Mark Wilf Ph. D. and Kenneth Klinko

OPTIMIZATION OF SEAWATER RO SYSTEMS DESIGN

ABSTRACT

The trend of investment and water cost in RO seawater systems is being evaluated. The cost data used for this evaluation are based on published information from operation of actual RO seawater installations and recent studies. The effect on process economics of major design parameters: recovery rate and feed water salinity based on three representative seawater water sources: Mediterranean, Atlantic and Pacific Ocean on energy consumption is analyzed. The objective of this evaluation is to determine economic feasibility of operating of seawater systems at higher recovery rates versus process optimization based a prevailing economic parameters. The optimized system design will be compared with the design of recent large seawater installations: 10,000 m3/day plant at Eilat, Israel, 40,000 m3/day seawater plants at Larnaca, Cyprus and the design proposed for the 95,000 m3/day RO plant at Tampa, Florida.

Introduction

The economics of seawater desalting using reverse osmosis technology have been continuously improving with a reduction of product water cost as a result of lower investment costs and decreased power consumption. The practical examples of the decreasing desalted water trend are recently built or awarded large (10,000 —95,000 m3/day) RO seawater projects: Eilat (Israel), Larnaca (Cyprus) and Tampa (Fl). In these projects the desalted water cost is significantly below \$1.0/m3 (\$3.8/kgallon). Low water cost is a result of lower investment and operating cost. The lower capital investment cost has been achieved by more efficient system designs and better selection of materials for construction. Power consumption has decreased due to improved efficiencies of high pressure pumps, power recovery turbines and optimization of recovery rate with respect to required feed pressure. At the prevailing prices of sweater membrane elements, the major water cost contribution results from the cost of process equipment and power consumption. The seawater RO process parameter which has the largest effect on investment and operating cost is the permeate recovery rate. The feed flow is inversely proportional to the design recovery rate; therefore, the recovery rate directly affects the size and cost of all process equipment and power consumption. However, in seawater RO systems, the recovery rate cannot be increased at will, as higher recovery results in higher average feed salinity, which results in higher osmotic pressure and increased permeate salinity. The system recovery rate has to be optimized with respect to membrane performance and process economics. The design objective is to produce required permeate salinity and to balance between decreasing equipment cost and increasing power consumption. With increasing recovery rate the equipment size and cost decreases due to lower feed flow. However, the specific power consumption initially decreases with recovery rate but then reaches a minimum and eventually increases. This trend is due to the necessity to operate RO membranes at higher feed pressure with increasing osmotic pressure at a higher recovery rate. Recent developments of RO seawater technology, improvement of membrane salt rejection, introduction of membrane elements that are capable of operating above 70 bar (1000 psi) and availability of directly driven interstage booster pumps, provide additional flexibility in optimization of the operating parameters.

Product Water Cost.

The cost of water produced in seawater RO systems is the result of contribution from the following components: equipment amortization, energy usage, consumption of chemicals, membrane replacement and cost of operation and maintenance. The desalted water cost decreased continuously over the years following lower contribution of each of the cost categories. Equipment cost decrease is a result of more efficient system design. More effective pretreatment equipment is being used together with simplified train design. It is also more frequent to utilize sites with existing supply of seawater feed. For example, it is more common to locate RO system on the sites of operating power plant or seawater distillation systems and utilize common intake and discharge structures (condenser outlet). Decrease of power usage results from the use of more efficient pumps, turbines and motors and operation at recovery rate close to the minimum of power consumption. Usage of chemicals has been reduced due to recognizing that the scaling potential of seawater is negligible under RO operating conditions. Higher recovery rate also contributes to lower dosage rate of chemicals used. Membrane replacement cost follows the trend of decreasing cost of membrane elements and lower replacement rate for long term contracts. Operation and maintenance is simplified due to larger degree of process automation and remote monitoring of performance. Historical values of capital cost of RO seawater systems, starting over two decades ago, are provided by Leitner (2). The listing includes large seawater RO systems in Middle East, US and Spain. The systems in Middle East outnumber installations at other locations. The capital cost ranges from

