

An ArcGIS Database for Water Supply/Demand Modeling and Management in Abu Dhabi Emirate, UAE

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ABSTRACT

A strategic environmental goal of the Environmental Research and Wildlife Development Agency of Abu Dhabi is a management regime for water resources. The first stage of a programme of development of a water resources management plan includes the compilation of all data and information pertaining to water resources in an ArcGIS – SQL Server database containing supply and demand data and resource monitoring information for all sectors of water use. Demand data relates to water use for domestic, industrial, agricultural, forestry, and amenity purposes. Water sources comprise groundwater, desalinated water, treated wastewater, and water imported to the Emirate. A supply-demand balance model has been developed, linking demand centers to supply sources in order to predict future water shortfalls and surpluses. In this paper the development of the GIS/Database and the supply-demand model, and their use as an important tool for future assessment, monitoring, and management of water resources is described. The developed model was used to predict the future gaps between water demand and supply for any eastern and central regions of Abu Dhabi Emirate up to the year 2020. The results indicated an increase of about 100%, 132%, 136% and 269% in water demand due to future development in, agriculture, forestry, amenity and domestic sectors respectively

Keywords: GIS database, Supply-Demand Modeling, Water Resources Management, Water Demand Centers, Water Supply Sources, Groundwater Management, Abu Dhabi Emirate.

1. Introduction

Water shortages and the degradation of water supplies threaten the development activities and health of people in many parts of the world. This is particularly true in GCC countries that are experiencing rapid population and development growth but have limited water resources and poor water resources management. Water management is the efficient and effective use of the water resource available by minimizing wastage, promoting recycling, and increasing water quality alongside sustainable economic development. Water management is a crucial issue to the survival of humans and all living things in the present era as it is a resource, which is getting scarcer. The amount of water we need and the availability is unbalanced. With proper water management we could minimize the effect of drought and thus famine being faced by developing countries. (perhaps these last two sentences could be removed – is the statement relevant to Abu Dhabi?)

In order to manage water better it is crucial to have an inventory of the water available, how it is being managed, the drainage area (what do you mean by drainage area here?), and the demand and supply of water. GIS has been extremely beneficial in mapping and data analysis, and thus greatly aids in the understanding and decision making involved in water resource management. Linked GIS-databases and water resources supply/demand modelling plays a vital role in providing the detailed information for water resources and demand centres to develop the solutions for improving the efficiency of managing the available water resources. Abu Dhabi Emirate has invested heavily in GIS and asset databases, but until recently these have not been in the field of water resources management and modelling. A GIS-water database together with an integral supply/demand model (SDM) has now been developed by the Environmental Research and Wildlife Development Agency (ERWDA), to provide decision makers with good quality, timely and reliable data.. A well designed GIS database can significantly reduce the time needed for data preparation and presentation during the modeling process. Recently, the use of GIS has grown rapidly in water resources assessment and management. The use of GIS in water management modeling is still at an early stage, but some successful applications have already been developed such as Maidment (1994), Fedra (1994 and 1995), Furst (2001), Kharad et al (2002), Sarma and Saraf (2002), Singh and Prakash (2003), and others.

The ability to link GIS to water supply/demand models can also provide a useful tool, enabling rapid and accurate prediction for future water management and planning scenarios. Simulation for future water management and planning scenarios allow decision makers to estimate the required investments in the water sector without disrupting supply or affecting the progress in the various development sectors due to any unpredicted gaps in water resources (Ali et al., 2003).

Recently many researchers have concentrated on using GIS technology in mapping and data analysis, thus greatly aiding in the understanding and decision making in water resource management (Tremblay et al., 1994). Schultz (2000) discussed the use of Arc-GIS as a tool for water resources management through producing digital maps and digital elevation models which can be processed together with remote sensing and other data within GIS databases thus increasing the potential for working with multi-temporal imagery (what do you mean by this?). Also he discussed how the combination of remote sensing with other information leads to new data types that allow integrated planning of water resources systems.

