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DECISION MAKING IN WATER RESOURCES PLANNING FOR SAUDI ARABIA

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ABSTRACT

A quantitative survey on the availability of ground and surface water in various regions of Saudi Arabia is carried out and the anticipated future demands are reviewed. Alternate feasible water development plans are evaluated to meet the increasing demands in various sectors. Demand relationships with time are established. Cost-capacity relationships for the selected sources are developed. An optimization scheme based on dynamic programming principles is formulated and applied to determine when and how much capacity should be added to the system to meet future demands.

INTRODUCTION

The need for treated water in the kingdom is expected to increase manyfold in the next two decades due to anticipated high growth rate of the urban population, improvements in the standard of living, and rapid industrial and agricultural development. To meet such demands, water resource development plans at the national and regional levels were prepared by the Ministry of Agriculture and Water [20]. The main objective of these plans is to ensure the supply of adequate quantities of potable water of acceptable standards for urban, industrial and agricultural developments. Dams to collect surface waters for both agricultural and recharge purposes are also being planned and constructed.

This paper presents an overview of the available ground and surface water resources and anticipated water demands in different sectors for the next two decades. Demand forecasting models are developed and the economics of water resource alternatives is studied. A methodology using dynamic programming principle is formulated and applied to optimize the expansion of the water resources system.

WATER RESOURCES IN SAUDI ARABIA-AN OVERVIEW

Many studies have been conducted in the past to evaluate the available ground and surface water resources in the Kingdom of Saudi Arabia [1,6,10,11, 16,17,19,20]. Among these, the national water balance study presented in the Third Development Plan [20] is the most comprehensive and most recent. The principal water consumers in this study are categorized as (a) residential, commercial and industrial consumers; (b) rural consumers including livestock;

and (c) agricultural consumers.

For management procedures, the Ministry of Agriculture and Water has divided the Kingdom into five water resources regions. These are: eastern, northern, central, western and south western regions. The boundaries of these regions are delineated on the basis of the availability of groundwater resources in each region, aquifer characteristics, existing and planned regional developments and distinct hydrological conditions. In each region four alternative water resources are suggested. These are; renewable resources, non-renewable resources, desalination, and reclamation from waste waters. Table 1 summarizes the water budget statistics for each alternative on a regional basis [20].

An evaluation of these alternatives shows that the western region is the most critical where future water demands are expected to be high. To meet such demands, desalination expansion is recommended as the most feasible water supply source.

Reclaimed water from urban waste waters is also suggested as a potential source for agricultural and industrial needs. Water will be reclaimed from urban waste waters particularly from cities with population over 100,000. These cities, at present, are: Riyadh, Jeddah, Dammam Metropolitan Area, Makkah, Al-Madinah, Taif, and Hofuf. It is anticipated that the reclaimed water will contribute the equivalent of 15% of the Kingdom's known conventional resources. Due to large proven ground water reserves in the central and northern regions, the shortage in these regions is not very critical since these reserves can easily be utilized to supply water to over 40% of the Kingdom's irrigated areas projected for the next 20 years [20].

WATER DEMAND FORECASTING MODELS

Water utilization data listed in Table 1 were used to develop simple water demand models. The coefficient of correlation was also computed to test the model validity. The demand forecasting model developed in this study is based on the following exponential equation.

$$D_t = a\, e^{b\, t} \tag{1}$$

where,

D_t is the estimated water requirements in million cubic meter/year at time t in different regions;

t is the time in years (t=0, at year 1399 H)

a and b are regression coefficients determined statistically from water utilization data.

