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Self-cleaning beach gallery design for seawater desalination plants

Robert G. Maliva*, Thomas M. Missimer

Schlumberger Water Services USA Inc., 1567 Hayley Lane, Suite 202, Fort Myers, FL 33907, USA
Tel. +1 239 4816494; Fax +1 239 4816393; email: rmaliva@slb.com

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ABSTRACT

Surface water intakes are a major capital cost for seawater desalination facilities, and their performance can greatly impact the operation of the entire system. Alternative intakes, based on the riverbank filtration concept, are increasingly being implemented because they are less expensive than conventional intakes and can also provide natural filtering of feedwater prior to the entry of water into the treatment plant. The basic concept is to use vertical or horizontal wells or galleries located near the seawater source to produce feed water, while taking advantage of the natural sand filtration provided by the beach sands and other sediments.

Although conceptually simple, the successful design of beach gallery intakes must consider a variety of sedimentological and hydrogeological factors. Production rates are dependent upon both the hydraulic conductivity of the beach sediments and the length of the flow path from the seawater source to the gallery. Beach galleries constructed inland above the high tide line thus require relatively great lengths or areas to produce a given amount of seawater. Inasmuch as beach galleries act as slow sand filters, they are subject to clogging at the sediment-water interface. Carbonate scaling has been a major problem in some systems constructed in carbonate sediments in tropical settings because of the supersaturation of seawater with respect to calcite. Beach sedimentation patterns can also impact the long-term performance of beach galleries. Improperly designed or constructed beach galleries may be exposed or damaged in beaches that experience erosion under normal or storm conditions. Prograding beaches are more problematical as the galleries become increasingly distant from the seawater source, which reduces potential production rates.

The self-cleaning beach gallery overcomes some of the inherent limitations of beach galleries constructed above high tide line. The gallery is a horizontal collection system within a single trench that is constructed between the low and high tides lines. The normal wave action keeps the sediment-water interface above the gallery clean by mechanically removing fine-grained sediment and marine organisms. The daily tidal cycle keeps the sediment above the gallery saturated and maintains a short travel time. The top of the gallery is set at about 4 m below normal low tide, so erosion should not be a concern and scaling can be managed. However, progradation of the beach may still adversely impact system performance.

The design of the self-cleaning beach gallery requires field testing to obtain site-specific data on the hydraulics of surficial sediments. The field testing should involve aquifer performance testing and a small-scale pilot test. Hydraulic flow modeling is necessary to evaluate potential gallery

*Corresponding author

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design options and potential water yields. An assessment of shoreline sedimentation dynamics should also be performed, which may involve a literature review or field investigations.

Keywords: Reverse osmosis; Desalination; Intake; Beach gallery

1. Introduction

Reverse-osmosis treatment technology has advanced greatly over the past several decades. The major operational problems that many seawater desalination facilities have experienced now stem more from the surface-water intake and pretreatment issues than from the actual membrane treatment process. For many desalination projects, a primary design challenge is obtaining an economical and reliable source of feedwater that has a suitable quality, including low suspended solids and dissolved organics concentration, and stable inorganic chemistry. Alternative intake designs, based on the riverbank filtration (RBF) concept, are increasingly being implemented as an alternative to conventional surface-water intakes. Where the local hydrogeology is favorable, alternative intake designs can result in substantial construction and operational cost savings.

The basic RBF design concept is to construct a shallow well or wellfield adjacent and parallel to the source-water body in order to take advantage of the natural filtration provided by sediments (Fig. 1). Although the term 'riverbank filtration' is well entrenched in the literature, the more general term 'bank filtration' may be more appropriate as RBF can be performed to obtain water from surface-water bodies other than rivers. RBF design options include a row of vertical wells, horizontal wells and galleries [1,2]. RBF is an old and proven technology. The first RBF system is believed to have been constructed in Glasgow, Scotland, in 1810, and RBF has been used in other cities in Europe, such as Berlin, for over a century [3].