This current study is being undertaken to determine the water availability and demand in various development sectors. The main objectives of this study are:

- to develop an understanding, on a regional basis, of the relationship between the available water resources in the eastern and central regions, with an extension to cover the whole Abu Dhabi Emirate at a later stage.
- to develop projections of water supply and demand, including water demand for domestic, agriculture, forestry and industrial/commercial sectors, and the implications of inter-sectoral competition for water on the development in these sectors
- to analyze the future alternatives for water supply and demand taking into account all the factors affecting the increase in water demand
- based on this analysis, to assess the impact of alternative water availability scenarios on water demand, taking into account policy reforms and investments in water and irrigation management.

Since the mid 1960s, the Emirate of Abu Dhabi has undergone major development, underpinned by large oil revenues and the commitment of the former ruler Sheikh Zayed to agriculture and to policy of 'greening of the desert'. Pre-development, a small population relied entirely upon groundwater within superficial aquifers. In the east of the Emirate, fresh groundwater was exploited by shallow wells and by natural aflaj, for potable use and for traditional oasis agriculture; westwards, the aquifer contained brackish to saline groundwater. At that time, total abstraction did not exceed 200 Mm³/y (including falaj flows) of which agriculture consumed 163Mm³/y and forestry, less than 1 Mm³/y (USGS, 1996). By contrast, year 2002 water use is estimated at over 3200 Mm³/y (ERWDA, 2002). Reasons for this enormous increase in demand are:

- a very high per-capita potable water consumption. Potable demand is increasing by 8%pa concurrently with a 6%pa population growth;
- continued expansion in the area under irrigation, comprising amenity planting, forestry and agriculture farms;
- few, if any constraints on water use.

Demand now far exceeds the capacity of the superficial aquifer and Abu Dhabi must increasingly use new water sources, specifically desalinated Gulf seawater and desalinated water imported from Fujairah on the Gulf of Oman. Development has led to environmental concerns in particular the local over-abstraction from the superficial aquifer, aquifer Stalinization?? salinisation and possible aquifer contamination from chemicals used in the agriculture sector. The proliferation of desalination plants along the Gulf, and the Emirates increasing reliance upon desalination, leads to both environmental and supply security concerns.

In order to accomplish the research objectives, a water supply demand model has been developed that attempts to project and analyze how water availability and demand evolve over the next two decades (from a base year of 2000), taking into account the availability and variability in water resources, water supply infrastructure, and irrigation and non-agricultural water demands, as well as the impact of alternative water policies and investments on water supply and demand. The developed GIS-database and SDM allow ERWDA to store and interrogate water resource data,

and to model and test existing and future water demand and water supply scenarios, and to contribute towards water policy formulation and the sustainable management of water resources.

2. Location of Study Area

The location of the project area is shown in Figure (1). It comprises the Eastern & Central Regions of Abu Dhabi and is bounded by the Dubai Emirate in the north, by the Oman border in the east, and by the Saudi Arabian border in the south. The study area is both under the jurisdiction of the Al Ain Municipality (Eastern region including Al Ain City) and the Abu Dhabi Municipality (Central Region including Abu Dhabi City).

3. Water Supply Sources

3.1 Groundwater

The superficial aquifer contains freshwater storage in the east of the Emirate while elsewhere, it contains brackish to saline groundwater. No regionally significant deep freshwater aquifers are known. The freshwater storage has long been over-exploited in particular by potable water wellfields in the region of Al Ain; its use is increasingly constrained by falling well yields and increases in salinity. Brackish to saline groundwater is found in the shallow aquifer through much of the Emirate, and it is utilized for almost all irrigation of farms and forest. In the eastern Region of Abu Dhabi, year 2002 farm well surveys (Mott MacDonald, 2004) show that agriculture is irrigated with mostly brackish water; of over 24000 farm wells sampled, 65% of wells have water of EC more than 6000 $\mu\text{S}/\text{cm}$ while in some areas forests are irrigated with groundwater exceeding 30,000 $\mu\text{S}/\text{cm}$. This use of brackish-saline groundwater in farm and forest irrigation leads to increasing difficulties in soil/salt management, crop yield reduction and constraints on tree growth. Continued expansion of agriculture and forestry may require the introduction of desalinated water into the irrigation systems yet to do so will clearly involve major infrastructure costs and government policy support. The total groundwater production from the eastern and central regions is about 1430 Mm^3/y .