In order to test the validity of the previous equation, the correlation coefficient 'ρ^2' was also computed. The regression coefficients and the respective correlation coefficients for each resource and area are listed in

TABLE 1 - NATIONAL WATER BALANCE [20]

(million cubic meters per year)

Region	Water Resources	1400	1405	1410	1420	Water Utilization	1400	1405	1410	1420
Central	Non-renewable	2000	2000	2000	2000	Urban & industrial	128	196	298	579
	Renewable	200	200	200	200	Rural & livestock watering	8	8	9	11
	Desalination	–	193	193	193	Irrigated agriculture	890	790	1090	1710
	Reclaimed from Urban wastewater	–	40	90	200	Surplus (Deficit)	1174	1439	1086	293
	Subtotal	2200	2433	2483	2593	Subtotal	2200	2433	2483	2593
Western	Non-renewable	–	–	–	–	Urban & industrial	219	343	479	897
	Renewable	225	225	225	225	Rural & livestock watering	7	7	7	8
	Desalination	52	237	392	777	Irrigated agriculture	125	200	255	405
	Reclaimed from Urban wastewater	–	85	155	330	Surplus (Deficit)	(74)	(38)	31	22
	Subtotal	277	547	772	1332	Subtotal	277	547	772	1332
Eastern	Non-renewable	1000	1000	1000	1000	Urban & industrial	68	153	231	402
	Renewable	–	–	–	–	Rural livestock watering	1	1	1	1
	Desalination	11	169	169	169	Irrigated agriculture	367	470	550	575
	Reclaimed from Urban wastewater	–	15	25	50	Surplus(Deficit)	575	560	412	241
	Sub total	1011	1184	1194	1219	Subtotal	1011	1184	1194	1219

TABLE 1 (CONTINUED)

Region	Water Resources	1400	1405	1410	1420	Water Utilization	1400	1405	1410	1420
Northern	Non-renewable	450	450	450	450	Urban & industrial	20	32	54	111
	Renewable	15	15	15	15	Rural & livestock watering	6	7	9	12
	Desalination	–	4	4	4	Irrigated agriculture	150	138	180	220
	Reclaim from Urban wastewater	–	–	15	40	Surplus (Deficit)	289	292	241	166
	Subtotal	465	469	484	509	Subtotal	465	469	484	509
Southwestern	Non-renewable	–	–	–	–	Urban & industrial	67	99	149	290
	Renewable	705	705	705	705	Rural & livestock watering	5	5	5	6
	Desalination	–	2	36	55	Irrigated agriculture	300	275	270	310
	Reclaimed from Urban wastewater	–	–	50	110	Surplus (Deficit)	333	328	367	264
	Subtotal	705	707	791	870	Subtotal	705	707	791	870
Kingdom	Non-renewable	3450	3450	3450	3450	Urban & industrial	502	823	1211	2279
	Renewable	1145	1145	1145	1145	Rural & livestock watering	27	28	31	38
	Desalination	63	605	794	1198	Irrigated agriculture	1832	1873	2345	3220
	Reclaim from Urban wastewater	–	140	335	730	Surplus (Deficit)	2247	2616	2137	986
	TOTAL RESOURCES	4658	5340	5724	6523	TOTAL UTILIZATION	4658	5340	5724	6523

Table 2. In all cases, except for the agricultural sector, the correlation coefficient 'ρ^2' is above 0.90. This implies that an exponential regression model similar to Equation (1) is suitable for forecasting demands in all sectors except in irrigated agriculture. The coefficient 'a' in Table 2 indicates the initial demand and 'b' the growth rate. The negative values of 'b' in the water forecasting model for the surplus mean that the surplus water is being utilized with time thus showing an improvement towards better water resources management.

A similar study on demand forecasting was conducted for major cities in Saudi Arabia. The cities selected were Jeddah, Riyadh, Dammam and Makkah. Based on the estimated annual demand data for these cities [2], the parameters of the demand forecasting model were computed and are listed in Table 3. It is found that the demand growth factor 'b' for Makkah, which is 0.1142, is relatively high compared to other cities where it varies from .055 to 0.082.

COST-CAPACITY RELATIONSHIP

Due to the lack of cost information on other alternatives, the cost evaluation made in this section is restricted to desalination only. The total cost of water supplied by a desalination system consists of the capital costs, variable operating costs, and the annual fixed operating and maintenance costs. The capital and fixed operations and maintenance costs are a function of the plant capacity while the variable costs are a function of the current output rate of the plant.

