Chapter 10
Self-cleaning Beach Intake Galleries: Design and Global Applications

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Abstract Of the various subsurface intake systems available for use, gallery intake systems have the greatest potential to provide the feed water requirements of very large-capacity seawater reverse osmosis (SWRO) systems because of their scalability and flexibility as far as hydrogeological constraints. A beach gallery system is constructed beneath the intertidal zone of the beach where the wave action continuously cleans the face of the filter media. While it is designed similar to a slow sand filter, a clogging layer tends not to form at the sediment/water interface which allows it to be operated at a higher infiltration rate compared to a seabed gallery system. Design of a beach gallery system active layer (uppermost layer) must be compatible with the grain size characteristics of the beach into which it is constructed. It also must be constructed with sufficient thickness to avoid damage during storm events that produce large waves, which that can temporarily change the beach profile. The beach must be sufficiently stable so as not to have a prograding shoreline that could increase the distance from the gallery face to the sea which would decrease the rate of recharge and cause the intake to fail. This intake type is most suited for use on sandy beaches with moderate wave energy.

10.1 Introduction

It has become increasingly recognized that subsurface intakes for seawater desalination systems can provide significant cost savings, environmental benefits, and increased reliability compared to conventional open-ocean intakes (Missimer 2009).

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T.M. Missimer et al. (eds.), *Intakes and Outfalls for Seawater Reverse-Osmosis Desalination Facilities*, Environmental Science and Engineering,
DOI 10.1007/978-3-319-13203-7_10

Subsurface intakes serve both as a means to abstract seawater and to provide initial pretreatment primarily through filtration and, in some cases, also through sorption and biochemical processes (Missimer et al. 2013; Rachman et al. 2014). The primary advantage of subsurface seawater intakes is that they can reduce the capital and operational costs of pretreatment systems and, for some design options, avoid the costs associated with subsea construction. Subsurface intakes avoid the ecological impacts of open-ocean intakes, especially impingement and entrainment of marine life. Alternative intakes can provide improved reliability through a lesser vulnerability to contamination and by providing a time buffer between a contamination event and impacted water entering the desalination system.

A variety of design options are available for subsurface intakes including vertical (beach) wells, slant and horizontal wells, beach trenches and galleries, horizontal collector systems, and subsea galleries. An attractive aspect of subsurface intakes is that they are a modular design and thus readily expandable by, for example, installing additional wells or gallery cells. A disadvantage of the modular design is that there is low economy of scale compared to an open-ocean intake type.

Subsurface seawater intakes are proven technologies in that they are essentially a new application of the over 200 year-old riverbank filtration (RBF) technology. Over the past two decades there have been an increasing number of applications of subsurface intake systems to new operational desalination systems. The selection of the type of intake for a given desalination facility depends upon local hydrogeology, which influences system unit capacity (e.g., well capacity and water yield per square meter of gallery area) and the degree of filtration, and, in turn system costs and benefits. An additional consideration is the likely reliability of the intake system and operation and maintenance costs. The technical challenge for subsurface intakes lies not in the need to develop new technologies, but rather the optimization of the application of existing technologies. Given site-specific hydrogeological constraints and desalination plant raw water requirements, the challenge lies in developing a design that most cost-effectively and reliably provides the required volume and quality of water.

Beach galleries are, in essence, large slow-sand filters constructed along a beach, which take advantage of the natural filtration provided by the native beach sand and an engineered sand filter to provide high-quality water. While similar in design to slow sand filters, they differ in that slow sand filters operate by gravity feed, whereas beach galleries use a suction pump to produce the filtered water. This allows some flexibility in design. An advantage of beach galleries is that they are self-cleaning in the sense the action of waves and activities of burrowing and bottom-feeding organisms (i.e., bioturbation) prevent the build-up of a surficial clogging layer (Maliva and Missimer 2010). This self-cleaning process may make this intake type closer to a rapid sand filter, rather than a slow sand filter. Furthermore, beach and seabed galleries are often the only two subsurface intake types that can practically provide feed water for very large capacity seawater reverse osmosis (SWRO) facilities (Missimer et al. 2013; Dehwah et al. 2014a). This chapter explores the optimization of the design and operation of beach gallery intake systems.

10.2 Basic Beach Gallery Design

10.2.1 Introduction: Slow Sand Filtration

Beach galleries are essentially in situ slow-sand filters and have the same basic design principles. Slow filters normally operate at average rates of 1.2–4.8 m/d with higher rates (9.6 m/hr or greater) possible for high-quality (low suspended solids) water or during peak periods (Crittenden et al. 2005). The design of slow sand filters was addressed in detail by Huisman and Wood (1974), Crittenden et al. (2005), and Hendricks (1991, 2011). Slow sand filters contain two main elements, the sand filter and underlying underdrain, which includes the main and lateral screens and gravel support (Fig. 10.1).

The underdrain screen and gravel pack function to efficiently collect the seawater with a minimal loss of head. The gravel support does not serve a filtration purpose, but instead acts to support the screen and filter sand, and to efficiently transmit water to the screen. The gravel support should be coarse enough, and have a high enough hydraulic conductivity, so as to minimize head differences across the gallery. The objective is to have a near uniform infiltration rate through the overlying filter pack. The gravel pack normally extends below the screen to increase its transmissivity and to provide space for any fine-grain materials that settles or is drawn into the gravel to accumulate without covering the screen. The seabed filter differs from the slow sand filter in that it is pumped from the base, but it still shares similarity in that it cannot be back-flushed for cleaning. Pumping is necessary because natural tide changes cause the hydraulic head across the filter to vary in time, which requires the pump to adjust to maintain a constant pumping rate.