The attraction of RBF for seawater desalination is that the wellfield or gallery can be a less expensive alternative to a conventional intake, and the filtration provided can result in reduced pretreatment requirements. RBF systems usually have minimal environmental footprints and can be designed to be visually un-intrusive and to not impact nearshore environments and the use of beaches. RBF-based intakes can also make seawater desalination facilities less vulnerable to disruptions due to surface-water contamination from either anthropogenic (e.g., oil spill) or natural (e.g., red tide) causes. A catastrophic oil spill in an area reliant on seawater desalination, such as parts of the Middle East, could result in the disruption of the operation of multiple desalination plants upon which the region relies for its water supply.

Alternative seawater intake designs that have been used or proposed for seawater desalination plants were reviewed by Missimer [4,5], Hunt [6], Voutchkov [7,8], and Jones [9]. There are five general classes of RBF systems that are suitable for alternative seawater intakes: vertical wells, beach galleries, horizontal (Ranney®) collector wells, seabed filters, and horizontally drilled wells located beneath the seabed. Only the first three design options were investigated in this study. However, the optimal design option for alternative intakes is strongly dependent on local hydrologic and geologic conditions and site circumstances. There

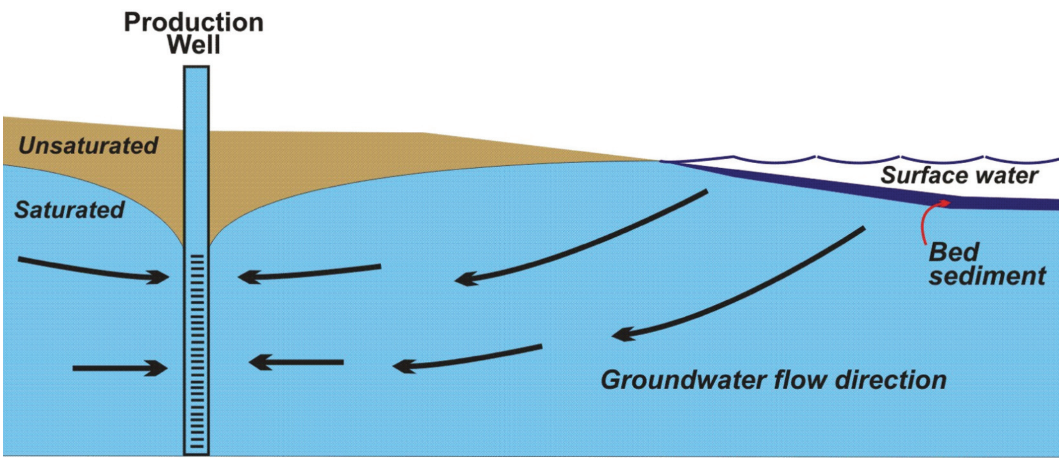

Fig. 1. Schematic diagram of a riverbank filtration system.

is no one universal optimal design. Seabed filters, which are essentially engineered or synthetic filters constructed on the seafloor, may be the preferred option where beach filtration is not viable [5,10]. Horizontally drilled wells have also been successfully used for feed water supply [11,12].

Alternative intakes have historically been widely used for feed water supply to small reverse-osmosis (RO) desalination plants. However, it has been increasingly been realized that alternative intakes are also a viable and economic option for large scale plants. The largest seawater RO the utilizes beach wells is the Sur Plant in Oman which has a capacity of about 160,000 m^3/day [13]. Horizontal wells using the Neodren® system are used to supply the San Pedro del Pinatar desalination plant in Spain with 172,800 m^3/day [11].

2. RBF design issues

There are three major design objectives for RBF systems: (1) maximization of well yields and system capacity, (2) maximization of the filtration of the recovered water and associated attenuation of any contaminants of concern, and (3) maintenance of long-term system performance. High yields are clearly advantageous from an economic perspective. Greater yields per vertical well or unit length of gallery, results in a reduction in construction costs, as a smaller well or wellfield could provide the target volume of water.

