Reverse Osmosis Design & Concentrate Discharge Evolution in Florida the Past Three Decades

Christophe Robert

Reverse osmosis (RO) membrane treatment emerged as a viable process to treat water in the 1960s. Over the years, implementation of membranes for drinking water treatment has progressed using more advanced membranes made from new materials and employed in various configurations.

An emphasis by regulatory agencies on protecting fresh groundwater sources has pushed utilities to consider alternative resources such as hard water, brackish water, and seawater. Because of its success in treating hard and brackish water, membrane treatment became a viable alternative to other treatment technologies in the municipal drinking water treatment area.

Also over the years, state and federal as well as local drinking water standards have become more stringent, and a multitude of new applications have therefore appeared as a result of the ability of membrane treatment to meet those stringent standards. Technology improvements have significantly increased the performance of RO membranes, and today's membranes are more efficient, more durable, and much less expensive, making membrane treatment a feasible alternative in many applications.

This article discusses the evolution of membrane facilities in Florida, as well as their design and concentrate disposal practices since the first reverse osmosis drinking water plant was built in 1974. For the purpose of this article "RO" will be used to describe both nanofiltration (a variation of RO) and reverse osmosis itself.

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Statewide RO Facility Capacity

Within the United States, Florida is the state with the most RO membrane facilities. The number of RO facilities producing drinking water has been increasing in Florida over the past 35 years and will continue to increase, considering that there are multiple facilities under construction (Coral Springs), under design (Miami-Dade and Oldsmar), or under development (Tarpon Springs). Today there are 67 operating RO facilities with a capacity greater than 1 million gallons per day (MGD) in Florida

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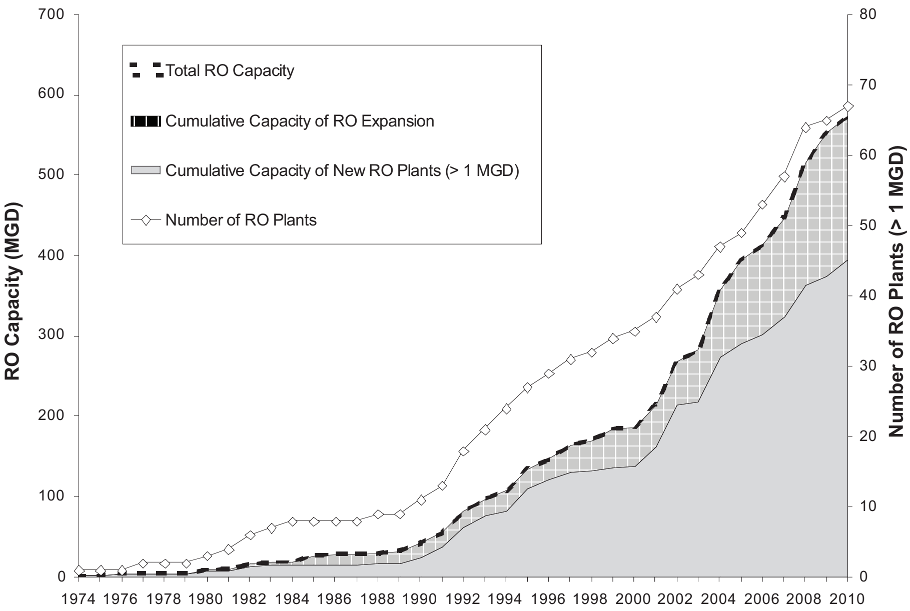

Figure 1. WTP Numbers and Capacity Evolution in Florida

Continued from page 19

Table 1 offers a breakdown of the facility number and capacity by county. Figure 1 presents the number of RO facilities over time, as well as the cumulative capacity of the new facilities and the cumulative capacity expansion of the existing plants.

Brackish groundwater has been the major alternative water source to freshwater in Florida, and the use of seawater as a water source is also becoming a reality. From 1974 to 1989, growth was fairly slow and only nine facilities larger than 1 MGD were built in the state. The first major RO facilities were built in the mid 1970s, and until the late 1980s the total capacity of RO water treatment plants was approximately 35 MGD (Figure 1).

In the past 20 years from 1990 to 2010, the construction rate has increased significantly, as 58 new facilities over 1 MGD have been built (Figure 1). In 2010, the total capacity of RO treatment facilities in Florida is nearing approximately 565 MGD, spread over 67 facilities.

