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Use of beach galleries as an intake for future seawater desalination facilities in Florida and globally similar areas

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ABSTRACT

Desalination of seawater using the reverse osmosis process can be made less costly by the use of subsurface intake systems. Use of conventional open-ocean intakes requires the addition of a number of pretreatment processes to protect the primary RO process. Despite using the best designs possible for the pretreatment, seawater RO membranes tend to biofoul because of the naturally-occurring organic material and small bacteria present in seawater. These materials are not completely removed by the pretreatment system and they pass through the cartridge filters into the membranes, thereby causing frequent and expensive cleaning of the membranes. Quality of the raw water can be greatly improved by the use of subsurface intakes which can substantially reduce the overall treatment cost. There are a number of possible subsurface designs that can be used including conventional vertical wells, horizontal wells, collector wells, beach galleries, and seabed filters. The key selection criteria for the type of subsurface intake most suited and most cost-effective for a site are based on the required volume of raw water and the local geology. The active shorelines of Florida are very well-suited for the development of beach gallery intake systems. These systems are installed beneath the active beach between the high and low tide zones of the beach. Since they are constructed with a depth to the screens between 3 and 5 m, they cannot be observed at surface and persons using the beach would be unaware of their existence. These galleries are simple to construct and they tend not to clog because the active wave action within the intertidal zone provides mechanical energy that continuously cleans the filter face. They also have other advantages, including: the water quality is seawater unaffected by substances present in freshwater aquifers occurring landward of the shoreline, the salinity of the water is generally constant, and there are no impacts on water users located inland from the shoreline. A comprehensive study of the grain size characteristics of Florida beaches has allowed an assessment to be made of the hydraulic conductivities of the Florida beach sands. Hydraulic conductivity values generally range from 1.8 to 24 m/day, which is more than sufficient to allow the design and construction

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of high-capacity galleries at a reasonable cost. This type of intake is particularly relevant to the northeast Florida shoreline adjacent to an area being considered for development of a large-capacity seawater desalination system.

Keywords: Seawater reverse osmosis; Desalination; Intake; Beach gallery; Design; Florida

1. Introduction

Some primary goals of desalination research are to reduce energy consumption, lower costs, and reduce environmental impacts. Desalination of seawater is a generally expensive and energy-intensive source of a new water supply. Globally, the cost of seawater treatment using membrane processes is currently about \$0.72 m^3. This cost is based on the following assumptions: the electrical energy cost is about \$0.04 kilowatt-hour, the total dissolved solids concentration of the raw water is about 35,000 mg/L, and the intake is an open-ocean type. Improvements in membrane performance, energy recovery, and plant design have combined to reduce seawater desalination costs from an estimated \$2.10 m^3 to the current cost over the last 25 years. However, there are several improvements that need to be made to lower pretreatment costs, reduce rates of biofouling, increase plant reliability under all natural conditions, and to reduce perceived environmental impacts (e.g. impingement and entrainment issues).

While considerable research has been conducted on improvements to membrane efficiency and energy recovery, little attention has been given to improvement of the raw water quality that enters a treatment facility. Seawater naturally contains suspended solids, algae, bacteria, and organic compounds that allow biofouling of the membranes, causing frequent cleaning and reduced life-expectancy, and increased operational costs [1]. Also, harmful algal blooms have caused the shutdown of seawater RO plants and have actually damaged expensive process equipment [2,3].

One method of improving raw water quality is to change the source of feedwater from an open-ocean intake to a subsurface intake. Subsurface intake systems have been used to provide raw water to a large number of small to intermediate capacity desalination plants globally [1]. Conventional wells [4], collector wells, horizontal wells [5], and seabed galleries [6] have been used as seawater RO intakes. Currently, the highest capacity operating subsurface intakes are the Sur, Oman wellfield (160,000 m^3/day) and the Fukuoka, Japan seabed gallery (103,000 m^3/day). Subsurface intakes have been demonstrated to effectively reduce the silt density index (SDI) and organic compounds within raw seawater [7–9]. The goal of using a subsurface intake is to reduce or eliminate pretreatment within a seawater RO facility, so the intake becomes an actual part of the pretreatment process, allowing direct pumping of raw water into the cartridge filters, similar to the operation of most brackish-water RO systems using well systems [10] (Fig. 1). Subsurface intakes allow alternative (d) to be used, commonly with a full bypass.

