Revue Paralia, Volume 6 (2013) pp 1.15-1.26
Keywords: Sea water desalination, Coastal well, Beach well, Subsurface flow drains, Horizontal directional drains, Seabed intake facility, Brine discharge

Review of maritime aspects of seawater desalination

Jean BOUGIS [1]

1. Consulting Engineer, 32 Chemin du Moulin, 06650 Opio, France.
jean.bougis@wanadoo.fr

Abstract:

For around thirty years, the production of fresh water from the desalination of sea water has been quickly developing for various uses: drinking water, domestic and industrial use, irrigation. After a brief historical reminder and an overview of various available industrial processes, the various maritime aspects are approached: indirect or direct sea water intake facilities, brines discharge, environmental requirements, marine structures seaworthiness, technological and economic criteria.

Received 3 February 2012, accepted 14 January 2013, available online 4 March 2013.

Translated version not certified, published under the responsibility of the article authors.

How to cite the original paper:
BOUGIS J. (2013). *Revue des aspects maritimes du dessalement d'eau de mer*. Revue Paralia, Vol. 6, pp 1.1–1.13.
DOI:10.5150/revue-paralia.2013.001 (disponible en ligne – http://www.paralia.fr – available online)

1. Historical Overview

Desalination (desalination or desalting) consists to produce fresh water from salt water or brackish water, usually by extracting fresh water and more rarely by salt extraction. The first units of seawater desalination appeared with the first steamboats. The use of seawater desalination to produce fresh water (drinking water, industrial and domestic use, irrigation) was developed in the second half of the twentieth century, mostly since the first oil shock of 1973. Until the 1960s, the distillation with beams drowned was the only industrial process available. High temperature heating, necessary to obtain acceptable performance, engendered frequent stops to descale the boiler. Some more efficient distillation processes emerged in the 1960s: FLASH, vapor compression, etc. At the same time appeared the first units using membrane processes. The progress accomplished by the reverse osmosis process (quality of membranes, energy recovery, lower costs, etc.) allowed its implementation for small and medium units and compete with the other distillation processes for large units.

2. Seawater desalination processes

Among the many desalination processes, only five are used on an industrial scale, three distillation processes and two membrane processes (MAUREL, 2001):

a) Multi effect distillation (MED).
b) Multi stage flash (MSF).
c) Vapor compression distillation (VCD).
d) Electro dialysis (ED).
e) Reverse osmosis (RO).

Schematically, a desalination plant consists of four units:

a) The intake of crude seawater and the discharge into the sea of the concentrate or brine.
b) The pretreatment, particularly important for membrane processes: removal of suspended solids, of organic matter, of "poisons of the membranes", of elements causing furring.
c) The desalination itself, that is to say, the separation of the permeate and the concentrate.
d) The post-treatment to make fresh water conform to the standards uses.

Thus the pre-treatments must be more or less advanced in terms of the quality of the available crude seawater and of the desalination process adopted.

3. Different kinds of seawater intakes

There are three main methods for collecting the crude seawater. They have sub-families that come in variations according to secondary criteria (specific sites, technological processes, ...). We will retain:

a) The taking of seawater from coastal wells.

b) The taking of seawater from infiltration under the beaches or under the seabed.

c) The direct seawater intake in open sea at the surface or at the bottom.

Despite a continuous transition, the concepts of coastal wells and beach wells are distinct:

The first are far enough from the sea to be implemented without maritime works and depend on hydrogeological properties of the ground on the entire site.

The last, located on the beach or in shallow water, require maritime works and depend only locally on geotechnical properties of the soil.

The choice of a solution must be analyzed in the light of several criteria:

a) Physical criteria of intake flow (importance and permanence of water flow, flexibility to adapt the flow of the water intake to that requested by the desalination plant, the distance between the intake and the desalination factory, ...).

b) Quality criteria for seawater obtained (constant physical properties: temperature, salinity, density, ...), mechanical quality (absence of plants, animals, larvae, eggs, zooplankton, phytoplankton of mineral particles or organic debris in suspension, ...), physicochemical and biological quality (no grease, oil, colloids, dissolved or suspended chemicals, heavy metals, microorganisms, turbidity, ...), from where the degree of pretreatment required depending on the selected desalination process.

c) Physical characteristics offered by the project's site: geographical, hydrogeological, geotechnical, hydrodynamic, energy, accessibility, etc.

d) Environmental criteria: access to the beach, sediment transport, geological characteristics of the soil, salinity and temperature of the concentrate, impacts on the human environment and on the natural terrestrial and marine environment (physical, fauna, flora, landscape, ...), administrative opportunities for access to the coast (protected areas, permissions, ...).

e) Economic criteria: investment costs, maintenance and upkeep costs and costs of filtration and pretreatment of the crude water.