Using data listed in Table 4 on multi-stage flash evaporation (MSF) plants installed in Saudi Arabia, a cost-capacity relationship was established as follows:

$$C_c = 43200\ (X)^{0.751} \tag{2}$$

where,

C_c is the capital cost in SR/m^3/day; and X is the capacity in thousand m^3/day.

Due to the lack of information on annual operations and maintenance costs for different MSF plants installed in Saudi Arabia, this cost-component could not be expressed as a function of capacity. However, a value of 24% of the known capital cost is suggested by Larson et al [12]. These relationships could be used in optimizing system expansion.

OPTIMAL EXPANSION OF WATER RESOURCES SYSTEM

As revealed in Table 1, water demand in each sector increases exponentially with time. To meet these demands, the planning of water supply ideally should consider the optimal timing and size of the additional plant capacity. Water resources planners and decision makers are faced with such critical issues since the expansion of these utility services generally depends upon

TABLE 2 - WATER DEMAND FORECASTING MODELS FOR SAUDI ARABIA*

	CENTRAL			WESTERN			EASTERN			NORTHERN			SOUTH-WESTERN			TOTAL		
Activities	Regression Coefficients		ρ^2	Regression Coefficients		ρ^2	Regression Coefficients		ρ^2	Regression Coefficients		ρ^2	Regression Coefficients		ρ^2	Regression Coefficients		ρ^2
	a	b		a	b		a	b		a	b		a	b		a	b	
Urban and Industrial	123.3	.0751	.99	213.7	.0693	.99	77.3	.0845	.92	19.2	.0858	.99	63.7	.0732	.99	500.5	.0744	.99
Rural and Livestock	7.6	.0171	.93	6.8	.0069	.77	1	0	1	3.8	0.353	.98	5.6	.0139	.10	25.8	.0177	.97
Agriculture	738.9	.0391	.85	129.9	.0565	.96	393.2	.0212	.79	136.3	.0222	.83	281.1	.0026	.10	1683.3	.0300	.95
Surplus (Deficit)	1784.5	-.0753	.78	-	-	-	663.6	-.0462	.95	332.1	-.0297	.92	357.5	-.0111	.46	2916.4	-.0453	.78
Sub Total	2253.8	.0074	.82	302.5	.0750	.94	1064.1	.0079	.60	459.7	.0047	.97	684.6	.0114	.93	4715.9	.0162	.96

* Type of model used is = $D_t = ae^{bt}$

where,

D_t is demand in million cubic meter per year at time t

t = 0 at 1399H and

= 1 at 1400H etc

TABLE 3 - URBAN WATER DEMAND FORECASTING MODELS* FOR SELECTED MAJOR CITIES IN SAUDI ARABIA

Items	Regression Analysis		
	a	b	ρ^2
Water Demand Model for Jeddah	158.74	.0821	0.920
Water Demand Model for Makkah	73.89	0.1142	0.948
Annual Groundwater Supply Model for Jeddah and Makkah Regions	154.74	.0533	0.622
Desalination Expansion Model for Jeddah and Makkah Regions	67.42	0.1562	0.952
Riyadh Water Demand Model	151.93	.0645	0.971
Water Demand Model for Dammam Metropolitan Area	106.04	.0558	0.990

* Demands in thousands cubic meter per day

TABLE 4 - COST EVALUATION OF SOME MSF DESALINATION PLANTS IN SAUDI ARABIA [22]

Location	Approx. operating year	Production water (1000 m^3/day)	Contract cost Million SR
Wajh I	1969	0.227	1.96
Jeddah I	1970	18.925	179.32
Khobar I	1973	18.388	162.45
Khafji I	1974	0.454	10.39
Jeddah II	1978	37.850	720.30
Jeddah III	1979	75.700	1800
Farasan	1979	0.500	42.19
Haql I	1975	0.454	44.59
Wajh II	1979	0.454	72.85
Duba II	1979	0.454	72.85
Jeddah IV	1982	189.250	2586
Yanbu/Medina I	1981	94.625	1372
Jubail I	1982	113.550	2298
Rabegh	1982	0.908	90.90
Khobar II	1982	189.250	3077
Jubail	1984	946.250	5419

a number of factors such as growth rate, expected economic life of the utility, economies of scale, annual discount rates on the investment and rate of interest on bonds issued for the utility construction.