Beach galleries are a new type of subsurface intake that has a very high potential to be used effectively for seawater RO plant intakes without a limit on capacity [1,11]. The fundamental concept is that a gallery is designed and constructed under the active intertidal zone of a beach (Fig. 2). Seawater infiltrates vertically into the filter and is pumped to a SWRO plant. The top of the gallery (filter) is continuously cleaned by the mechanical energy of wave action, thereby eliminating the potential for clogging. A large-capacity system has been designed and recommended for construction at the Tia Maria seawater RO plant site in southern Peru [12].

Based on the high hydraulic conductivity and moderate wave activity on Florida East Coast beaches, the general environment is well-suited for the use of this type of seawater RO system intake. Also, the use of a beach gallery intake system would eliminate the environmental impacts of entrainment and impingement of marine organisms and reduce the cost of operating traveling screens and disposal of marine debris.

2. Methods

An analysis of the character, grain size distribution, porosity, and hydraulic conductivity of Florida East Coast beaches was conducted to assess their suitability to be used for development of a beach gallery intake system. The sediment grain size characteristics were obtained from a very detailed investigation of these beaches conducted by the Florida Geological Survey [13]. Hundreds of grain size analyses were conducted systematically along the shoreline with the samples collected from the active swash zone, the upper beach face, the mid-beach, and the back-beach.

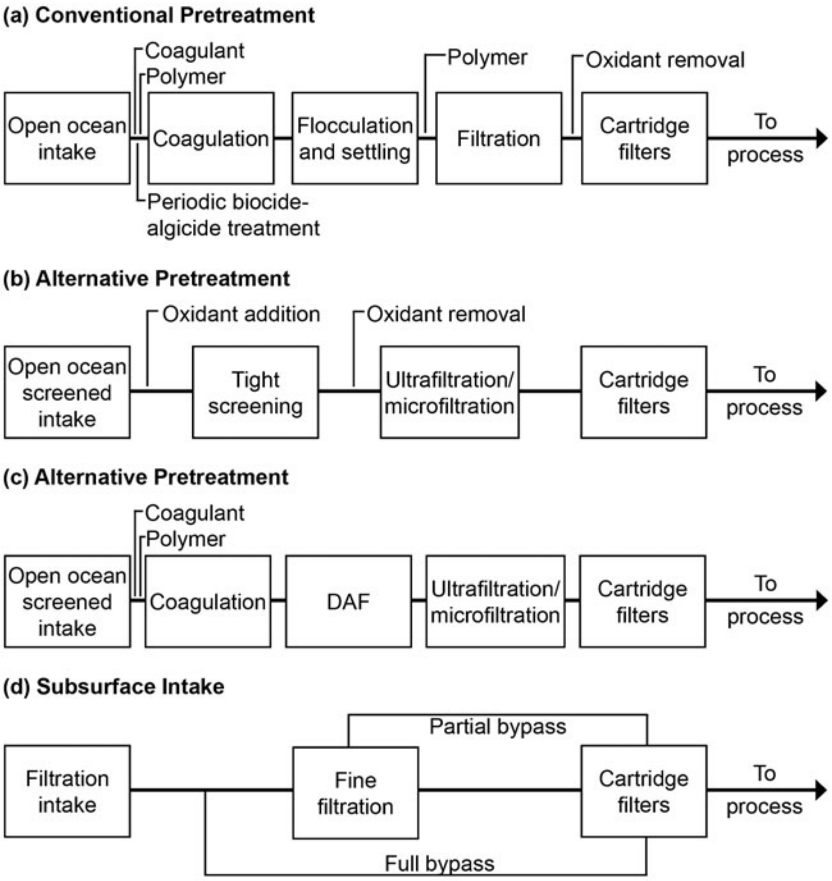

Fig. 1. Various pretreatment process trains for seawater reverse osmosis water treatment (modified from Missimer et al. [10]).