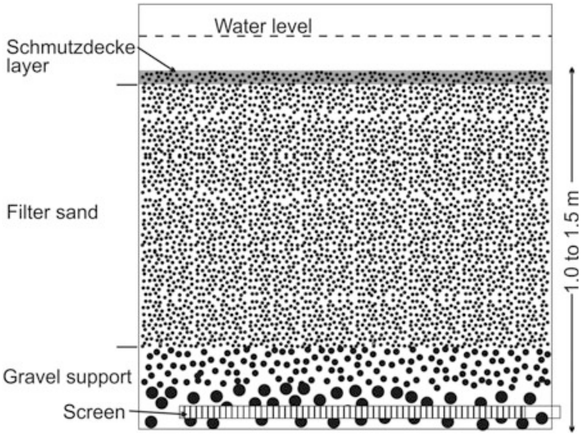

Fig. 10.1 Conceptual diagram of a slow sand filter

10.2.2 Design and Function of the Media and Hydraulic Retention Time

The filter sand needs to be fine enough to provide sufficient filtration of suspended materials of concern. Hendricks (1991, 2011) recommended that the d_{10} of the filter sand (sieve size that permits 10 % of the sand to pass through) be 0.2–0.3 mm with a corresponding uniformity coefficient (UC, d_{60}/d_{10}) between 1.5 and 2.0. Coarser sand may be used (0.3–0.4 mm) as long as the uniformity coefficient is less than 3. Crittenden et al. (2005) suggest that average grain size of the media can range from 0.3–0.45 mm and the bed depth is normally 0.9–1.5 m.

An important aspect of the slow sand filter design is the quality of the water to be treated and the hydraulic retention time of the water within the filter. There are limits on the turbidity of the raw water that can be effectively treated. Crittenden et al. (2005) suggest that the slow sand filtration process is effective for raw water with a turbidity range of 10–50 NTU. The hydraulic retention time of most slow sand filter systems ranges from 5 to 6 h. Hydraulic retention time from a set of slow sand filters with differing thicknesses and an assumed uniform hydraulic conductivity is given in Table 10.1. There is an offset between the lower hydraulic conductivity of the surficial layer and the increasing hydraulic conductivity with depth in the media. The key issues controlling the hydraulic retention time are the design infiltration rate and the bed thickness. Increased hydraulic retention time tends to increase the degree of water treatment.

In freshwater systems, a biologically active gelatinous mat, composed of deposited and synthesized material, forms at the top of the filter sand. This unit is called the schmutzdecke (German for ‘dirty skin’) layer. The schmutzdecke layer is an important part of the filtration process and is where much of the biological treatment occurs. Growth of the schmutzdecke layer increases hydraulic resistance across the slow sand filter and it must be periodically scrapped off in order to maintain acceptable filtration rates. To maintain the same degree of biological treatment, the scrapped filter must be given time to “ripen”. This process can take between 12 h and several days in freshwater systems. Repeated cleanings by scrapping also reduces the thickness of the filter and changes the hydraulic retention

Table 10.1 Hydraulic retention time as a function of infiltration rate and bed thickness

Infiltration rate	Infiltration rate	Bed thickness	Hydraulic retention time
m/hr	m/d	m	hr
0.05	1.2	0.9	18
0.1	2.4	1.0	10
0.2	4.8	1.25	6.25
0.3	7.2	1.3	4.3
0.4	9.6	1.4	3.5
0.5	12.0	1.5	3.0

time. New sand can be added to the surface of the filter to replace the material removed. The typical run length before reconstruction of the full filter bed is 1–6 months. Because of the development of the schmutzdecke layer in freshwater systems, most of the water treatment occurs within the upper 10 cm of the filter, so the hydraulic retention time is not so important. This is not necessarily the case in in marine systems. Column experiments conducted using seawater from the Red Sea showed that a period of several months was required for the system to remove up to 50 % of the total organic carbon (TOC) entering the column (Dehwah et al. 2014b)

Design of the slow sand filter media requires that the grain size distribution of the created layers allow proper support without breakthrough of fine grains into the next lower layer. The gravel support consists of multiple layers with an upwardly decreasing grain size. The layers need to be design so that they are stable, minimizing settling of finer grained sand and gravel into underlying layers. Huisman and Wood (1974) proposed the following general rules for the design of the gravel support, which are still widely accepted:

1. d_{90}/d_{10} for a given layer ≤ 1.4
2. d_{10} lower layer/d_{10} upper layer ≤ 4
3. d_{10} top layers/d_{15} filter sand ≥ 4
4. d_{10} top layer/d_{85} filter sand ≤ 4
5. d_{10} bottom layers $\geq$ 2d (drain orifice or screen slot diameter)

Huisman and Wood (1974) noted that the requirement for a highly uniform sand ($d_{90}/d_{10} < 1.4$) may be too restrictive (i.e., expensive to meet) and that a ratio of 2 would be acceptable if the ratio of d_{10} values between layers is less than 3. The recommended minimum thickness of the gravel layers is three times the diameter of the largest grains or 5–7 mm for finer materials and 8–12 mm for coarse gravel (Huisman and Wood 1974). The use of fine sand in the top layer tends to provide a higher degree of removal of algae, bacteria, and viruses (Amy et al. 2006; Jenkins et al. 2011; Lujan and Missimer 2014). The upper sand layer, however, must be compatible with the natural beach sand or it would be rapidly scoured away. In some cases, a finer layer may have to be placed below the upper active layer with a downward coarsening below that level, or the uppermost layer must be significantly thickened, to increase hydraulic retention time.