3.2 Treated Sewage Effluent

The total treated sewage effluent production is currently about 87.3 Mm^3/y and this is all used in the irrigation of amenity and road verges plantations both in the cities and along major highways (ERWDA, 2002). USGS (1995) provided figures for TSE discharge at Al Ain up to 1994, starting in 1982. From 1995, TSE quantities were based on actual outputs for 2002 and assumed upgrades to the sewage treatment works in 2006, 2015 and 2020.

Figure 1: General Location Map for the Study Area.

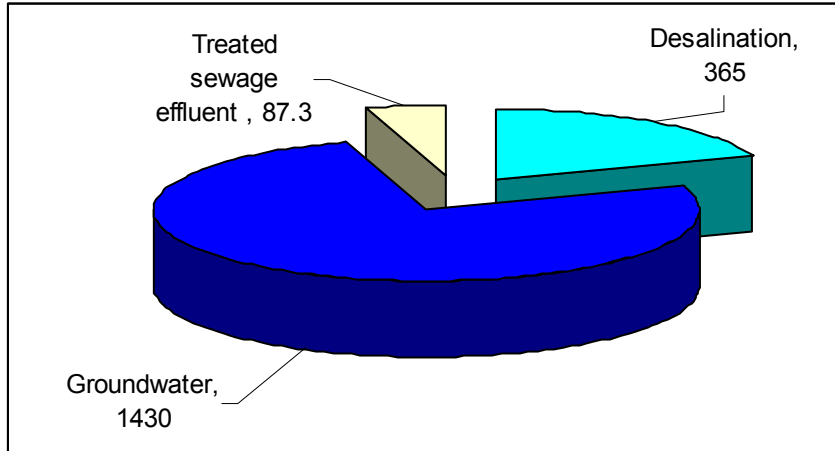


3.3 Seawater Desalination & Imports

The total desalinated water use in the eastern and central regions is about 365.0 Mm³/y out of this quantity about 132.4 Mm³/y (please check this figure – this water began flowing only in 2003 and only 6 Mm³/yr was delivered then I think only slightly more was delivered in 2004 is

imported from Fujairah plant to Al Ain City. Desalinated seawater is largely used for domestic supplies and its current use in farming is limited. Potable water supply deficits in Al Ain will shortly be alleviated with desalinated supplies to be piped from the Fujairah I desalination plant (effectively imports to the area). Figure (2) presents the current water resources in the study area.

Figure 2: Available Water Resources in the Study Area.



4. Demands for Water

4.1 Domestic Demand

Domestic demand is determined from population and per-capita water consumption, both specified for individual years of the simulation period. Bulk demand for industries is not included as a separate demand centre but is located within the respective settlement and is specified as a daily rate for individual years as a bulk demand. Per capita demand is specified in l/d and demand is thus derived from:

$$DWS = POP * PCD * 10^{-6} + BULK \quad (1)$$

Where:

- DWS : requested demand for water supply [tcmd]
- POP : population
- PCD : per capita daily gross water need [l/d]
- BULK : bulk demand [tcmd]

Demand constraints relate to the capacity of the water supply distribution and storage system to deliver the requested demand to the customers. This constraint is expressed as a value [tcmd] for the years of the simulation period. It is normally equal the design capacity of the distribution and storage system. Table (1) illustrates the data specification. Current consumption in the domestic sector in the eastern and central regions is estimated at 450 Mm³/y (ERWDA, 2002). Per capita consumption is very high by world standards, between 300-500 litter/capita/day (ADWEA, 2001). Unmetered or illegal use and wastage can locally increase consumption to 2000-5000 litter/capita/day. The SDM will allow future policy options, where this level of consumption is constrained by engineering, metering or price measures, to be tested.