For this research, 10 samples were used from the beaches St. Johns County to serve as a typical segment of shoreline (Table 1). The porosity of the sediment was estimated to be 0.35 by comparison of the grain size characteristics of similar distributions with measured laboratory porosities. The hydraulic conductivity of each sample was estimated using two different numerical methods that were chosen based on a new computer program developed by Rosas et al. [14]. The most accurate of the 20 methods used in the program for beach sands are those developed by Fair and Hatch [15] and Zamarin as presented in Lu et al. [16]. The coefficient used for estimation of grain shape and packing in the Fair and Hatch [15] method was five.

The average wave height ranges from 0.5 to 1.5 m along the shoreline of St. Johns County, and for most of the Florida East Coast, depending upon season conditions. During storm conditions the wave heights can be very high and wave excavation along the beaches can temporarily remove 0.6–1.3 m of sediment at the shoreline.

Florida East Coast beaches are dynamic and some segments of the shoreline are actively eroding, while others are accreting. For this analysis and preliminary design, it was assumed that the beach where the gallery would be constructed is either stable or actively eroding.

3. Results of research

3.1. Characteristics of northeast Florida beaches

Florida East Coast beach sediments are a compositional mix of medium to fine grained quartz and carbonate sands, and gravel (size) consisting of shell (mostly marine mollusks) and a variety of other skeletal fragments [13]. The mean grain diameter of the sediments varies considerable, typically being higher as the percentage of shell increases. The 10 sample analyses used in this research were selected based on a low shell percentage (<15%) to allow a conservative preliminary design for the gallery system to be developed. There is a general tendency that higher percentages of shell generally have a higher hydraulic

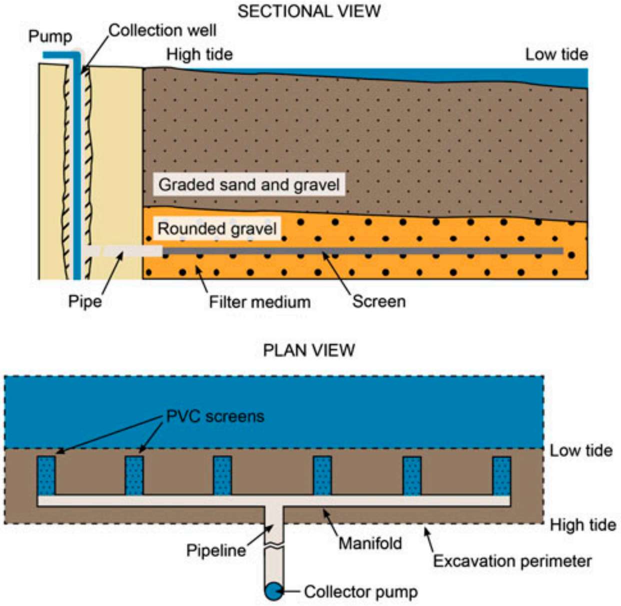

Fig. 2. Conceptual design of a beach gallery system (modified from Missimer, 2009 [1]). Note that the primary infiltration interface lies within the intertidal zone where the mechanical energy of waves keeps the filter clean.

conductivity. The mean grain diameter for the 10 reference samples is 0.185 mm (Table 1).

3.2. Hydraulic conductivity of St. Johns County beach sands

The estimated hydraulic conductivity of the 10 reference samples from St. Johns County using the Fair and Hatch [15] and Zamarin equations [16] yielded a range of 2.1–15.3 m/d with averages for the methods of 4 and 8.7 m/d, respectively. For the development of a preliminary beach gallery design, the average of all samples using the two methods was made, which yielded a value of 7.9 m/d. During the process of designing an actual system, a large number of sediment samples should be collected for analysis spatially along the shoreline, in several offshore transects of the proposed site, and vertically beneath the beach from a core. It is necessary to measure the sediment and hydraulic properties of the uppermost layer, because the sediment will move back and forth over the top of the constructed gallery and will affect the head loss across the filter to some degree.