$700/m3-day (Key West, Fl) to $2500/m3-day (Jeddah, SA), with majority of the entries at $1,100/m3-day level ($2.66/gpd, $9.46/gpd and $4.40/gpd respectively). Leitner evaluated representative water cost, at an Arabian gulf location, as being $1.31/m3 ($4.97/kgallon) for system of 23,000 m3/day (6 MGD) product capacity. This 1989 water cost estimation can be compared with the water cost produced in current large RO systems. The entries in Table 1 include water cost values for recent operating plant (Eilat) and contractual values for projects being completed recently (Larnaca, Cyprus) and to be built in the near future (Tampa, Fl). The Eilat plant is a single pass system, which process Red Sea seawater blended with concentrate of the local brackish water plant (combined feed salinity 36,000 ppm TDS) at 50% recovery rate. Operation with blended feed results in lower product water cost due to operation at higher recovery rate and lower feed pressure. The availability of RO concentrate is limited, and therefore, the future RO units at this location are designed to operate on sweater only (about 42,000 ppm TDS) at 45% recovery rate. The design of Larnaca and Tampa plants are of two pass configuration.

Table 1.

Location	Permeate capacity, m3/day (MGD)	Status	Recovery rate (configuration)	Total water cost, $/m3 ($/kgallon)
Eilat Israel	20,000 (2.6)	First phase (10,000 m3/day) operational since 1997	50% (single pass)	0.72 (2.72)
Eilat Israel	20,000 (2.6)	Under design	45% (single pass)	0.81 (3.06)

Larnaca, Cyprus	40,000 (10.6)	Commission in March, 2001	50% (partial double pass)	0.83 (3.14)
Tampa	94,600 (25.0)	2002	60% (partial double pass)	0.55 (2.10)

The Larnaca plant is designed to process Mediterranean seawater (about 40,500 ppm TDS) at 50% recovery rate. The additional processing of permeate is required to reduce boron concentration in the permeate below 1 ppm. At the Tampa site the feed water is of variable salinity, ranging from 18,000 ppm TDS to 31,000 ppm TDS. Partial second pass processing is necessary to maintain chloride level in the permeate below 100 ppm over the whole range of feed water salinity and temperature. A wide range of feed salinity combined with fluctuation of feed water temperature creates a significant challenge for the design of high pressure pumping system. The required range of feed pressure to the membranes will be provided using a system of multiple pumps, variable speed drives and permeate backpressure.

Parameters of the RO Process

The operating parameters for seawater RO system are mainly a function of feed water salinity and temperature. For example, for seawater feed of about 38,000 ppm TDS salinity and water temperature in the range of 18 - 28 C, the RO systems are designed to operate at a recovery rate in the range of 45% - 50%, with an average permeate flux in the range of 7 - 9 gfd (11.9 —15.0 l/m2-hr). At the above operating conditions, the feed pressure is in the range of 800 - 1000 psi (55 - 70 bar) and permeate salinity is in the range of 300 - 500 ppm TDS. For a given feed water salinity and salt rejection of the membrane elements used, the permeate salinity is a function of feed water temperature, recovery rate and permeate flux. An increase in feed water temperature results in an increased rate of salt and water diffusion across the membrane barrier at the rate of about 3%-5% per degree Centigrade. Because RO plants usually operate at a constant flux rate, the changes of permeate salinity closely follow the changes in feed water temperature (1). Permeate salinity is inversely proportional to the average permeate flux. Higher permeate flux increases the dilution of salt ions which passed through the membrane, and therefore results in lower permeate salinity. The average permeate flux rate in seawater systems is maintained at relatively low values: 7 - 9 gfd (11.9 —15.0 l/m2-hr) for surface seawater feed and 9 - 10 gfd (15.3 - 17.0 l/m2-hr) for seawater from beach wells. The difference in flux rates between the two water source types results from better quality of the well water and therefore, a lower fouling rate for the membranes. These flux values are relatively low and only about 50% of the permeate flux values used in brackish RO systems. Attempts to operate seawater systems at significantly higher flux rates have usually resulted in irreversible flux decline. Until recently, the design recovery rate of new commercial seawater RO systems has been increased subsequently to the availability of membrane elements with increasingly higher salt rejection. So far, the maximum recovery in seawater RO systems has been mainly limited by the membrane salt rejection or the ability to produce permeate water of potable quality. Figure 1 displays permeate salinity as a function of recovery rate and permeate flux. The calculation were conducted for Mediterranean seawater feed of salinity of 40,500 ppm TDS and feed temperature of 20 C for a recovery range of 40 - 60% and flux rate of 8 - 11 gfd. Nominal 99.7% salt rejection membrane elements were used. For calculations of permeate quality, the membrane salt passage was increased by 30%. This is to account for projected 10% per year salt passage increase during 3 years of an average membrane life. As expected, a higher recovery rate requires operation at an average flux rate above the standard value of 8 gfd. This is to maintain permeate salinity of 400 ppm TDS, especially during the periods of higher feed water temperature. The obvious questions are what is the optimum recovery rate of seawater systems in respect to product water cost, is such recovery achievable with the current performance of commercial seawater membranes, and is it possible to operate RO membranes on surface seawater at a higher flux rate.