Table 1: Overview of Demand and Supply used in the SDM

Demands		
Demand Centre	Determination of Use	Remarks
Settlements	Domestic demand determined from population and per-capita consumption. Bulk demand is determined as a daily average quantity	Links to treated sewage effluent are defined
Amenity	Gross demand is determined from water requirements for a mix of trees and groundcover vegetation, taking account of irrigation efficiency	Amenity is normally supplied from treated sewage effluent supply sources
Agriculture	Water use for different vegetation classes (representing up to three crop mixes) is based on net requirements, cropped area and irrigation efficiency and is amalgamated for individual farm units into Agriculture demand centers	Irrigated from groundwater sources but desalinated water is being introduced.
Forestry	Individual forest areas are grouped into forestry demand centers. Demand is based on forest water requirement, taking into consideration the maturity of forest trees and the efficiency of irrigation.	Irrigated from groundwater sources although use of desalination water may occur in future
Industry	Demand depends on the nature of the industry and its size. Demands are specified as average daily quantity for individual years	Sources of water include groundwater and desalination water
Supplies		
Supply Source	Determination of Use	Remarks
Groundwater	The supply source is defined as a group of individual wells (a wellfield). Installed capacity determines maximum output, while actual output is controlled by demand and by constraints described above.	Wellfields serve Settlement, Agriculture and Forestry demand centres
Desalination	The design capacity of desalination plant(s) are user specified. Design capacity is constraint by age, while water delivery to demand centres may be reduced by leakage from conveyance systems	Individual desalination plants may be grouped into one supply source
TREATED SEWAGE EFFLUENT	The maximum output from a sewage treatment works is determined by its design capacity. Actual output is a function of sewage input and treatment process	Input to sewage treatment works is linked to Settlement water use
Imports	Import capacity is user specified for individual years	

4.2 Amenity

Amenity areas include parks, golf courses, road verges and central reservations. They comprise a mixture of trees and groundcover vegetation (grasses and flowers). In many cases these areas are irrigated with tertiary treated sewage effluent supplied from sewage treatment works. Demand is determined from net vegetated area, from the mix of trees and groundcover vegetation, from the crop water requirement (crop and climate dependent), the efficiency of irrigation and the extent of 'under irrigation'. The latter represents the moisture stress imposed on the vegetation and reduces crop consumptive use. The demand is calculated as follows:

$$DA = NAA * (PT * CUT + (100 - PT) * CUG) * (0.0001 / eff) \quad (2)$$

Where:

DA	:	demand for amenity area [tcmd]
NAA	:	net irrigated are [ha]
PT	:	percentage of net area covered by trees
CUT	:	net water requirement for trees [mm/d]
CUG	:	net water requirement for groundcover vegetation [mm/d]
eff	:	irrigation efficiency

Current consumption in amenity, parks, road verges, and gardens in eastern and central regions is estimated at 219 Mm³/y (ERWDA, 2002).

4.3 Agriculture

The water requirements for farm demand canter are calculated in a similar manner to forest areas, except that more crops are considered. From net crop consumptive use of individual crops, percentages of the crops within a crop mix and irrigation efficiency, the gross water requirement follows from:

$$DAG = \Sigma\{Max(0, \Sigma[(Q_{net} * p) * Area * (0.01 / eff)]\} \quad (3)$$

Where:

DAG	:	farm water demand as summation of individual farm units [tcmd]
Q _{net}	:	net irrigation requirement for individual crop [mm/d]
p	:	percentage of crop within crop mix [%]
Area	:	area of farm unit [ha]
eff	:	irrigation efficiency [%]

Up to three crops are allowed for each crop mix, with percentages of individual crops defined for each crop mix. In the last 35 years, there has been a major expansion in agriculture principally through development of non-traditional new farms or Citizens Farms. Over 72000 ha of farms are estimated to consume 1692 Mm³/y or 61% of all water used in the Emirate, a 345 % increase on 1994 estimates (ERWDA, 2002 and Mott MacDonald, 2004). Water use is unregulated although it may be constrained by aquifer capacity.

4.4 Forestry

The water requirement for forests depends on the following:

- Area of trees cover (digitised from Landsat imagery)
- Net consumptive use of trees, depending on climatic factors, species and maturity of trees
- Gross irrigation requirement, which depends on:
 - Net consumptive use

- Irrigation efficiency, which is a function of irrigation technique, frequency of irrigation, soil properties, leaching requirements, etc.

The net crop water requirement is specified as a function of maturity as follows:

$$DF = \Sigma(\text{Max}\{f1, \text{Min}[(\text{year}_i - \text{year}_0) / N] * Q_{fmax}\} * \text{Area} * 0.01 / \text{eff}) \quad (4)$$

Where

DF	:	forest water demand as summation of individual forest units [tcmd]
f1	:	factor determining minimum water requirement at early stage of forest
Q _{fmax}	:	net irrigation requirement for mature forest [mm/d]
year _i	:	year for which gross water requirement is calculated
year ₀	:	year when forest was planted
N	:	number of years when maturity is reached
Area	:	area of farm unit [ha]
eff	:	irrigation efficiency [%]

The demand for a forest unit is zero for years prior to year of first planting.