4. Preliminary design of a beach gallery system

4.1. General concept

A beach gallery has the general characteristics of a slow sand filter, but it has a mechanism that allows the surface of the filter to be mechanically agitated, thereby providing a cleaning process (no surface scraping required). It will operate functionally similar to a rapid sand filter, but without the required backflushing for cleaning. Therefore, the design criteria for a beach gallery lies between a slow sand and rapid sand filter which allows a higher design infiltration rate compared with a slow sand filter (Table 2).

Research on slow sand filtration pretreatment of seawater shows that both straining and biochemical processes are active in the filter, about 99% of particles greater than two microns in diameter are removed, SDI is reduced to less than 4.0, 99% of the time and below 3.0, 90% of the time; and algal toxins are removed at percentages ranging from 89 to 94% [18]. Therefore, it is believed that beach galleries will achieve similar removal percentages. Perhaps, a primary issue is that the time required for ripening of the filter to maximize the effectiveness of the biochemical removal processes. Operation of a seabed gallery system in Fukuoka, Japan showed that the filter ripened within several weeks of initial operation and that the SDI continued to lower after seven years of continuous operation without cleaning [6]. At Fukuoka, wave orbital motion and bioturbation (mixing of the sediment by worms other in fauna that are sediment eaters) are believed to control the binding of fine-grained sediment and assimilation of organic materials, thereby keeping the filter from clogging. Both the processes of wave-action and bioturbation are likely to keep a beach gallery from clogging.

4.2. Design of a beach gallery cell

Design of a beach gallery system is dependent on the natural hydraulic conductivity of the beach sand, the desired thickness of the filter, the design infiltration rate, and the maximum head loss desired across the filter which is a function of bed thickness, average hydraulic conductivity, and infiltration rate. The desired retention time is another consideration for the removal of organic compounds that are related to biofouling. An example of the design process is given for a site in St. Johns County with the beach sand grain size and hydraulic characteristics as given in Table 1.

It was assumed that a regional seawater RO plant with a permeate capacity of 90,900 m^3/d was being designed and constructed. The plant would treat seawater with a conversion rate of 50% based on the local total dissolved solids concentration of about 35,000 mg/L. The plant would contain 12 trains each producing 7,600 m^3/d of permeate and requiring 15,200 m^3/d of feedwater or a total feedwater capacity

Table 1
Mean grain diameter and hydraulic conductivity of reference samples from St. Johns County, Florida

Sample No.	Percentage of shell	Mean grain diameter (mm)	Hydraulic conductivity (m/day) (Zamarin)	Hydraulic conductivity (m/day) (Fair and Hatch)
SJ-01-SS	5.51	0.23	9.9	9.5
SJ-02-SS	3.73	0.17	7.6	6.6
SJ-03-SS	1.77	0.17	5.3	6.3
SJ-04-SS	2.39	0.18	10.9	6.6
SJ-06-SS	1.93	0.18	6.7	6.9
SJ-25-SS	12.3	0.26	15.3	11.4
SJ-26-SS	3.16	0.17	13.9	5.9
SJ-29-SS	2.12	0.17	7.0	6.0
SJ-30-SS	1.98	0.16	2.1	5.8
SJ-32-SS	1.56	0.16	7.7	5.2

of 181,800 m^3/d. An assumption was made that the shoreline was either stable or that some erosion was occurring at a moderate rate.

A computer program was used to optimize the design of the gallery with consideration of the number of layers within the filter, the thickness of the layers, the desired infiltration rate at the top of the filter, and the head loss across the filter thickness that would have to be overcome by pumping (suction head). The key issues are the overall footprint of the gallery (construction cost), the retention time in the filter to remove particulates, algae, bacteria, and organic compounds, and the reliability of the system (no clogging and no storm damage).