Figure 1 shows that while the construction rate of new RO facilities has been following a linear trend during the past 20 years, the total treatment capacity from those facilities has been increasing exponentially. This exponential increase arises from the fact that in addition to construction of new facilities, existing RO facilities were also expanded—that is, the capacity of the new facilities increases linearly, similar to the increase in the number of new facilities, but the increase in existing facility expansion capacity is exponential.

The increase in RO treatment utilization can be attributed to several factors:

- The need to use alternative water supplies, such as brackish waters, to protect the freshwater sources such as the upper Floridan Aquifer, and rivers/lakes, which require removal of dissolved solids.
- The reliability, efficiency, and the cost competitiveness of RO systems versus other water treatment systems.
- Replacement of aging lime softening treatment facilities.
- Stringent federal water quality regulations; more specifically, disinfection byproducts.
- Stringent local water quality requirements such as color, taste, and odor.
- The need to meet the water demand increases.

As an example of alternative water supply use, Palm Beach County built a 10-MGD RO facility (Lake Region) to replace the surface

Table 1. Breakdown of Plants, Capacity and Disposal Alternatives by County

County	Number of Plants	Total Capacity (MGD)	Deep Well Injection	Shallow Well Injection	Surface	Sewer	Land Application
Palm Beach	12	151	6	2	3		1
Broward	10	116	8		1		
Collier	6	71	4		1	1	
St. Lucie	4	43	4				
Lee	6	35	6				
Hillsborough	1	25			1		
Indian River	3	21			3		
Miami-Dade	2	21	2				
Sarasota	4	17	2		2		
Martin	3	15	2		1		
Brevard	3	10	2		1		
Monroe	3	9	1	2			
Flagler	2	8			1		
Pinellas	2	7				2	
St. Johns	2	6				2	
Volusia	1	4					1
Charlotte	1	3	1				
Hendry	1	3	1				
Glades	1	2					1
TOTAL	**67**	**566**	**39**	**4**	**14**	**5**	**3**

water plants of the cities of Belle Glade, Pahokee, and South Bay that were treating Lake Okeechobee water. The facility was financed by the three cities, Palm Beach County, and the South Florida Water Management District. The city of Clewiston also built a RO facility to replace its surface water plant that was treating Lake Okeechobee water.

Those two plants were built to produce a high-quality drinking water by treating brackish groundwater from the Floridan Aquifer and to significantly reduce drinking water quality issues, particularly disinfection byproducts, color, taste, and odors associated with using surface water from Lake Okeechobee. This groundwater use eliminated conflicts between the use of Lake Okeechobee as a source of drinking water and the water needs for Everglades restoration to help "drought-proof" the local water supply.

Brackish groundwater has been the major alternative water source to freshwater in Florida, and the use of seawater as a source water for potable use is also becoming a reality. The first U.S. seawater plant was built in Florida in 1980. It is owned by the Florida Keys Aqueduct Authority (originally a 3-MGD facility, currently a 2-MGD facility located on Stock Island, 1 MGD of treatment capacity being relocated to Marathon), but it is operated only as an emergency facility.

In 2002, the first major seawater facility in the U.S. was built in Florida; it is owned by Tampa Bay Water, a regional authority. The implementation of the Tampa Bay Water seawater plant was part of the regional water master plan in which supply from groundwater would be limited, and construction of a surface water treatment plant and a seawater desalination facility were the alternatives required in order to meet the increasing water demand in the Tampa area.

It is likely that other seawater desalination plants in Florida may follow the example of Tampa Bay Water. Several projects such as the Coquina Coast project in Flagler County may result in the construction of a regional seawater facility.

Drinking water standards have become more stringent over the years, and currently the emphasis is on limiting the formation of disinfection byproducts. The original trihalomethane maximum contaminant level (THM MCL) was 0.10 mg/L in 1979. The Stage 1 Disinfection/Disinfection By-Product Rule (D/DBPR) changed the THM MCL to 0.08 mg/L as a running annual average of all sampling locations in the distribution system. Now the Stage 2 D/DBPR applies the existing 0.08 mg/L MCL to each sampling location.

In order to keep free chlorine for disinfection and avoid switching to chloramines in situations where DBPs are an issue, a utility would have to reduce the organic content in the raw water. Membrane treatment in Florida has been the premiere choice over other organic removal processes such as carbon adsorption or enhanced coagulation. Not only can organic contents be removed, but hardness and/or salts are also reduced, making the membrane process the logical choice in many situations.

One of the recent examples is the city of Boca Raton, which implemented the largest U.S. nanofiltration facility (40 MGD) to soften groundwater from 250 milligrams per liter (mg/l) as $CaCO_3$ to 70-90 mg/l as $CaCO_3$, and to reduce the total organic carbon (TOC) concentration from 12 mg/l to less than 1 mg/l in order to meet the DBP MCL requirements.