The rate of groundwater flow is expressed by Darcy's law,

$$Q = -kA(\mathrm{dh}/\mathrm{dl})$$

Where Q = flow rate (L^3/T), k = hydraulic conductivity (L/T), A = cross-sectional area (L^2), and (dh/dl) = hydraulic gradient, which is the change in head (h) over the water flow path (l). From Darcy's Law, flow towards a well is a function of the hydraulic conductivity of the sediment along the flow path and the hydraulic gradient. Hydraulic conductivity is dependent upon local sediment characteristics such as grain size and sorting. The design issue is locating a site in which the surficial sediments have a suitable hydraulic conductivity for a proposed system. The factor that can be more readily adjusted during RBF design is the hydraulic gradient. The gradient can be increased by decreasing the vertical or horizontal distance (dl) between the well screens and the source-water body. However, there can be a trade off between well yields and the efficacy of filtration. An RBF system constructed in coarse-grained sediments with wells located close to the source-water body, will have relatively high yields but poor filtration. Conversely, fine-grained sediments and longer flow paths favor good filtration, but at the expense of lower well yields.

The performance of RBF systems will tend to decline over time due to clogging of the wells and the sediment-water interface in the source-water body. Most water wells, whether they are standard production wells or RBF wells, experience clogging over time with an associated reduction in specific capacity. The clogging may be due to physical clogging of the screen with sediment, biological encrustations, and chemical precipitates. Periodic well rehabilitation is usually necessary in order to restore well performance. The frequency and methods used for well rehabilitation vary between systems. An important design consideration is that well and gallery construction, especially the wellheads and risers, should allow for anticipated rehabilitation activities. In general, it is simpler and less expensive to rehabilitate vertical wells than horizontal wells.

The clogging of the sediment-water interface is comparable to the clogging that occurs at the top of a slow sand filter. A biological active layer, analogous to the biologically active schmutzedecke layer of slow sand filters, may form at the interface. While the layer is an important element of the filtration process, it must periodically be removed to maintain flow. Accumulation of fine sediment at the interface can also reduce flow through the interface. RBF systems work best using streams and rivers with sufficient currents (at least episodically) to scour the sediment-water interface and remove any low permeability layers that may form. Stagnant water bodies, such as lakes and some low-energy shorelines adjacent to tidal-water bodies, are poorer candidates for RBF systems.

3. RBF-based alternative design issues

RBF-based alternative system designs have several specific design issues. These RBF-based designs include galleries and Ranney® collector wells. Beaches are relatively high-energy depositional environments and, as a consequence, the sediments tend to be well-sorted, usually clean (minimal clay and silt) sands. Depending upon the location, the sands may be medium-grained or coarser. Hydrogeological conditions may be particularly favorable for a RBF system.

Marine bodies experience tidal fluctuations in water levels, which can vary greatly between locations. Broad intertidal areas may be present that are periodically inundated and exposed. During low tides, the distance between RBF wells and surface seawater may be substantially increased. A key design constraint for beach

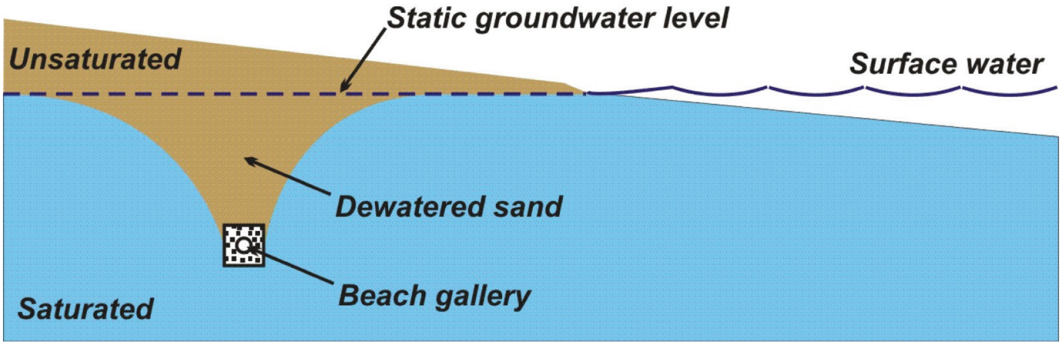

Fig. 2. Cross-section diagram of a beach gallery. Water production rates are limited by dewatering of overlying sand down to the gallery.