Process Economics

Recovery rate has a major impact on the economics of the seawater RO process. The size of all process equipment which is determined according to feed or concentrate flow will decrease with increased recovery rate. This applies to the size of the feed water supply system and power consumption of intake pumps. The size of all pretreatment equipment; storage tank, booster pumps, filtration equipment and chemical dosing systems is determined according to the feed flow. The same considerations apply to sizing of concentrate piping and of the outfall facility. The design permeate flux rate affects the number of membrane elements installed, number of pressure vessels, manifold connections and size of membrane skid. The effect of the recovery rate on investment and water cost will be examined in an example for a 6 mgd (22,700 m3/day) system operating on three representative seawater sources. The cost estimation of the conventional reference design is based mainly on the data developed by G. Leitner (2), P. Shields and I. Moch (3).

Parameters of RO System Performance Calculations.

The evaluation was conducted for three representative seawater sources: Mediterranean; approximate salinity 40,500 ppm TDS, Atlantic Ocean; approximate salinity 38,500 ppm TDS and Pacific Ocean; approximate salinity 34,000 ppm TDS. Calculation of membrane performance was conducted for the RO system recovery range of 40% - 70%. Equipment cost was estimated for a RO system treating seawater feed from open intake, utilizing conventional pretreatment with two stage gravity filtration. The equipment cost data was based on published cost estimation (1,2) and other communications.

Product water cost was calculated based on the following cost parameters:

Plant life	20 years
Interest rate	8%
Power cost	\$0.06/kWhr
Annual membrane replacement rate	20%
Membrane replacement cost	\$700/element
Cost of treatment chemicals	\$0.05/m3 (\$0.19/Kgallon)
Efficiency of pumps	83%
Efficiency of ERT	83%
Efficiency of electrical motors	94%
Average permeate flux rate	13.5 l/m2-hr (8gfd)

System cost.

Table 2 summarizes equipment cost for the 22,7000 m3/day (6 mgd) RO seawater system utilizing conventional pretreatment. The basic case equipment cost was estimated for the RO system design at 45% recovery rate. With increasing recovery rate the size and cost of equipment decreases. However, the rate of cost decrease declines with increasing recovery, converging to a very small savings at the high recovery end.

Feed Pressure Requirements.

The feed pressure requirements depend on the osmotic pressure of the feed water (feed salinity), feed water temperature and the design permeate flux.

Figure 2 presents the osmotic pressure of the concentrate vs. recovery rate for the three feed water sources evaluated. Figure 3 displays required feed pressure for a given water source and recovery rate calculated for an average permeate flux rate of 13.5 l/m2-hr (8 gfd). The pressure requirement was calculated for a single stage array system. For two stage system the feed pressure will be higher due to additional pressure drop across the second stage.

Energy Requirement and Water Cost.

The energy requirement is directly related to feed pressure and feed water flow. Higher recovery rate requires higher feed pressure to overcome increasing average osmotic pressure. However, the feed flow rate decreases with increasing recovery. Figure 4 shows the plot of energy requirement vs. recovery rate. The energy includes electricity consumed by intake pumps, pretreatment system and high pressure feed pumps. The minimum energy value is at about 50% -55% recovery rate and varies with feed water salinity.

