



Integrating large scale seawater desalination plants within Israel's water supply system

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Abstract

The paper lists and reviews the issues, considerations and factors that faced planners in Israel in introducing large scale seawater desalination plants within the national and regional water supply systems. Most importantly, the paper quantifies the cost and benefit consequences of these factors, thereby establishing their relative weight, importance and significance. Cost consequences relate not only to the effect each factor had on desalinated water costs at their inlets to the national or regional water supply grids, but also to its effect on overall investments and operating costs related to expanding the entire water supply system to meet projected increases in demand, including seasonal, multi-seasonal and local storage capacities, distribution line sizes, pumping energy requirements, etc., and to dealing with deteriorating groundwater quality, including rehabilitation of salinized and/or contaminated wells, etc. Benefits included factors such as potable water supply reliability and quality enhancement, expanded and environmentally safer water reuse potential, etc. As will be shown, the challenge was to create a master plan which accounts for all these factors and optimizes their overall cost-benefit ratio both short and long term.

Keywords:

1. Introduction

These days, as I speak to you, Israel's second large seawater desalination plant, a 30 million m³/year SWRO plant, is being put into operation in Palmachim. This plant's output, together with the output of the 100 million m³/year Ashkelon plant, which started operating in 2005, will raise Israel's total seawater desalination capacity to

130 million m³/year, which are about 8% of the country's total potable water resources. By 2010 desalination capacity will reach 315 million m³/year, or about 17% of total potable water supply. By 2020 we expect these figures to rise to 650 million m³/year and 30%, respectively.

This growing dependency on seawater desalination, not only for meeting projected shortfalls due to increased demand, but also for improving drinking water quality, to counter the continuous deterioration in groundwater quality, had been

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forecast already fifty years ago, in the late 1950's. The government's response at the time was long range — to sponsor and support R&D in novel cost reducing desalination processes which could serve the country's needs in the future. A wide range of technologies was investigated, supported by budgets that, though modest in absolute terms compared to other national efforts, were probably the highest, world-wide, as a percent of the gross national product or overall annual government budget.

The original and unique processes and designs generated by these government sponsored efforts are familiar to all the veteran desalination experts. They include vacuum freezing - vapor compression (VFVC), also known as the Zarchin Process, secondary refrigerant freeze desalination (SRFD), low temperature mechanical vapor compression (LT-MVC), low-temperature thermal vapor compression (LT-TVC) and low-temperature multi-effect distillation (LT-MED). Hundreds of these energy-efficient and reliable seawater desalination plants were sold over the years throughout the world, wherever markets were politically open to Israeli exports.

In Israel itself, however, desalination was limited for many years to relatively small brackish water reverse osmosis desalination plants serving remote settlements in the southern, arid Arava area not reached by the national water supply grid. The largest of these plants was built in Eilat, at the northern tip of the Red Sea's Gulf of Aqaba and, after gradual expansion, produces today 45,000 m³/day from brackish water sources and 10,000 m³/day from seawater. Elsewhere in the country, water conservation measures, the transport of Sea of Galilee water from the north via the National water carrier (NWC), expanded utilization of local aquifers through a growing web of wells and the effective distribution of these blended surface and ground waters to all consumers through regional grids that included redundant loops to ensure reliability, combined with increased agricultural water use efficiency

and the partial shifting of agricultural irrigation to recycled treated wastewater, succeeded in putting off the need for seawater desalination.

By the mid-1990s, however, after several multi-year cycles of drought and over-pumping of natural water reservoirs, it became clear to the Israeli Water Commission (IWC), which is the official government agency charged with national water resources, that all lower cost alternatives have been exhausted and the time has come to start introducing and integrating large scale seawater desalination plants into the country's water supply system. The task of planning and managing the implementation of this mega-scale desalination program was assigned to the IWC's Planning Division. To assist it, the Planning Division contracted the services of ADAN Technical & Economic Services Ltd., a Tel Aviv consulting company which specializes in desalination, water and wastewater treatment, energy and the environment.

The issues, considerations and factors that faced this planning team, their costs, benefits, relative importance, significance and effect on the long range desalination master plan (DMP) that was subsequently drawn, the DMP's implementation process and its current status are the topics of this paper. They are presented and discussed within the following outline:

- the IWC's overall goal
- the DMP planning methodology
- the key planning issues
- factors and considerations relating to each planning issue
- resultant planning figures and DMP details
- the DMP's implementation
- status of ongoing projects and current plans
- summary and closing comments

2. The IWC's overall goal

The goal of the IWC was to assure that desalinated water will be available, reliably and at lowest cost, in the quantities, locations, quality and

schedule required to meet the projected gaps between supply and demand and compensate for the continuing deterioration in groundwater quality.

3. The DMP planning methodology

Studies pertaining to the preparation of the DMP were initiated in 1996 [1]. The earliest outline of the DMP was completed in 1997 [2]. The methodology used in preparing the DMP was:

- The first step was to estimate the desalinated water needs throughout the planning horizon and establish the optimal sizes and distribution of plants that will satisfy the total requirement at the end of this planning period. The objective was to derive, before-hand, the layout of plants that will have the best desalinated water cost-benefit ratio for the eventual total desalinated water production capacity, and use this layout as the target and guide in planning the step-by-step buildup of this capacity.
- A 20 year planning horizon was selected.
- Three water demand development scenarios were examined. The most probable scenario was selected for planning the final, optimal layout of plants.
- Potential desalination plant sites along Israel's Mediterranean Sea coast were identified, examined, rated and ranked by order of preference according to the criteria described in Section 5.2.
- The minimal and maximal desalination plant capacities at each site were established on the basis of the considerations described in Section 5.3.
- Optimal desalinated water quality was established, as described in Section 6.4.
- The costs that were examined and minimized were not only the costs of producing the desalinated water and delivering it to the national and/or regional water supply grids, but also all

other investments and operating costs related to expanding the entire water supply system to meet the projected demands, including seasonal, multi-seasonal and local storage capacities, downstream distribution lines, pumping energy requirements, etc. Thus, potential savings and/or postponement of investments in some of this infrastructure, external to the desalination plants' "black boxes" or "islands", also played a role in establishing the desalination plants' distribution, sizes and installation schedules.