4. Seawater intake by coastal wells

Coastal wells are similar to terrestrial wells in groundwater, but are drilled on the coastline at depths sufficient to obtain seawater or brackish water by infiltration through the soil (see Figure 1a). This type of seawater intake has the following advantages:

a) It is very suitable for desalination by reverse osmosis: neither suspended solids nor algae, low fouling index (ability of the flow to clog a membrane under standard conditions: FI ~ 2), low index of total organic carbon (concentration of organic compounds, fixed or volatile: TOC <1 mg / l).

b) It permits to limit and simplify pretreatments.

c) It can be used in coastal areas formed from inhospitable cliffs or rocky plateaus affected by a significant and permanent agitation.

d) It is insensitive to sediment transport.

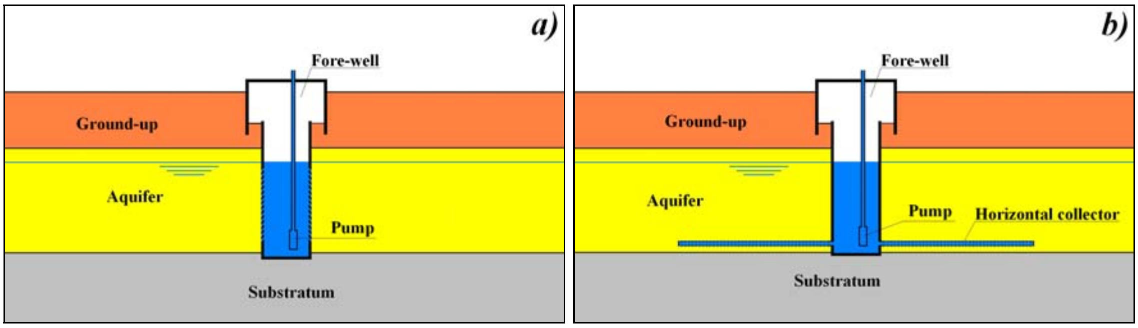

Figure 1. a) Coastal well – b) Beach well with radial collector (Ranney).

However, it has disadvantages:

a) It provides only low flow rates (risk of clogging of the soil and dewatering of the well if the filtration rate is too high), of the order of 10 to 50 l/s per well, which should be separated by several hundred metres to avoid interferences between their salt water intake.

b) Possible interactions between salt water and freshwater which flows toward the sea (constant salinity necessary for the good efficiency of the facility).

c) Need for geological and hydrogeological elaborated investigations.

d) The need for monitoring physical, chemical and biological characteristics of water.

5. Seawater intake by infiltration under beaches or under the seabed

Seawater can be captured under a beach or under a foreshore with beach wells, drainage trenches, horizontal directional drilled drains or infiltration field under the seabed.

5.1 Beach wells

The beach wells are similar to coastal wells, but they are drilled directly into the seawater aquifer or in the salt wedge, in top of a beach, on the beach, on the foreshore or on the bottom in the shallows. Their drainage capability can be improved with horizontal radial drains whose length is generally of the order of several diameters (5-20) of the well (Ranney wells) (see Figure 1b). This type of seawater intake has the following advantages:

a) It provides a high seawater quality that can be comparable to that of coastal wells according to the thickness of traversed ground and filtration rate.

b) It provides higher flow rates than coastal wells (greater permeability of the soil), of the order of 50 to 300 l/s per well, which should be separated by 100 to 150 m to avoid interferences between their intakes of salt water.

c) No interaction between salt water and fresh water.

d) A beach well requires a depth less than that for coastal wells.