wells and galleries is that pumping in supratidal and intertidal areas (i.e., areas above mean low tide) can cause local dewatering of sediments, which will limit well yields (Fig. 2). Well yields are limited by the depth of the well screen below static water level, which affects the volume of water that can be produced from local storage. As the horizontal distance between wells or galleries and the shoreline (mean low tide line) increases, the rate at which surface seawater can replenish the pumped water will decrease, which will also limit well yields. In order to produce a given amount of water during low tide periods, it becomes necessary to construct longer (and thus more expensive) wells and galleries. It is therefore desirable to locate RBF wells as close to the mean low tide as possible in order to maximize well yields and reduce construction costs.

Beaches and other near-shore environments are dynamic environments. Shorelines can migrate rapidly, particularly in response to major storm events. The relative location of RBF systems with respect to the mean high or low tide line can change rapidly over time. The worst-case scenario is that rapid erosion occurs and a RBF system becomes exposed and destroyed. System operation could also be compromised in prograding beach systems, as the RBF system is stranded progressively further from the shore and the source of the seawater. A sedimentological investigation is therefore necessary to assess beach migration patterns and rates. Historical aerial photographs are an excellent data source to assess beach dynamics, particularly historic rates of retreat or progradation. An additional issue is that seawater in tropical and subtropical areas is often supersaturated with respect to the calcium carbonate minerals calcite and aragonite. Shallowly buried wells have experienced rapid clogging due to carbonate scaling.

Using a gallery aligned parallel to the shoreline as an example (Fig. 3), the design parameters include (Fig. 3), the hydraulic conductivity of the beach sediments (k), depth of the wells below mean high and low static groundwater levels (Z_h, Z_l), length of the wellfield (L), discharge rate (Q) of the wells, and the distance from mean high and low tide lines (D_h, D_l).

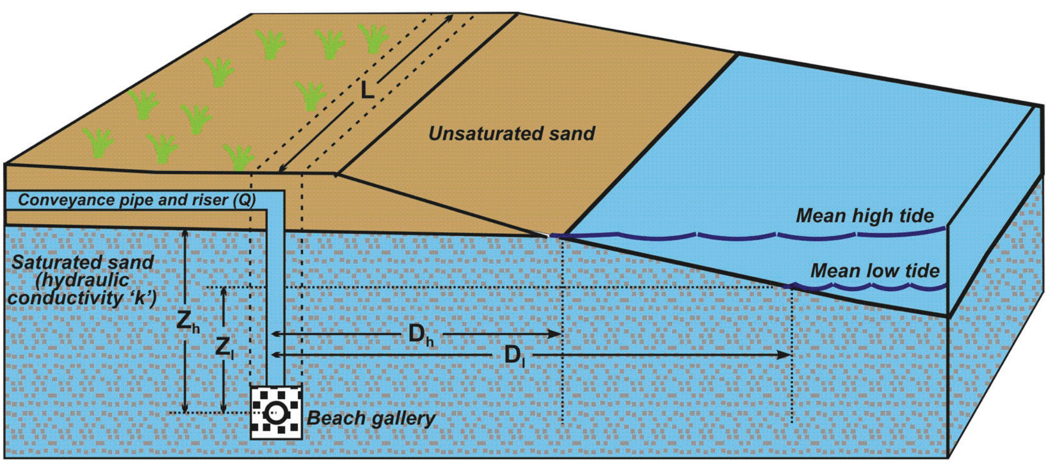

Fig. 3. Diagram of a single-trench beach gallery (not to scale'' showing some main design parameters.