- The benefits examined and maximized related not only to the incomes generated by increased (or non-curtailed) water-consuming economic activities and productivity, but also benefits derived by all sectors from the resultant improvement in overall water supply quality.
- The final step, once the desired final layout of plants was established, was to plan the step by step program, the "road-map", for achieving this layout. The program was flexible, geared to supplying the needs as they actually developed, i.e. the time scale for each plant installation could differ from the plan, but the end result would still be the same.

4. The key planning issues

The key issues in the planning process were, therefore, to determine:

- (1) the desalinated water requirements throughout the planning horizon;
- (2) the optimal geographic distribution of the total desalination capacity required at the end of the planning horizon;
- (3) the minimal and maximum capacities applicable at each geographic location;
- (4) the optimal desalinated water quality, cost-benefit wise;
- (5) the preferred desalination process(es);
- (6) the optimal desalination plants' installation schedule.

5. Factors and considerations relating to each planning issue

5.1. Total desalinated water requirements

The factors relevant to this determination were:

- Total projected water supply capacities from all sources and at all qualities, including brackish water, flood water catchments, wastewater reuse, etc.;
- Domestic water demand, based on projected population and per capita demand growth rates;
- Industrial water demand, including use, where possible, of brackish and treated wastewater;
- Agricultural allocations, including treated municipal wastewater and, where possible, brackish water;
- Demand by other users, e.g. nature conservation, aquifer rehabilitation and neighboring entities.

The three different water demand development scenarios were mainly a result of:

- different assumptions for population growth rates — between 1.7 and 3.5% per year;
- different assumptions for domestic per capita demand growth and growth rate — between 107 and 120 m³/year/capita;
- different values for the amounts of wastewater available for reuse — between 50 and 70% of total municipal water supply;
- different allotments of potable water to agriculture — between 400 and 600 million m³/year.

Desalinated water requirements were established on the basis of the amounts required to make up for the growing gap between supply and demand, so as to assure a 90% water supply reliability goal to all consumer sectors.

The available water supply sources, the projected demands of various consumer groups and the desalinated seawater capacities for the most probable scenario which served as the basis for the DMP are shown in Section 6.1.

5.2. Geographic distribution of desalination plants

The main facts and considerations relevant to planning the geographic distribution of the desalination plants were:

- Israel's main population and industrial centers, which require high quality water and whose steady growth in demand is the driving force behind the country's developing water shortages, are spread out along the Mediterranean Sea coast, i.e. relatively close to potential desalination plants' sites.
- So are the country's main power generation plants, which utilize the seawater as coolant and have the potential to share existing infrastructures and services with the desalination plants (seawater intake, brine disposal line, workshops and service facilities, security arrangements, etc.) and, most importantly, low cost energy. It should be noted that at the time the DMP was initially drawn thermal desalination technologies were predominant and the ability to utilize low grade steam that could be cogenerated in these power stations was deemed highly important.
- Israel has interconnected and integrated national and regional water supply systems, i.e. water shortages and needs are not local. Local needs can be supplied through these grids from a variety of sources at a variety of qualities. This means that only large blocs of water are relevant to national planning and these can be supplied through a relatively small number of large mega-plants, each enjoying economies of scale (the capacity at each plant, however, can be developed gradually, in incremental phases).
- Israel's power stations are, similarly, large and few and connected by a national grid. They are mostly sufficiently removed from nearby cities so that they have the added benefits of relatively low land costs and easier environmental permitting.

- The skeleton of the integrated water supply system is the National Water Carrier (see map in Fig. 1), which delivers Sea of Galilee water, blended along the way with inputs from various underground water sources, to the arid south. Tying directly into the NWC will enable the desalination plants to operate continuously at their nominal capacities, with only minimal investments in on-site operational storage, and, if the points where this water is introduced into the NWC are chosen properly, it will be possible to use its full existing delivery and distribution capabilities efficiently, postponing the need to invest in enlarging its main trunk and/or adding downstream delivery lines. Lowest desalinated water costs require such continuous plant operation, to minimize the desalinated water's fixed cost component. The NWC's water flow will then be adjusted to meet demand only by varying its inputs from its various natural water supply sources — the Sea of Galilee and the aquifers becoming, essentially, the system's capacitance.

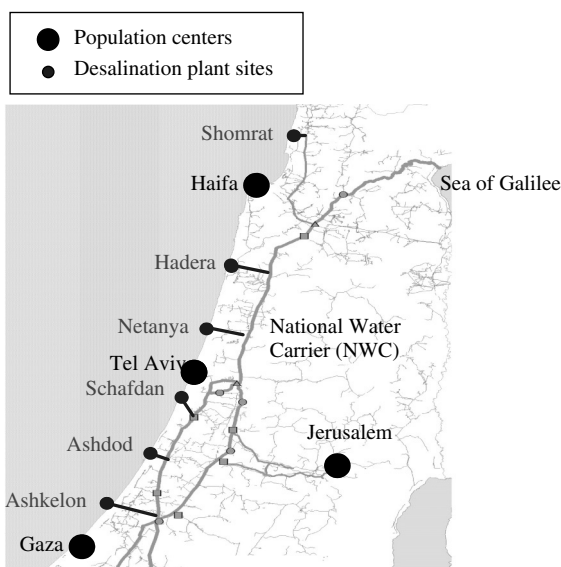


Fig. 1. DMP selected plants locations.