The following water cost components are affected by the recovery rate: energy, chemicals and capital cost. Figure 5 shows a plot of the combined contribution to the water cost of these three components. Because chemicals and capital cost decrease with increasing recovery rate, the minimum value of water cost shifts to higher recovery rate as compared to the energy vs. recovery plot (Figure 4).

Total Water Cost.

The total water cost includes recovery sensitive components such as enrgy, chemicals and capital. It also includes operation and maintenance cost and membrane replacement contribution, which are not directly affected by the recovery rate. Figure 6 shows the plot of the total cost vs. recovery rate. The minimum value is at about 55%-65% recovery rate, shifting to slightly higher values at lower feed salinity (Pacific Ocean).

The Effect of Power Cost Rate.

The calculations of water cost, displayed in Figure 5 & 6, were conducted at the power rate of C6/kWhr. Figure 7 shows the values of water cost at power rates of $0.03/kWhr - $0.12/kWhr for the mid range of feed water salinity (Atlantic). As expected, at higher power rate the minimum cost shifts to lower recovery. At the lowest range of the power rate the recovery rate has little effect on water cost.

Conclusions.

The water cost considerations indicate that in seawater RO systems the optimum recovery rate is in the range of 50% - 60%. The recovery value corresponding to cost optimum depends on feed water salinity and power rate. The calculations were conducted under assumptions that high pressure and regular pressure elements are equivalent with respect to cost, performance and operational longevity. It is likely that adding a high pressure section to the system for operation at high recovery and feed pressure significantly above 70 bar would increase unit capital cost and may increase the membrane replacement cost component. This would result in shifting the minimum water cost toward lower recovery values.

The conclusion of the above evaluation is that designing seawater RO system for recovery rate exceeding 55% can only provide cost benefits in cases of low feed salinity and low electricity cost. Increasing power cost shifts the optimum of the total water cost to lower recovery rates. High cost of intake and concentrate discharge structure will shift the optimum to a higher recovery rate.

An additional parameter that has to be consider is the resulting permeate salinity. For design cases, when a high recovery rate design will result in an increase of permeate salinity, which will subsequently require a change of RO system design from a single pass to a two pass configuration, most likely the produced water cost will be higher than can be achieved in a conventional system.

References

1. M. Wilf and K. Klinko, Performance of commercial seawater membranes, desalination, 96 (1994) pp 456 — 478.
2. G. Leitner, Cost of seawater desalination in real terms, 1979 through 1989, and projections for 1999, Desalination 76 (189) 201 — 213.
3. P. Shields and I. Moch, Evaluation of global sea water reverse osmosis capital and operating cost, Proceedings of the ADA Conference, Monterey, California, August 1996, vol. , 44 - 60.

Fig 1. Projected permeate salinity for Mediterranean feed,
at permeate flux rate range: 8 - 11 gfd