However, it has disadvantages:

a) It requires access to the beach for construction and operation (maritime works), which makes it difficult to use in coastal areas formed by cliffs.
b) It can become sensitive to sediment transport if the filtration rates are sufficient to generate a significant fattening of the beach.
c) It requires geological and hydrogeological elaborated investigations

5.2 Drainage trenches

Seawater intake is made through a perforated pipe buried below the level of the lowest tides in a trench in the middle of a bed of gravel or ballast surrounded by a geotextile filter. The perforated pipe is connected via a waterproof pipe to a well which is filled with sea water under the effect of gravity. The drain can be protected against scour (surf zone) by burying it deeper. The gravels are then covered with a layer of filter sand and with a permeable "rip-rap" protection. There are two types of drainage trenches:

a) The trench is parallel to the coastline under the beach (see Figure 2a): seawater seeps into the drain by the side and partially above and below. The section of the gravel bed can be taller than wide.
b) The trench is normal to the coastline under the foreshore (see Figure 2b): seawater seeps into the drain essentially from above. The trench is covered either with the original materials if their permeability is satisfactory or with filler materials of higher permeability.

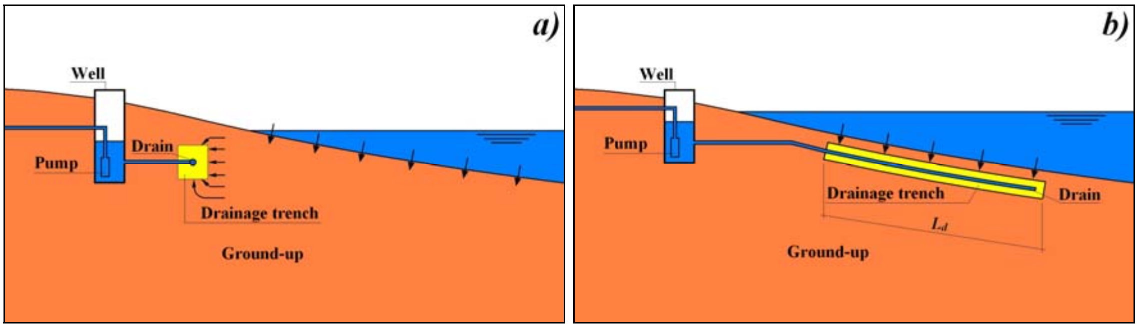

Figure 2. Drainage trench a) parallel to the coast - b) normal to the coast.

5.3 Horizontal directional drilled drains

A variant of the trench normal to the coastline consists in sinking (in soft ground) or drilling (in fractured hard ground) a drain under the seabed. The drain length permits to adjust the flow rate depending on soil characteristics. This directional drilling technique can go far under the sea without altering the integrity of the seabed.

5.4 Infiltration fields

The installation of multiple drains, parallel or converging in drainage trenches or directional drilling, permits to limit the distance out to sea. In semi-slow filtration (0.2 to 0.6 m/h), a field may provide a draining surface flow rate of 0.06 to 0.18 l/s/m^2. The first desalination plant powered by a draining field is that of Fukuoka, Japan - 2005: 2 ha for 1.2 m^3/s of seawater ; thus 0.06 l/s/m^2 (PANKRATZ, 2008).

6. Direct seawater intake

6.1 Seawater intake from a channel

The more the flow of seawater intake is important the less the losses are acceptable. A water intake from a channel to the coast is therefore necessary for very high flow rates. Nuclear power plants were designed with this scheme (~ 45 m^3/s per unit).

6.2 Seawater intake from immersed wells

The filtration in basin involves collecting seawater through a coarse grid (10 to 20 cm) in order to retain solids which can clog or damage the pipe. It is not possible to install a pump on the pipe and the water must be supplied through a siphon (gravity or vacuum) in a pumping tank where it is filtered. This method is generally adopted for high flow rates (a few m^3/s to a few tens m^3/s), for example for cooling a medium sized power plant. There are two types of seawater intakes concerning immersed wells:

a) Seawater intake at free surface through a pipe: The pipe is supported by a structure (dedicated gateway, wharf, dike core, jetty core, groyne, ...). Equipped with a vacuum priming system, it plunges below the free surface and draws water through a tulip designed to avoid vortex formation, and in the case of a little submerged intake, the depression of the free surface (see Figure 3a). The tulip is protected by grids.

b) Deep seawater intake through galleries or pipes: Seawater is brought through a drilled tunnel or through a pipe, buried in the surf zone, and then placed on the bottom and ballasted or anchored beyond. Seawater is drawn through a tulip or a well with grids (see Figure 3b).