In the SDM only area and gross irrigation requirement is specified, both as annual values for each forest demand centre. This is necessary to accommodate both forest expansion and the variability of the factors controlling gross water requirement. Irrigated forest plantations have expanded from less than 250 ha in 1969 to over 250,000 ha at present, under a national policy of ‘greening the desert’. The forests in eastern and central regions are estimated to consume over 124 Mm³/y (ERWDA, 2002).

5. GIS Database Development

5.1 Design and Structure

The database design incorporates:

- Input of water related non-geographical or attribute data (such as names, designations, entity types and data specific to that entity. Entities considered include, for example, wellfield and borehole sources and a discrete irrigated area with a water demand).
- Input of water related time-series data for these entities (such as well water levels or demand changes in response to a changing population). All water-resource specific entities have a time component, which allows water demands and supplies to vary over the study period adopted.
- Links with the ArcGIS to allow the spatial attributes of the entity (geographical position, shape etc), to be linked with attribute data for that entity.
- The means to represent links and link-constraints (typically pipeline conveyance systems) between water sources and water demand centres.
- User selection of specific supply sources and demands, and also the ability to allow some supplies and demands (e.g. forests and farms) to be grouped into larger groups (e.g. forestry and agriculture), for ease of manipulation in the SDM.

- User selection of Global Settings, used within the SDM to calculate water use by irrigated crops, forest and amenity planting. These include farm/forest type defined by cropping/planting pattern, crop/tree water requirement and irrigation efficiencies.
- Output screens.

The overall structure and data flows across the Database-GIS are shown in Figure (3). Information held in the database is employed within the SDM and the database structure essentially mirrors the SDM whose structure is shown in Figure (4). Table (1) provides an overview of demand and supply incorporated in the model. The objectives of water demand and supply balance modelling are twofold, namely (a) to assess the current status of supply sources and demand centers, in terms of their current capacity to supply water (sources) and their current requirements for water (demand centers) and (b) to provide a planning tool to allow rapid judgment of the future impacts of changes in supplies and demands on the supply/demand balance.

Supply sources include groundwater, desalinated water and treated sewage effluent. *Demand centers* are user-defined areas of defined type that require a quantified supply of water of a required quality from linked supply sources. The demand centers included are listed in Section 3. For the chosen assessment area, supply to demand links are defined, generally on the basis of the existing or planned conveyance systems.

5.2 Rules and Constraints related to the SDM

The following rules and constraints are built within the database and the SDM:

- The SDM uses yearly time steps with both supply and demand quantities expressed as average daily totals for the respective years.
- There are constraints associated with the links between supply sources and demand centers. For example, treated sewage effluent supply sources cannot be linked with Settlement, Industry and Agriculture demand centers.
- Constraints can be attached to both demand centers and supply sources. They may, for example, include the capacity of a distribution/storage network in a Settlement demand centre (constraint linked to the demand centre), or the reduction in output from a Wellfield when brackish groundwater requires desalination (constraint linked to the supply source).
- Constraints may, in reality, also relate to transmission facilities between supply sources and demand centers. Wherever possible, however, these constraints are linked to either demand centers or supply sources. Constraints are summarized in Table (2).

5.3 Model Output

The content of a SDM scenario output screen is user specified; typically it will comprise a GIS map of the supply sources and demand centers examined in the scenario, tabulated results and a graphical output summarizing forecast supply-demand variations over the chosen time period. Figure (5) displays the results of a modeled scenario for a demand centre, the city of Al Ain. The figure is annotated to show the salient features of model output. A priority can be assigned to