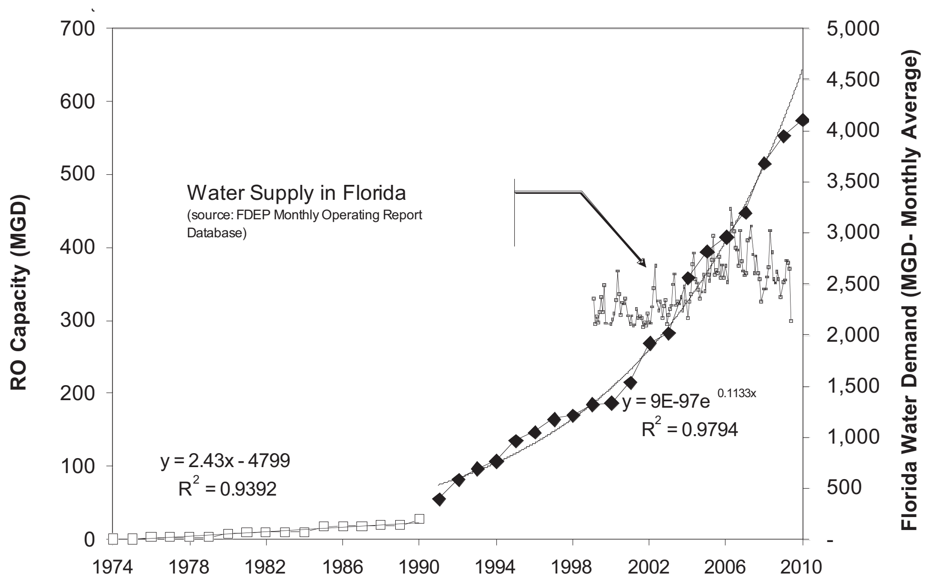

Figure 2. RO Capacity Trends in Florida

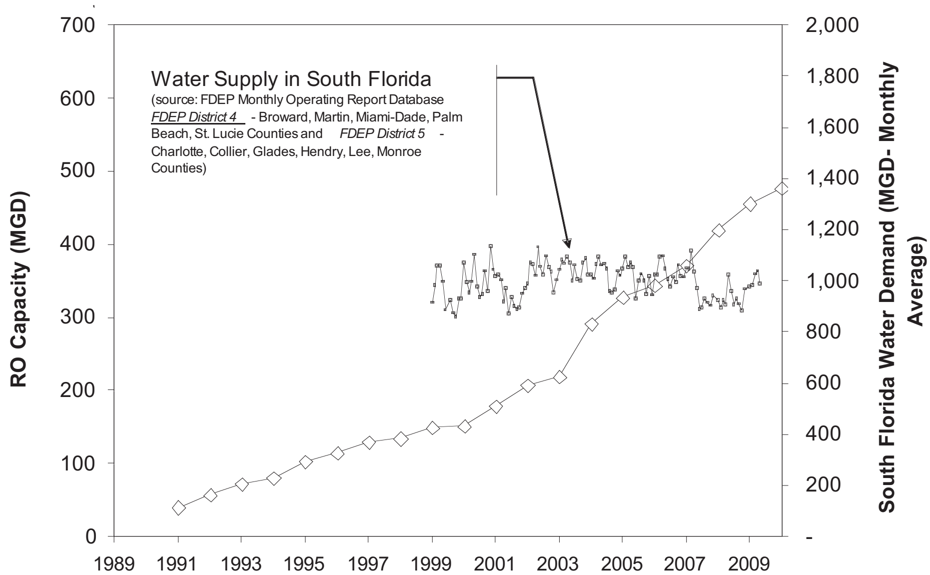

Figure 3. RO Capacity Trends in South Florida

The water demand increase is not the only driving factor for the increase in RO treatment. As shown in Figure 2, while the RO capacity is increasing exponentially, water usage in Florida did not increase exponentially (Florida Department of Environmental Protection database). Even in South Florida where the largest RO growth occurred, the water demand remained constant over the past 10 years (Figure 3).

