** Oxnard's normalized permeate flow during 3 years of operation

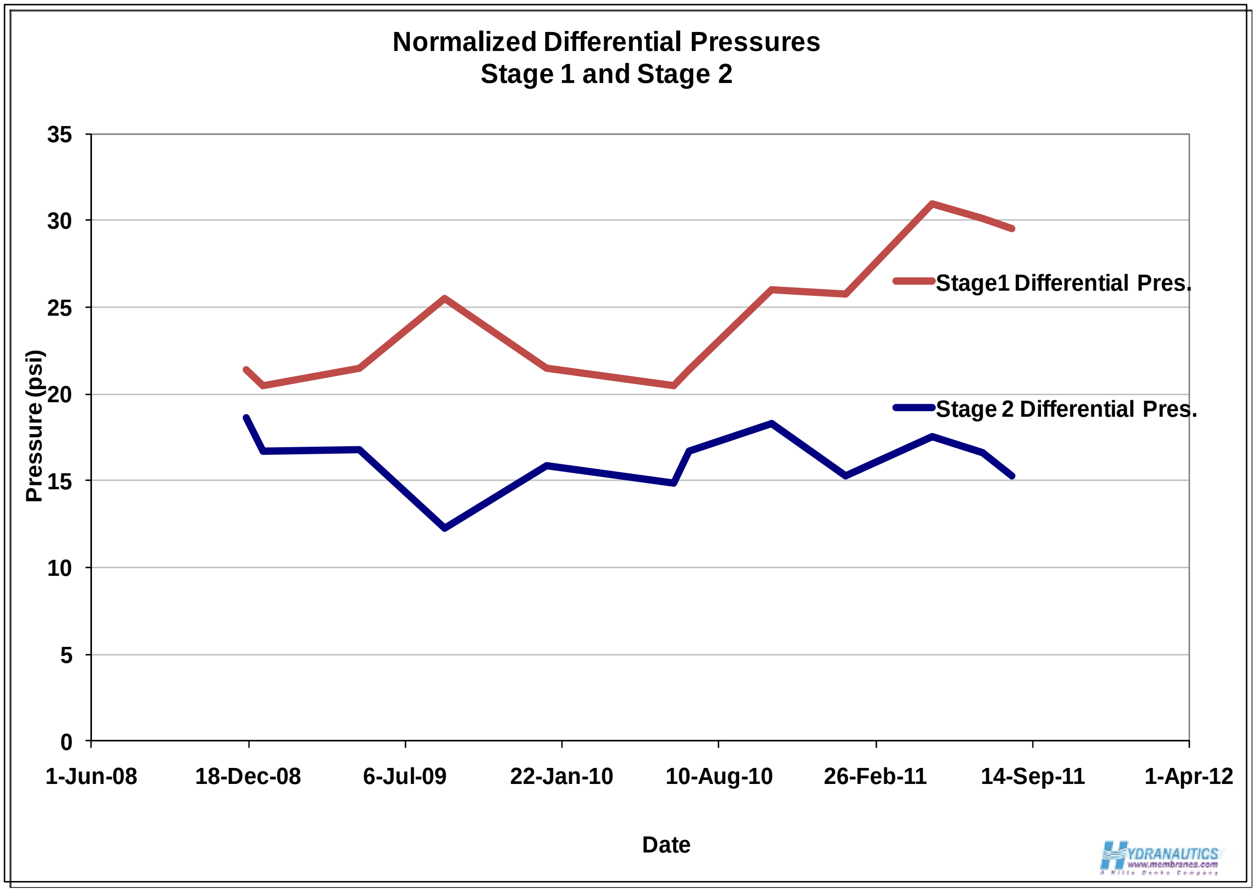


**Figure 6:** Differential pressures, stage 1 and 2

## Conclusion

As part of its effort to successfully manage dwindling water resources, the City of Oxnard operates a unique, energy saving, two stage brackish water reverse osmosis (BWRO) system to treat local groundwater for potable use. By utilizing a novel hybrid design approach which places higher fluxing membranes in the first stage, while higher rejecting membranes are installed in the second stage, the Oxnard Desalter has successfully saved on operating cost for the past three years since startup in late 2008. Oxnard's unique hybrid design, balanced with interstage ERD, has demonstrated 18% lower energy consumption and better permeate quality compared to conventional hybrid design that does not utilize the ERD. The reduced energy consumption associated with the Oxnard design paid for the higher capital associated with an ERD within 2.2 years.

The Oxnard Desater utilizes membrane technology that was available at the time of commissioning in 2008. Currently available membranes and element manufacturing techniques, including the use of a thicker 34 mil spacer, offers multiple advantages for the design and operation of an RO such as the Oxnard Desalter. These newer membranes, if installed in the Oxnard Desalter, would result in lower rate of fouling, reduced differential pressures and feed pressures, an additional 24% reduction in energy consumption, and a shortened payback period of 1 year on the ERD.

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