To accomplish the objective of optimal capacity expansion in the field of water resources planning, mathematical optimization techniques have been applied in the past [2, 4, 5, 8, 9, 13, 15, 18, 22]. Scarato [18] has presented a minimum cost method to determine optimum timings and size components to meet future water demand. In other studies, the dynamic programming technique has been used in deciding the optimal sequences for the construction of water supply projects [5, 15]. Hinomoto [8] has developed a multi-stage capacity expansion model that is used to expand municipal water treatment systems. Zukovs et al [22] have used a dynamic programming formulation for optimal capacity expansion of wastewater treatment plants servicing sewerage system.

This section briefly describes the application of dynamic programming in the expansion of water supply systems to meet domestic and industrial demands in urban areas. The methodology presented in this study is restricted to the expansion of water supply systems based on desalination only. However, it can be modified for expanding desalination processes used in conjunction with available ground and surface water resources [7, 14].

Dynamic programming is a mathematical technique which is useful for making a sequence of interrelated decisions [3]. Formulations, using this technique, require decomposition of the state and decision variables into a number of stages. At each stage, a policy decision is made which then transforms the current state into a state associated with the next stage.

In this study, the total capacity needed for a planning period 'T' is the state variable. Each one year interval is a single stage with a total of 'T' stages. The decision variables involved are the capacity increment and the time. The total true cost at the beginning of a time period is the summation of the discounted cost of capacity increment '$X_{t,s}$' and the optimal discounted cost of system expansion at the beginning of period 's+1' to meet demand up to the end of planning period 'T'. The objective here is to minimize the total discounted cost which can be mathematically represented by the following equation:

$$f^*_t(X_{t,T}) = \text{Min}\left[C(X_{t,s}) + (1+r)^{-(s-t)}\, f^*_s(X_{t,T} - X_{t,s})\right] \qquad (3)$$

$$X_{t,s}$$

$$t \epsilon T \begin{bmatrix} t = 1,2\ldots, T \\ s = t,t+1,\ldots, T \end{bmatrix}$$

where,

$f_t^*(X_{t,T})$ is the minimum discounted sum of capital and opertating costs for the desalination plants installed in beginning of year 't' and thereafter to meet water demand;

$X_{t,s}$ is capacity increment between beginning of period 't' and end of period 's';

$C(X_{t,s})$ is the discounted capital and operating costs for capacity increment '$X_{t,s}$' and is discounted to the beginning of period 't';

$X_{t,T}$ is the total water demand from the beginning of period t to the end of period T;

r is the discount rate; and

$f_s^*(X_{t,T}-X_{t,s})$ is the minimum discounted capital and operating costs for the system to meet demands in year s and thereafter.

All costs in the above equation (3) are discounted to the beginning of year 't'.

Using the backward dynamic programming algorithm, the initial condition is defined as follows:

At period 'T',

$$f_T^*(X_{T,T}) = \text{Min}\ [C(X_{T,T})] = C(X_{T,T}) \qquad (4)$$

Knowing the optimum value at the period 'T', the recursive equation at period T-1 can be written as follows:

$$f_{T-1}^*(X_{T,T}) = \text{Min} \begin{bmatrix} C(X_{T-1,\ T-1}) + (1+r)^{-1} f_T^*\ (X_{T-1,T}X_{T-1,T-1}) \\ \\ C(X_{T-1,T}) \end{bmatrix} \qquad (5)$$

Similarly, the generalized recursive equation at 't' can be expanded using all possible combinations of 's' and 't' in Equation (3).

The capital and operating costs discounted to the beginning of period 't' as a function of plant capacity $X_{t,s}$ are computed using the following algorithm:

1. Capacity $X_{t,s}$ is computed as follows:

$$X_{t,s} = D_s - D_{t-1} \qquad (6)$$

where,

D_s is the total water demand at the end of period 's'; and D is the total water demand up to the beginning of period 't' or the end of period t-1; These demands can be computed using the water forecasting model of

Equation (1).