Beach galleries have similar design as slow sand filters used for water treatment with the exception that they are topped with the natural beach sand, which may or may not be of an appropriate size for filtration purposes (Fig. 10.2). The sand filter needs to be designed to provide effective filtration of suspended solids and to meet water quality targets, such as maintenance of a silt density index of less than 3 and removal of all algae and most bacteria, and be stable. The suspended solids include silt and clay-sized siliciclastic sediment and organic matter, planktonic organisms, and any fine material within the surficial sand layer that may be mobilized. If the filter sand is too coarse, then filtration goals may not be achieved. If the sand is too fine grained, then it may provide excellent filtration, but too much flow resistance to provide adequate water production rates. The overall thickness of the filter should

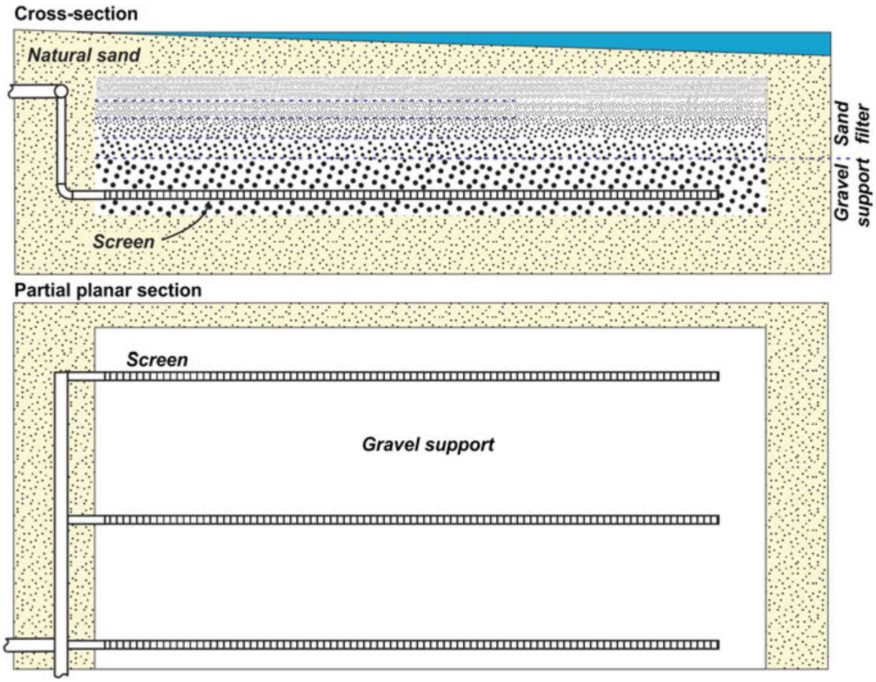

Fig. 10.2 Conceptual diagram of a beach gallery. Thickness of gravel support and sand filter is approximately 1.5–2 m

achieve a hydraulic retention time within the range of 6–8 h, which may require a greater thickness of constructed filter layers than the minimum thickness suggested Huisman and Wood (1974).

Proper design of a sand filter requires balancing filtration capability with system unit capacity, which is a function of the average vertical hydraulic conductivity of the filter. Thicker layers of finer-grained sediments improve filtration, but decrease the effective hydraulic conductivity, which requires the suction pumping to be increased to achieve the desired system capacity. The effective vertical hydraulic conductivity can also be reduced if there is mixing of sand between layers where the uppermost layer has a lower hydraulic conductivity compared to the next lower layer. This issue can necessitate a filter design using a thicker upper layer.

10.2.3 Use of Geotextile Fabrics in Design and Construction

Geotextile fabrics can be used to stabilize the walls of the gallery and minimize the mixing between layers, such as between the native beach sand and engineered filter sand and between the filter sand and underlying gravel pack. The pore size of the geotextile fabrics should be selected to retain the finer grained sediments. The main potential drawback of the use of geotextile fabrics is that they can be preferential sites of biological growth and thus become clogging layers which would require periodic removal and reconstruction of the gallery cell. In general, the use of a geotextile fabric to line the sides of a gallery is recommended, particularly where there is high water production from lateral flow into the gallery. Internal use of a geotextile fabric is generally not recommended, because of the potential for clogging and associated impedance of vertical flow.