A preliminary design of the filter structure is presented in Fig. 3. The uppermost layer of the filter would be composed of natural beach sand from the site and the underlying layers would be engineered siliciclastic sands. The upper layer is 1.5 m in thickness and has a hydraulic conductivity of 7.9 m/d, which is the average of the sites evaluated on the natural beach. This upper layer will tend to produce most of the straining and biochemical processes that remove undesirable material if the filter functions similar to a typical slow sand filter. However, it is probable that in a seawater system, biochemical activity may occur throughout a greater thickness of the filter. The layered design of the filter media shows a progressive increase in the mean grain diameter which will prevent the infiltration of finer-grained sand into the next lower layer. The lowest layer is high hydraulic conductivity gravel that will contain the basal collection screens. This gravel layer will allow high rates of water movement into the collection screens and also will tend to distribute the head loss in the layer throughout the footprint of the gallery, thereby inducing an even infiltration rate at the surface. Although the filter design could be simplified by using a geofabric above the basal gravel layer and not using grading, there would be a head loss across the geofabric which could induce growth of bacteria within the geofabric pores leading to internal clogging of the filter. Therefore, it is believed that the grading produces a more conservative design and would function with less potential for long term operational difficulties.

The horizontal collection screens would be designed to keep screen slot velocities at about 3 cm/s (Fig. 2). So, the likely diameter of the screens would be 30.48 cm with an open slot area of about 35%. For the 30,300 m^3/d galley cell yield, the total screen length would be about 137 m. The screens would be attached perpendicular to a header pipe collector. All pipe diameters would be sized to keep velocities below 1.5 m/s. This is a rather conservative design and the screen slot velocities could be increased because there is high hydraulic conductivity gravel surrounding the screens and no fine sand. An increase in the design slot velocity to 6.1 cm/s would reduce the required screen length by 50%. Therefore, sound engineering judgment is required to optimize the gallery screen and collection piping design.

The surface area of a gallery cell is dependent on the maximum infiltration rate. Since the RO plant design includes 12 trains at about 7,600 m^3/d each, a beach gallery would contain six primary cells that would each feed two trains each and one standby cell would be added for emergency use in the event of an operation disruption (e.g. pump failure) (Fig. 4). Therefore, each gallery cell would have a capacity of 30,300 m^3/d. At a surface infiltration rate of 7 m/day, the required area of each gallery cell would be about 4,430 m^2. If the infiltration rate would be increased to

Table 2
Design criteria for slow sand and rapid sand filtration [17](from Crittenden et al., 2005)

Process characteristic	Slow sand filtration	Rapid sand filtration
Filtration rate	0.05–0.2 m/h	5–15 m/h
Media diameter	0.3–0.45 mm	0.5–1.2 mm
Bed depth	0.9–1.5 m	0.6–1.8 m
Required head	0.9–1.5 m	1.8–3 m
Run length	1–6 months	1–4 days
Ripening period (fresh water)	Several days	15 min- 2 h
Pretreatment	None required	Coagulation
Dominant filtration mechanism	Straining, biological activity	Depth filtration
Regeneration method	Scraping	Backwashing
Maximum raw water turbidity	10–50 NTU	Unlimited with proper pretreatment

10 m/d, the gallery cell area would be decreased to about 3,000 m^2. Each cell could be rectangular in shape with dimensions of 30.5 × 145 m for the low infiltration rate or 30.5 × 98 m for the high infiltration rate. Each gallery would have a dedicated pump to allow a high level of reliability to be achieved. In the event of a pump failure or some type of problem within a gallery, the standby gallery would be activated.