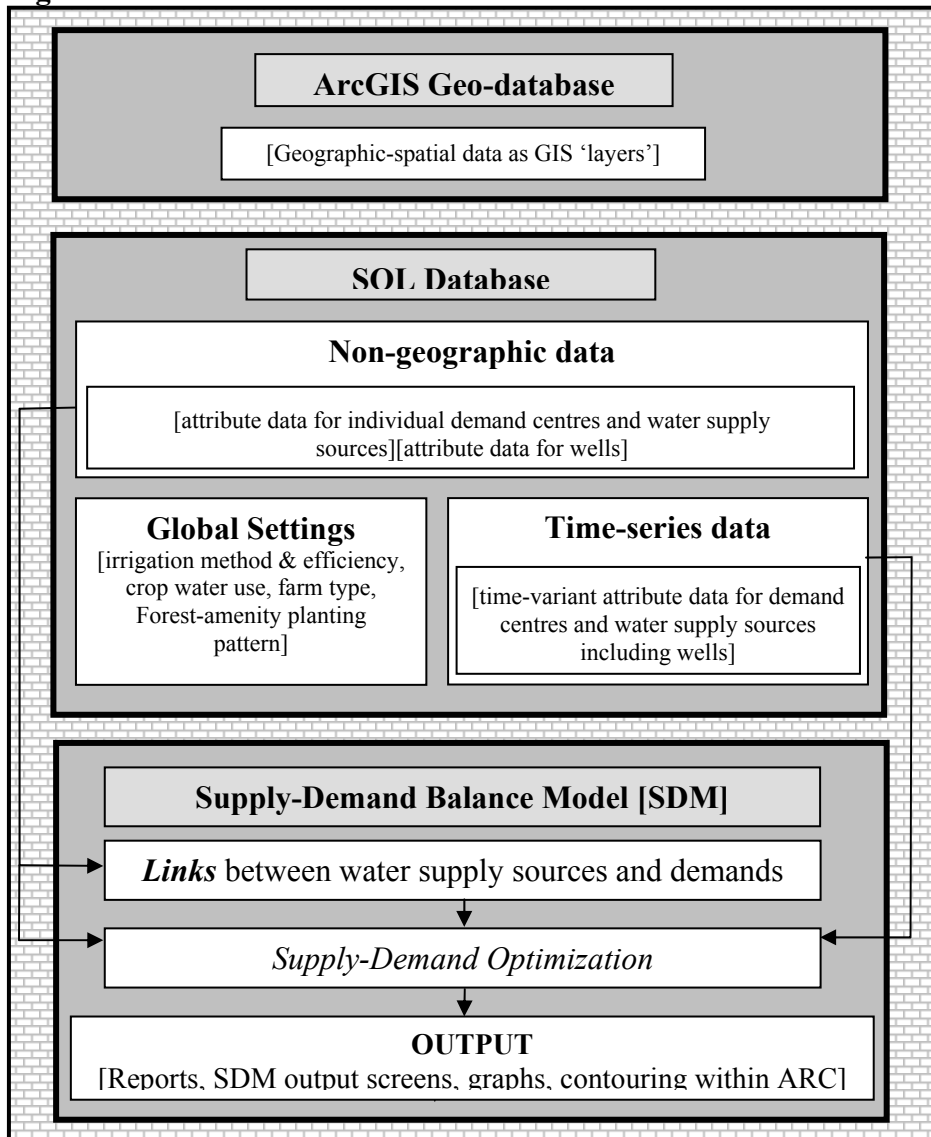
demand centers and this affects the allocation of water from linked supply sources. The concept of prioritization is illustrated in Table (3).

Table 2: Demand/Supply Constraints

Demand Centre	Potential Constraints	Remarks
Settlement	Distribution and storage network	It is likely that the distribution network and storage facilities have been designed to a specified capacity.
Supply Source	Potential Constraints	Remarks
Groundwater	Pump capacity	Output cannot be more than the capacity of the pumps.
	Q/h relationships	Pump capacity (Q) is a function of pumping head (h) and generally reduces when the pumping head increases.
	Groundwater levels	Groundwater levels directly affect the pumping head. If levels continue to drop, the pumping level in the well may drop below the intake level of the pump, thus reducing output.
	Water quality	Water quality may constrain the use of the water for certain purposes or require treatment, thus losing output in the process.
	Environmental constraints	These could include groundwater level constraints related to environmentally sensitive areas.
Sewage Treatment Works	Treatment capacity	Output cannot exceed the treatment capacity of the works.
	Wastewater supply	Output is constrained by the quantity of wastewater supplied.
Desalination Plants	Treatment capacity	
Imports		Imports relate to water supply from outside the project area

The example indicates an Al Ain requirement of 409 tcmd in 2002, although this is constrained by the capacity of distribution system to 300 tcmd. Demand is met from five supply sources (two wellfields, 2 desalination plants and imports from Fujairah). In 2002 and 2003, a supply deficit is evident while desalinated water import from Fujairah contributes to a notional oversupply for year 2004. The contribution of groundwater from the Al Ain wellfields is shown to reduce to zero over the period 2002 to 2007, as desalinated water replaces problematic wellfield sources. The deficits and oversupplies can be minimized by use of the SDM optimization routine or by manual intervention by reallocation of supply. The increase in constrained demand (to 500 tcmd in 2004) reflects distribution system improvements.