From the first facility built in the mid 1970s to the latest facilities built in Florida, RO technology has evolved significantly and equipment costs as well as power requirements associated with an RO facility have decreased

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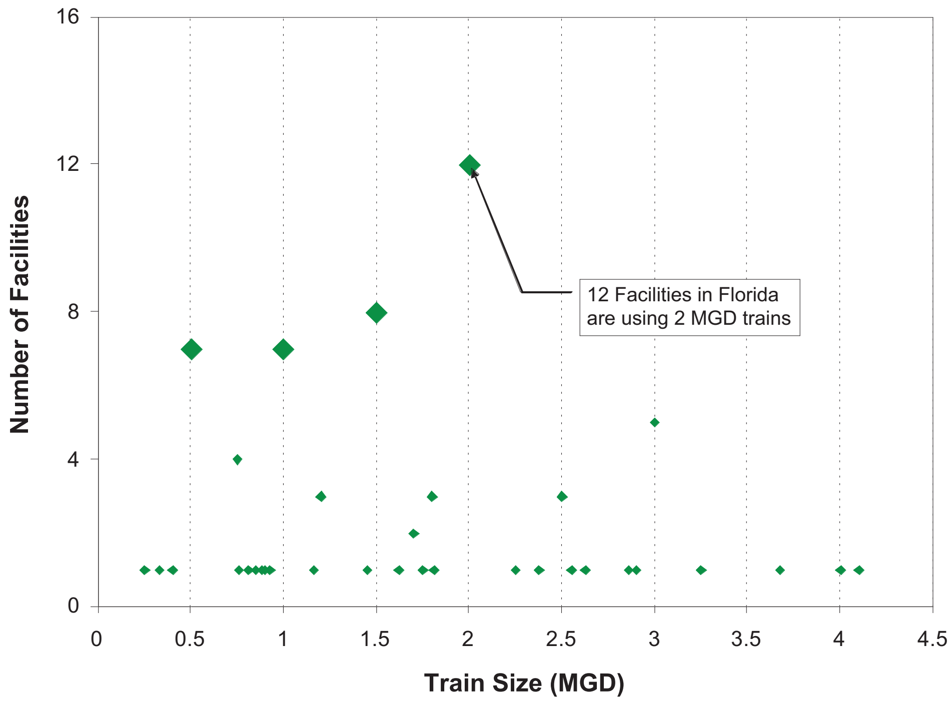

Figure 4. Train Size Breakdown

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significantly. The following sections present an overview of how RO facility design and equipment have changed. An overview of concentrate disposal trends also was researched, since it is a key aspect of an RO project.

Reverse Osmosis Train Design

The design of a membrane facility must include consideration of several general critical parameters such as raw water quality, finished water quality goals, total capacity, and individual train capacity. Water quality is the basis for selection of a design flux, recovery, and type of membranes.

The recovery of a membrane facility is a function of specific concentrations of anions and cations in the raw water to be treated. The flux is usually selected by the designer with the flux being typically lower for high TDS waters. Those design criteria will then dictate the stage configuration, the number of pressure vessels, and the number of membranes for a specific RO train flow rate.

RO Train Size

RO trains are independent units to produce purified water. Multiple trains are used to meet the required design capacity for the water treatment plant.

Ninety-five percent of facilities in Florida use membrane trains with a capacity equal or less than 3 MGD, with 2 MGD being the most common size. Figure 4 shows the distribution of the train sizes. There are only three RO facilities with trains producing more than 3.5 MGD in Florida: Boca Raton, Fort Myers, and Tampa Bay Water.

The train capacity selection is a compromise between having too many trains and having too few trains. When deciding on the number of trains to design and install, one must consider that installing too many trains is more costly than installing fewer because of the economy of scale. Also, the plant operation would likely be more complex in a facility operating more trains than a facility with fewer trains.

On the other hand, operating more trains has the advantage of removing only a small fraction of the plant's capacity during normal maintenance activities such as membrane cleaning and cartridge filter change-out. It is therefore the decision makers' responsibility to find the middle ground that makes the most sense for the utility that is implementing a membrane treatment facility.

Within trains having the same water production capacity, the physical size may be significantly different from one train to another. The physical size of a train is directly correlated to the desired production rate and the selected flux (flow per membrane surface area), as demonstrated in Table 2. For example the train capacity for both Fort Myers and Tampa Bay Water are approximately the same, but the train for Tampa Bay Water contains twice as many membranes as the Fort Myers train.

Train Configuration

A train configuration can consist of one pass or two passes, with the two-pass configuration being a system where the permeate of the first pass is further treated in a second pass. Typically this configuration is used for seawater treatment, for example in the Tampa Bay Water Desalination facility, where the first pass permeate could be further treated when the finished water chloride goal is not met with only one pass.