- The most favorable points for tying into the NWC with large blocs of water are its existing pumping stations and operational reservoirs. The capacities that the NWC could absorb at these potential junction points throughout the planning period were, therefore, a key consideration.

The above noted facts guided the selection of a series of locations alongside or near existing power stations and other utilities that could also share infrastructures and services. These locations were examined and rated on the basis of:

- Their actual distance to the nearest potential NWC junction point and the type and ownership of properties through which the inter-connecting lines would have to cross, i.e. estimated product delivery costs;
- Their actual proximity to the power stations and other utilities and their available infrastructures and services, i.e. estimated potential savings in the desalination plants' own infrastructures;
- Their proximity to the major coastal urban centers, whose water supply quality would be improved most by the plants' product, i.e. maximizing the benefits from such water quality improvement (see Section 5.4);
- Their distance downstream from the NWC's northern pumping station i.e. maximizing the savings in energy currently consumed to pump the Sea of Galilee water southward;
- Their distance from existing sources of seawater contamination (e.g. Haifa bay) or potential sources for such contamination (e.g. oil spills, wastewater and floodwater discharges);
- The availability of specific plots within these locations with:
 - (1) sufficient area, including reserves for future expansions;
 - (2) minimal land use and other statutory permitting problems, including the need

for archeological rescue excavations, environmental constraints, etc.;

- (3) reasonable land purchase or leasing costs;
- (4) reasonable accessibility (no need to invest in lengthy access roads);
- (5) reasonable distances to the sea and potential seawater intake sites;
- (6) minimal need for arranging and/or paying for rights of way for seawater supply, brine disposal and product delivery pipelines through private properties.

The ranking of these potential plant locations by order of preference was then determined on the basis of the actual cost-benefit ratio of each site (see Section 6.2).

5.3. Minimal and maximal capacities at each geographic location

The maximal capacities of plants at each potential location were determined on the basis of:

- The maximum desalinated water absorption capacity of the NWC and or regional grid at their projected input junction points;
- Site area limitations, if any;

The minimal capacities of plants at each potential location were determined on the basis of:

- The economies of scale of the potentially acceptable desalination processes — too small an initial capacity would be uneconomical and could eliminate some processes (e.g. thermal distillation plants, that have better economies of scale than membrane processes) and/or beneficial schemes (e.g. hybrid thermal and membrane plants);
- The economics of starting with a smaller plant and expanding plant capacity in phases, according to actual growth in demand, thereby benefiting from postponed investments, vis-à-vis over-sizing and benefiting from initial economies of scale.

5.4. Desalinated water quality

It was foreseen that the blending of high quality desalinated water with NWC water could significantly reduce the TDS, chloride and sodium concentrations in the regional water supplies, and most importantly their hardness and nitrate levels, thereby providing distinct benefits to all the water consuming sectors:

- Domestic consumers will benefit from the softened water supply through (a) reduced scaling and extended lifetimes of electric and solar water heaters and piping, particularly hot water piping; (b) savings in soap and detergents, ion-exchange softening resins and regeneration salts; (c) avoiding dried spots on dishes; and (d) softer and cleaner laundered clothes.
- Industrial consumers will save on their water softening and demineralization costs (1/3 of all the water used by Israeli industry is currently softened) and particularly on the high costs of disposing spent ion exchange regeneration solutions to approved sites (discharge to sewers is forbidden by law), on heat exchanger, hot water pipes and other equipment maintenance costs, and on cooling towers inhibitor costs.
- The agricultural sector will benefit from the lower salinity municipal water supply since it will reduce the chloride and sodium levels in the municipal wastewater which is destined to be reused for irrigation. This will avoid damaging crops and soils and wastewater usage could be reduced by 15–20% from current requirements, which include such an excess in order to rinse salt concentrations from the crops' root zones.

The low nitrate levels will enable, through blending, the use of high nitrate well water. These wells would otherwise require nitrate removal by electro-dialysis (ED), ion exchange or reverse osmosis. Israel's drinking water standard for

nitrate has recently been tightened from 90 to 70 ppm max. These limits make 30% of all coastal aquifer wells non-potable.

The questions that had to be resolved were: what is the optimal desalinated water quality for achieving all above benefits, what is the value of these benefits and how much is it worth investing in or paying for higher desalinated product quality.

5.5. Preferred desalination process(es)

When the initial DMP was drawn, thermal desalination plants were the most prevalent, reliable and economic plants world-wide. The technologies related to seawater reverse osmosis plants (pretreatment, membranes, energy recovery devices, etc.) were rapidly developing, but there was only minimal long-term experience with these newer technologies and no experience, in fact, in large SWRO plants, with scaled-up special items of equipment. Also, due to the foreseen new sources of relatively low cost and clean natural gas in Israel, self generation of heat and/or power for hybrid thermal/membrane desalination plants, alone or within dual purpose water and power cogeneration stations, was deemed an attractive possibility.

The study of alternative desalination processes and the selection only 2 preferred processes and energy utilization schemes was meant to standardize the plants operating throughout the country and limit them to only those tested and proven processes that are most relevant to the plant capacities required in Israel and are most suitable for its non-OPEC country energy costs. The large inefficient thermal plants common in the OPEC countries, where internal energy costs are only a fraction of world-wide prices, were deemed from the outset to be inappropriate.