Commonly used geotextile fabrics are composed of polyester (PET), polypropylene (PP), polyethylene (PE) and polyamide or nylon (PA) and may have either a woven and nonwoven construction. Most common geotextile polymers are unaffected by microorganisms, bacteria, and fungi. Although bacteria and other organisms do not feed on geotextile polymers, they can destroy their function as a filter by growing on the surface of fabric, and/or blocking the pores (Kossendey et al. 1996; Cook 2003; Rollin 2004; Rowe 2005). Some nylon based geotextile fabrics have been damaged by consumption by marine isopods which was found during a beach erosion control experiment on Captiva Island, Florida. Burrowing macrofauna may also damage geotextile fabrics. Although both needle-punched nonwoven and woven geotextiles are used for filtering (e.g., in leachate collection systems); woven textiles appear to be a better choice for use in beach galleries because of a lower susceptibility to biological clogging. Needle-punched nonwoven geotextiles provide a particularly large surface area for biofilm development (Rowe 2005). Key variables in the selection of geotextiles for long term maintenance of permeability are maximizing the percent open area (POA) and apparent opening size (AOS). The AOS needs to be of an appropriate size to retain the adjoining sediment while maintaining the desired flow rate.

10.2.4 Design of the Underdrain or Collection System

A key design issue in any gallery cell is the maintenance of a uniform infiltration rate at the surface of the filter. Uneven infiltration can lead to areas of excessive infiltration that encourages clogging at the surface or below the depth of wave-agitation. Design of flow control in underdrain systems in marine galleries was addressed by Mantilla and Missimer (2014).

Design of the system requires that a uniform flow is maintained in the screen slots, which is related to keeping the suction heads in the collection system piping as constant as possible. Commonly, the applied suction head is highest in the proximal screens and lessens toward the distal boundaries of the piping. Head loss with the piping system is controlled to a degree by the pipe junction geometry and number of junctions. Careful design of the piping system to maintain an equal head loss requires some pipe modeling to balance the diameter of the collection pipes with the intersection types and the screen locations. The density of screen slots and their apertures also play a role in achieving a proper balance (see Chap. 11).

10.2.5 Construction Materials: Sand, Gravel, and Pipes

The sand and gravel in the engineered filter should be well-rounded and not angular. It should be similar in density to the natural beach sand, so that it does not scour or leave an unnatural mound in the littoral zone. The upper layer that is in contact with the natural beach sediment is of primary concern. Therefore, gallery cells constructed within a predominantly quartz sand beaches should have an upper layer composed of quartz sand. Beaches can be composed of predominantly carbonate sands or a mix of carbonate and siliciclastic sands. The upper layer of the filter should be designed to generally match the composition with reasonable percentages based on the heterogeneity of beach sediment composition.

Seawater containing dissolved oxygen is extremely corrosive to any type of metallic material. Because beach galleries are always constructed with a bed thickness of less than 7 m, non-metallic materials, such as polyvinylchloride (PVC) and high density polyethylene (HDP) can be used for construction of underdrain screens and connecting pipes. These materials come in a variety of diameters and strengths that may be required based on field conditions.

10.2.6 Design of the Underdrain Screens

PVC screens used for underdrains should contain uniform-aperture, machined slots. Because of the coarse gravel in which the screens are placed, the slots do not necessarily have to be the wedgewire or "v" types used in the water well industry or used in passive screen intake systems (Chap. 6). There may be a limit to the diameter of PVC screens which can be used based on standard manufactured produce and compressive strength of the material. Machine slotted HDP can be used, but may be a special order material. The width of the screen slots must be less than the diameter of the smallest particular in the basal gravel unit because these screens cannot be easily "developed" to remove fine-grained material from the feeder pipes.

10.2.7 Design of High Capacity Beach Gallery Intakes

For medium to large-capacity systems (>1890 m^3/d), a modular design is preferred with each module or cell having an independent pumping system. A modular design can provide for redundant capacity, which allows for one cell to be taken off

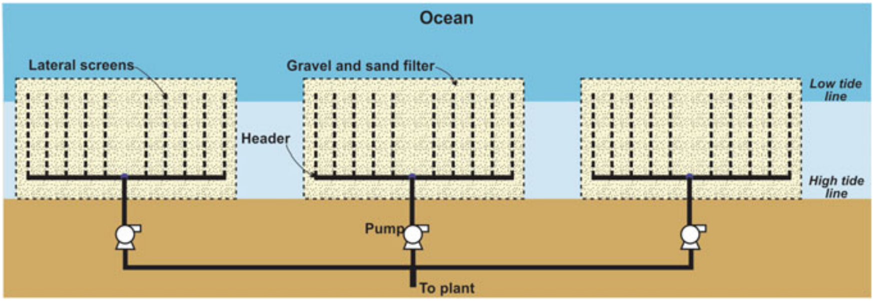

Fig. 10.3 Multiple cell beach gallery intake system configuration

line for maintenance activities without having to shut down the entire desalination system. The first cell should ideally be constructed and tested early in a project to obtain data on system capacity and water quality. Gallery cells could be pumped under suction using a variety of engineered pump scenarios. Each cell should be equipped with a dedicated pump to achieve high system reliability with redundant capacity. The configuration of the gallery cells should lie parallel to the beach and fully within intertidal and subtidal water to assure continuous vertical recharge (Fig. 10.3).