Figure 3: Database-GIS Structure



6. Model Application

The model has been applied to estimate the water demand for eastern and central regions of Abu Dhabi Emirate by year 2020. Table (4) shows the modeled results for year 2002, 2010, 2015 and 2020. The results indicated an increase of about 100%, 132%, 136% and 269% in water demand due to future development in, agriculture, forestry, amenity and domestic sectors respectively. This increase in water demand will increase the pressure for using the desalination water in agriculture and amenity sectors, possibly blended with existing brackish groundwater. The increase in amenity planting water demand can be met from expansion in TSE output.

Figure 4: SDM Design Concept

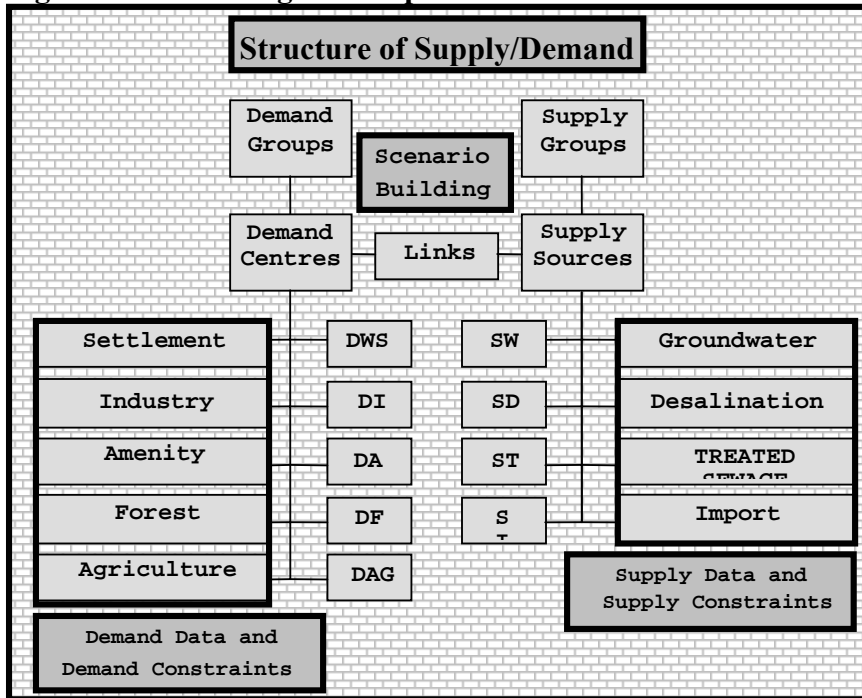


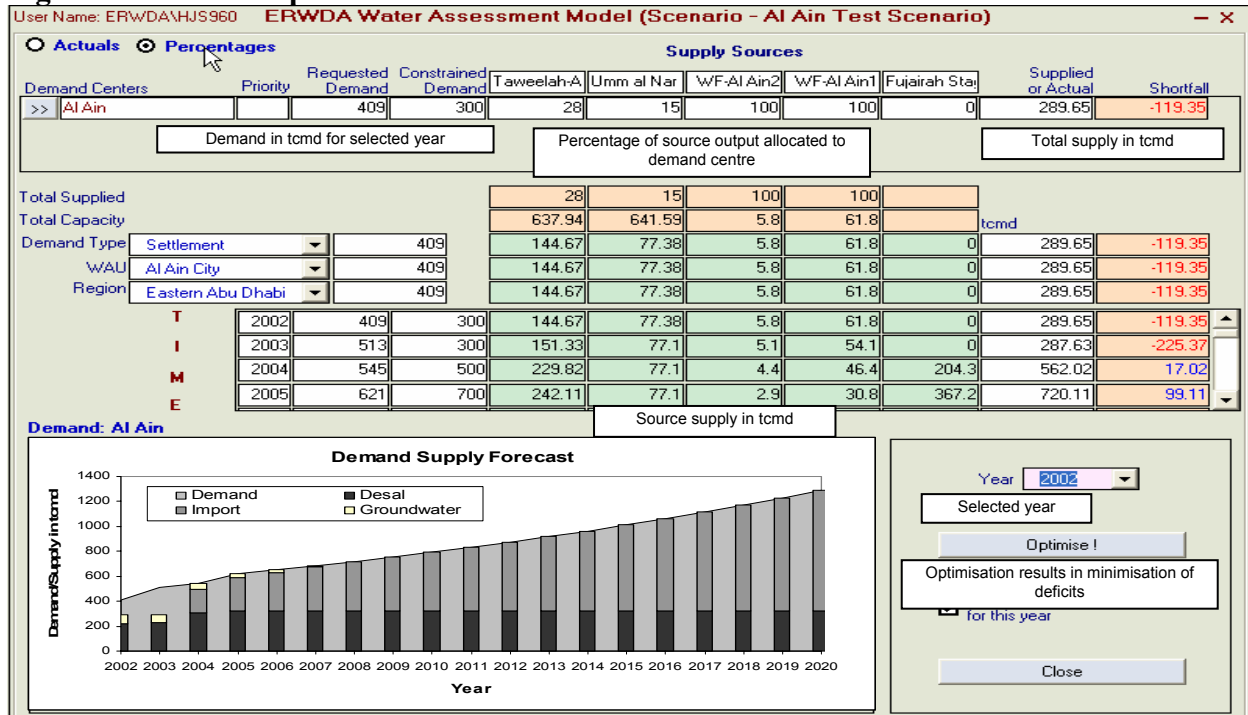
Table 3: Example of Priority Rules

	Without priority				With priority			
	Constrained supply equals 300 tcmd							
Demand	Priority	Demand	Supply	Deficit	Priority	Demand	Supply	Deficit
D1	1	200	171	29	1	200	200	0
D2	1	100	86	14	2	100	67	33
D3	1	50	43	7	2	50	33	17
Total		350	300	50		350	300	50

Table 4: Modeled Increase in Water Demand for the Eastern and Central Regions of Abu Dhabi Emirate by year 2020.

Year	2002			2010	2015	2020		
Sector	Area [ha]	Present	Groundwater	Predicted	Predicted	Area [ha]	Predicted	Groundwater
		Use [Mm3y]	Pumpage [Mm3y]	Use [Mm3y]	Use [Mm3y]		Use [Mm3y]	Pumpage [Mm3y]
Agriculture:	59,807	1,692	1,430	2,453	2,728	130,050	3,385	1,310
Forestry:	59,000	124	115	211	250	112,000	288	139