Once the preferred processes were selected it was possible to project, based on their specific characteristics, the potential plants' performance

figures and their site, infrastructure and auxiliaries requirements, including:

- area requirements;
- civil engineering works requirements;
- seawater requirements (including cooling water for thermal plants);
- plants conversion ratios and resultant brine rejection flows and salinities;
- type(s) and sizes of energy supply systems;
- sensitivity to possible escalations in fuel and other key operating costs;
- product quality range;
- maximal single desalination unit sizes (based on designs currently available and sufficiently tested and proven in commercial plants);
- typical economies of scale;
- operational versatility and flexibility;
- environmental constraints.

5.6. Optimal desalination plants' installation schedule

Establishing the optimal desalination plants installation schedule involved the following factors and considerations:

- the ranking of all identified locations based on site-related costs and benefits (see Section 6.2);
- the desalinated water absorption and transportation capabilities at each point in time at the NWC junctions closest to the identified sites (as demand grows in the various population centers being supplied by the NWC, additional absorption and transport capacities will become free and available, at different projected rates, downstream of these consumption centers);
- projected difficulties and delays in getting statutory approvals and permitting at some of the preferred sites (in some cases rezoning and/or changing land usage permits were required).

6. Resultant planning figures and DMP details

6.1. Total desalinated water requirements

The initial total desalinated water requirement estimates throughout the planning horizon were updated periodically according to actual developed demands by all user sectors. The latest demand projection, updated in 2004, is presented in Table 1. The corresponding total planned desalinated seawater capacity is shown in Table 2.

6.2. Optimal geographic distribution of desalination plants

Six sites were found to be most suitable for installing large desalination plants according to the considerations noted in Section 5.2 (see layout of these sites and their connections to

Table 1

Projected water demand by consumer sectors — in million m³/year

Year	2005	2010	2015	2020
<i>Agricultural</i>				
Potable water	530	530	530	530
Brackish water	160	140	140	140
Treated wastewater	300	500	600	700
Total	990	1170	1270	1370
<i>Industrial</i>				
Potable water	85	90	95	100
Brackish water	40	40	40	40
Treated wastewater	0	5	13	15
Total	125	135	148	155
<i>Domestic</i>				
Potable water	720	840	960	1080
Nature conservation	25	50	50	50
<i>Aquifer rehabilitation</i>				
Potable water	100	100	100	0
Neighboring entities	100	110	130	150
Total demand	2060	2405	2658	2805

Table 2

Seawater desalination within Israel's projected sources of water supply — in million m³/year

Year	2005	2010	2015	2020
<i>Potable water</i>				
Natural sources	1470	1470	1470	1470
Desalinated brackish water	30	50	80	80
Desalinated seawater ^a	50	315 ^b	500	650
Sub-total	1600	1835	2050	2200
Brackish water	160	140	140	140
Treated wastewater	300	450	520	600
Total	2090	2425	2710	2910

^aCapacities required to assure 90% water supply reliability to all consumer sectors and rehabilitate the depleted aquifers with the allotments shown in Table 1.

^bDesalinated seawater capacity currently authorized by the Israeli government.

the NWC in Fig. 1). They and their main characteristics are presented, in order of their distribution from north to south, in Table 3.

The estimated site-specific costs and benefits associated with each of these locations, for a minimal-size plant, 50 million m³/year (see Section 6.3), are shown in Table 4. The costs of other site-related infrastructure and civil engineering works were found to be, more or less, equal at all potential sites and are, therefore, not included in this comparative table.

As seen from Table 4, plant site can affect total desalinated water costs by anywhere from 5 to 11 US\$/m³, their benefits from 13 to 15 US\$/m³ and their total cost-benefit equation by 2 to 10 US\$/m³. Comparing these figures to the overall desalinated water costs projected in Section 6.5 for plants of this minimal capacity at a typical site, we see that the site related costs are on the order of 7–18%, the benefits 18–25%, and their combined total 3–16% of total water costs.

Table 3
Identified desalination plant sites characteristics

Plant site	Length of seawater intake line (km)	Length of product delivery line (km)	Estimated land costs (USD/sq.m.)
Shomrat — alongside the kibbutz	4	6	20
Hadera — alongside power station	1	20	80
Netanya — near Ramat Poleg	1	15	200
Schafdan wastewater treatment plant site	2	10	50
Ashdod — alongside power station	1	6	160
Ashkelon — alongside power station	1	20	50

The ranking of the sites, based on Table 4 figures, was:

- (1) Ashdod
- (2) Ashkelon
- (3) Hadera
- (4) Schafdan
- (5) Netanya
- (6) Shomrat

6.3. Minimal and maximal capacities at each geographic location

It was found that all in all, at the end of the planning horizon, the NWC, in its present

configuration (i.e. without any additional investments) will be able to absorb and transport (mostly north to south, but in a few sections also south to north) up to 500 million m³/year, providing this total capacity is distributed properly along its length.

At each identified junction no more than 100 million m³/year can be absorbed. This was established as the maximal plant capacity at any location.

The minimal plant capacity at any location was established, on the basis of estimated unit water costs, as 50 million m³/year. Up to this capacity, with all technologies, there are distinct

Table 4
Comparison of site related costs and benefits^a

	Shomrat	Hadera	Netanya	Schafdan	Ashdod	Ashkelon
<i>Costs – US\$/m³</i>						
Seawater supply & brine discharge ^b	7.1	2.2	4.4	5.4	2.2	2.2
Product delivery to NWC ^b	3.9	6.4	5.6	4.1	1.4	6.8
Land costs	0.2	0.6	1.5	0.4	1.2	0.4
Total costs	11.2	9.2	11.5	9.9	4.8	9.4
<i>Benefits – US\$/m³</i>						
Water quality improvement	13	13	13	12	12	11
Savings in NWC pumping energy	0	1	1	1.2	2.6	4
Total benefits	13	14	14	13.2	14.6	15
Benefits less costs	1.8	4.8	2.5	3.3	9.8	5.6

^aBased on a 50 million m³/year plant, 20 year amortization period, 7% interest and 6 US\$/kW h power cost.