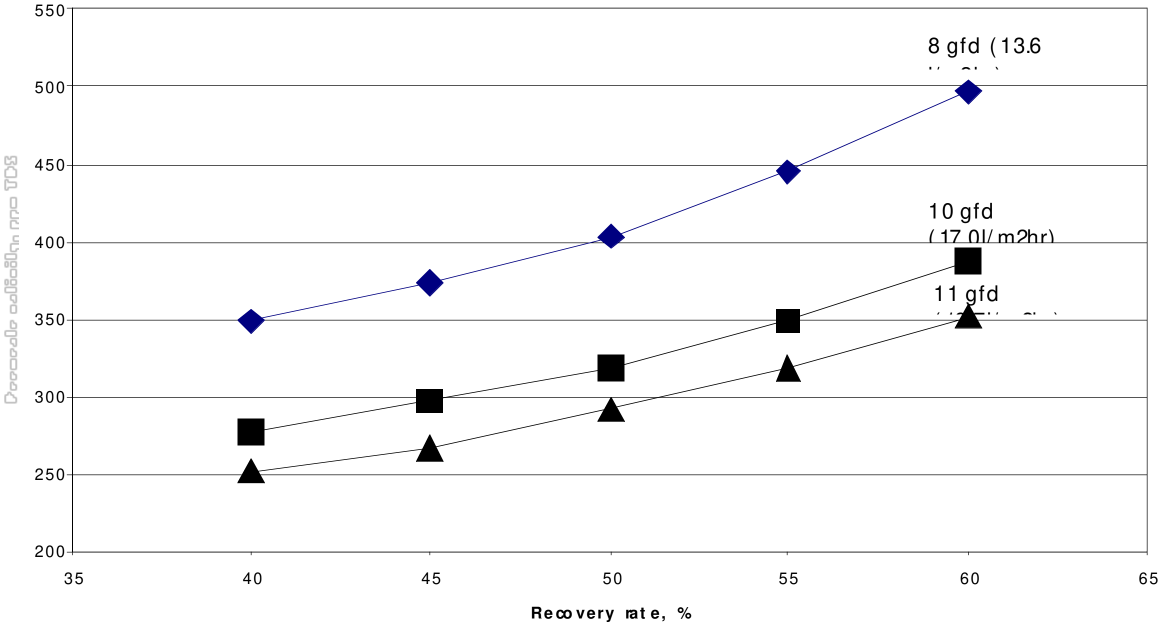

Fig 2. Osmotic pressure of the concentrate

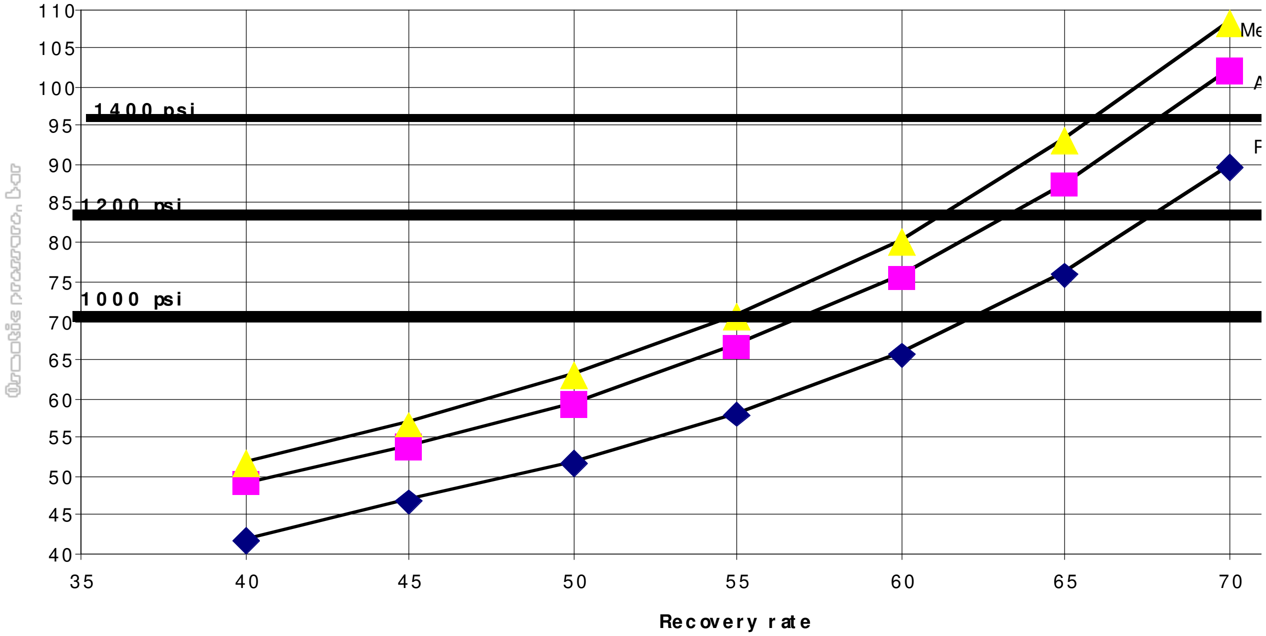

Fig 3. Feed pressure vs recovery