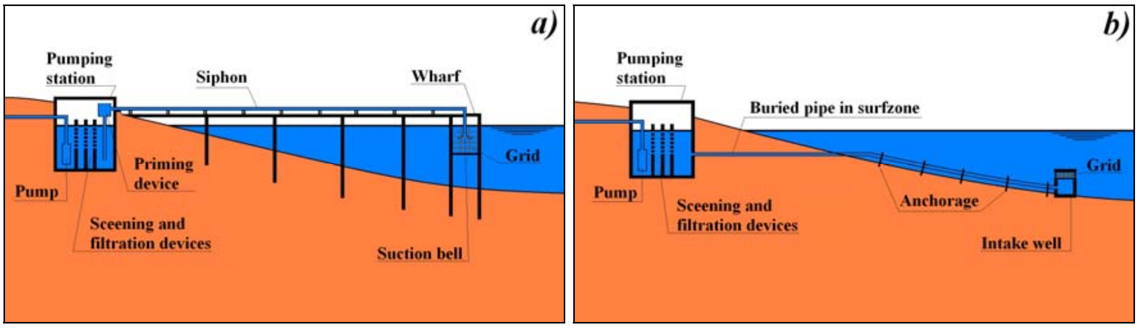

Figure 3. Sea water intake a) at free surface - b) at the seabed.

6.3 Seawater intake from passive screens

The filtration at intake involves collecting seawater through a passive screen whose mesh size ranges from a few tens of microns to a few millimetres. This filter allows the installation of a pump directly on the suction line without exposing it (deterioration by solid bodies and fish, abrasion by fine particle, ...). This procedure is usually reserved for low flows and average speeds (a few m^3/h at a few hundred m^3/h). Periodic cleaning of the strainer is required (water or compressed air blowing, intervention at sea).

a) Seawater intake at free surface: The principle is the same as above, but the tulip is replaced by a screen, vertical or horizontal, installed near the free surface. The pump is located on the pipe, on the ground or at the end of the gateway to discharge the water on the almost entire length of the pipe; electricity must then be brought to the extremity of gateway. The use of submersible pumps complicates the maintenance and upkeep for facilities not easily accessible.

b) Seawater intake at seabed: The principle is the same as before, but the water is sucked through a passive screen installed above the bottom and protected by a cover or by grids. The pumping station is located on the ground at an altitude close of lower sea level. Water is sucked into the pipe and then discharged to facilities located at higher levels. For no too large charge losses, the water supply can be by gravity to the pumping station.

6.4 Velocity field at the intake grids

The suction velocity of seawater at intake grids must be limited to avoid catching fish. If, for a given flow, the grids surface is sufficient to impose an average velocity, maximum velocity is more complex to manage. A parametric study (BOUGIS, 2011), performed with a Navier-Stokes model, permitted to link the homogeneity of the velocity field with the different parameters of the problem (ratio of grids dimensions, flow and thickness e of the wall). Thus, for a given average speed V_{rmoy}, the maximum V_{rmax} is all the more smaller that the outside radius of the tower r_e is important and that the height h of the grids is low. Using formula (1) permits to size the gates of cylindrical towers, independently of the flow rate, by controlling the velocity of aspiration.

$$\frac{V_{r\,\max}}{V_{r\,\mathrm{moy}}} = 1.31 + (0.81 - 1.23\,e)\left(\frac{h}{r_e}\right) + (0.24 + 0.14\,e)\left(\frac{h}{r_e}\right)^2 \qquad 0 < e < 0.75\ \mathrm{m} \quad \text{and} \quad \frac{h}{r_e} < 2 \tag{1}$$

For miscellaneous shaped towers it is necessary to realize specific modeling.

7. Sea discharge of the concentrate

At the exit of the desalination plant, the flow of crude seawater was separated into two parts: a flow of fresh water and a brine flow which contains all the salt.

There are three methods to reject the concentrate to the sea:

a) The discharge to the coast by means of a channel.

b) The discharge through an emissary.
c) The discharge by seepage under the sea.
The choice of the type of sea discharge depends mainly on environmental and economic criteria.