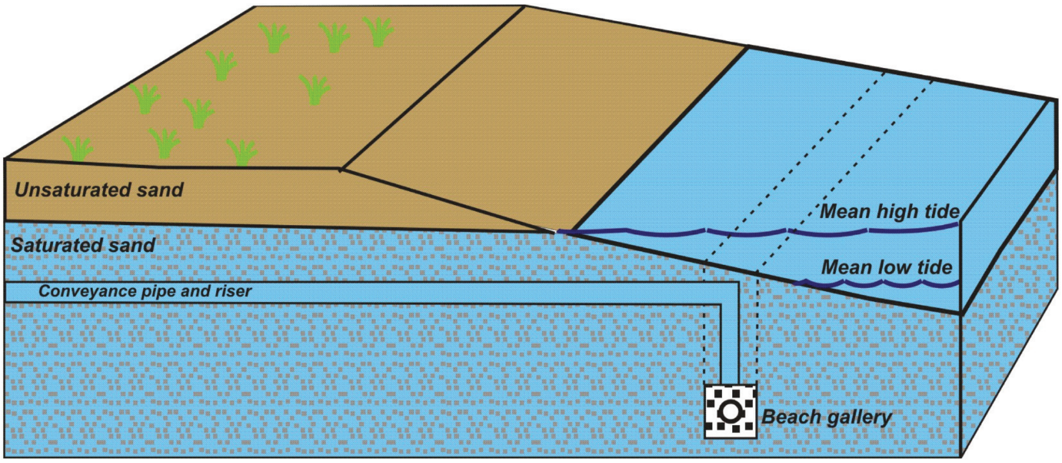

Fig. 4. Diagram of the self-cleaning beach gallery (not to scale). The gallery is constructed between the mean low and high tide lines to increase the rate of recharge of seawater and to take advantage of the natural scouring action of waves.

A test program is necessary to obtain site-specific hydrogeologic data, especially the hydraulic conductivity of the beach sediments. The test program should include a series of test borings (with cores preferred) located parallel and perpendicular to the proposed RBF system and location. One or more test production wells and a series of piezometers should be installed and an aquifer performance (pumping) test conducted to determine the values of aquifer hydraulic parameters. Ideally, the aquifer performance test should be performed over the duration of a tidal cycle. Slug tests can also provide supplemental hydraulic conductivity data. Grain-size analyses from anticipated well depths are needed to design the well screen (preferred screen-slot size) and to determine the appropriate gravel (filter) pack material.

Groundwater flow modeling is a key element for the optimization of the design of RBF systems. A model developed for the surficial aquifer at the proposed RBF system site can provide a tool to evaluate the performance of different design scenarios. The model should be calibrated against aquifer performance test data, and a number of assumptions on the position of the shoreline can be entered into the model to test remedial measures if the shoreline is not as stable as desired (e.g., post-storm recovery of the shoreline and its effect on the facility performance).

4. Self-cleaning beach gallery concept

A key design issue with respect to maximizing the yield of RBF systems is to minimize the distance between the production zone (well screen) and the seawater source. The self-cleaning beach gallery concept addresses this issue by using a single trench construction located between the mean high and low tide lines (Fig. 4). Higher pumping rates, and thus well yields per unit length of the gallery, are possible because of the more rapid recharge that would occur due to the proximity of the gallery to the surface seawater source [4].

The daily tidal cycle keeps the sediment above the gallery saturated and maintains a short travel time. The self-cleaning beach gallery also takes advantage of the natural scouring action of water to keep the sediment-water interface above the beach gallery clear by mechanically removing fine-grained sediments and marine organisms. The wave action takes the place of the current scouring by flowing water in conventional RBF systems.