^bCapital recovery and pumping costs.

economies of scale. From this capacity on, up to about 100 million m³/year, added benefits diminish, and above 100 million m³/year economies of scale become only marginal.

6.4. Optimal desalinated water quality

The maximum desalinated water chloride concentration was established initially as 150 ppm, so that after the expected addition of about 100 ppm of chloride by domestic and industrial users, its content in the treated municipal wastewater would not exceed 250 ppm. This is the limit set for agricultural irrigation, the main wastewater reuse application. Sodium and boron concentrations were similarly limited by irrigation water quality constraints and typical municipal usage additions to 100 and 0.2 ppm, respectively.

The product's pH, Langlier Index and turbidity limits were dictated by Mekorot, the national water utility company that operates the NWC and most of the regional water supply systems, as 7.0–8.0, 0 to +0.5, and 0.5 NTU max, respectively. Mekorot was given the responsibility of accepting the product of all the desalination plants at their battery limits, chlorinating and storing it operationally and pumping it to the NWC.

The original DMP's goal was to minimize post-treatment costs by blending the slightly corrosive product with local marginal and even brackish well water. Such low grade water sources, all with high natural hardness content, were identified near most of the preferred desalination plant sites, and their blending with the high quality desalinated product would enable incorporating them into the potable water system without the need to desalinate them first.

Studies performed by the IWC's consultants, ADAN Technical & Economic Services Ltd., determined that the value of softening water supplies to domestic and industrial consumers ranged from 5 to 15 US\$/m³, depending on the local water quality, its blend ratio with desalinated water and the main types of consumers

at each desalination plant site. It was also determined that the benefits to agricultural users from reducing product water's chloride concentration from 150 to 20 ppm and the boron concentration from 0.5 to 0.3 ppm was in the range of 4 US\$/m³.

6.5. The preferred desalination process(es)

Two desalination technologies and plant schemes were identified as being most suitable for the relevant plant capacities and for Israel's specific energy costs [3]:

- (1) A single-purpose seawater reverse osmosis (SWRO) plant operating with grid supplied power;
- (2) A hybrid SWRO and low-temperature multi-effect distillation (LT-MED) plant, with an independent combined-cycle power station utilizing natural gas, in two options:
 - (a) a power station sized to supply only the desalination plants' heat and power requirements, without any export of power — the "Water Factory" concept;
 - (b) a power station sized to export power to the grid during peak power demand periods, thereby increasing its cogenerated heat output and enabling the incorporation of larger thermal desalination plants, and, more importantly, reducing total water costs by crediting them with the profits from exported power sales.

When the initial DMP was prepared, estimated water costs from 50 million m³/year plants based on these technologies, at the plants' battery limits, based on Israeli energy, capital and other relevant costs prevailing at the time [3], were:

- (1) The single-purpose SWRO plant — 65–74 US\$/m³
- (2) The hybrid LT-MED/SWRO plant without power export — 61–65 US\$/m³ with NG and, should NG not be available, 72–75 US\$/m³ with LFO.

- (3) The hybrid LT-MED/SWRO plant with power export — reductions of up to 20 US\$/m³ from item 2 indicated costs, depending on the designed power to water ratio.

Note: the above costs include typically expected site-related costs such as land, civil works, seawater supply and brine discharge (see Section 6.2), but excluding the costs of product delivery to the NWC.

6.6. The DMP's desalination plants' installation schedule

The initial DMP's desalination plants' capacity and installation schedule, based on the most probable water demand scenario foreseen at the time, is shown in Table 5.

As can be seen, this schedule dealt with only the first 500 million m³/year of total desalinated water output, the capacity that could be absorbed by the NWC without additional investments in downstream infrastructure, as noted in Section 6.3. It spread this capacity evenly in the order of the sites' ranking, starting with the highest ranked site, Ashdod. This ensured that more population and industry centers would

benefit soonest from the resultant water supply quality improvement. Water quality improvement, as shown in Table 4, was the major benefit from the large desalination program and a prime factor in planning the layout of the plants.

The build-up of capacity was in incremental steps of 50 million m³/year, the smallest recommended plant size at any site as noted in Section 6.3, reaching no more than 100 million m³/year at any site, the maximum capacity that could be absorbed by the NWC at any single junction point.

7. The DMP's implementation

7.1. Reserving potential desalination plant sites

The first steps taken to implement the DMP were to reserve within the National Outline Scheme (NOS) that was being drafted at the time (as the master plan for all land uses in Israel up to the year 2020) sites sufficient for the installation of desalination plants with a total capacity of at least 775 million m³/year (including the expansion of the existing SWRO plant in Eilat to 20 million m³/year).

The distribution of this capacity within the NOS section devoted to water, code named TAMA-34b, is shown in Table 6. As can be seen, the reserved sites did not include Netanya, since new permitting problems were discovered with this particular site, but included two new sites, one within Haifa Bay and the second another Ashdod site. The large capacities at the Schafdan and Ashdod sites allowed for routing some of the product also directly into these nearby metropolitan areas' water distribution systems.

7.2. Contracting of plants to date

Typically, as with many other long-range master plans, the original DMP had to be altered and adapted to fit reality and the changing situation on the ground.