7.1 Coastal discharge by a channel or an overflow

Brine discharge to the coast involves either dropping the concentrate into the sea from a cliff, or letting it run on the beach, on a concrete weir or on a riprap weir, or rejecting it into a channel which flows to the sea like a river (see Figure 4a). This solution, like seawater intake from a channel, involves simply to organize and to regulate the discharge.
The channel may be a civil engineering work or a riprap structure. A protective grid prevents the risk of obstruction by foreign objects floating. This type of discharge, highly polluting, has been selected for the Ashkelon desalination plant in Israel, with a discharge rate of about 4 m^3/s.

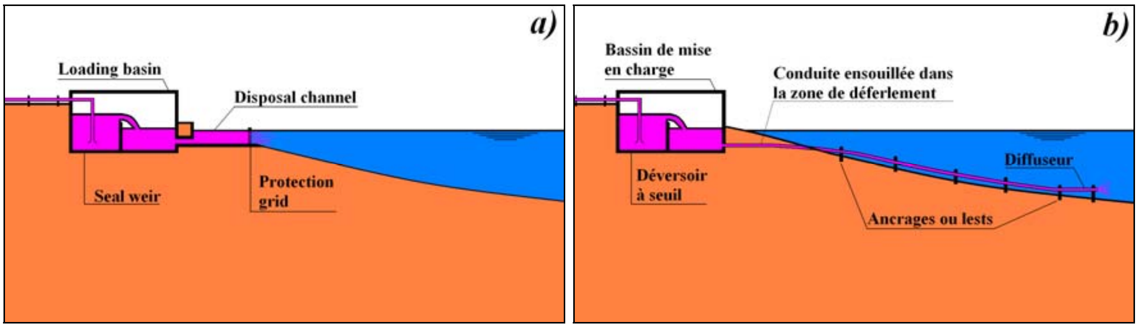

Figure 4. Effluent discharge a) by a channel - b) by an emissary.

7.2 Discharge by a gallery or an emissary

The brine is discharged into the sea by a drilled tunnel (hard floors) or dark tunnel (soft ground) under the sea or an emissary, buried generally in the surf zone, and then placed at the bottom of the sea (see Figure 4b). Its end is provided with a more or less sophisticated diffuser according to tolerated impact on wildlife and flora. It is anchored or ballasted to remain stable under the action of waves and currents. The fastening device of the conduit depends on its weight, depending on whether it is heavy (slough) or light, and the nature of the soil which can be soft or resilient. The buried light emissaries must be weighted to prevent them from coming back to the surface under the action of alternating pressures in the soil.

7.3 Discharge by infiltration under beaches

The brine discharge by seepage under the beaches is like seawater intake by infiltration under the seabed. This solution does not seem widespread (factory test of Long Beach, California - 2005). The advantage of this process is not clear and the opportunity to use it must be analyzed with caution.

7.4 Concentrated discharged by station

Unless the topography does not allow it, the discharge station of brine must be by gravity. The station comprises a recovery chamber of the effluent followed by a loading chamber for entry into the discharge pipe (see Figure 4). The two chambers are separated by a seal weir, which allows:

a) To dispense with discharge pumps and with associated protective devices.
b) To eliminate the influence of the downstream flow on the upstream flow.
c) To maintain the upstream pressure independent from sea level and flow.

7.5 Outfall diffuser exit

The density difference between brine and seawater favors the establishment of a density current that flows slowly over the seabed. Dilution of the hypersaline water mass in the environment is slow and requires very large distances up to more than 4 km, as in Alicante, Spain (FERNANDEZ-TORQUEMADA, 2005). The shape of the outlet section influences the propensity to dilute effluent into the sea. An optimized diffuser has many orifices distributed over a distance of several tens of metres or more. The outlets are raised above the bottom by one to two metres. Each outlet has a limited cross section and its axis is inclined 45 ° upwards; the impact of the jet on the bottom increases the dilution. However, the presence of a diffuser increases the losses and prevents the use of a pipe cleaning pig.