A range in infiltration rates from 7 to 10 m/d was chosen based on conservative design criteria. The hydraulic retention times in the upper layer of the filter (most biologically active layer) would range from 3.6 to 5.2 h and 7.2 to 10.3 h if the two uppermost layers are considered. Slow sand filters are designed with hydraulic retention times as low as 4.5 h. A comparison of the design range for the St. Johns County beach gallery system to slow sand filter design criteria are given in Table 3.

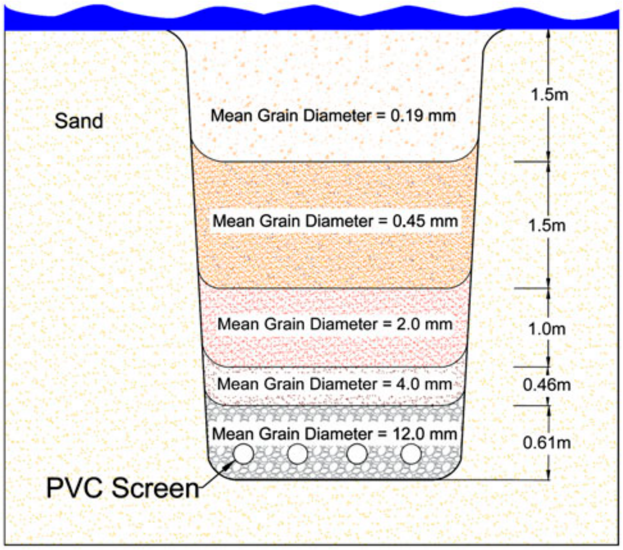

Fig. 3. Preliminary design of a beach gallery cell based on the St. Johns County, Florida beach sand grain size and hydraulic characteristics.

4.3. Design of a multi-cell beach gallery system

The preliminary design of a beach gallery intake system for a 90,900 m^3/d (24 MGD) seawater RO plant includes the construction of six primary, independent cells and another standby cell. The cells would be constructed in an elongate orientation along the beach face (Fig. 4). Each cell would be equipped with a pump that has the capability of producing the required suction head to overcome the head loss within the filter and to deliver the feedwater to the plant at the desired pressure. The pump station could be located on the back-beach or at distance from the beach depending on the pump design. To keep the pumping station more publically acceptable, it could be combined with another public beach facility, such as a rest room facility, clothes changing area, or a

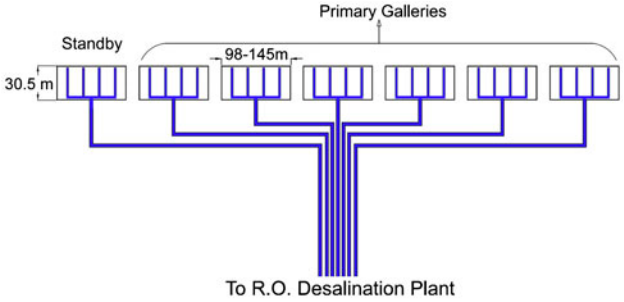

Fig. 4. Preliminary design layout for a beach gallery system for a 90,900 m^3/d seawater RO facility using gallery cells to produce 30,300 m^3/d of raw water each to feed two trains (7,600 m^3/d of permeate for each train).

Table 3
Preliminary design of a beach gallery system using two different infiltration rates used on the beach grain size data collected from 10 sites in St. Johns County compared to the slow sand filter design criteria

Process characteristic	Slow sand filtration	I = 7 m/d	I = 10 m/d
Filtration rate	0.05–0.2 m/h	0.29 m/h	0.42 m/h
Media diameter	0.3–0.45 mm	0.19	0.19
Bed depth	0.9–1.5 m	5.1 m	5.1 m
Required head	0.9–1.5 m	2.1 m	2.1 m
Run length	1–6 months	Unlimited	Unlimited
Ripening period (fresh water)	Several days	?	?
Pretreatment	None required	None	None
Dominant filtration mechanism	Straining, biological activity	Straining, biological activity	Straining, biological activity
Regeneration method	Scraping	Wave action	Wave action
Maximum raw water turbidity	10–50 NTU	None	None
Hydraulic retention time	Minimum 4.5 h	6.1 h	4.2 h

small restaurant. The gallery cells and the connecting piping would all be underground and would not produce visual impacts to the beach.