Table 5
Original desalinated water capacity build-up program

Plant location	Plant capacity — million m ³ /year		
	2005	2010	2015
Ashdod	50	50	100
Ashkelon		50	100
Hadera		50	100
Schafdan		50	100
Netanya		50	50
Shomrat		30 ^a	50
Total	50	280	500

^aThe current regional water system's absorption capacity limit.

Table 6
Sites reserved within the National Master Plan TAMA-34b

Desalination plant site	Total projected capacity—million m ³ /year
Shomrat	30
Haifa Bay	30
Hadera Power Plant	100
Shafdan	200
Palmachim	100
Ashdod Industrial Zone	150
Ashdod Power Plant	45
Ashkelon	100
Eilat	20
Total	775

The schedule in Table 5 was prepared before a prolonged drought, combined with the continuing and even accelerating growth in the price-inflexible demand by the municipal sector, led to a national water supply crisis. In spite of the severe curtailment of water allotments to agriculture, industrial and domestic users, water levels in all the major natural water storage reservoirs fell below their minimal “red lines”, threatening their quality through sea and brackish water intrusion.

As a result of this crisis, the Israeli government, on March 1999, authorized the initiation of a wide range of new water projects. These related to water-use conservation, contaminated wells rehabilitation, wastewater reuse, additional brackish water desalination, and, for the first time (over-ruling Ministry of Finance objections), also large scale seawater desalination [4].

The initial seawater desalination authorization (with its all-important budget approvals) instructed the Water Commission to prepare international tenders for the immediate installation, financing and operation, on a long-term basis, of plants totaling 200 million m³/year, utilizing private sector financing and contracting. This figure was later upped to 400 million m³/year and

today, as noted earlier, after a further revision, stands at 315 million m³/year by 2010.

The need to introduce, urgently, large quantities of desalinated water forced the IWC to modify its original DMP schedule. At the time of the government resolution, in 1999, there was only one site within the DMP’s list of preferred locations that was available immediately for installing a large seawater desalination plant, i.e. required only minimal statutory approvals and permits — an area within the Eilat-Ashkelon Oil Pipeline Company’s Mediterranean Sea terminal at Ashkelon (the National Outline Scheme TAMA-34b noted above was approved only in 2004).

A build, operate and transfer (BOT) tender for a 50 million m³/year plant was issued for this specific site in September 2000. Three bids were received and the contract with the winning bidder, V.I.D., a special purpose company (SPC) formed by a consortia of IDE Technologies Ltd., Veolia Water S.A. and Elran Infrastructures Ltd., was signed on November 2001. A subsequent contract, doubling the capacity to 100 million m³/year, was signed in April 2002. Financial closure for the complete project was reached in January 2003 and the notice to proceed in construction (NTP) issued in April 2003.

The lack of additional sites at the DMP’s preferred locations capable of being approved and permitted rapidly meant that tenders for the other urgently needed plants had to be on the basis of build, own and operate (BOO) schemes, whereby all bidders had to pre-qualify first, inter alia, on the basis of their ability to offer their own suitable and immediately available sites. To draw a sufficient offering of such scarce sites, smaller sites, that could accommodate plants with capacities below the preferred minimum, had to be allowed. The capacities of the plants in the BOO-tender (issued in May 2001) were, therefore, reduced to 15–30 million m³/year.

Bids for six potential sites were received in response to this second tendering process. The construction of four plants, each with a capacity

of 30 million m³/year, was contracted in October 2002 — at Shomrat, Haifa Bay, Palmachim and Ashdod. Only the Palmachim project's special purpose company (SPC), Via Maris Desalination Ltd., owned by Granit Hacarmel Investments Ltd., TAHAL Consulting Engineers, OCIF Investments and Developments Ltd, Middle East Tube Co. Ltd. and Oceana Marine Research Ltd., managed to arrange the necessary financing and receive the NTP.

In November 2006, following a lengthy tendering process, a BOT contract was signed for a 100 million m³/year plant to be installed alongside the large power station complex, at Hadera. The plant will be built by H₂ID, an SPC owned by IDE Technologies Ltd. and Housing and Construction Holding Co. Ltd.

7.3. Contracted plants' designs

The main design features of the plants' contracted to date are:

- All designs are based on the seawater reverse osmosis (SWRO) process (reflecting the large improvements in this technology over the past few years).
- The plants utilize various multi-pass desalination schemes to reduce both boron and chloride concentrations in the product (see resultant product quality in Section 7.3).

- The plants utilize advanced energy-recovery devices to reduce specific energy consumptions to below 4 kW h/m³.
- The plants rely on conventional multi-media gravity filters, in lieu of UF, for feed pre-treatment.
- Where possible on-site self-generation of power, utilizing newly available natural gas supply sources, was selected, in lieu of purchasing power from the national electric company.

7.4. Contracted plants' water quality

As a result of incentives (bonuses) built into all tenders [4], the actual bid and contracted product qualities, after post-treatment, were as exhibited in Table 7. The benefits from this extremely high quality water are already evident in the towns downstream of the operating Ashkelon plant, as shown in Section 7.5.2.

Meanwhile, following further deliberations and considerations, particularly relating to the possible adverse effects from introducing the desalinated water into the local water supply systems (the possible dissolution of some of the protective scale coatings and the release of entrapped corrosion products and the formation of "red water"), new requirements have been imposed on all existing and new seawater

Table 7
Contracted and actual desalinated water quality

Quality parameter	Units	Contractual requirements			Ashkelon actual quality
		Ashkelon	Palmachim	Hadera	
Chlorides	ppm	20	80	20	10–15
Boron	ppm	0.4	0.4	0.3	0.2–0.3
PH	ppm	7.5–8.5	7–8	7.5–8.3	8–8.5
LSI	ppm	0.2–0.5	0.5–0.5	0–0.5	0–0.5
Alkalinity (CaCO ₃)	ppm	–	–	80<	45–50
Hardness (CaCO ₃)	ppm	60>	75–100	80–120	90–110
Turbidity	NTU	0.5	0.8	0.5	0.15–0.2

Table 8
New product quality requirements after post-treatment

Quality parameter	Units	Recommended values
Alkalinity	ppm as CaCO ₃	>80
Calcium	ppm as CaCO ₃	80–120
CCPP	ppm as CaCO ₃	3.0–10
pH		<8.5

desalination plants post-treatment sections. These are summarized in Table 8.