10.2.8 Alternative Beach Gallery Cell Design

An alternative to the standard design of beach gallery cells is the use of a modular plastic crate system instead of a gravel support. Modular crate systems, such as the polypropylene Flo-Tank® system developed by the Atlantis Corp, could be adopted for use in beach galleries (Fig. 10.4). The tanks are covered with a geotextile and then overlain with a sand filter consisting of engineered and/or natural beach sand. The advantages of this system include: the crates modules are light-weight, have a very large open area, and could be reused if the system requires maintenance.

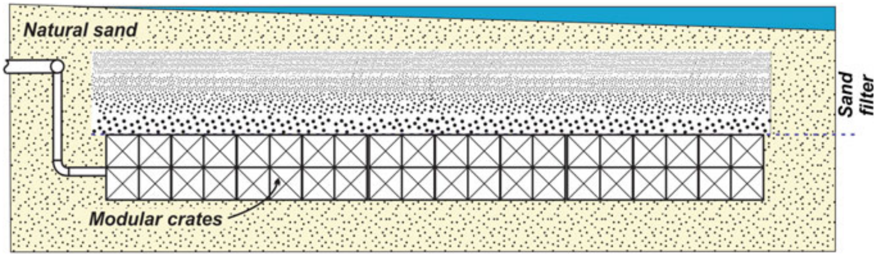

Fig. 10.4 Alternative beach gallery intake design using modular plastic crates

10.3 Optimization of Design

Variables that need to be incorporated into the beach gallery design include:

- area of each cell
- gallery media depth
- screen and gravel pack design (screen type, length, pattern, diameter, slot size and area, and gravel size)
- screen, collection pipe, and conveyance pipe dimensions and materials
- sand-and-gravel filter design (number, thickness, and grain size of layers)
- composition and shape of sand-and-gravel material
- geotextile fabric (whether or not to use and type)
- location of the gallery with respect to high and low tide lines

Additional design considerations include:

- source of water (flow paths)
- location of any sources of contamination or hypersaline water below the gallery
- constructability
- sedimentology of the project site (beach dynamics)
- ease of maintenance

The source of water refers to whether seawater is produced predominantly by vertical infiltration downward through the top of the gallery or if there is significant lateral flow from either the seaward or landward direction. In the former case, the gallery should be constructed either in the subtidal part of the beach (below the low tide line) or perhaps partly subtidal and partly in the lower part of the intertidal zone, so that it is submerged either all or most of the time. The key issue is that recharge to the gallery must be able to maintenance the required yield under all conditions, so that the gallery is never dewatered.

Occurrence of hypersaline water beneath the shoreline occurs in many parts of the Middle East and North Africa and in other areas, such as Australia and Cyprus. The source of the hypersalinity is commonly from sabhkas that are large supratidal flats that tend to trap seawater at spring high tides and become evaporation basins with a seaward trending density-driven flow. A beach gallery design from a medium capacity SWRO beach at Larnaca, Cyprus contained the gallery cells within concrete vaults to prevent any upward movement of high salinity water into the gallery structure (Missimer 2009).

Construction on a beach, in general, requires some knowledge of beach dynamics, such as whether the beach in retreating (being eroded) or prograding (growing seawards). Information about the history of a beach may be discerned from careful observations of current conditions and examination of a series of historical aerial photographs and maps. Some shorelines can be highly unstable. Figure 10.5 shows the location of the shoreline at Cape Hatteras, North Carolina (USA), which has migrated approximately one kilometer between 1860 and 1980 (Everts et al. 1983). The position of the shoreline can be determined relative to fixed

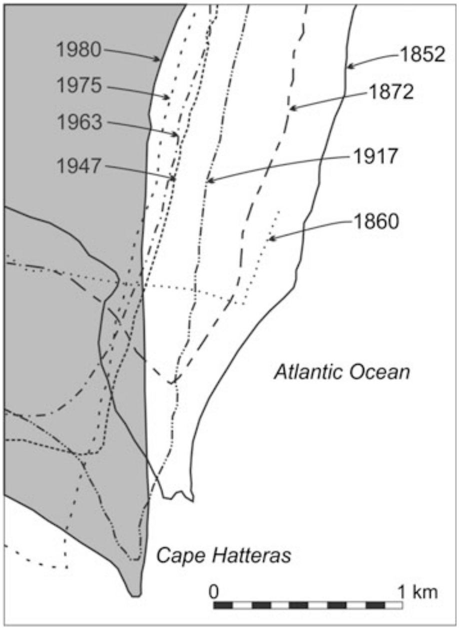

Fig. 10.5 Diagram showing changing position of mean high tide line at Cape Hatteras, North Carolina Island in 1980 is shaded gray (after Everts et al. 1983)

reference points. At Cape Hatteras, the shoreline adjacent to a lighthouse constructed in 1870 migrated 460 m inland. The lighthouse was moved inland in 1999 as the shoreline had retreated dangerously close to it.

It is important to appreciate that the erosion and growth of a beach may occur seasonally or during storm events, so conditions observed during a fair weather or single day visit may not be representative of what may happen in the future. In the case of a retreating beach, the concern is that erosion could expose and destroy the gallery. Progadation of a beach could strand the gallery future inland, causing the recharge flowpath to increase which, would decrease the yield of the gallery. Another issue is that seasonal beach profile changes occur on all beaches based on weather changes and these measured changes must be incorporated into the design of the gallery cells. In general, changes in the beach dynamics can be accommodated in the design of the gallery system. For example, if a beach is generally stable with the exception of potential severe storm impacts, the upper layer of the gallery could be increased in thickness to well below the maximum storm excavation depth. This would protect the gallery, but may increase the pumping head loss across the filter which would lead to some increase in operating cost. However, the thicker media would also lead to a higher degree of treatment of the inflowing water which may balance the overall cost.