Amenity	6,480	219	57	344	423	15,320	518	57
Domestic	n/a	451	22	772	1,135	n/a	1667	0
Totals	125,287	2,486	1,624	3,780	4,536	257,370	5,858	1,506

Figure 5: Model Output Screen



7. Conclusions

The Database-GIS and SDM was developed in the period 2002-2004. ERWDA use this tool in resource data acquisition and assessment, resource modelling and the development of a water resources strategic management plan for Abu Dhabi. Despite major development over the last 35 years, little systematic collection of resource data has occurred; in particular, very little is known of irrigation water use yet over 70% of water use is by the agriculture and forestry sector. The assumptions embedded in the system (in particular the Global Settings) will demand revision by ERWDA as data improves. Nevertheless, the tool is flexible and will allow any rational supply-demand scenario to be tested. System use, and calibration with reliable data, will inevitably point to data uncertainty and elements which need field investigation and measurement.

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Annex 1: List of Acronyms and Abbreviations

ADWEA:	Abu Dhabi Water & Electric Authority
EC	: electrical conductivity
ERWDA:	Environmental Research and Wildlife Development Agency
GIS	: geographical information system
Ha	: hectare
lcd	: litter/capita/day
Mm3/y	: million cubic meters per year
SDM	: supply-demand model
tcmd	: thousand cube meters per day

TSE : treated sewage effluent
USGS : United State Geological Survey