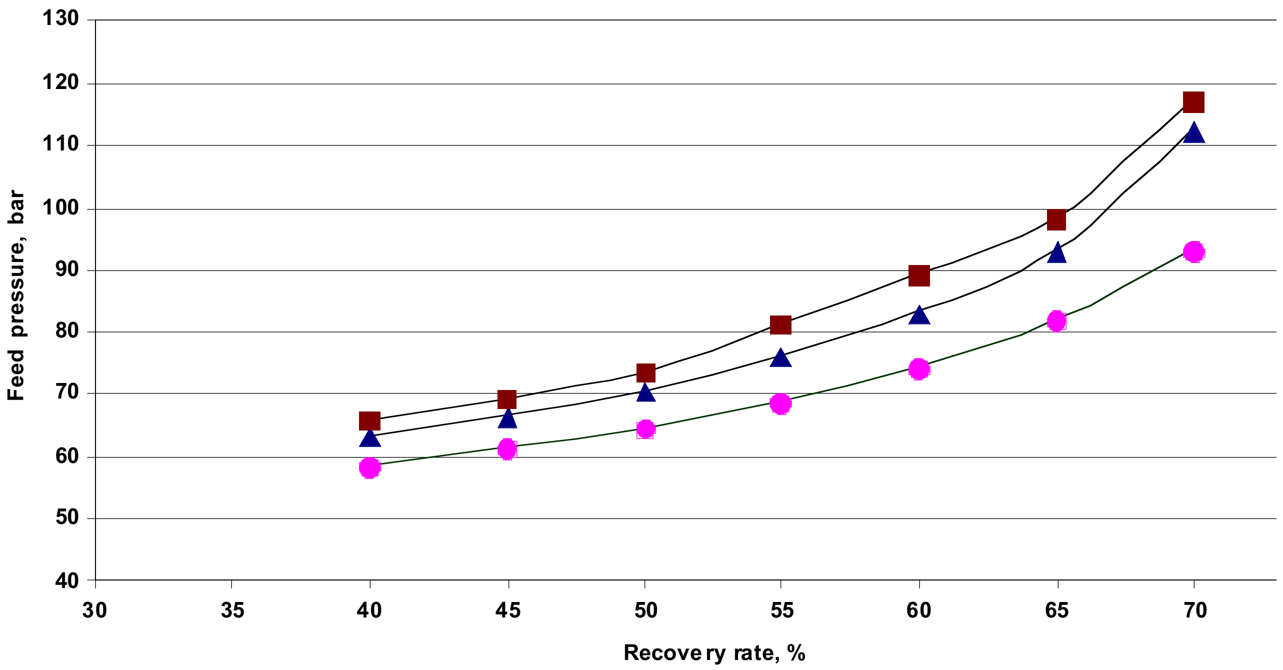

Fig 4. Energy requirement

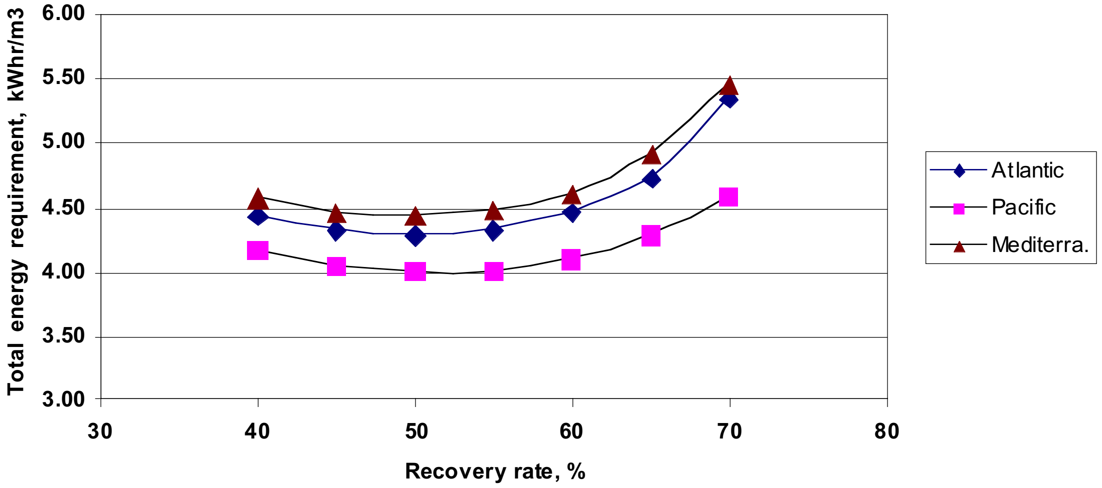

Fig 6. Water cost evaluation