Constructability is another important issue, particularly with respect to locally available resources and weather conditions. Public acceptance of some duration of beach closure may also be an issue. Locally available resources include both construction contractors and materials, such as properly graded sands. An important cost issue is whether or not a gallery construction requires installation of temporary sheet piling or a coffer dam, which depends upon cohesiveness (stability) of the native sands, tidal range, and wave intensity. The preferred situation is where the excavation walls are stable and wave energy is minimal, which would allow for construction without sheet piling. Installation of the beach gallery could be performed using a backhoe and pumps to dewater the excavation during low tide periods. A sand barrier could be installed seawards of the excavation to allow for dewatering through the tidal cycle. Alternatively, temporary inflatable water barriers may be used. Construction scheduling is another important issue, because many beaches are intensively used for recreational activities. Because of the modular nature of a beach gallery design, construction can be staged to close only the segment of the beach where a single cell is being constructed. As each cell is finished, the construction site would be moved to the next location, thereby limiting the lateral extent of closure to the public.

Ability to maintain the intake is an often under-considered issue for all subsurface intake systems in general. Most wells require periodic maintenance. Similarly, various physical, chemical, and biological processes could impact the long-term performance of beach and subsea galleries. The selection of alternative intake options should consider the type, potential frequency, and costs of rehabilitation activities. For example, although horizontal wells can provide much greater flow rates than vertical wells, they may be much more difficult and expensive to maintain. In the case of beach galleries, clogging of screens, the gravel pack, and the sand-and-gravel filter may require re-excavation of the gallery. Subsurface intake systems should have robust designs that can accommodate some loss of performance over time and thus reduce the need for rehabilitation actions. The costs of rehabilitation activities should be considered in cost-benefit analyses. An example of a design to accommodate some degree of clogging is to use variable frequency drives (VFD’s) on the production pumps to allow a constant flow rate during changes in head loss. Fluctuations in tides may requirement the use of VFD’s anyway.

10.4 Design Process

Design of a beach gallery system requires the collection of detailed information on the hydraulic properties of shallow strata in and in the vicinity of the beach. The aquifer characterization program should be designed to obtain information of bulk aquifer properties and the degree and type of aquifer heterogeneity. The shallow aquifer testing program should include some or all of the following elements:

- test well installation and aquifer pumping tests
- slug testing
- grain-size analyses (in the geological profile and across the beach face)
- core collection and permeameter testing

Groundwater modeling is an indispensable tool for beach gallery design. A high-resolution model was developed using the MODFLOW (Harbaugh 2005) and MT3DMS (Zheng and Wang 1999) codes to simulate different beach gallery design options. A sub-meter grid size in the core area of the model allows for the incorporation of the individual layers of the sand-and-gravel filter (Fig. 10.6). The MT3DMS solute-transport code is used to trace the source of water that is produced from the gallery. By assigning the water above the gallery with a concentration of 100 and all other waters to a concentration of zero, the percentage of water that enters a gallery by downward flow can be calculated.

Simulations of an investigated gallery site consisting of fine-grained sand with a hydraulic conductivity of less than 1 m/d indicated that lateral flow into the gallery would be negligible. Nearly all of the water is produced by downward infiltration through the top of the gallery. The optimal design of the gallery would be to construct the system just below the low tide line where it could be continuously submerged. The depth of the standing seawater is not significant to the design of the filter media and system hydraulics (but affects the collection pump design). The modeling results also indicated that the depth of the gallery had a minimal effect on water production. The optimal design involves maximizing the surface area of the gallery to produce the desired capacity.

A key constraint of the design of galleries is the thickness of the upper native sand layer, where it has a low hydraulic conductivity. In layered systems, the effective vertical hydraulic conductivity of the sand-and-gravel filter depends upon the thickness and hydraulic conductivity of the least permeable layers, which in the modeled system was the native beach sand. Where the near-surface sediments have a moderate to high hydraulic conductivity, lateral flow may be important and a deeper trench may be a better design. The important issue is that a properly constructed groundwater model can be used to evaluate various design scenarios to

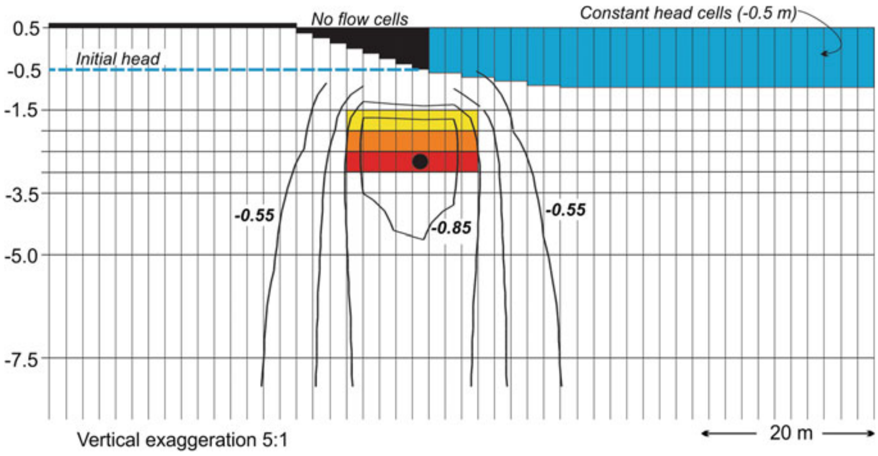

Fig. 10.6 Cross-section diagram of beach gallery showing modeled heads

understand the sensitivity of the system to different parameters and to determine the optimal design for a given site.