Modeling of the performance of RBF options for a proposed desalination system along the Pacific Coast of South America indicates that the self-cleaning beach gallery design could result in double or more the yield of a traditional beach gallery located above the mean high tide line. Doubling the well yield per unit length of gallery halves the needed gallery length for a given water volume, which can result in a substantial cost savings.

The design specifics need to be determined based on local sedimentologic and hydrologic conditions. The top of the gallery should be located at a sufficient burial depth so that erosion associated with a receding beach should not be a concern, unless the erosion is extreme. Modest erosion would shift the gallery to a shallow subtidal position, which would not adversely impact system performance. Beach progradation is more of a concern if the beach face migrates a substantial distance seawards, away from gallery. Progradation would decrease the recharge of the beach sands near the gallery and decrease the capacity of the system.

The burial depth should also be sufficient to allow for some stabilization of water quality, particularly the reduction in scaling potential. Seawater is often supersaturated with respect to calcite (calcium carbonate). It is desirable to have the excess calcium carbonate precipitate out in a diffuse manner in the formation rather than be concentrated at the well screen and cause clogging.

As a rough generalization, the top of the gallery should be located 2–4 m below normal low tide to provide adequate filtration, protection from erosion, and water stabilization. However, it must be emphasized that the design of beach galleries (and other alternative intakes) must be based on site-specific hydrologic and geologic data.

Typically, the beach galleries are designed in segments that are separated by a predetermined distance. This allows for minimal interference between the galleries and also allows maintenance if required in the future. It is recommended that construction be performed in phases with the initial gallery constructed and tested prior to the installation of the remaining additional galleries. Installation in phases will add greater certainty to the estimated operational capacity of the entire system. Construction of the self-cleaning beach gallery can be performed most efficiently by the timing of construction to occur at daily low tide periods and periods of exceptionally low tides during the monthly cycle.

All necessary construction materials should be delivered to the beach site at a staging area located above the maximum high tide altitude. Construction of the gallery and the pipeline connecting it to a pumping station located on the back-beach would occur simultaneously. As the construction of the gallery should occur at low tide, the contractor must schedule the initiation of construction when low tide occurs during daylight hours or provide intense lighting if nighttime construction is necessary. The recommended sequence of construction activities is as follows:

(1) Interlocking sheet-piling should be driven or jetted to a depth 1.5 m below the proposed base of the gallery, creating a perimeter that completely surrounds the gallery. The edges of the sheet-piling perimeter should extend 2–5 m outside of the primary gallery area to allow for dewatering and construction activities.
(2) The sand within the area surrounded by the sheet-piling should be excavated using a dragline and/or extended-shaft bucket rigs. This will require that a key ditch be cut on both sides or the complete perimeter of the excavation to allow dewatering as the sand is being removed. The dewatering trenches should be constructed to their ultimate depth of 1–2 m below base elevation of the gallery. The excavation should be completed in 1–2 days, especially if two excavation devices are used simultaneously, which is recommended. Sand removed from the excavation should be placed landward of the excavation to allow easy access for the refilling process and to prevent it from being washed away at high tide.
(3) The gallery should be dewatered to a depth sufficient to allow the excavation bottom to dry. The bottom of the excavation at 5 m (or an alternative depth below surface) should be graded so that it has a uniform depth and is relatively flat. This task could be performed either manually or using machinery.
(4) A basal geofabric layer should be installed on the excavation bottom. The geofabric should extend upwards 1–2 m outside of the specified gravel fill area. The basal half of the gravel layer should be installed.
(5) The screens, end caps, connecting piping, and riser pipe shall be installed in the excavation. The riser pipes should allow for access to the gallery for rehabilitation activities. It is recommended that the gallery piping and screens be pre-assembled into manageable components to facilitate installation. Care should be taken to allow the polyvinyl chloride (PVC) and High-density polyethylene (HDPE) welds to set before covering.
(6) The upper gravel layer is then installed, and the top surface of the gravel shall be raked to be flat and tapered at the edges as specified. The upper geofabric is installed and the edges welded to the lower geofabric, so that the gravel layer is encased.
(7) The excavation is then refilled using the excavated beach sand and the sheet-piling carefully removed (vibratory removal is recommended). The sheet-piling removal must be accomplished without creating shear on the edges of the gallery filter gravel or geofabric.
(8) The excavation site shall be graded to a similar slope to the original beach profile. Any irregularities will be smoothed by the next sequence tide change. The riser pipe should extend above the surface at least 1 m above the high tide line until it is attached to the pipeline leading to the pump station.