A single pass can be a one-stage, a two-stage or a three-stage configuration. The concept of a stage is that the concentrate of one stage is further treated in the subsequent stage of the system. Selecting a stage configuration is a function of possible water recovery. A one-stage system would be used for situations where the recovery would be up to 60 percent (seawater), a two-stage for up to 85 percent (brackish water), and a three-stage for up to 90-95 percent (freshwater).

As mentioned earlier, the Tampa Bay Water desalination facility is a two-pass system: the first pass is a one-stage configuration system and the second pass is a two-stage configuration system. This facility is currently the only two-pass system in Florida.

The two-stage array design configuration is the most widely used one-pass configuration in Florida, since water recovery up to 85 percent is achievable with adequate pretreatment prior to the RO process. Adequate pretreatment includes the use of an antiscalant and/or acid to

Continued on page 24

Table 2. Train comparison

	Unit	Ft. Myers	Tampa Bay Water
Train Size	MGD	4	4.1
TDS	mg/L	3,000	30,000
Flux	gfd	13	8
Pressure Vessels		96	168
Elements/Pressure Vessel		7	8
Number of Elements		672	1,344

St. Lucie West District RO Water Treatment Plant: Two 1.7 MGD trains (two-stage system, 20:12 array configuration, seven elements per pressure vessel, side-port pressure vessels, interstage boost/energy recovery device.

Continued from page 22

prevent precipitation of salts on the membranes.

A three-stage configuration may result in a water recovery of 90 to 95 percent, but the risk of precipitation is more significant; therefore, this approach commonly is not used except for treatment of freshwater. Only a few facilities in Florida use a three-stage configuration. For example, Boca Raton can operate two trains as a third stage to treat the concentrate of the other two-stage trains. Those two trains also can be operated as a two-stage system to treat groundwater directly. Utilities such as Fort Myers converted their original trains from a three-stage to a two-stage configuration.

Interstage Boost Pump/ERD

Interstage booster pumps and/or energy recovery devices (ERDs) have been integrated into membrane systems for a long time, and now there are several facilities using either one or both technologies. The purpose of interstage booster pumps (between stage 1 and stage 2 of a membrane system on the concentrate stream) is to balance fluxes and therefore water production between the first and second stages. The concept is to reduce the feed pressure of the first stage and then boost the feed pressure of the second stage. This configuration has the advantage of not over-pressurizing the first stage in order to still have enough pressure in the second stage.

The two most common configurations to provide interstage boost pressure are 1) installing a conventional motor and pump and 2) installing an energy recovery device on the concentrate line to transfer the excess energy on the concentrate to stage 2 feed water. Because energy costs may represent up to 50 percent of a system's operational costs in a brackish system, and up to 80-90 percent for a seawater facility, there has been a trend to reduce energy costs through improvements in membrane performance and by utilizing energy recovery devices that reduce energy requirements by 10 to 50 percent.

Marco Island was the first major facility treating brackish water to utilize an energy recovery device/interstage booster pump in 1997. Currently several facilities in Florida utilize the interstage boost pump/ERD, including Collier County, the cities of Port St. Lucie and Jupiter, and the St. Lucie West District. Tampa Bay Water utilizes the Pelton Wheel ERD to transfer the concentrate energy into the feed stream in order to reduce the size of the feed high-pressure pumps. While such devices are not widespread in Florida yet, it is expected that ERD will be a common practice in the future as energy costs increase.

Pressure Vessels

One of the improvements in membrane treatment facilities that can reduce the cost of RO trains is the design of pressure vessels. Recent improvements in pressure vessel design include side-port technology and large diameter pressure vessel development.

One of the major improvements is the use of multiple side ports on the ends of the pressure vessels that allow the elimination of headers to which the pressure vessels are connected, allowing for direct connection between pressure vessels. The cost of this type of pressure vessels is higher than conventional pressure vessels, but overall costs are reduced because a significant amount of piping is eliminated. Currently many new facilities utilize RO trains with side-port pressure vessels, including Martin County and Ormond Beach.

Another pressure vessel technology change is the use of a middle port that officials in the city of Jupiter are considering for their new 14.5 MGD plant. This design is for the purpose of improving flow distribution and reducing piping head losses.

Even though there are no plants in Florida utilizing large-diameter membrane systems, there have been several applications in the U.S. over the past few years. Examples include the Tate Monroe Association in Ohio and the city of Waupun, Wisconsin. The large-diameter systems have the advantages of requiring a small footprint and fewer construction materials.