As can be seen from Table 8, the qualitative corrosivity–passivity Langlier Index requirement was replaced by the quantitative calcium carbonate precipitation potential (CCPP) requirement and a minimum alkalinity requirement was added.

7.5. Contracted plants' water prices

Table 9 presents the water prices at the plants' battery limits for the three plants contracted so far, at the time of contracts signing and in December 2006, including adjustments due to recognized cost escalations. The exhibited prices are in US\$/m³, at the New Israeli Shekel to US Dollar exchange rates prevailing at these times.

The low initial water costs (i.e. at contract signing dates) vis-a-vis the costs projected within

the DMP (see Section 6.5 above) are due mainly to:

- the large improvements in SWRO plants' energy consumption and main components' costs;
- the economies of scale gained with the very large plants;
- the assumptions by the government of critical project risks, to attract lower cost financing [5];
- the long water purchase periods of the BOT and BOO agreements (25 years).

The higher current water prices, which are more in line with the DMP's estimates, reflect the large escalations in energy costs over the past two years.

7.6. Contracted plants' benefits

7.6.1. Water supply reliability

The importance of the desalination plants' output to the water supply system is borne out by the supply and demand statistics of the past year, which was a below average rainfall year. These show that in spite of all the new projects relating to water-use conservation, wastewater reuse, etc. authorized by the government in 1999 (see Section 7.1 above) and executed since then by the IWC, potable water demand exceeded natural replenishment by about 250 million m³. This gap is about equal to the combined outputs of the Ashkelon, Palmachim and Hadera plants.

Table 9
Contracted desalination plants water prices

Plant	Contracted water price — US\$/m ³					
	Ashkelon ^a		Palmachim		Hadera	
	Contract date	December 2006	Contract date	December 2006	Contract date	December 2006
Total price	50.9	65.5	56.2	73.6	59.5	60.9

^a Average for two separate 50 million m³/y contracts.

It is clear that without the 100 million m³/year contributed by the Ashkelon plant, the only plant operating so far, water levels in all the natural reservoirs would have fallen dangerously low, making necessary new water allotment reductions, with all their economic implications.

Based on the incomes generated with the resultant non-curtailed water supply by the least profitable economic activity, agriculture, with the lowest value crops (which would be the first to be eliminated), we have estimated these implications, i.e. the benefits from the desalinated water input, at 1.2–2.5 US\$/m³, depending on type of crop and water productivity, and, for the total annual output of the Ashkelon plant, at 12–25 million USD [5].

Had we calculated these benefits on the basis of potential losses in income due to curtailment of water supply to other, more profitable crops, let alone to commercial and/or industrial consumers, whose incomes from water related productivity are significantly higher, they would have been proportionately larger.

7.6.2. Water supply quality improvement

Table 10 exhibits actual improvements in water supply quality at the major domestic and industrial centers downstream of the Ashkelon desalination plant. The variations in the data are due to different blending ratios between

Table 10

Water supply quality before and after blending with Ashkelon plant product

Location	Season		TDS			Hardness			Cl		
			ppm	Reduction		ppm as CaCO ₃	Reduction		ppm	Reduction	
				ppm	%		ppm	%		ppm	%
Beer Sheba	Winter	Before	647	266	41	323	132	41	193	105	54
		After	381			191			88		
	Summer	Before	573	148	26	267	57	21	180	71	39
		After	425			210			109		
Kiriath Gat	Winter	Before	633	87	14	338	65	19	165	26	16
		After	546			273			139		
	Summer	Before	478	148	31	212	46	22	145	80	55
		After	330			166			65		
Ofakim	Winter	Before	598	265	44	310	141	46	168	102	61
		After	333			169			66		
	Summer	Before	429	121	28	195	38	24	119	61	51
		After	308			157			58		
Shderot	Winter	Before	475	183	39	250	105	42	150	94	63
		After	292			145			56		
	Summer	Before	393	30	8	185	17	9	99	15	15
		After	363			168			84		
Netivot	Winter	Before	557	288	52	277	138	50	170	125	74
		After	269			139			45		
	Summer	Before	374	97	26	177	35	20	89	42	47
		After	277			142			47		

the desalinated water and NWC and local wells' water, driven by seasonal demand variations.

The following figures illustrate the consequential improvement in the wastewater quality at two of these municipalities' wastewater treatment plants (WWTP):

Beer Sheva WWTP

Conductivity before operation of the desalination plant — about 2.0 dS/m.

Conductivity after operation of the desalination plant — about 1.5 dS/m.

Improvement — 25%

Shderot - Shaar Hanegev WWTP

Chloride concentration before operation of the desalination plant — 330–400 ppm.

Chloride concentration after operation of the desalination plant — 240–280 ppm.

Improvement — 27–30%

It is seen that, as predicted, the domestic and industrial consumers are benefiting from reduced water supply hardness (reduction of up to 46% during the winter) and the agricultural sector, which reuses the treated wastewater, is benefiting from its lower salinity (reductions of up to 74% in chloride content and up to 50% in TDS, which lower the wastewater salinity by 25–30%). There is no doubt that as larger quantities of desalinated water are introduced upstream into the NWC, these figures will improve further.