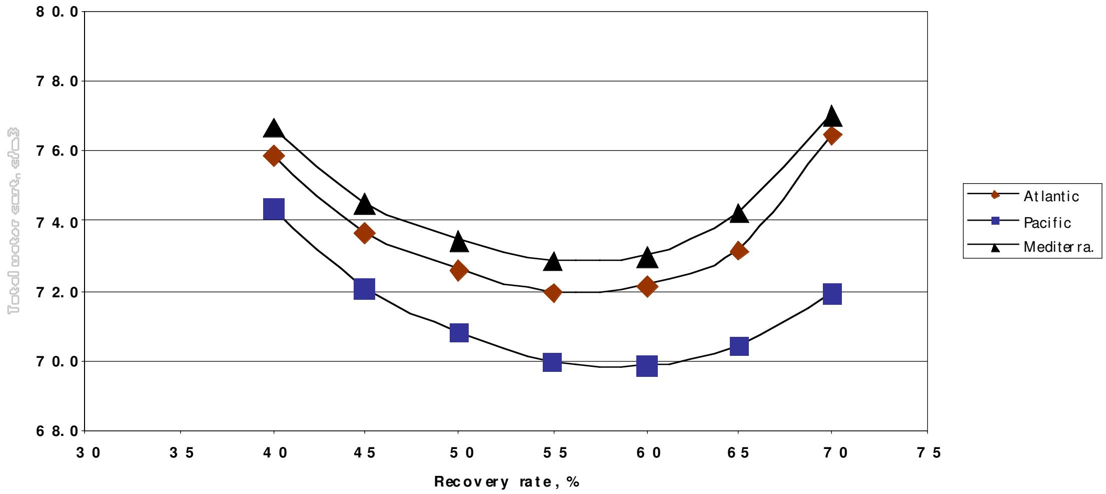

Fig 5. Selected water cost components: energy, chemicals, capital

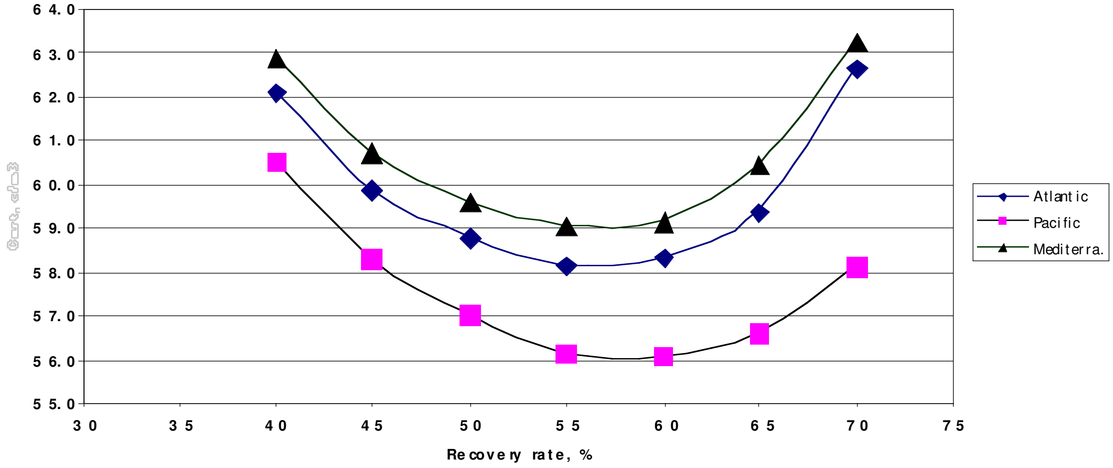

Fig 7 Water cost evaluation