Once it is determined that a beach gallery is likely to be a technically feasible and economic option, then the next step in the design process is the construction and testing of a small-scale pilot system. The pilot system does not need to be very large (it could be as small as 10 m^2), but its design and location with respect to the beach should be a close as practical to that of a full-scale system. The objectives of the pilot testing program are to obtain proof of concept for the site and sufficient data to design a full-scale system. Pilot testing program data are normally used for calibration of the groundwater model for multiple cell systems. The sophistication of the test program needs to match the proposed capacity of the SWRO capacity desired with more data required for large capacity systems.

10.5 Potential Performance Issues

Beach galleries are based on the proven slow-sand filter technology, so there is a high probability that a properly constructed system will perform as expected. The filtration rate through slow-sand filters in freshwater systems declines over time due to the development of a biological clogging (schmutzedecke) layer. However, in the limited testing performed on seawater in the laboratory and at a pilot facility, no schmutzedecke layer formed at the filter surface (Desormeaux et al. 2009). However, regardless whether an upper biological layers forms or not, the self-cleaning nature of beach galleries (wave turbulence) would likely prevent the formation of a significant clogging layer. If a layer were to form, then it could be removed by raking or scraping the beach.

Beach galleries should ideally be constructed in locations where the beach is stable (i.e., neither significantly prograding or retreating) over the anticipated operational life of the gallery. If the position of the beach is unstable, then the gallery design needs to incorporate the likely range of shifts in the position of the beach with respect to the gallery. For example, if a beach is prograding, then the gallery design should incorporate future conditions in which the gallery is located further from the intertidal and subtidal zones. This may necessitate the construction seaward of the beach as a seabed gallery with transition to a beach gallery.

The integrity of the grain-size layering in the sand-and-gravel filter can be compromised by the activities of burrowing organisms, which are present in the intertidal and, to a greater degree, in subtidal zones. The mixing of sediments would tend to reduce their sorting and either increase or decrease their hydraulic conductivity (increase could be caused by burrow filling with coarse material), thereby changing the infiltration rate. In the beach environment, it is unlikely that significant quantities of fine-grained sediment would be incorporated into burrows. Filter-feeding infauna would tend to bind fine-grained sediments and organic residues into fecal pellets that would be hydraulically neutral (hard pellets). In warm tropical areas, the downward flow of seawater could result in calcium carbonate precipitation, which could gradually clog the screen, gravel pack and sand-and-gravel filter. However, the rate of flow through the gallery is limited by the lower hydraulic conductivity sand at the top of the sand-and-gravel filter. Considerable clogging of the screen and gravel pack could occur without reducing system performance.

Beach galleries should have reliabilities comparable or favorable to that of other subsurface intake designs and conventional open-ocean intakes. It is recommended that all subsurface intakes have robust designs that can accommodate some loss of performance over time. The design should incorporate a substantial safety factor and reserve capacity to achieve a high system reliability factor. Gallery modules could be designed to operate at higher flow rates than the required rates. Another option is to plan on the installation of addition gallery modules, as needed to maintain the raw water supply. The overall system design would include plans for the location of the additional modules, including piping and instrumentation, especially if SWRO capacity expansion is being anticipated. The galleries should also be designed to facilitate future rehabilitation activities, if ever needed. For example, sheet piling might be left in place to facilitate the excavation and reconstruction of the galleries, if ever needed. This should occur only of the sheet piling will remain below the beach surface, because it could become a source of turbulence resulting in accelerated wave-induced erosion and disruption of the upper gallery layer.

10.6 Global Applications

Beach galleries are a potential feasible subsurface intake design anywhere in the world where there is a moderate to high-energy beach in which clean (clay-free) sands are deposited. Beach galleries have considerable design flexibility in that the engineered sand filter can compensate for sub-optimal sediment characteristics. This design option has a wide range of potential capacities and can accommodate very large systems depending on the available beach lateral area which may be a limiting factor. A key aspect of the design is that once constructed, the beach can be restored to essentially initial conditions with no significant visual impacts. Pumping stations and support infrastructure can be located off the beach.

A key issue is that a beach galley intake system must avoid the environmental issue of impingement and entrainment of marine organisms, which is a major political issue in the United States and the European Union. Also, similar to all subsurface intake systems, the beach gallery system would become part of the SWRO facility pretreatment process train and would reduce the need to use chemicals and the energy costs of the in-plant pretreatment systems used in open-ocean intake systems.