Even though the cost of a large pressure vessel is significantly higher than the cost of multiple conventional pressure vessels for the equivalent water production (typically one large 16-inch or 18-inch diameter pressure vessel is equivalent to four to five eight-inch diameter pressure vessels), the additional cost may be offset by other savings. It is the decision makers' responsibility to evaluate the cost of conventional pressure vessel configurations versus the large diameter configuration, while maintaining membrane performance, and then make the decision that will benefit the utility.

Membranes

The first few membrane plants built in Florida primarily used hollow-fiber type reverse osmosis membranes. The main hollow-fiber membranes were the DuPont B9 and B10, as well as DOWEX. Those membranes were used at the RO plants operated by Cape Coral, Venice, Indian River County, Island Water Authority (Sanibel/Captiva), Sarasota, and the Florida Keys Aqueduct Association (FKAA).

By the early 1990s, most plants stopped using hollow fiber membranes and instead utilized spiral wound membranes. On the other hand, Sarasota didn't convert to spiral wound membranes until the early 2000s, and the FKAA is still using hollow fiber membranes (DuPont and Toyobo) at their two emergency seawater plants on Stock Island and Marathon.

The conversion to spiral wound elements was attributed to the fact that DuPont stopped producing hollow fiber membranes for the municipal market in the late '90s, and the fact that spiral wound elements were available from multiple manufacturers competing in the market, decreasing the cost of elements over the years. Also, the design of RO systems is more flexible with the use of spiral membranes, and the hollow fiber membranes are more susceptible to fouling.

Some early plants were also built using 8.5-inch diameter membrane elements (IWA, Cape Coral, Fort Myers, St. Lucie West District, Vero Beach), and, as for the hollow fiber membranes, most facilities converted their 8.5-inch diameter membrane system to the current standard 8" diameter system. Out of the five facilities

Continued on page 26

Table 3. Membrane Element Price the Past Three Decades

	Element Price	Price ft²	Normalized Price/area	CPI	1978 = 1 CPI	Norm 78 Price/area
1978	$950	$6.33	$1	71	1	1
1989	$875	$2.92	$0.46	124	1.75	0.26
1995	$750	$2.27	$0.36	152	2.14	0.17
2000	$645	$1.79	$0.28	172	2.42	0.12
2002	$435	$1.18	$0.19	180	2.54	0.07
2006	$550	$1.38	$0.22	200	2.82	0.08

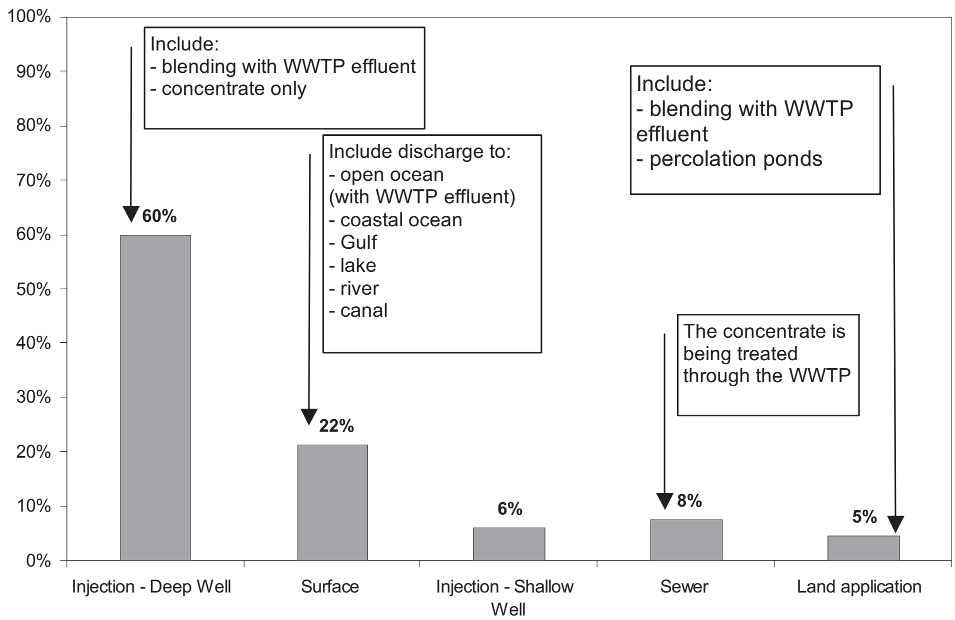

Figure 5. Concentrate Disposal Distribution in Florida

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mentioned, Cape Coral and Vero Beach are still using the 8.5-inch membrane elements, but Vero Beach is considering replacing its 8.5-inch system with the 8-inch system.