As the gallery is being constructed, the conveyance pipe from the gallery riser to the pumping station can be installed. The pipe should be installed at a sufficient depth (1 m or greater) so that it is unlikely to be exposed by erosion or interfere with beach activities. Care must be made to keep the inside of the pipe free of any sand or sediment.

After the first gallery is installed, it should be tested by pumping it at the design rate for as long a period as practicably possible. A minimum test duration of 1 week is recommended, but a several week long test should be considered if it can be performed at an acceptable cost. During this time, the pressure in the gallery should be measured and the water quality should be measured for silt density index and other parameters that could affect the membrane process design. Based on the results of the testing of the initial gallery, the design of subsequently installed additional galleries may be modified. Also, the desired redundancy in yield can be assessed, as well as the distances between galleries. Overall, this type of design is inexpensive and flexible, especially if the construction sequencing is conducted in a logical manner.

5. Ranney® collector wells

Horizontal (Ranney®) collector wells are widely used for freshwater supply [14]. These systems consist of a central caisson with an interior diameter of 4–8 m and a series of laterals extruding through the walls of the caisson into the aquifer. The laterals are typically screened and act as horizontal wells. The advantage of these wells is the large yields that can be obtained. However, they are large fixed structures located near a dynamic shoreline, so there have been objections concerning visual impacts to the beach. Also, from an operational viewpoint, when maintenance must be performed on the laterals, the well must be shut down, which requires some additional redundancy in their use. Nevertheless, Ranney® collector wells have a very good performance recorded in fluvial applications along freshwater streams in the United States.

5.1. Relative costs for wells, beach galleries, and Ranney® wells

An analysis was performed to assess the comparative capital costs for the 2,200 L/sec intake required for a seawater membrane plant to be located in southern Peru. Three alternatives were assessed: (1) self-cleaning beach filters, (2) Ranney® collector wells, and (3) a conventional open-ocean intake. Vertical beach wells were not considered because the beach sand had a relatively low hydraulic conductivity, which would result in a great number of wells being needed to provide the necessary yield. The estimated costs in declining order were: 1) open-ocean intake = \$15 million, 2) Ranney® collector wells = \$7.5 million, and 3) self-cleaning beach gallery = \$2.5 million. The Ranney® collector well system would require the installation of a 100% redundancy to allow for system operation during maintenance of the laterals and cleaning of the caisson. The self-cleaning beach gallery was segmented into four galleries with one full gallery used as a back-up, in case any maintenance is required. The open-intake design contained no redundancy.

6. Conclusions

Alternative intake systems are conceptually simple. The main technical challenge is to determine the type of system that will perform best at a given location and optimizing the system design. The self-cleaning beach gallery design is a modification of the proven RBF technology to more cost-effectively supply feedwater to reverse-osmosis desalination facilities. The self-cleaning beach gallery shares the general benefits of RBF systems of providing a less expensive alternative to conventional intakes and initial pretreatment. Like all RBF systems, the performance of self-cleaning beach gallery is dependent upon local sedimentologic and hydrologic conditions, and the systems must be designed based on careful consideration of site-specific hydrogeological constraints. The main technical challenge is achieving an optimal balance between gallery yield (water produced per meter) and the effectiveness of filtration. Therefore, groundwater modeling is a critical component of the gallery design process. The costs of the self-cleaning beach gallery may be less than 20% of the cost of a conventional open-ocean seawater intake and may save up to 25% in treatment facility operating costs because of the reduction in the pretreatment processes.

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