10.7 Discussion

10.7.1 Permitting and Public Involvement

In the United States and the European Union, there are rather stringent regulations that apply to constructed works along the shoreline and in the bottom of tidal water bodies. Construction of a beach galley system would require a variety of environmental permits to be obtained. Some of these permits may require the preparation of environmental impact assessments and all of them have access to public input and political approval. Therefore, many desalination facilities around the world are having difficulties in obtaining environmental permits for construction and operation of intake and outfall systems. Commonly, the objective of some stakeholders is to defeat the use of desalination in general, because they view it as an energy-intensive process and that expansion of the water supply may enable additional local population growth and development. This opposition is commonly focused on the axillary parts of the facilities that are most vulnerable to undefined impacts.

A key method of defusing public opposition is to clearly make the case of the reduced environmental impacts of using subsurface intakes and the long-term reduction in the cost of facility operation. A life-cycle cost analysis should be performed during the facility design to clearly assess a SWRO facility using an open-ocean intake with extensive pretreatment versus a beach gallery system with a much less intensive pretreatment system. Missimer et al. (2013) demonstrated that the amortized capital cost using a subsurface intake system, especially using periods from 15 to 30 years, will produce a lower cost of water treatment and a lower water cost to the consumer. Another key issue is that the lower use of chemicals during treatment (e.g., chlorine and ferric oxide) reduces impacts to the marine environment and the lower electric use in pretreatment reduces the carbon footprint of the facility.

Use of a beach gallery system must be presented to the public early in the design and permitting process to allow sufficient time to engage and educate the public. This should include the use of public involvement experts and the use of computer programs, such as STELLA, to allow interactive and informative presentations that may convince key societal groups to support the most environmentally sound intake type. The most common issues that tend to be raised include: (1) closed beach access during construction, (2) future impacts to intertidal infauna, (3) visual impacts to beach users, and (4) impingement of fish eggs. These issues can be reasonable addressed. Beach access limitation can be lessened by proper construction scheduling with phased construction, thereby closing only small parts of the beach. Certain beach infauna will be impacted during construction, but the filtration of organic material within the beach system will increase growth rates of many organisms, such as polycheates, and may improve the nearshore environment. Visual impacts should be minimal or non-existent because once the gallery cells are constructed there will show no surface expression. Pumping stations can be located off the beach or be collocated with life-guard stations of changing facilities to hide them. The impingement issue is new and is addressed in the next section.

10.7.2 Environmental Issues

The newest criticism on subsurface intakes, gallery types in particular, is the inference that these systems cause impingement of fish eggs onto bottom sediments and "hide" the same impacts as open-ocean facilities. Fish eggs tend to be neutrally buoyant and are part of the ichthyoplankton within the marine water column. A key aspect of the maintenance of fish eggs within the water column is motion within the marine environment. The infiltration velocity in a beach gallery system is unlikely to be greater than 15 m/day. Therefore, the maximum inflow velocity into the sediments would be about 0.02 cm/s. To allow attachment of the eggs to the sediment in the beach intertidal zone, the wave breaking area, the water column would have to be essentially still with no wave orbital motion, no wave-generated turbulence, and no currents. The creation of a "still" condition in the intertidal zone of a beach may be limited to some types of very restricted water bodies that are likely to have a muddy shoreline, not geologically conducive to the development of a beach gallery intake system. Brownian motion may be sufficient to keep the fish eggs in motion without causing attachment, even in a relatively still environment.

10.7.3 Innovative Designs

Beach gallery systems are a relativity new design concept for seawater SWRO, introduced in a series of publications between 1991 and present (Missimer and Horvath 1991; Missimer 1994, 2009; Maliva and Missimer 2010). A few small SWRO systems currently use these systems, which are located at island facilities in the Caribbean. As more sophisticated and larger capacity designs are constructed and operated, design innovations will evolve that will produce some economies of scale and will involve innovative construction methods, not yet utilized. This will tend to reduce cost and will give SWRO facility owners and operators more confidence in the technology and design concept.

10.8 Conclusions

Beach galleries are a viable subsurface seawater intake design option that is particularly advantageous in locations with a small thickness of transmissive near surficial sediments, which precludes wells as a design option. The galleries can be constructed to be unobstrusive and thus not interfere will use of beach. The key design and construction issues are obtaining a sand filter that provides sufficient yield (rate divided by gallery area) to economically meet plant raw water requirements while also meeting treatment requirements. The sand filter also needs to be stable in that infiltration rates do not decline over time. Although a beach gallery is self-cleaning, its performance may decline if it is buried by beach progradation (addition of sediment causing the length of the infiltration flow pathway to increase) or if vertical hydraulic conductivity is reduced due to sediment and filter material mixing by bioturbation (i.e., introduction of fine sediments into coarse sand layers) or subsurface clogging by biological growth and/or carbonate cement precipitation. If the vertical hydraulic conductivity is increased in burrows of marine infauna that are filled with coarse sediment, then the treatment function of the upper gallery layer would be reduced. Such issues can be adequately addressed in the system design to achieve the necessary modifications required for successful operation. The system design and cost-benefit analysis should also consider the potential requirement for system rehabilitation, which may require excavation and reconstruction of the galleries. However, the simple design and low material costs may make beach galleries an economically viable option even if major rehabilitation work is periodically required. A key issue is to make the beach gallery design robust to deal with a variety of natural system events and processes that could affect performance.

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