8. Environmental constraints

Because of its salinity and concentration of chemicals (pretreatment, membranes rinsing and chemicals used against dirty marks, descaling and corrosion) (LATTERMAN & HOPNER, 2003), the flow generates impacts on wildlife and plants, including stenohaline benthic organisms:

a) The loss of life at the outlet of the outfall in an area up to 1 ha.
b) The seabed anoxia caused by benthic species, consuming oxygen during periods of low hydrodynamics.
c) The lack of light on seabed affects photosynthesis of marine plants, accentuated by the turbulence due to the jets.
d) Massive reductions in the populations of sea urchins, starfish, shrimps, etc.
e) An increase in the mortality of Posidonia meadows with abundant necrotic tissue and falling leaves etc.

The affection thresholds vary considerably from one species to another.

9. Seakeeping of marine structures

Direct seawater intake and brine discharge works are composed of a number of elements: lines, anchors, weights, concreting, trenching, suction wells, diffusers. Subjected to the action of currents and waves, they sometimes undergo very important efforts, which should be evaluated for sizing the civil engineering works to ensure external stability (sliding, tipping, tearing), but also its internal stability (deformation, structural damage, breaking).

Given the relationship between the characteristic dimensions of the various elements and the wavelength of swells considered, the implementation of diffraction - radiation software is exceptional. The efforts are evaluated with the asymptotic generalized Morison formula which distinguishes:

a) The inertial force, proportional to the immersed volume and to the fluid acceleration.

b) The drag force, proportional to the cross-flow surface and to the square of the fluid velocity.

c) The lift force, proportional to a surface and to the square of the fluid velocity.

The three coefficients of proportionality are empirical hydrodynamic coefficients (CM, CD and CL) coming from the literature. They were determined by tests on physical models or on digital models (Navier-Stokes), under specific assumptions.

The hydrodynamic coefficients for pipes, immersed in an unlimited fluid and subjected to continuous and uniform current, have long been known. Studies of orbital oscillating flows, especially near the seabed or near the free surface, are relatively new and were only partially and inadequately broadcasted in maritime domains not connected with offshore oil exploitation. Much attention must be paid to the hydrodynamic coefficients, used in Morison's formula, that depend naturally on Reynolds number, on relative roughness of the pipe and on the Strouhal number, but also on the number of Keulegan and Carpenter K_c and of the relative free distance E_D between the pipe and the bottom. (SUMER & FREDSØE, 2006).

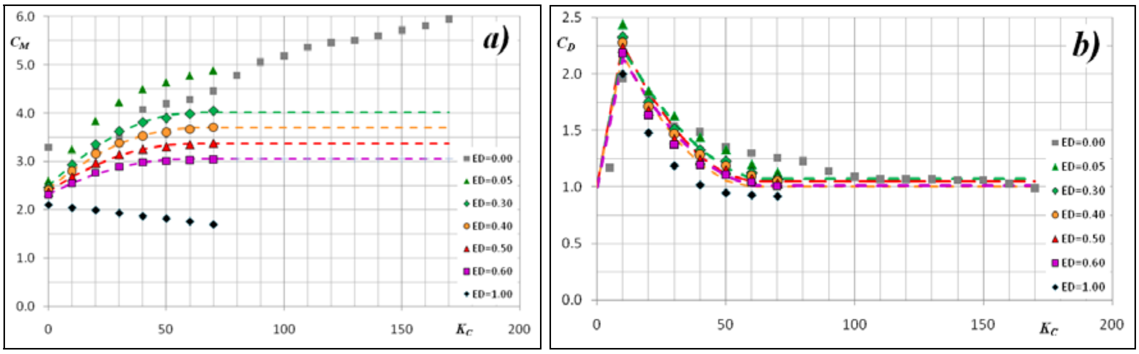

Figure 5. Coefficients a) of inertia - b) of drag (from SUMER and FREDSØE, 2006).

The proximity of the bottom greatly increases the efforts, especially for small numbers of Keulegan and Carpenter (oscillation amplitudes are not too large with respect to the diameter, of the order of less than 50 to 100 times), which is commonly the case for seawater intakes and brine outfalls. The significant variations of coefficients with respect to the period requires to use spectral analysis (see Figure 5).