7.7. Main environmental protection issue encountered to date

The main environmental issue encountered to date (environment being the major theme of this conference) has been the high iron content of the brine discharge stream at Ashkelon after mixing with the filters' backwash water. The plant doses the seawater feed with about 15 ppm of ferric sulfate coagulant and the reject brine

stream, after mixing with the filters' backwash water, contains about 28 ppm of ferric sulfate, of which about 5 ppm are ferric ions. Though the brine is mixed with the Ashkelon power station cooling water discharge, it discolors the sea with a red plume. The Israeli Ministry of Environment (as will be discussed in another paper at the conference) views this, as well as the total annual discharge of iron to the sea, about 450 tons per year, as problematic and demands its resolution.

8. Status of ongoing projects and current plans

The current situation, status of ongoing projects and plans are:

- Total approved desalination capacity
315 million m³/year by 2010
- Current distribution, capacity and status of contracted plants
Ashkelon — 100 million m³/year — operating since 2005
Palmachim — 30 million m³/year — starting operation in May 2007
Hadera — 100 million m³/year — expected operation — end of 2009
- Current projects in pre-tendering phase
Ashdod — 45 million m³/year
Added capacity by expansion of existing plants — 40 million m³/year
- Current projects in longer term planning (by 2015)
Schafdan — 100 million m³/year
Added capacity by expansion of existing plants — 85 million m³/year

Table 11 summarizes the above information. Fig. 2 presents the layout of the plants. Figs. 3 and 4 show recent aerial photos of the Ashkelon and Palmachim plants. Fig. 5 shows a three-dimensional artist's concept of the Hadera plant.

Table 11
Current and programmed desalinated water capacity

Plant location	Plant capacity — million m ³ /year		
	2007	2010	2015
Ashkelon	100	100	100
Palmachim	30	30	30
Hadera	—	100	100
Ashdod	—	45	45
Schafdan	—	—	100
To be bid ^a	—	40	125
Total	50	315	500

^aAs expansion, by existing plant owners-operators.

9. Summary and closing comments

Planning for the introduction and integration of large scale seawater desalination in Israel began in earnest about ten years ago, in the mid-1990s. The planning methodology consisted of conducting a series of studies into the main issues related to the huge investments and operating costs associated with this new national water source, and deriving, on the basis of these

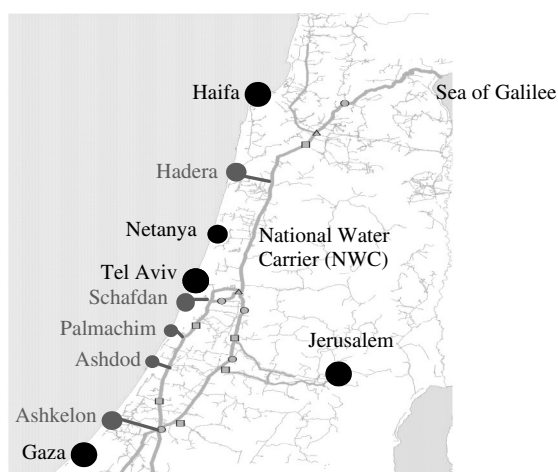


Fig. 2. Current & planned plants locations.



Fig. 3. 100 million m³/year Ashkelon plant.

studies' findings, an optimal long-range desalination master plan (DMP).

The execution of this plan was initially blocked by the Israeli Ministry of Finance, which looked at seawater desalination as a last resort of action to be adopted only after the development and utilization of all other water supply sources and after a water pricing reform would reduce agricultural demand. It was subsequently rushed through on a fast-track basis due to evolved water supply shortages. Though these politically driven constraints and postponements required repeated updating of the DMP, it has proven, nonetheless, to be a valuable, flexible tool.

It was used to guide a multi-project tendering and site permitting process which resulted not



Fig. 4. 30 million m³/year Palmachim plant.



Fig. 5. An artist's concept of the 100 million m³/year Hadera plant.

only in the ordering of plants capable of producing very high quality and low cost desalinated seawater, but in maximizing the benefits from this high-quality product by distributing it preferentially to the consumers that stand to gain the most from their water supply's quality improvement.

The Israeli Water Commission will continue to update and utilize this tool in the coming years, expanding its planning horizon and adding further desalination capacity, until, as we expect, desalinated seawater will eventually constitute as much as 50% of total potable water supply.

References

- [1] Daniel Hoffman and Amnon Zfati, Considerations governing the selection and design of optimal seawater desalination plants for integration within conventional water supply systems, in: The International Conference on Water Resources Management Strategies in the Middle East in memory of the late Prime Minister Yitzhak Rabin, Herzelia, Israel, 24–26 November 1996.
- [2] Amnon Zfati, A framework for integrating large-scale seawater desalination into the water supply system, Submitted to the Planning Division, the Israel Water Commission, February 1997 (in Hebrew).
- [3] Amnon Zfati and Daniel Hoffman, Techno-economic evaluations and characterization of the optimal desalination plants for Israel, Submitted to the Planning Division, the Israel Water Commission, January 1998 (in Hebrew).
- [4] Yosef Dreizin and Oded Fixler, Large seawater desalination tenders — the Water Commission's objectives, approach and requirements, Israel Water Commission, in: The 7th Annual Israel Desalination Society Conference, Tel Aviv, Israel, 2–3 March 2005.
- [5] Yosef Dreizin, Ashkelon seawater desalination project — off-taker's self costs, supplied water costs, total costs and benefits, *Desalination*, 190 (2006) 104–116.

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