This conversion to 8-inch elements is driven by the fact that only a limited number of membrane manufacturers produce custom-made 8.5-inch diameter elements, and therefore a facility may not have as many membrane replacement options as with the 8-inch elements. Currently membrane facilities in Florida are built exclusively with the 8-inch pressure vessels and membrane elements.

In the early 1980s, a few utilities such as Island Water Authority and Englewood used cellulose acetate (CA) membranes, but by the latter part of that decade, those facilities had switched to thin-film composite (TFC) polyamide (PA) membranes.

The main advantages of using a TFC PA membrane instead of a CA membrane are its better rejection of dissolved solids and organics, its higher productivity at lower operating pressures, its greater structural stability, and its ability to be cleaned over a wider pH range. The downside of the PA membrane is that it is not chlorine-resistant and it is more expensive. Generally, however, using a PA membrane results in a less expensive system.

The overall costs of RO trains (pump, frame, pressure vessels, membranes and auxiliary equipment) have decreased over the years, making membrane treatment a cost-competitive treatment alternative. As an example, membrane element costs have decreased significantly over the years. As seen in Table 3, the cost of membranes decreased by a factor of 12 in the past 30 years (J. Birkett & Truby, 2007).

Not only has the cost decreased, but the performance of the membrane elements has improved over the years. Now membranes can produce more water while lowering salt passage at lower pressure. Membrane surface area has increased for the same element physical size (8-inch diameter by 40 inches long), and the life expectancy has increased from three years to seven years. Less-expensive treatment and improved performance have made RO treatment one of the premiere drinking water treatment alternatives in Florida.

In summary, the eight-inch TFC PA spiral wound membranes are used in a majority of the facilities in Florida because of their advantages noted in this section. The performance of these membranes has increased over the years in terms of water production and water quality, and the cost of the membranes has decreased.

Concentrate Disposal

A major concern with the use of reverse osmosis to treat water is the generation of the byproduct stream called concentrate. In Florida, the five main alternatives to dispose of concentrate are deep well injection, shallow well injection, surface water discharge, sewer discharge, and land application that includes public access reuse (Reiss Engineering, 2003).

Figure 5 shows the distribution of concentrate disposal for RO water treatment plants over 1 MGD in Florida (the breakdown by county is shown in Table 1). As seen in the figure, the majority of concentrate disposal is accomplished via deep well injection. The second-most used disposal method is surface water discharge. The least-utilized options for concentrate disposal are shallow well injection, discharge to sewer, and land application.

It is important to note that concentrate disposal for all RO plants over 4 MGD in Florida is either deep well injection or surface water discharge. Even though deep wells require more capital investment and could be the most expensive alternative for relatively small facilities, there are now several facilities under 3 MGD that use deep well injection, such as Greater Pine Island (conversion from land application to deep well injection in the early 2000s) and the city of Clewiston. The average facility capacity for each concentrate discharge is:

- Deep Well Injection: 9.3 MGD
- Surface Water Discharge: 11.3 MGD
- Sewer Discharge: 2.8 MGD
- Land Application: 2.9 MGD
- Shallow Well Injection: 1.7 MGD

Note that discharge to sewer and land application typically are more feasible for low flows, and the largest plants using either sewer discharge or land application are no larger than 4 MGD, which corresponds to a concentrate flow of less than 1 MGD.

Since the early ’90s, only five facilities have selected surface water discharge as a concentrate disposal alternative; in the same period of time, 34 facilities selected deep well injection for concentrate discharge (Figure 6).

There are different types of surface water discharge, including discharge to the ocean, either with blending of wastewater effluent (city of Hollywood, city of Boca Raton) or without blending (South Martin Utilities); discharge to canals (Indian River County); discharge to lakes (city of Cape Coral); and discharge to man-made

Continued on page 31

Deep well injection

Continued from page 26

wetlands (Indian River County). South Martin Utilities is the first utility in Florida to discharge non-blended concentrate only to the ocean.

Even though surface water discharge is still used and will be used for future RO plants (as in planned for the future Tarpon Springs RO plant), several facilities in Florida (city of Fort Myers, Inland Water Authority, Englewood Water District) converted their surface water discharge to deep well injection.

For example, the city of Fort Myers has been disposing of concentrate via a deep well since 2004. The city stopped disposing to surface water when it converted its membrane softening plant to a brackish reverse osmosis plant. That conversion resulted in significantly higher TDS in the concentrate, and surface water discharge was not feasible, which led to the use of deep well injection.