2. For any desalination process under consideration, the capital cost $C_c(X_{t,s})$ for capacity $X_{t,s}$, is computed using the derived capital cost-capacity relationships. Similarly the annual fixed operating cost, $C_f(X_{t,s})$ is computed using an operating cost-capacity relationship if available, otherwise it may be determined as a percentage of the total capital cost.

3. The variable operating cost $C_v(X_{t,s}U_r)$ depends upon the capacity and the plant usage rate U_r. This rate increases annually for a given plant from period 't' through period 's' and stays constant indefinitely thereafter at the maximum value. Due to lack of data on plant use-rates, this cost component has not been considered separately in the present study.

4. The total discounted cost $C(X_{t,s})$ is computed as follows [8]:

$$C(X_{t,s}) = \left(\frac{1+r}{r}\right) \alpha\, C_c(X_{t,s}) + \sqrt{\frac{1+r}{r}}\, C_f(X_{t,s}) \qquad (7)$$

where,

r is the discount rate

$\alpha = \dfrac{i}{1-(1+i)^{-n}}$ is the amorization factor and is a function of the function of the interest rate 'i' and plant life 'n' years.

ILLUSTRATIVE EXAMPLE

Considering the case of desalination expansion in the western region of the Kingdom of Saudi Arabia (Table 1) for a planning period, T = 10 years, the expansion of desalination to meet the demand in the region is expressed by the following equation:

$$D_t = 201e^{.1246\,t} \qquad (8)$$

where,

D_t = Amount of water to be supplied by desalination in 1000 m^3/day at time t (t=0 at 1399H).

The other factors assumed in this study are: discount rate, r = 10%; interest rate, i = 5%; and plant life n = 20 years.

The cost capacity relationship for the desalination plants installed or proposed in the Kingdom of Saudi Arabia, as given in Equation (2), is rewritted for the period t>s as:

$$C_c(X_{t,s}) = 43200\ (X_{t,s})^{0.751} \qquad (9)$$

where,

$C_c(X_{t,s})$ is the capital cost in SR/m^3/day.

TABLE 5 - CAPACITY INCREMENT $X_{t,s}$ INSTALLED AT THE BEGINNING OF YEAR 't' TO MEET DEMAND THROUGH 's' (THOUSANDS m^3/DAY)

t s	1	2	3	4	5	6	7	8	9	10
1	30	64	103	147	197	253	317	390	472	564
2		34	73	117	167	223	287	359	141	534
3			39	83	133	189	253	325	407	500
4				44	94	150	214	286	368	461
5					50	106	170	242	324	417
6						56	120	193	275	367
7							64	136	218	311
8								72	154	247
9									82	175
10										93

TABLE 6 - THE TOTAL DISCOUNTED COST $C(X_{t,s})$ (MILLION SR)

t s	1	2	3	4	5	6	7	8	9	10
1	1077	1887	2710	3536	4404	5320	6297	7347	8478	9703
2		1183	2089	2977	3886	4833	5841	6915	8067	9312
3			1300	2295	3269	4267	5310	6414	7594	8860
4				1427	2521	3588	4685	5831	7042	8338
5					1568	2768	3941	5145	6400	7735
6						1722	3039	4329	5649	7028
7							1890	3337	4754	6201
8								2075	3663	5220
9									2278	4023
10										2500

$X_{t,s}$ is the capacity in thousand m^3/day.

The average annual operating cost is taken at 24% of the capital cost [12].

Using the above data, the capacity increment, $X_{t,s}$, and the associated total discounted costs $C(X_{t,s})$, are calculated for all possible combinations of t and s (t=1,2,...,10 and s=t, t+1,...,10). These are listed in Tables 5 and 6.