5. Discussion

Use of beach galleries as intakes for seawater desalination systems can provide a considerable savings in operational costs by reducing pretreatment requirements and by eliminating environmental impacts of entrainment and impingement [19]. Elimination of marine debris disposal from materials gathered in traveling screens is another cost savings. While no direct cost can be ascertained regarding reduction of environmental impacts, there is a potential reduction in cost of predesign permitting of an open-ocean intake which can take months or years of effort to collect marine productivity data and overall water quality variations.

A minor environmental impact will occur during construction of the beach gallery system. Typically, construction of beach galleries requires the driving or jetting of temporary sheet piling and some dewatering to allow construction of the galleries. If the construction materials (pipe, screens, gravel, and sand) are delivered to the site in a timely manner, the time of the season is selected during low storm frequency periods, and primary construction is scheduled during low tides, individual gallery cells can be rapidly constructed, providing minimal time periods during which public access to a small segment of the beach would be inhibited (few weeks for each cell). A critical factor is that upon completion of construction, a beach gallery system is buried beneath the beach and will show no surface indication of its presence. Public beach users will be unaware of it operation and can enjoy uninhibited use of the beach.

There is virtually no capacity limit on the use of beach galleries. The number of cells can be increased to meet the plant design requirements. During the beach gallery design and construction, some additional testing of the individual cell capacities and resultant water quality improvements should be made to develop an optimized system design. Conservative infiltration rates can be used initially, but may be increased in time to reduce the overall gallery footprint which effectively controls construction cost. Additional gallery cells can be added as seawater RO facilities are expanded in an incremental manner.

Another positive impact concerning the use of beach galleries as an intake system is that infiltration of seawater is directly vertical within the intertidal zone and there is no impact on landward-occurring freshwater resources or other water quality issues within the coastal zone. A back-beach gallery system has recently been proposed to be used for seawater RO intakes [20]. While this design concept has some merit, it will induce some freshwater to move into the intake from the up-gradient side, thereby potentially having some impact on the freshwater resources inland of the back-beach area. Furthermore, the fresh groundwater resources inland of the shoreline commonly contain dissolved iron in concentrations that could create a potential fouling problem in seawater membranes, especially as it mixes with seawater entering from the seaward side of the gallery. The back-beach area is commonly part of a zone, where freshwater moves toward the sea and mixes with seawater creating some unusual water chemistry that can create difficulties in the treatment process (e.g. tannic acid, iron, and other metals). Also, the water quality data presented in Cowles et al. [20] shows the occurrence of higher than normal seawater salinity at

41,000 mg/L compared with the normal 35,000 mg/L in the Atlantic Ocean. This higher salinity water would reduce the conversion rate in the RO process.

6. Conclusions

Based on the grain size distribution and hydraulic conductivity data, it is technically feasible to design and operate beach gallery intakes in the St. Johns County area and it is likely that it is also feasible throughout most of the Florida shoreline where sandy beaches are present. A key factor is to choose relatively stable shoreline areas where there is no active accretion of the beach (seaward progradation) because the infiltration of seawater should occur within the active intertidal (surf) zone, allowing continuous vertical water movement and not allowing depletion of inflow by water level drawdown (greater length flow pathway). If beaches are activity eroding, a beach gallery is still feasible because it will still function well in the subtidal environment as long as it does not lose a significant part of the filter media [21]. In eroding areas, the depth of the gallery should be increased to allow it to function under the seabed and to allow loss of some of the upper layer thickness.

The capital cost of constructing beach galleries is greater than that for open-ocean intakes. However, the reduction in operating costs and the lesser degree of environmental impacts suggests that a life-cycle cost assessment will demonstrate that beach galleries will produce lower water treatment costs over periods of 15–30 years.

Acknowledgments

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