10. Criteria for choosing the site of implantation

When choosing a site for a desalination plant, contradictions can exist between the criteria dedicated to the seawater intake and those dedicated to brine outfall:

a) For seawater intake, one seeks an area away from any discharge, protected against agitation and permitting to ensure the sustainability of the supply whatever the weather and sea states.
b) For brine discharge, one prefers an open site with a strong hydrodynamism (current, agitation) with the possibility of diluting the brine with other discharges having complementarity (lower temperature, lower salinity, etc.).

The relative disposition between seawater intake and brine discharge is also very important to reduce the risks of direct, indirect or delayed recycling from brine discharge toward seawater intake.

The most important factors are:

a) The shoreline topography and altitude of the site that affect the pumping of water supply and the loading of emissary by gravity.
b) The sedimentary cover and sediment transport that determine the depth of the water intake and /or disposal and the need for filtration of the waters abstracted.
c) The bathymetry of seabed that determines the length of the pipes of the intake and/or outlet.
d) The vulnerability of the discharge area and the requirements for effective dissemination of the effluent that determine the conversion factor or the need for dilution prior to discharge.

11. Criteria for choosing the seawater intake method

The different methods of seawater intake are analyzed according to flow demand, the selected desalination process and characteristics of the site; indirect seawater intakes are preferred for the quality of their waters.

Afterwards a compromise must be found between the technical criteria (water quality, topography, etc.), economic (investment and operation) and environmental.

The analysis of fifty projects, done in the world before 2005, showed that for flow of seawater below 0.5 m^3/s (producing 20 000 m^3/d), the investment costs are generally to the advantage of indirect seawater intakes (see Figure 6). Beyond the direct seawater intakes often become less expensive. The cost of civil ingeneering works for seawater intake and brine discharge is commonly 5 to 15% of the total investment, or even more for low capacity units. Indirect water intakes requiring less pretreatments, inducing 10 to 20% lower operating costs.

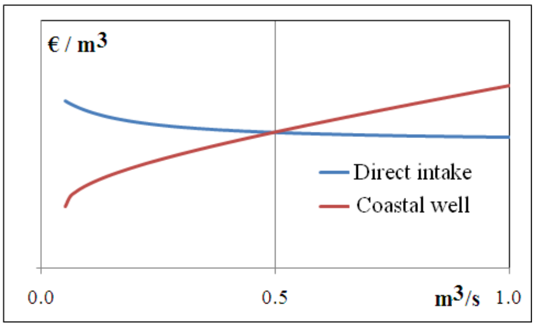

Figure 6. Comparative costs of the water intakes for direct and indirect flow.

12. Acknowledgments

Part of this synthesis was prepared within the framework of the strategic study on the desalination of sea water in Morocco (BOUGIS, 2009) conducted in collaboration with ADI Society of ONA group (Rabat), for the Secretariat of State in charge of Water and Environment to the Ministry of Energy, Mines, Water and Environment of Morocco. All those who made this work possible are thanked.

13. References

BOUGIS J. (2009). *Contribution pour les aspects hydrodynamiques à l'étude stratégique sur le dessalement de l'eau de mer au Maroc*. Rapport RET.08.478.02.01, 48 p.

BOUGIS J. (2011). *Répartition de vitesse à l'entrée des tours de captage d'eau de mer*, 2ème Conférence Méditerranéenne Côtière et Maritime, Tanger 22-24 novembre, pp 279-282. doi:10.5150/cmcm.2011.058

FERNANDEZ-TORQUEMADA Y. (2005). *Preliminary results of the monitoring of the brine discharge produced by the SWRO desalination plant of Alicante (SE Spain)*, Desalination, n° 182, pp 395-402.

LATTERMANN S., HÖPNER T. (2003). *Seawater desalination*. Impacts of Brine and Chemical Discharge on the Marine Environment, L'Aquila: Desalination Publication, 142 p.

MAUREL A. (2001). *Dessalement de l'eau de mer et des eaux saumâtres*. Technique & Documentation, Paris, 226 p.

PANKRATZ T. (2008). *Global overview of seawater desalination intake issues*. Alden Desalination Intake Solutions Workshop, Holden (Massachusetts), 16 October, 46 p. [URL http://www.aldenlab.com]

SUMER B.M., FREDSØE J. (2006). *Hydrodynamics around cylindrical structures*. Advanced Series on Ocean Engineering, World Scientific Publishing Co, Singapore, Vol. 26, 530 p.