Two other cities, Hollywood and Boca Raton, may also stop discharging to surface water in the near future. Those two cities discharge their concentrate with domestic wastewater effluent into the open ocean, but legislation (Senate Bill 1302 signed by the governor in June 30, 2008, draft 403.085 F.S.) will reduce over time, and ultimately eliminate, reliance on ocean outfalls to dispose of domestic wastewater in Southeast Florida in order to protect the coastal environment and encourage reuse practices. Those cities, therefore, may select another alternative for concentrate disposal unless they use the existing ocean outfalls for concentrate only.

Even though the deep well alternative is likely more expensive in terms of infrastructure construction than other discharge alternatives, it can be viewed as a more reliable and permittable option than surface water discharge, especially in South Florida where deep well injection has been shown to be successful. Obtaining a concentrate discharge permit into state surface water requires a NPDES permit and several regulatory requirements have to be met. In addition, demonstration of meeting criteria may require field studies and analytical modeling.

For example, obtaining a permit for surface water discharge requires meeting surface water standards of the water body to which the concentrate is discharged. In the situation where the standards can not be met, mixing zones could be granted by the Department after it is demonstrated that the mixing zones meet all regulatory requirements through a dilution analysis model.

Out of the 14 surface water discharges, at least 10 of them include mixing zones. Most of the mixing zones are for combined radium (226+228) and gross alpha, radionuclides that occur naturally in the groundwater and exceed the surface water standards.

The NPDES permitting process can be expensive and can take several years. For example the permitting process for Tampa Bay Water took several years, involved completion of multiple studies, and required the use of multiple specialty consulting firms.

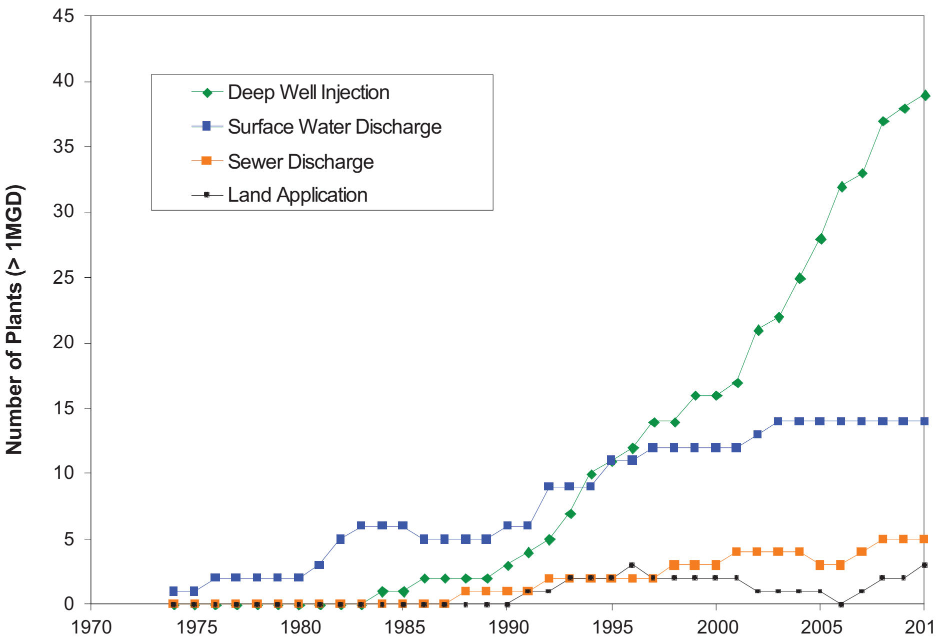

Figure 6. Concentrate Disposal Alternative Evolution

Conclusions

For the past three decades, reverse osmosis treatment capacity in Florida has increased tremendously as a result of several driving factors, including the need to treat alternative waters requiring desalting and the need to meet increasingly stringent water quality standards. In general, the design of membrane plants has not changed much in the last three decades, but improvements to membrane system components (membranes and pressure vessels) have been realized and options are becoming more diversified. Those improvements and the resulting diversification make the design and operation of membrane plants more customized, more flexible and less expensive for utilities.

On the other hand, because of more stringent disposal regulations, concentrate disposal alternatives are limited and may be the limiting factor in selecting reverse osmosis treatment. Solutions do exist for concentrate disposal, however, such as offshore brine discharge. As the cost of non-membrane alternatives increases, the viability of membrane treatment will continue to increase.

References

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- Reiss Engineering, Inc. "Investigation of Demineralization Concentrate Management", St. Johns River Water Management District, 2003.