Using the backward dynamic programming optimization algorithm, the minimum discounted cost and the optimum decision for system expansion are determined as follows:

(i) At the end of the planning period T=10, there is only one capacity to be considered, i.e., $X_{10,10}$ or 93,000 m^3/day. The total discounted cost for this capacity is $C(X_{10,10}) = \text{SR } 2500 \times 10^6$.

Hence

$$f^*_{10}(X_{10,10}) = C(X_{10,10}) = 2500 \times 10^6$$

For the 9th year, two alternatives are to be evaluated. These are mathematically represented as follows:

$$f^*_9(X_{9,10}) = \text{Min} \begin{bmatrix} C(X_{9,9}) + (1+r)^{-1}\, f^*_{10}(D^9_{10} - X_{9,9}) \\ C(X_{9,10}) \end{bmatrix}$$

$$= \text{Min} \begin{bmatrix} 2278 + (1.1)^{-1} \times 2500 = 4551 \\ \text{or} \\ 4023 \end{bmatrix} \times 10^6$$

$$f^*_9(X_{9,10}) = 4023 \times 10^6$$

Hence the optimum decision is that a capacity of 175,000 m^3/day should be added at the beginning of year 9 to meet the demand up to the end of year 10. Its associated total discounted cost would be 4023 million Saudi Riyals.

Similarly, using the recurisive relationship of Equation (3), the optimum decisions for years 8,7,...,1 are obtained. Table 7 lists the optimal expansion plan. From this table, the optimum solution for year 1 is the final solution to the present formulation which implies that in order to meet the total demand of 564,000 m^3/day at the end of year 10, the capacity expansion should be done in two stages. In the first stage, it is necessary to install a plant capacity ($X_{1,5}$) in the beginning of year 1 to meet demand through year 5. This capacity is 197,000 m^3/day. In the second stage, it is necessary to install a capacity ($X_{6,10}$) in the beginning of year 6 to meet demand through year 10. This capacity would be 367,000 m^3/day. The total discounted cost for both stages would be 8767 million Saudi Riyals.

TABLE 7 - DYNAMIC PROGRAMMING SOLUTIONS TO OPTIMUM EXPANSION OF DESALINATION PLANTS IN WESTERN REGION

Year t	Optimum Expansion Plan	Discounted Total Cost (Million SR)
10	$f_{10}^{*}(X_{10,10})$	2500
9	$f_{9}^{*}(X_{9,10})$	4023
8	$f_{8}^{*}(X_{8,10})$	5220
7	$f_{7}^{*}(X_{7,10})$	6201
6	$f_{6}^{*}(X_{6,10})$	7028
5	$f_{5}^{*}(X_{5,10})$	7735
4	$f_{4}^{*}(X_{4,7}) + (1+r)^{-4} f_{8}^{*}(X_{8,10})$	8250
3	$f_{3}^{*}(X_{3,6}) + (1+r)^{-4} f_{7}^{*}(X_{7,10})$	8502
2	$f_{2}^{*}(X_{2,6}) + (1+r)^{-5} f_{7}^{*}(X_{7,10})$	8685
1	$f_{1}^{*}(X_{1,5}) + (1+r)^{-5} f_{6}^{*}(X_{6,10})$	8767

CONCLUSIONS

The dynamic programming formulation presented in this study is a useful tool for water resources planners and decision makers in developing an optimal plan for increasing the desalination capacity in a given region over a given period of time and at a minimum cost. This formulation yields optimum capacity increments and the optimum period necessary for the expansion of a given system to meet future demands. Due to rapid industrialization and agricultural developments and also due to improvements in the standard of living, the future water demands in different regions can best be demonstrated by a simple exponential regression model. The criteria for optimization is to minimize the total discounted costs. Although the formulation presented in this study is an attempt towards its application in desalination expansion, it can be modified and applied for optimum conjunctive use of desalinated water along with other feasible water resource alternatives such as available ground and surface waters and water reclaimed from urban wastes. The effectiveness of this methodology in regional water resources planning depends upon the availability of data on capital, and operating costs for each alternative. A multi-decision stochastic dynamic programming optimization model can be formulated and the constraints on supply and demand with time can be defined for optimum water resources expansion.

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